Structural Health Monitoring of Civil Infrastructure:

from Research to Engineering Practice

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Outline

- ◇ Background and Motivation
- ◇ Enabling Wireless Smart Sensor Technology
  - ☐ High-fidelity Hardware
  - ☐ Service-oriented Software Framework
- ◇ Full-scale Implementations
- ◇ Future Directions
- ◇ Conclusions

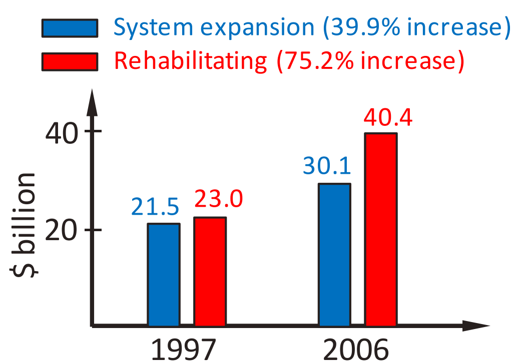
Why Monitor Infrastructure?

❑ 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

Fatigue (Bay Bridge in CA, 2009)



Capital investment (US DOT 2008)

Sung-su bridge collapse in Korea (1994)

I-35 bridge collapse in MN (2007)

Why Monitor Infrastructure?

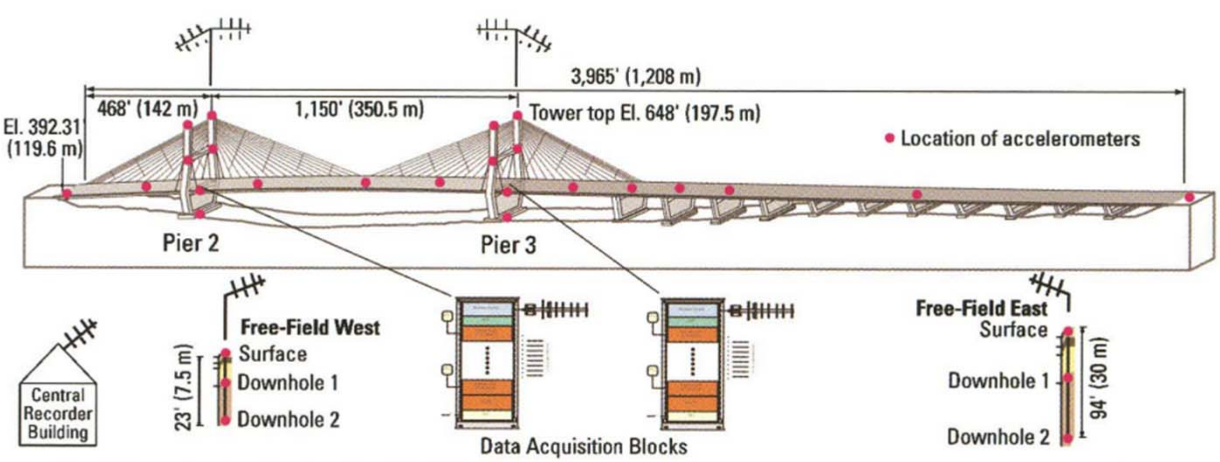
- To validate the structural designs and characterize performance (e.g., develop database)
- To assist with infrastructure maintenance
- To design appropriate retrofit measures
- Improve seismic risk assessment
- To monitor and control the construction process
- To characterize loads in situ
- Assess 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

Cabling & instrumentation for 400 wired strain sensors



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

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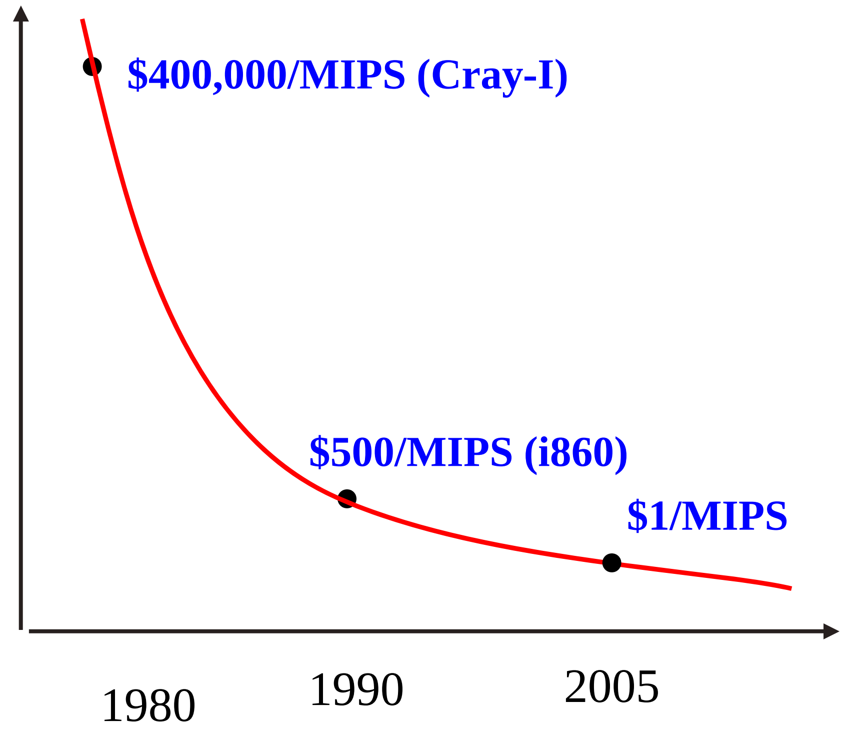
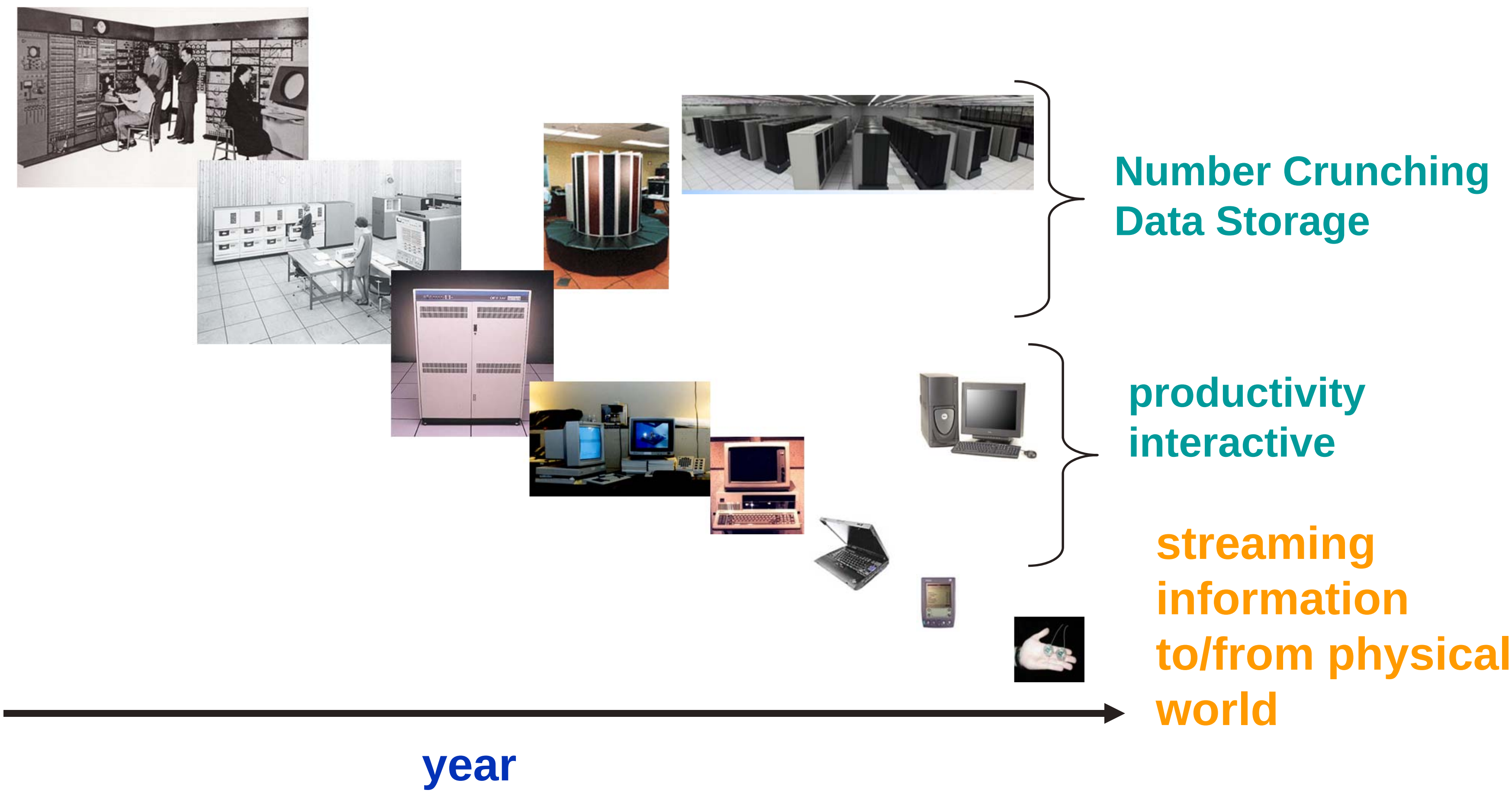
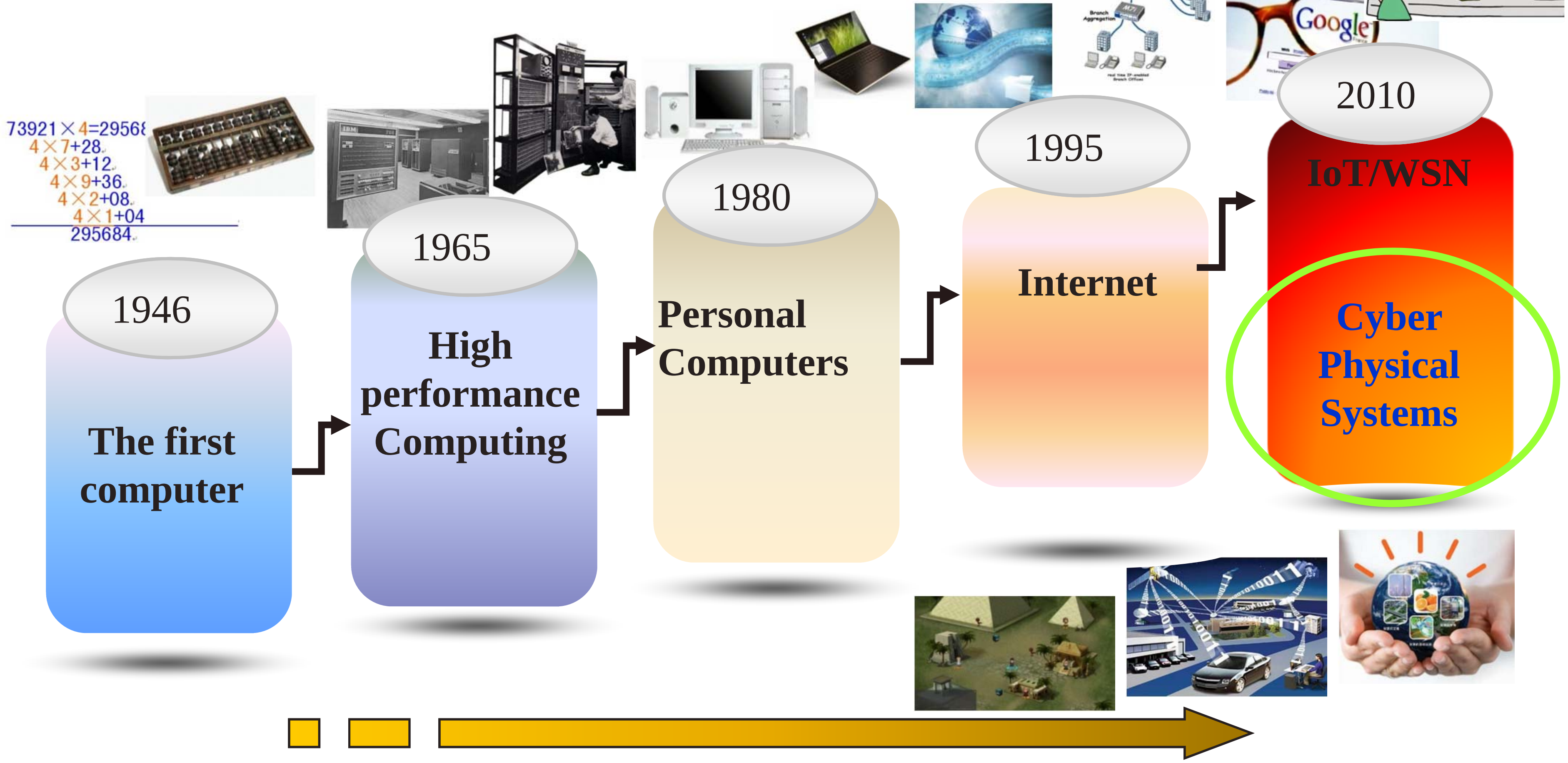
Computers are Faster and Cheaper



Where Computing is Done



Networking Plays an Important Role

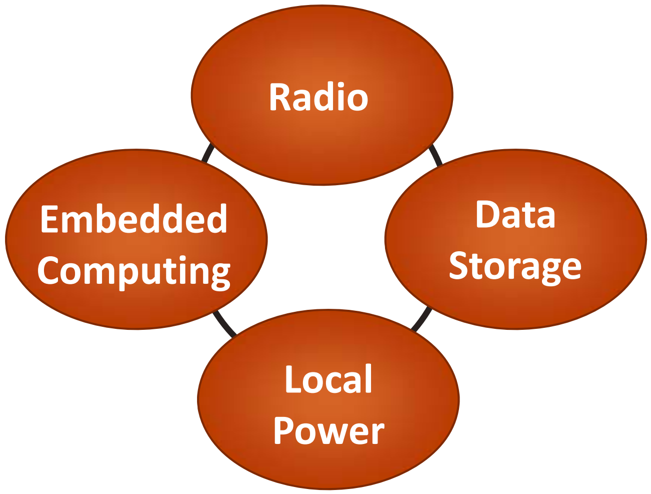


Vision of the Future: *Internet of Things*

- 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

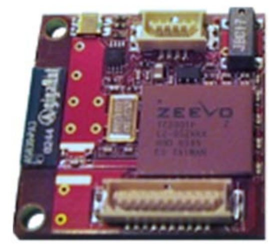
WINS 1 (1999)

SmartDust
WeC (1999)

BTnode rev3 (2004)

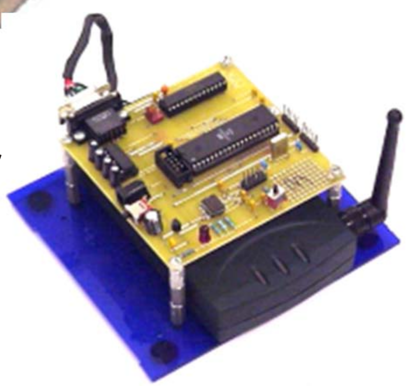
U3 (2002)

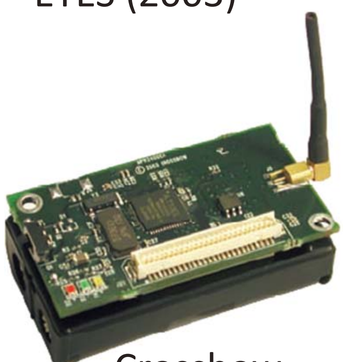
EYES (2003)



Intel Imote (2004)

Prototype by
Prof. Lynch
(2002)





Crossbow
Mica2 (2004)

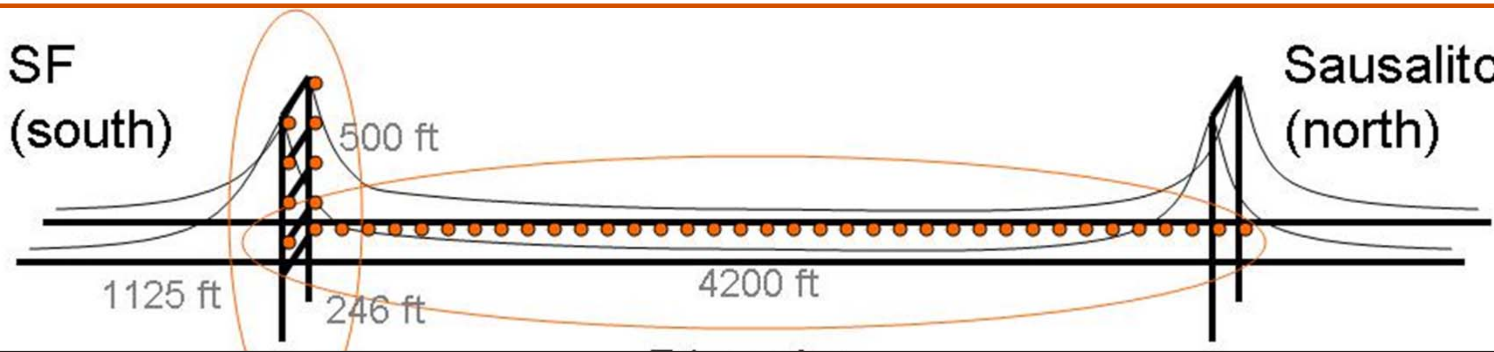
Imote2 (2006)

Full-scale Implementations to Bridges (selected)

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

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)

Implementation	*Purpose*	*Sensor Platform*	*# of Nodes*	*Sensor (channels)*	*Test duration*	*In-network Processing*	*Results*
Stork (Meyer *et al*. 2010)	Validation of long-term field test using wireless sensor network	Tmote Sky	**6**	Accel. (6)	**Long-term**	**None**	Cable tension force
Ferriby Road (Hoult *et al*. 2010)	Evaluation of the potential of wireless sensor network	MicaZ	**7**	Crack (3) Inclin. (3) Temp (7) Humid.(6)	**Long-term**	**None**	Crack growth and inclination of deck
New Carquinez (Lynch *et al*. 2010)	Wireless system proof-of-concept	Narada/ Imote2	**30**	Accel. (14)	**Long-term**	**SSI Modal Analysis**	Mode Shapes

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

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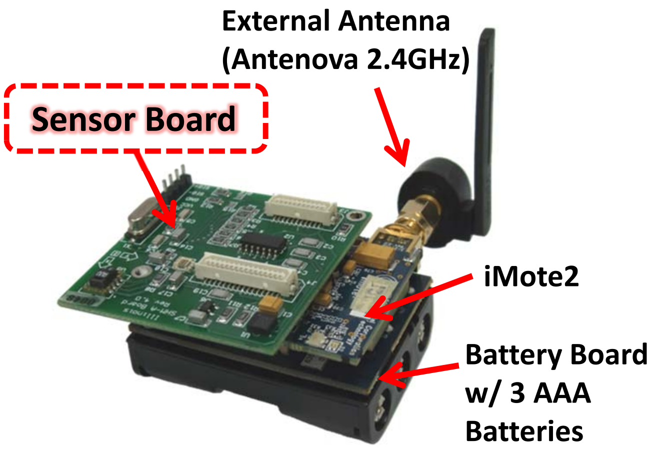
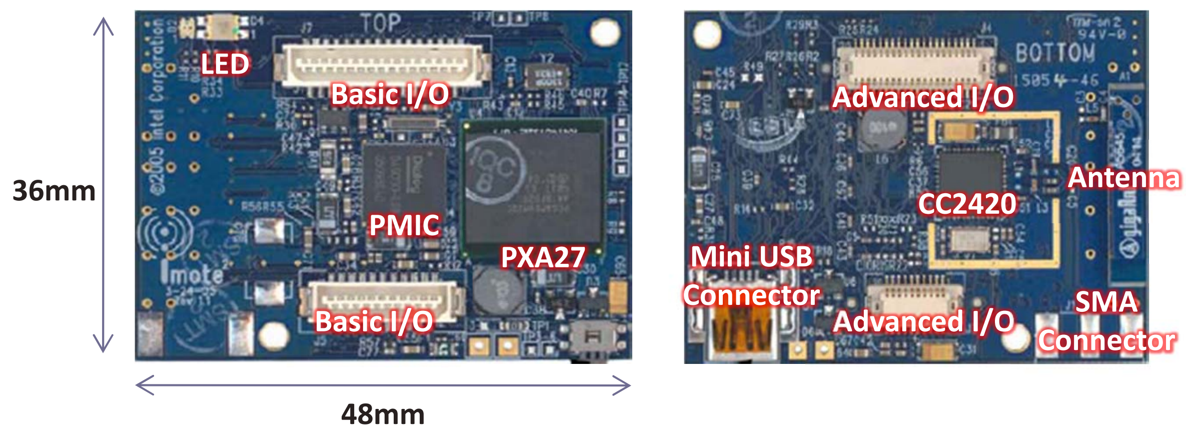
Imote2 with Sensor Boards



From MEMSIC (2010)

	MicaZ	Telos	iMote2
Microprocessor	Atmel ATmega128L	TI MSP430	Intel XScalePXA271
Clock speed (MHz)	7.373	8	**13-412**
Active Power (mW)	24	10	**44 @ 13 MHz**
Non-volatile memory (bytes)	128 K (Flash) + 512 K (EEPROM)	48K (Flash)	**32 M (Flash)**
Volatile memory (bytes)	4 K	1024K	**256 K + 32 M (SDRAM)**
Dimensions (mm) / Weight (g)	58*32*7 / 18	65*31*6 / 23	36 *48*9 / 12

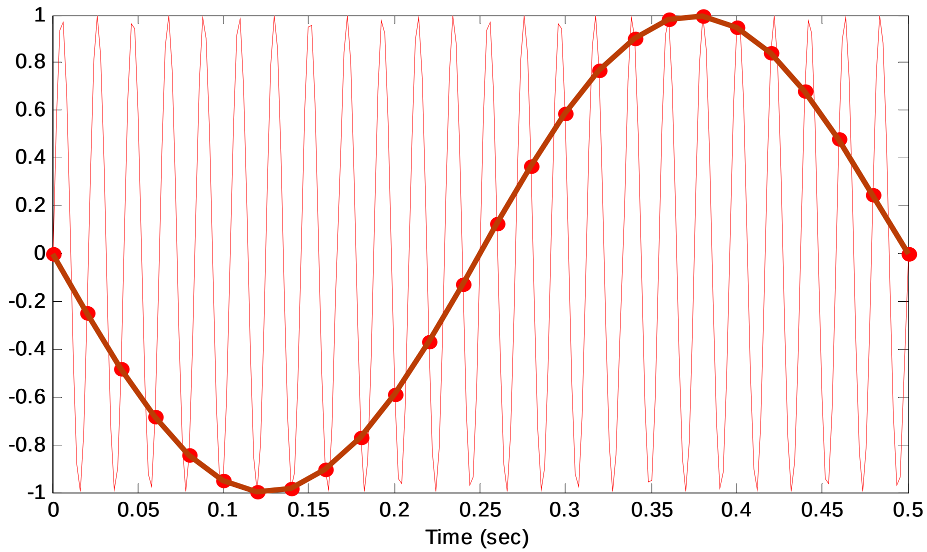
Imote2 and Basic Sensor Board



Imote2: Top and Bottom

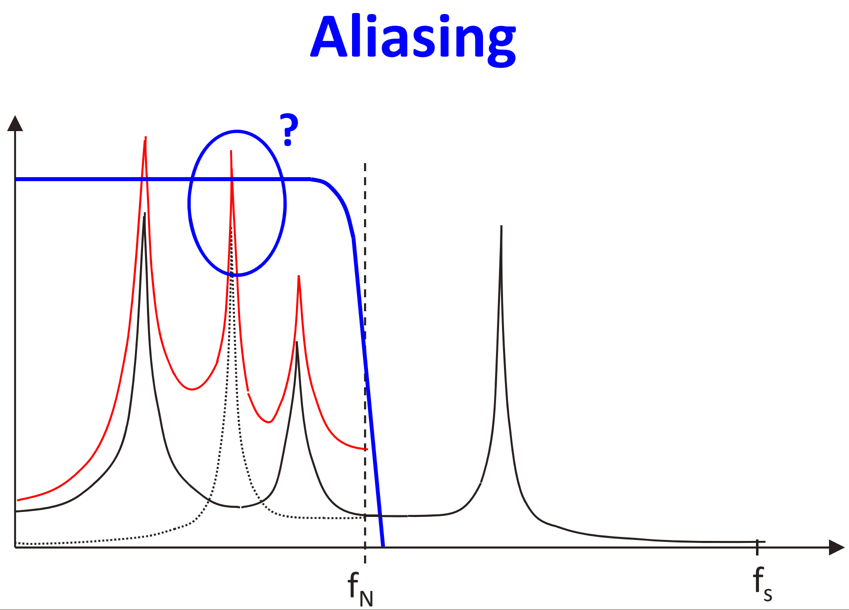
Basic Sensor Board

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



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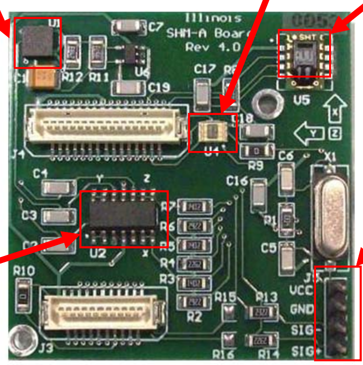
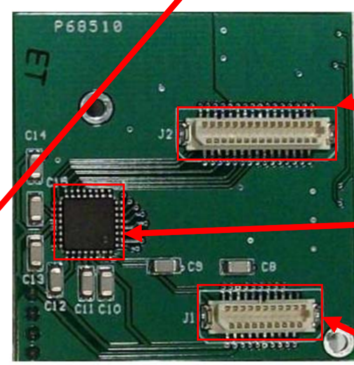
Multifunctional Sensor Boards

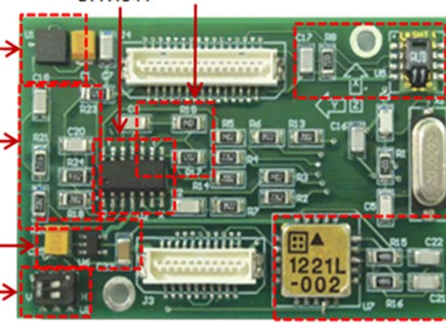
SHM-A and SHM-H Board



SHM-A Board (top)



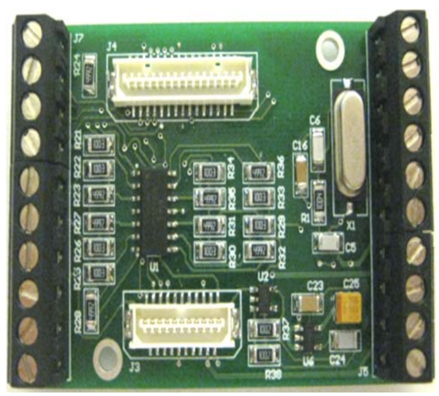
SHM-A Board (bottom)



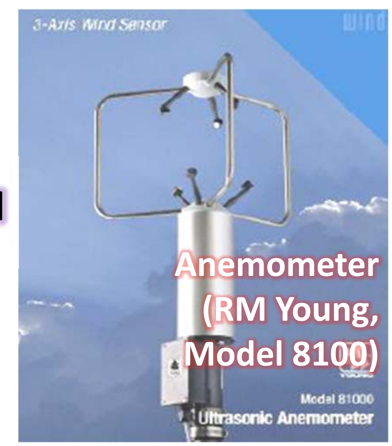
SHM-H Board

SHM-DAQ Board

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

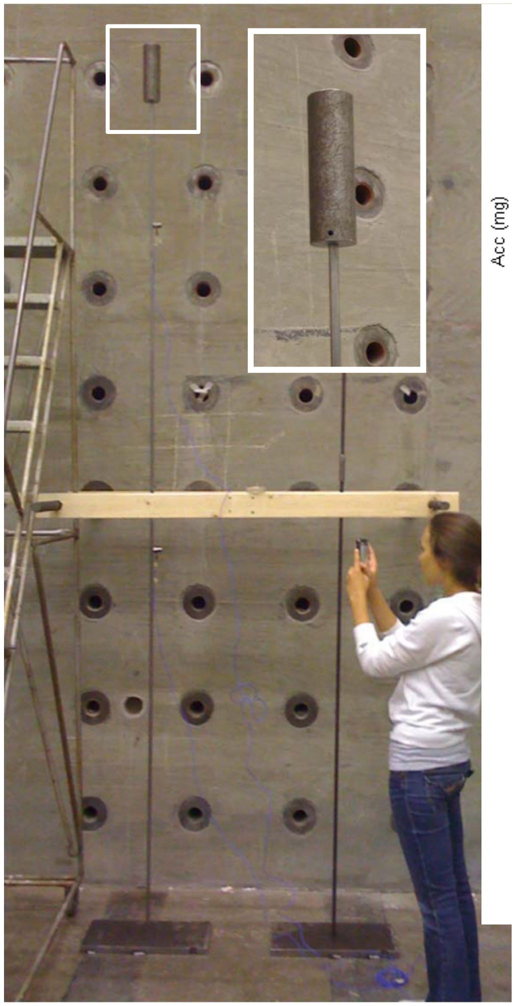


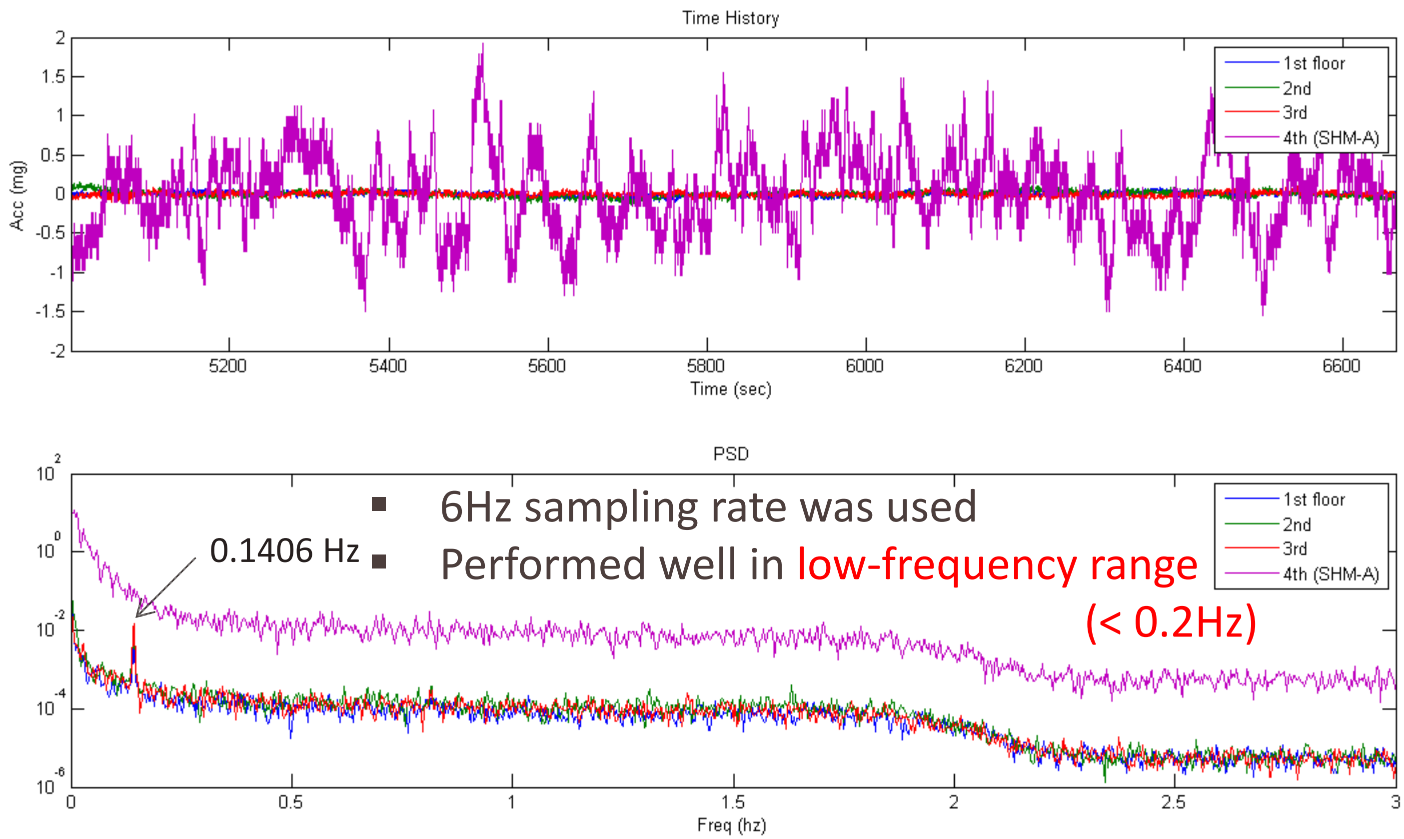
Interfaced
Voltage



High-sensitivity Accelerometer board (SHM-H board)

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





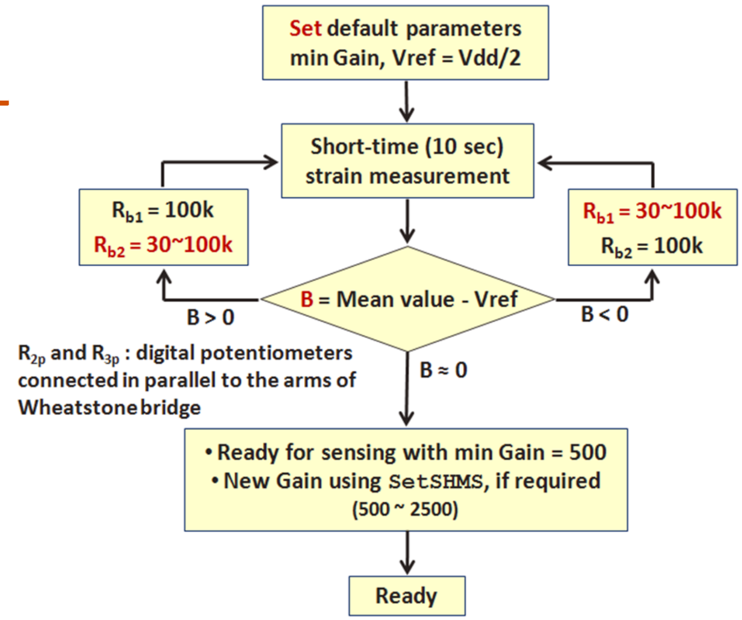
- 6Hz sampling rate was used
- Performed well in low-frequency range (< 0.2Hz)

FE analysis (1~3th freq.): 0.14Hz, 4.42Hz, 14.57Hz

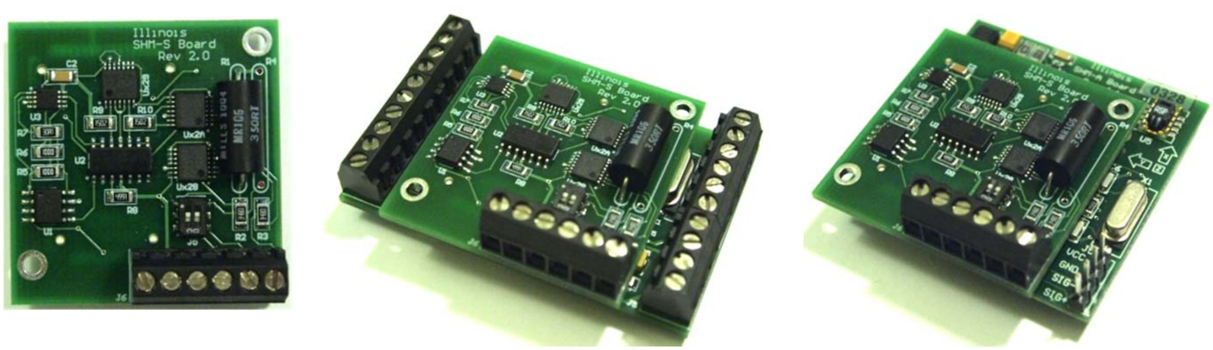
Strain monitoring using SHM-S board

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



RemoteCommand SHMSAutoBalance

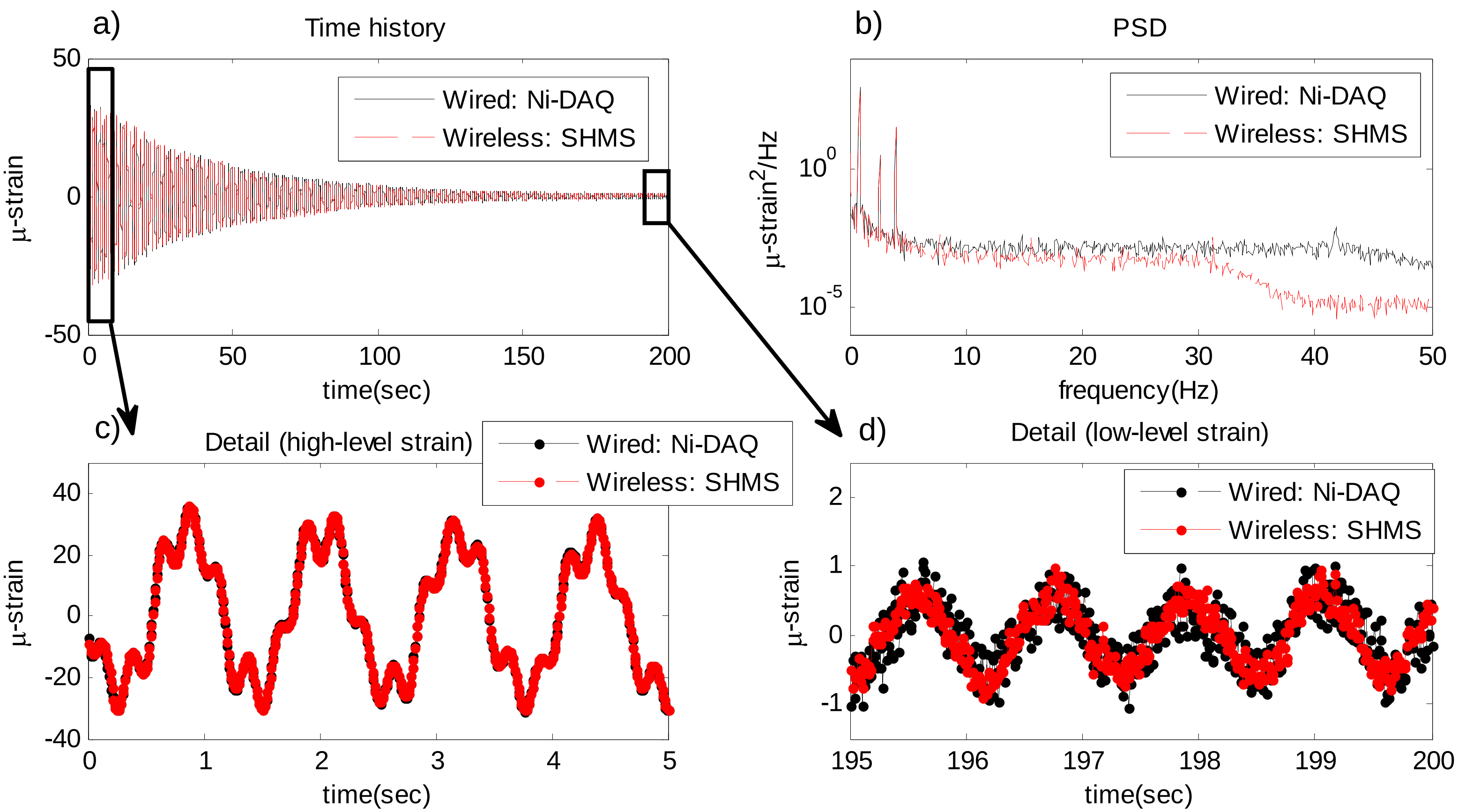


SHM-S board: top, stacked on SHM-DAQ and stacked on SHM-A

Tokyo Sokki magnet strain checker

High-precision Strain sensor board (SHM-S board)

❑ SHM-S vs. Ni-DAQ (foil type)

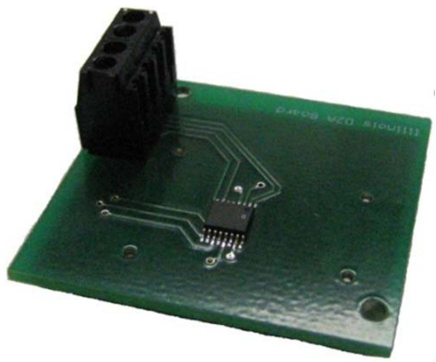


Pressure and D2A Sensor Board

SHM-D2A Board

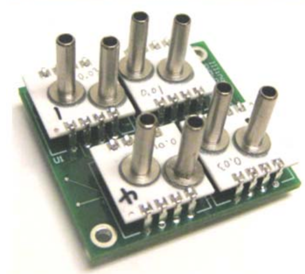
- 16bits, **Digital to Analog** conversion of 4 channels

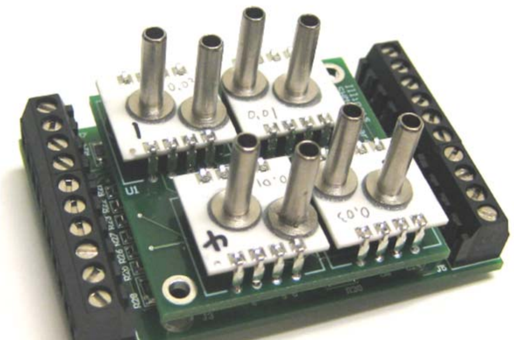
TI-DAC8565



SHM-P Board

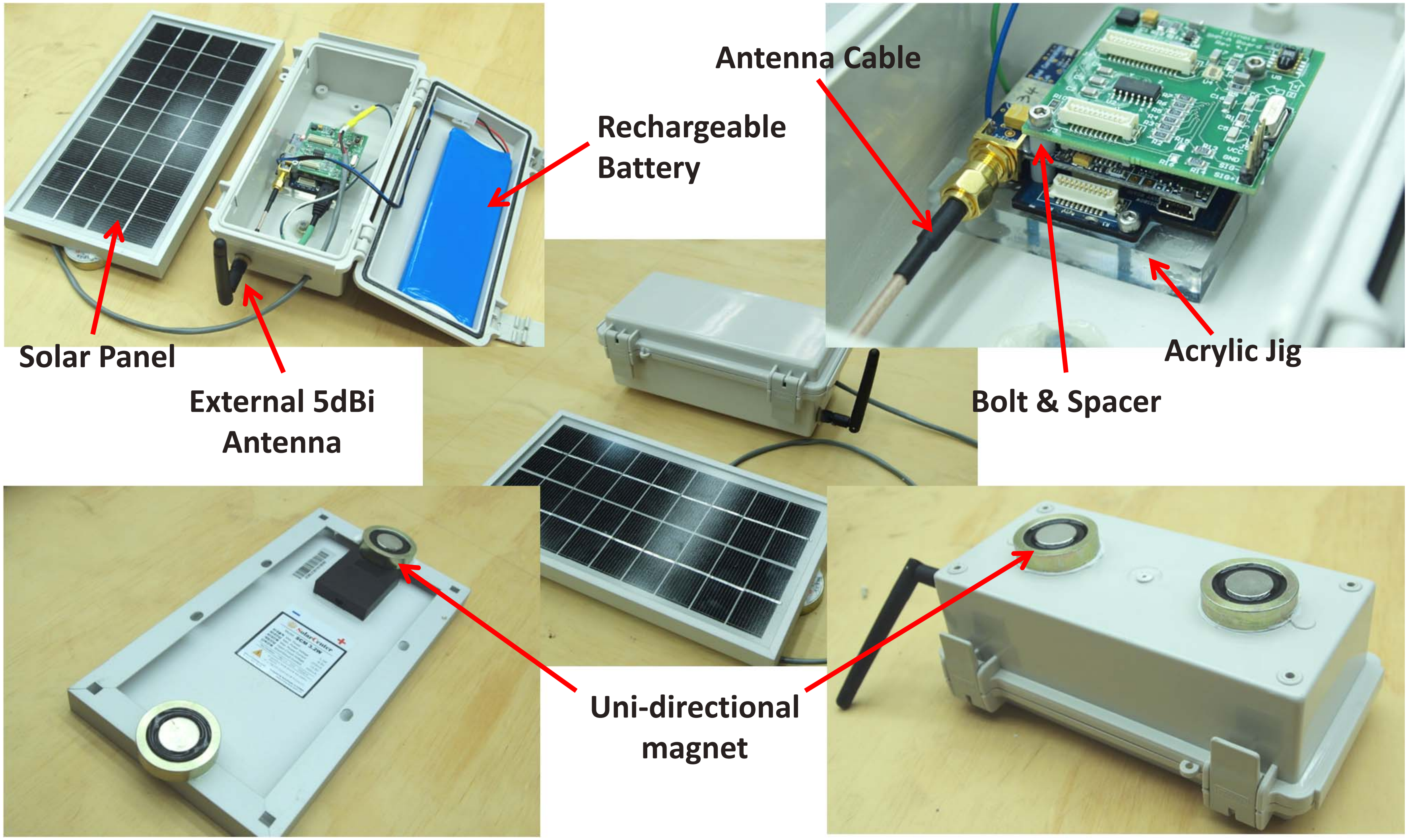
- Measure wind/air **pressure**





Stacked with SHM-DAQ Board

Imote2 Sensor Enclosure

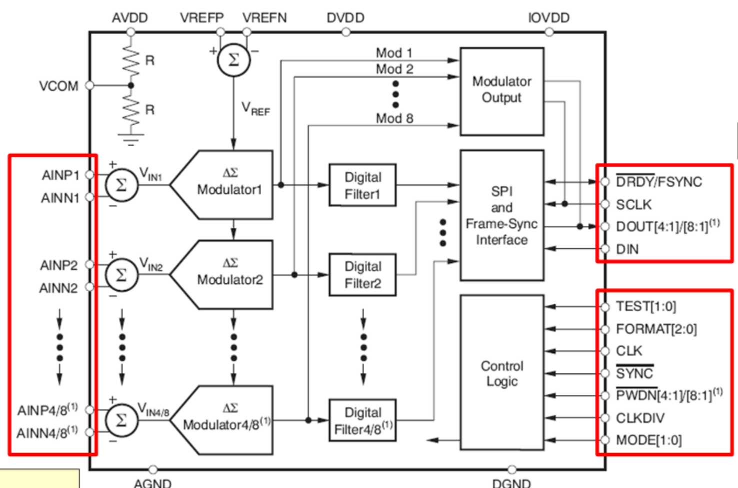


Future Hardware Enhancement

❑ **24-bit DAQ** (TI ADS1274, Delta-sigma type ADC)

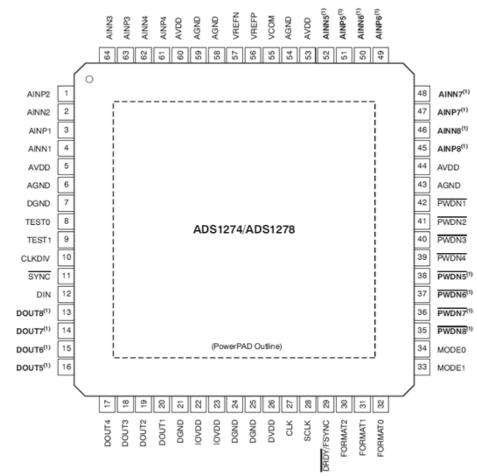
- Delta-sigma noise shaping technology
- Low-power consumption suitable for wireless sensor application
- Support full capabilities of low-noise/high-sensitivity sensors
- Make it easy to implement/design new external sensor boards

- **signal conditioning circuit for -5 ~ 5V analog input**
- **3-pole AA-filter**



SPI of Imote2

[Block diagram of ADS1274/1278]



Others
- **clean power supply**
- **low-noise design** (separation of digital/analog parts, low-noise components)
- **reclock circuit** for restraining f_{SCLK}/f_{CLK} = 1, ½, ¼ …

Function selection
- **low-speed mode** (7mW/ch)
- **enable power down mode** (while no-use)
- **low-power Crystal** (27Mhz)
- **TDM & dynamic output format** (need only DOUT1, memory saving)

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Service-oriented Software Framework

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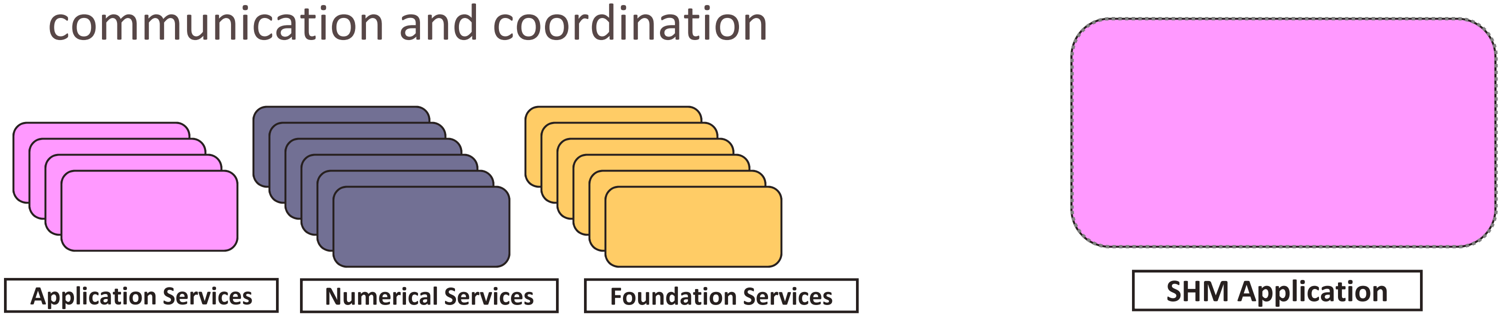
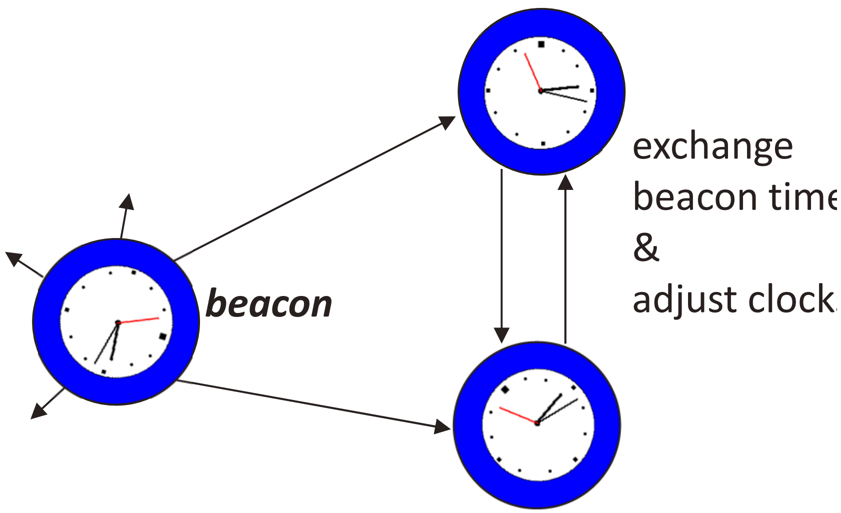
Service-Oriented Architecture (SOA)

- 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…



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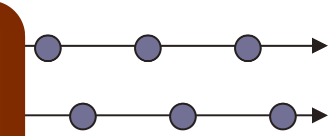
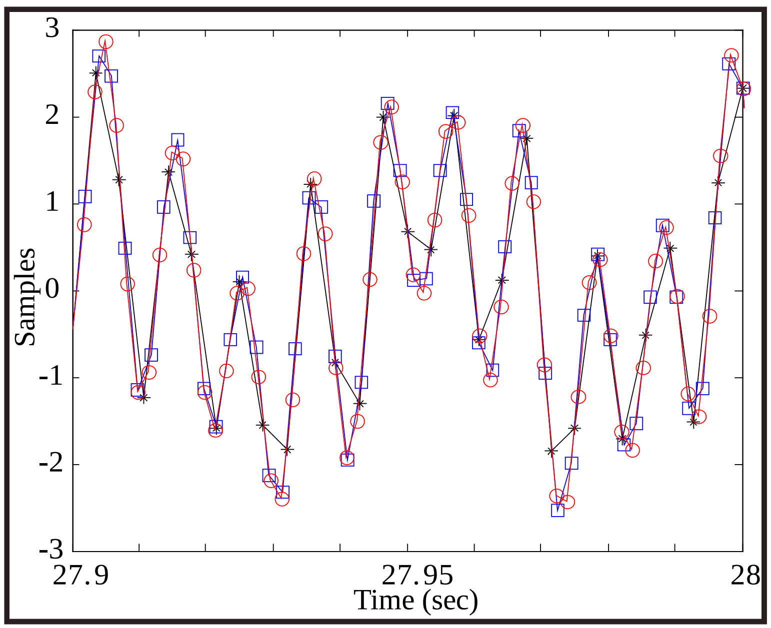
Synchronized Sensing Service

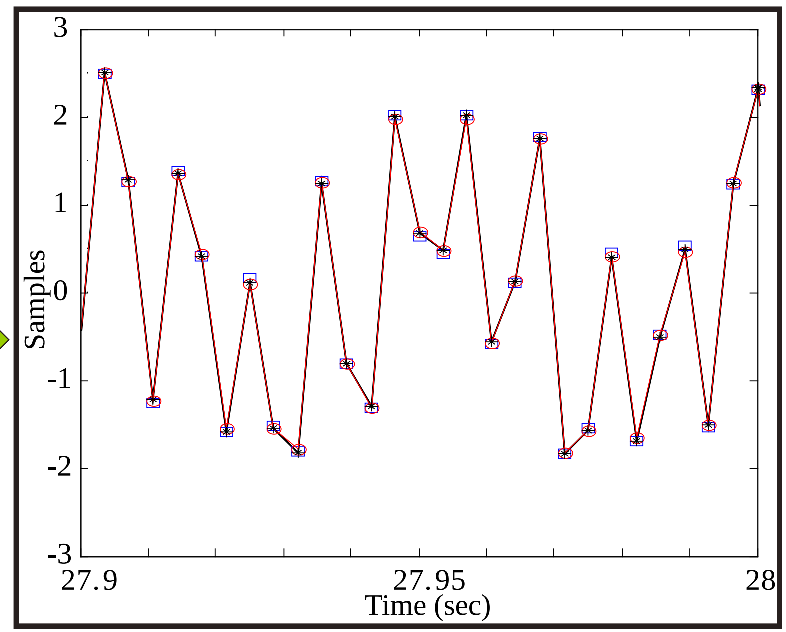
- Uncertainty in start of acquisition
  - Independent processors

$t_{0,1}$



Resampling middleware service achieves synchronized sensing

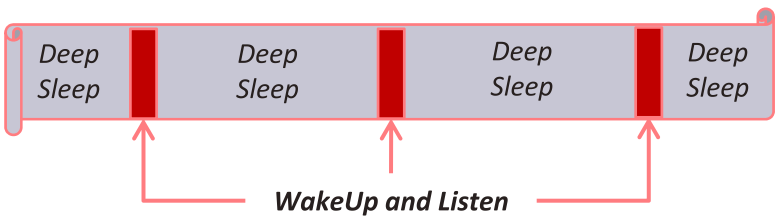


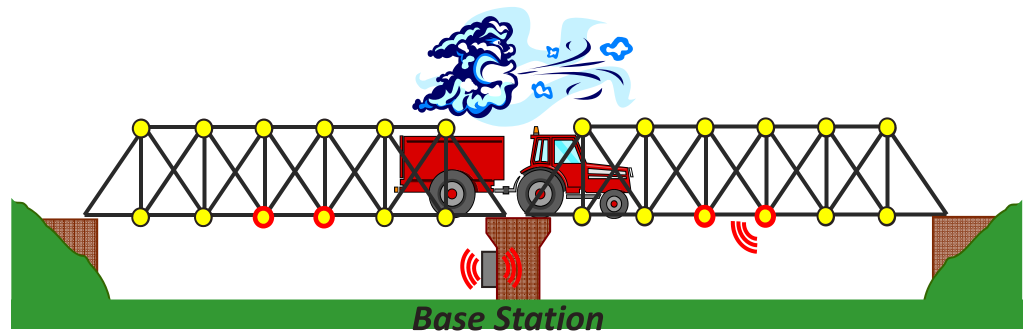


Power Management and Energy Harvesting

Effective Power Management with Autonomous Operation

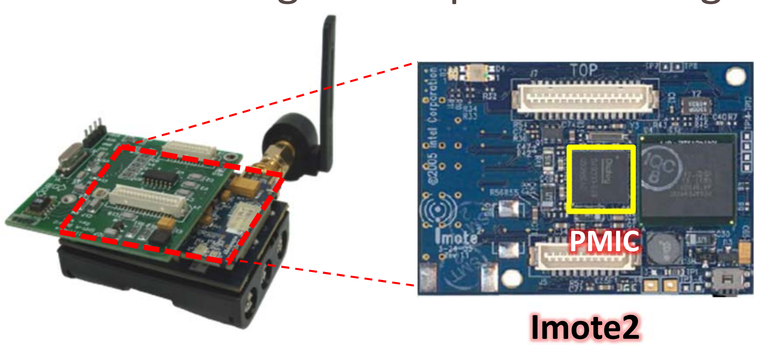
- SnoozeAlarm:
- ThresholdSentry:
- AutoMonitor:





Energy Harvesting

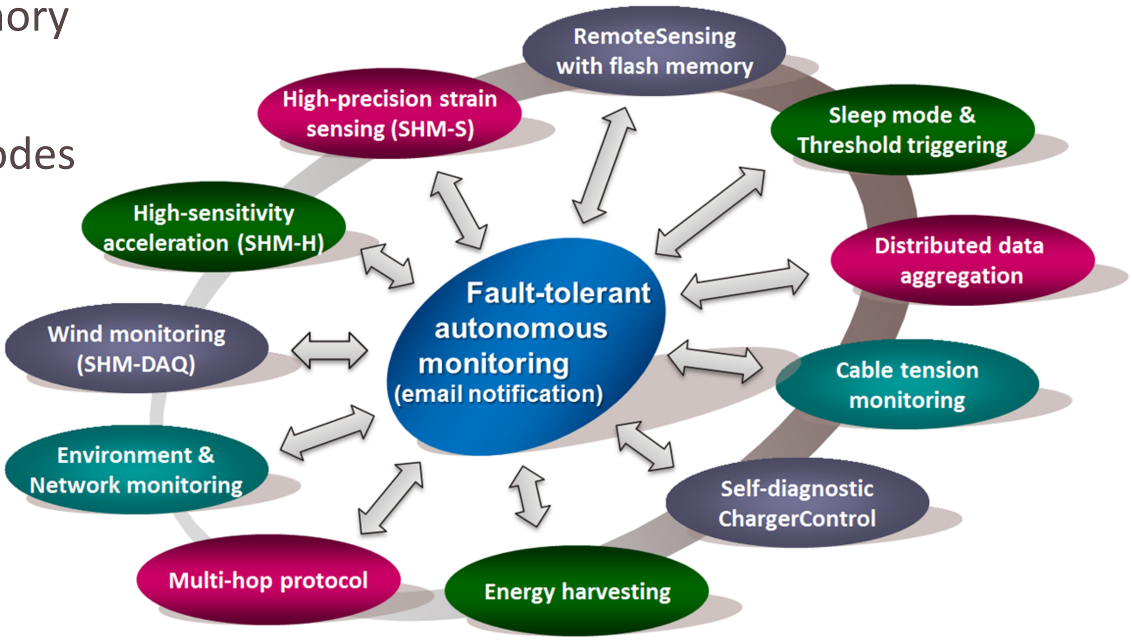
- Solar panel (or Micro wind turbine) + Rechargeable Battery
- PMIC charger manipulates voltage and current for fast and stable charging.



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…

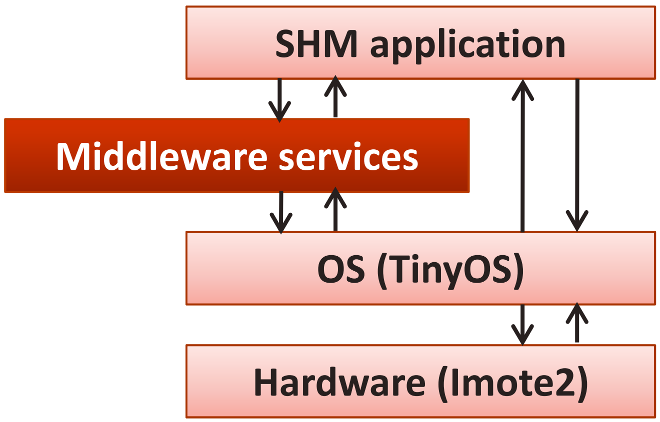


Enhanced operation

- 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



http://shm.cs.uiuc.edu

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

Full-scale Implementation

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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)

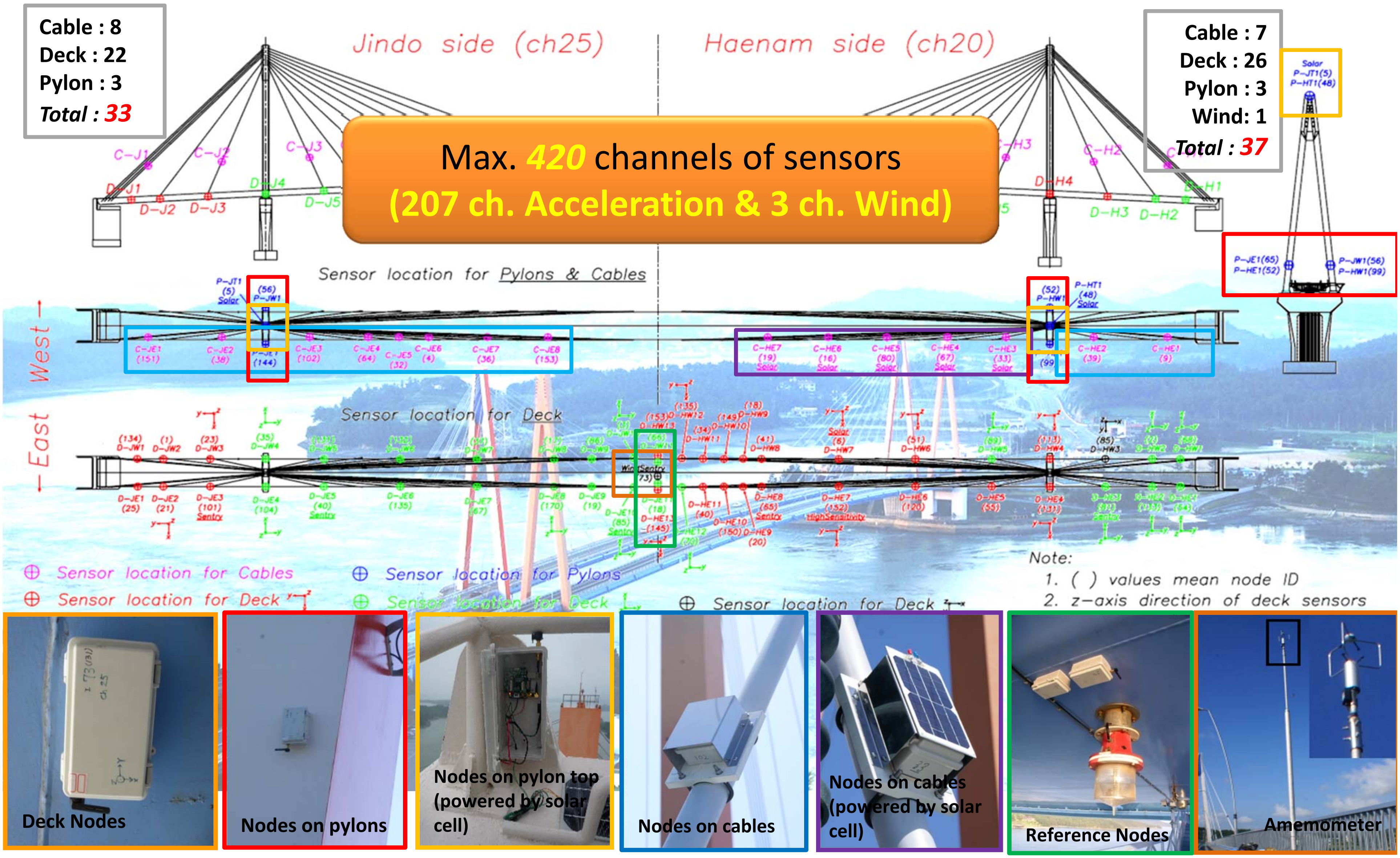
Korea : H.J. Jung & C.B. Yun (KAIST), H.K. Kim (SNU)

J.W. Seo (Hyundai Institute of Const. Tech.)

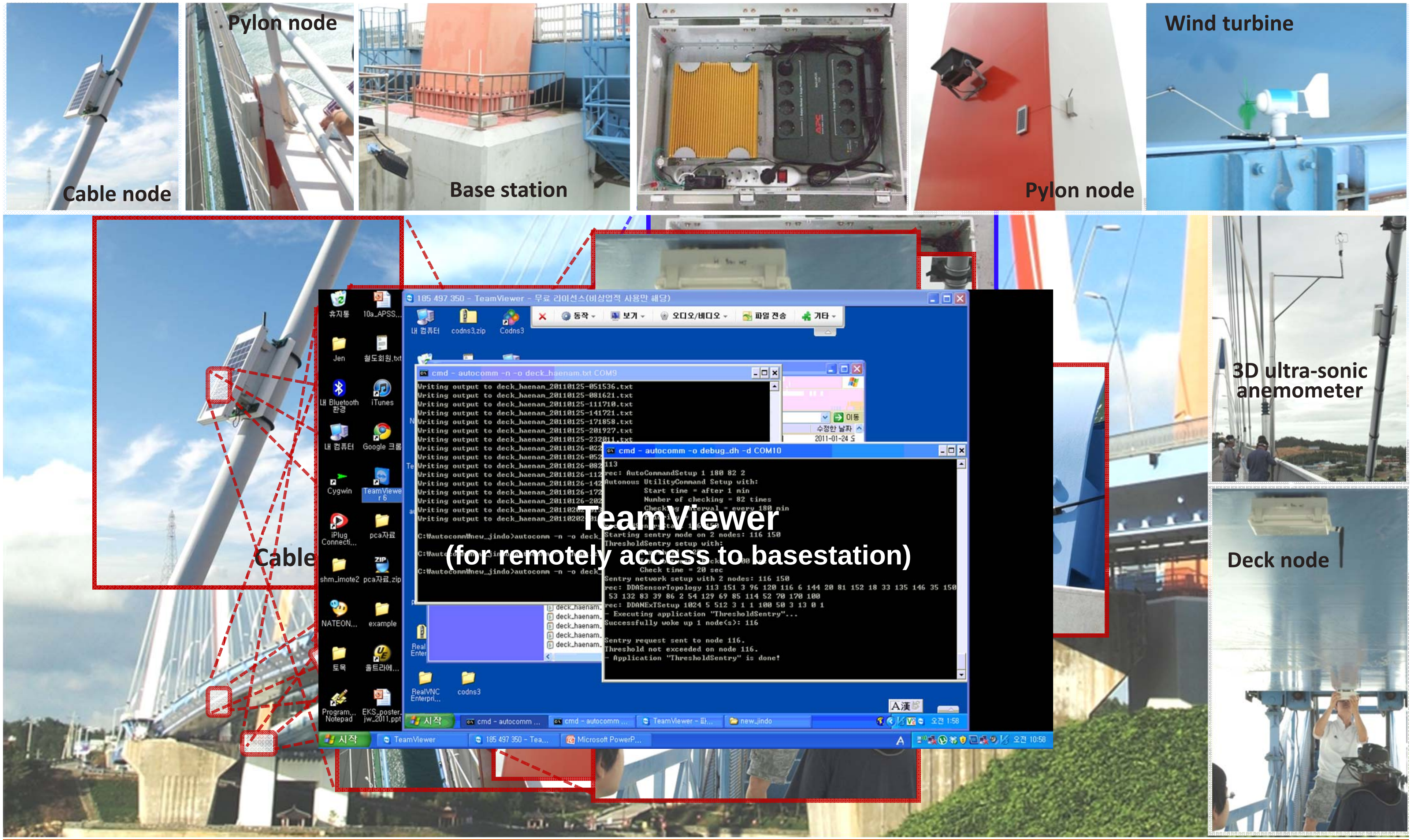
Japan : Y. Fujino & T. Nagayama (U. of Tokyo)

2nd Jindo Bridge	
Type	Cable-stayed bridge
Spans	70+344+70 = 484m
Girder	Steel box (12.55m width)
Design velocity	70 km/hr
Designed by	Yooshin cooperation (2000, Korea)
Constructed by	Hyundai construction (2006, Korea)

Deployment in 2009 (70 Nodes)



Deployment in 2010



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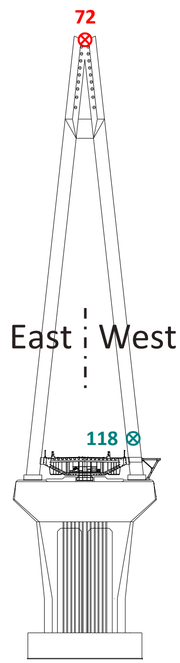
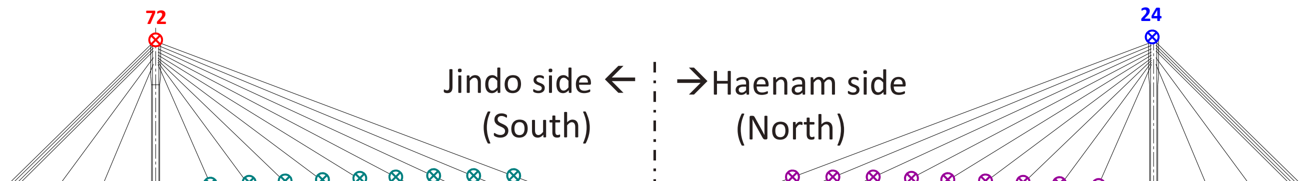
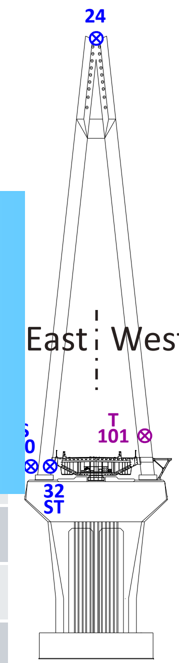
Deployment in 2010







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

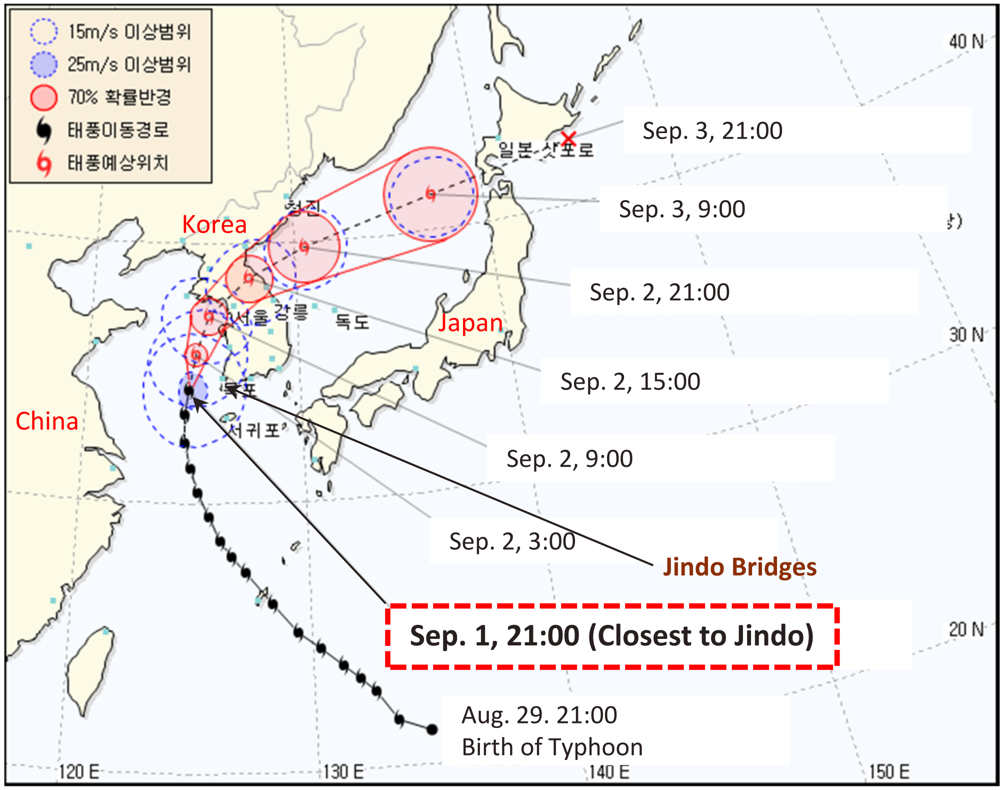
SHM-DAQ board (wind)		1 nodes	-	2 nodes	-
Sentry node		3 nodes	2 nodes	3 nodes	2 nodes
Temperature node (exposed)		1 nodes	-	1 nodes	1 nodes
Functionalities	Common	RemoteSensing, AutoUtilsCommand, ChargerControl, ThresholdSentry and SnoozeAlarm			
	Particular	DDA	CTE	DDA	CTE
Communication protocol		Single-hop	Single-hop	Single-hop	Multi-hop

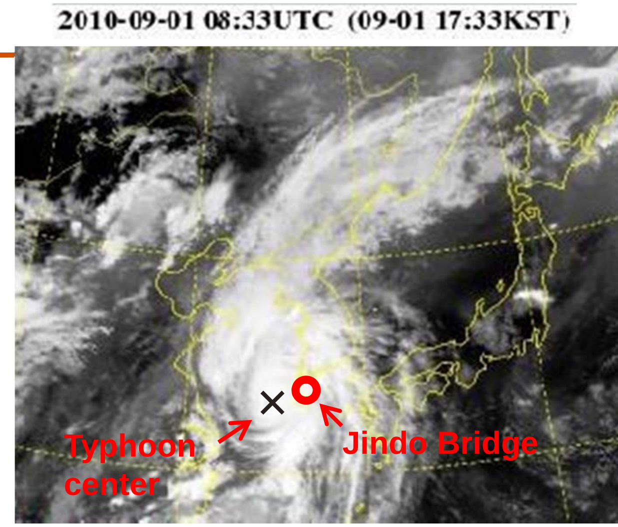
W : Anemometer (SHM-DAQ) **WT : Wind Turbine power** **S : Strain sensor (SHM-S1)**

T : Temperature **H : High-sensitivity (SHM-H)** **ST : Strain + Temp correction (SHM-S2)**

Evaluation

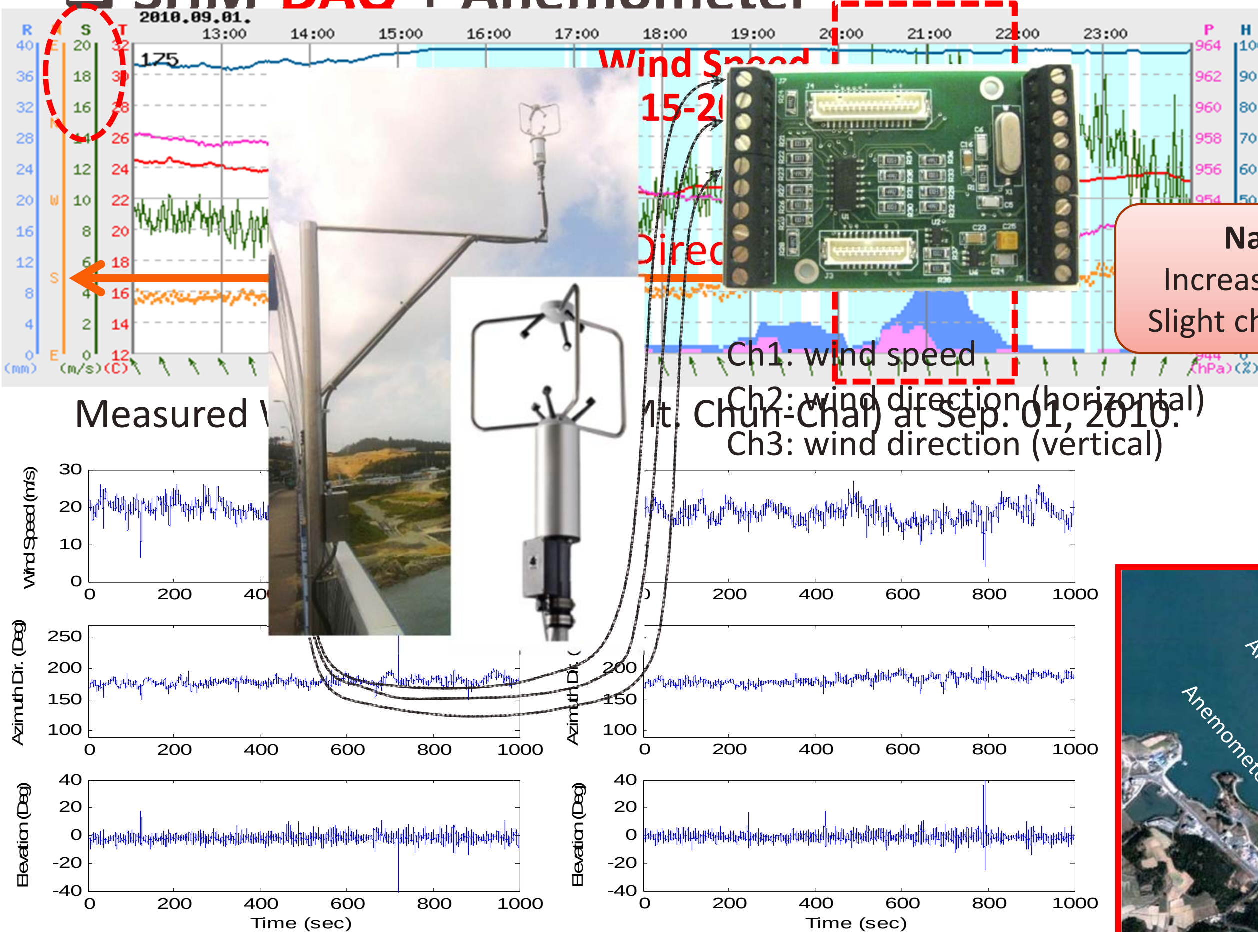
❑ Typhoon Kompasu (2010.09.01)





Evaluation: Wind Monitoring

❑ SHM-DAQ + Anemometer



Ch1: wind speed
Ch2: wind direction (horizontal)
Ch3: wind direction (vertical)

Measured W… Mt. Chun-Chal) at Sep. 01, 2010.

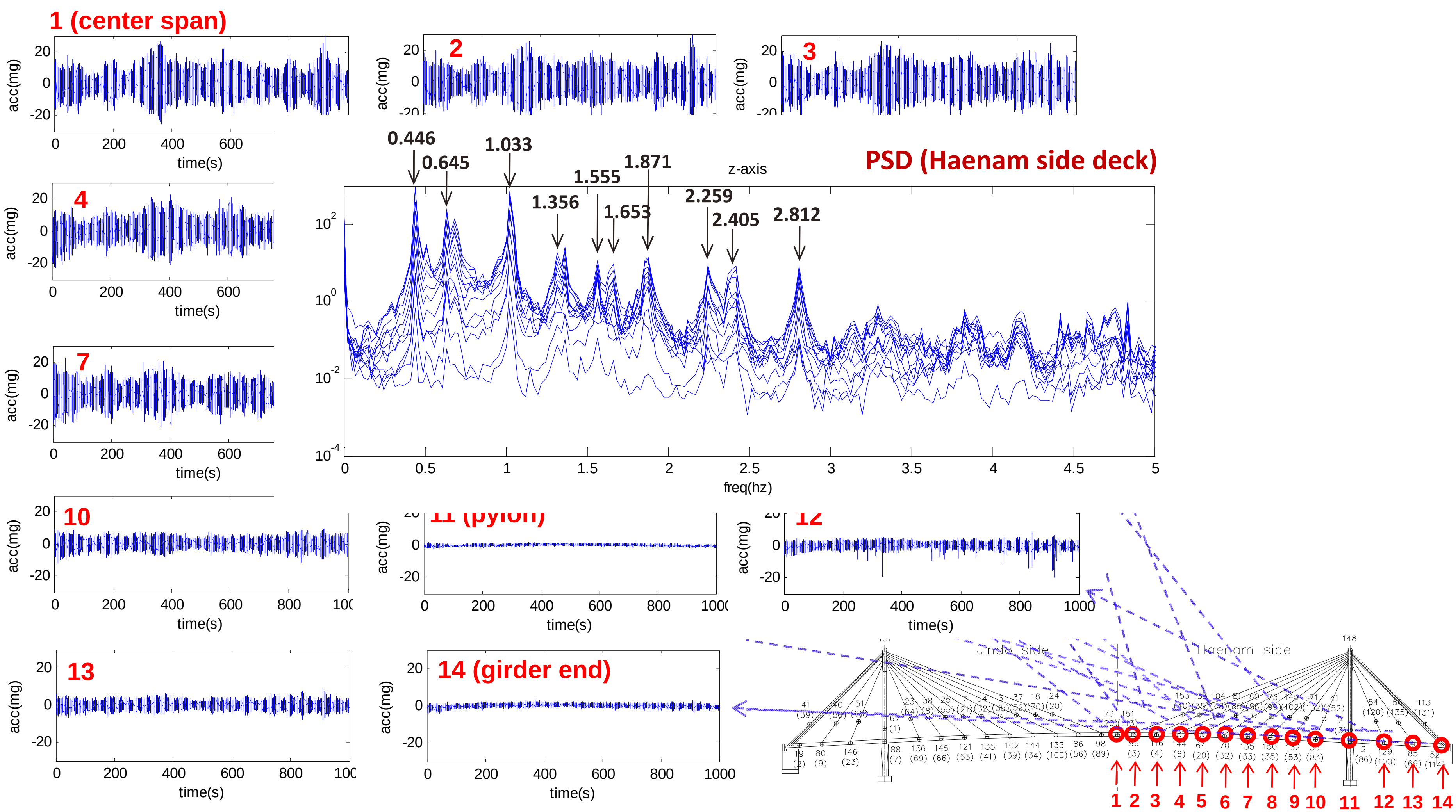
Anemometer:
Jindo-side (at 21:14)

Anemometer:
Haenam-side (at 21:12)

Narrow Strait:
Increased wind speed -
Slight change in direction

SSTL

Evaluation: Acceleration Responses

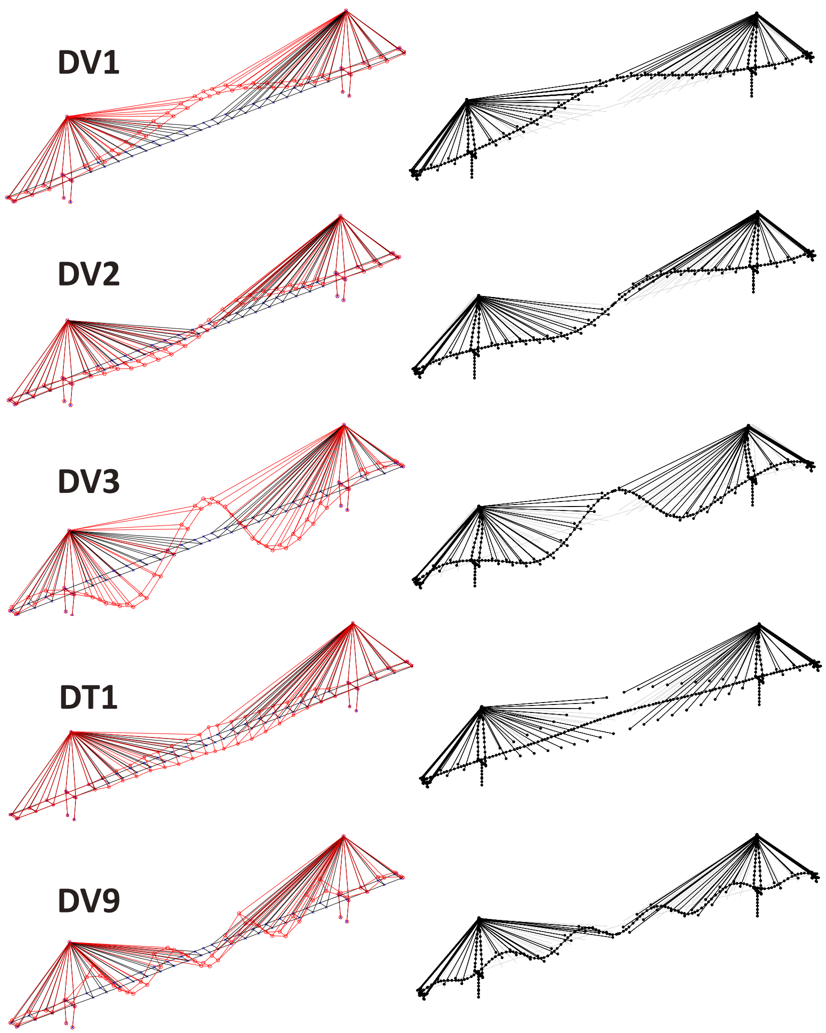


Evaluation: System ID

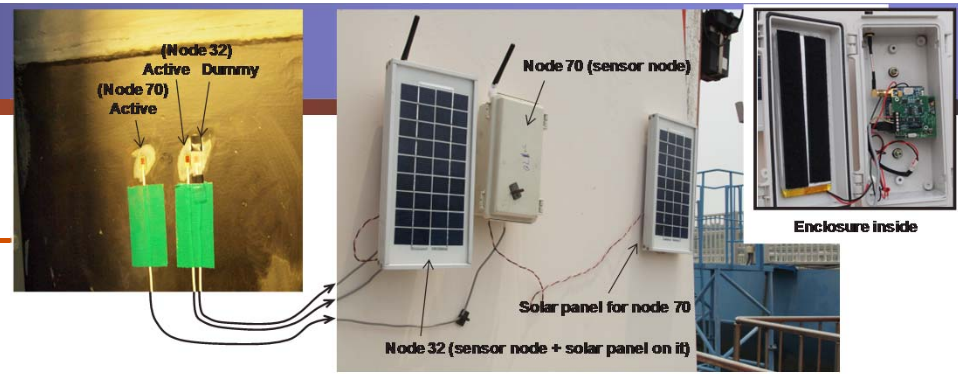
- NExT & ERA method
- Identified frequency range: 0~3Hz
- 1000 seconds data at 25Hz sampling

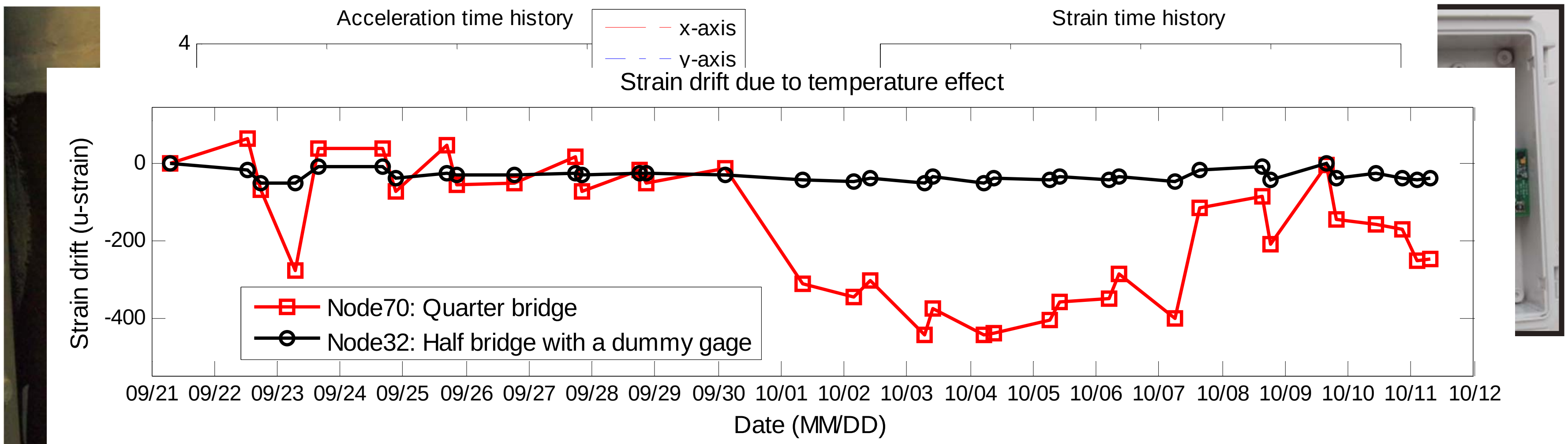
Identified natural frequencies (Hz)

Mode Name	Wired System (2007)	FE analysis	WSSN (During Kompasu)		
			Haenam	Jindo	Avg.
DV1	0.440	0.442	0.446	0.446	0.446
DV2	0.659	0.647	0.645	0.647	0.646
DV3	1.050	1.001	1.033	1.033	1.033
DV4	1.367	1.247	1.356	1.342	1.349
DV5	1.587	1.349	1.555	1.549	1.552
DV6	1.660	1.460	1.653	1.635	1.644
DT1	-	1.789	1.798	1.802	1.800
DV7	1.856	1.586	1.871	1.870	1.871
DV8	2.319	2.115	2.259	2.261	2.260
DV9	2.808	2.561	2.812	2.813	2.813

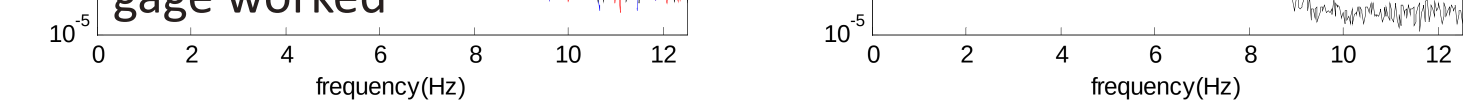


Evaluation: Pylon Strain



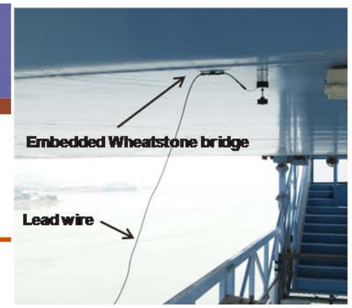


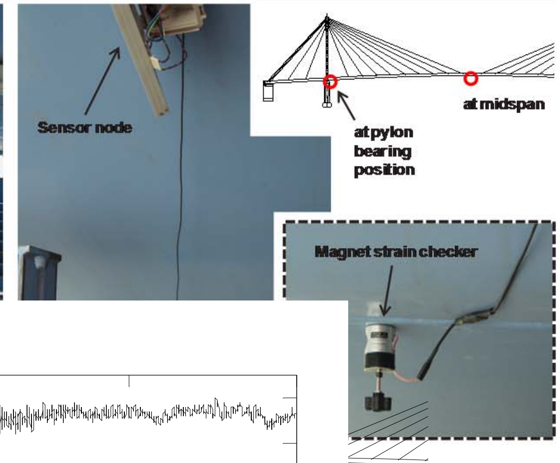
- Temperature compensation using the half bridge with a dummy gage worked

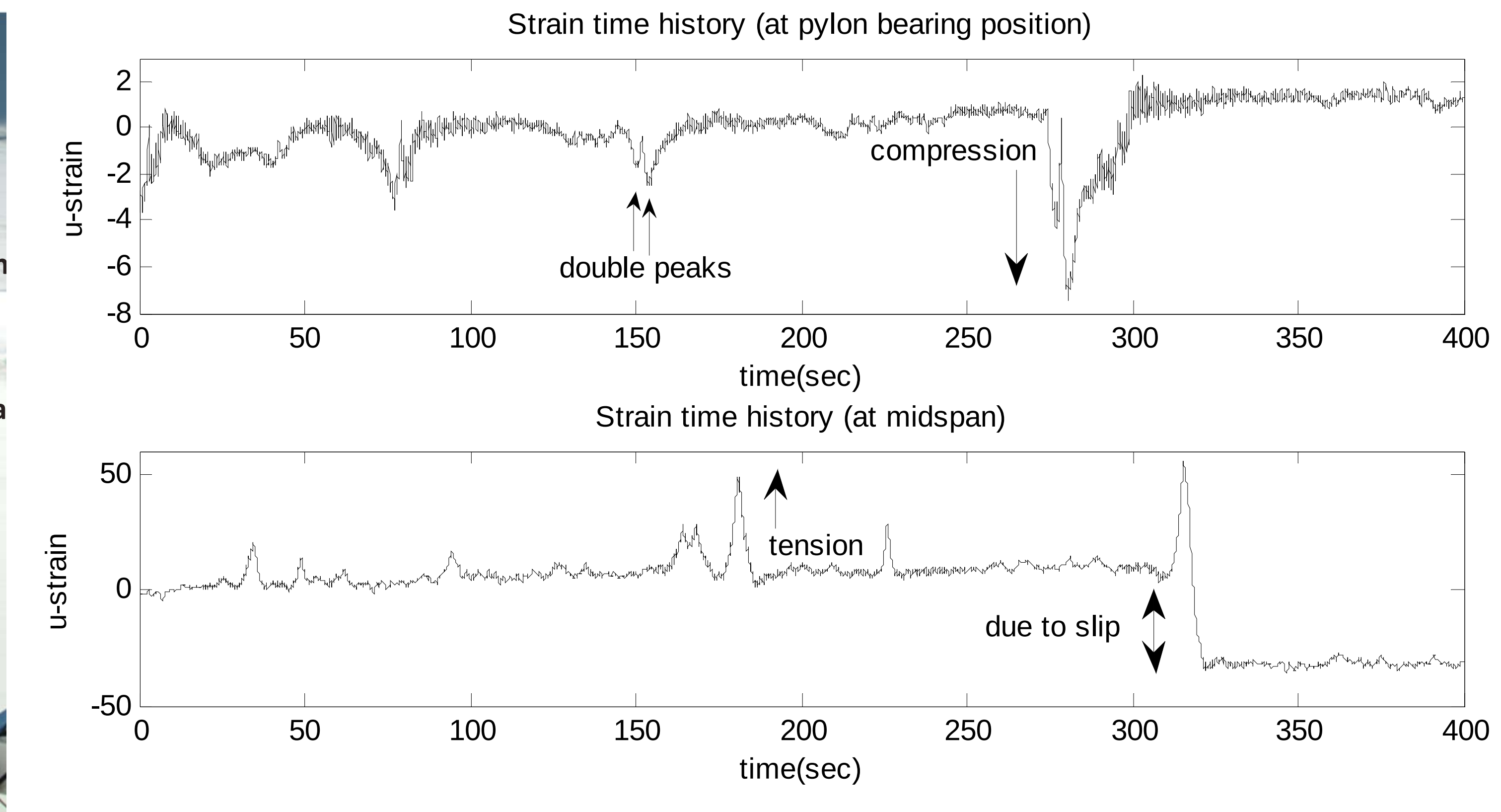


- Synchronized acceleration & strain sensing at 25Hz
- For pylon, strain measurement was more informative

Evaluation: Girder Strain







span

- 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

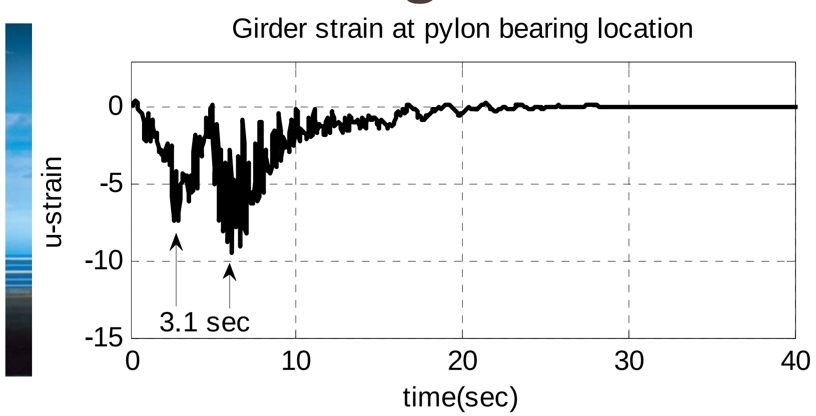
At midspan

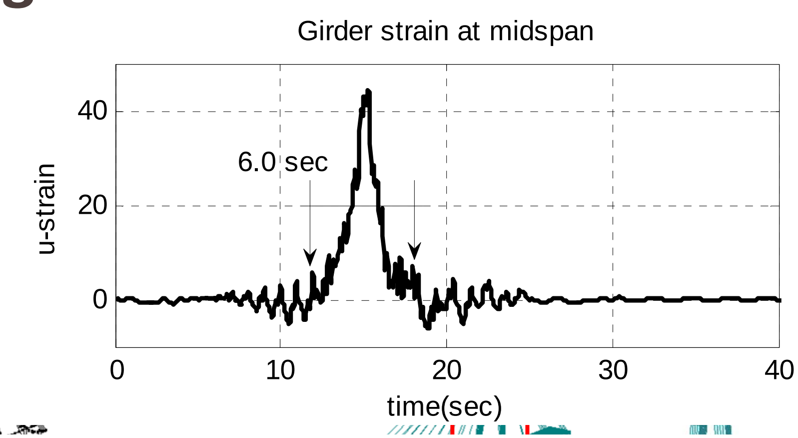
At bearing location

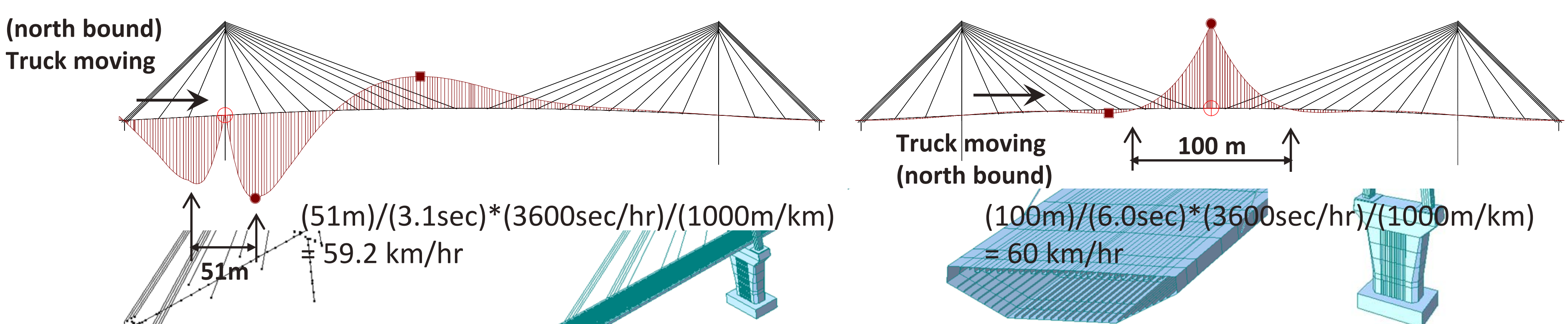
Using magnet strain checker with SHM-S

Evaluation: Strain Analysis

❑ Truck loading simulation using FE model

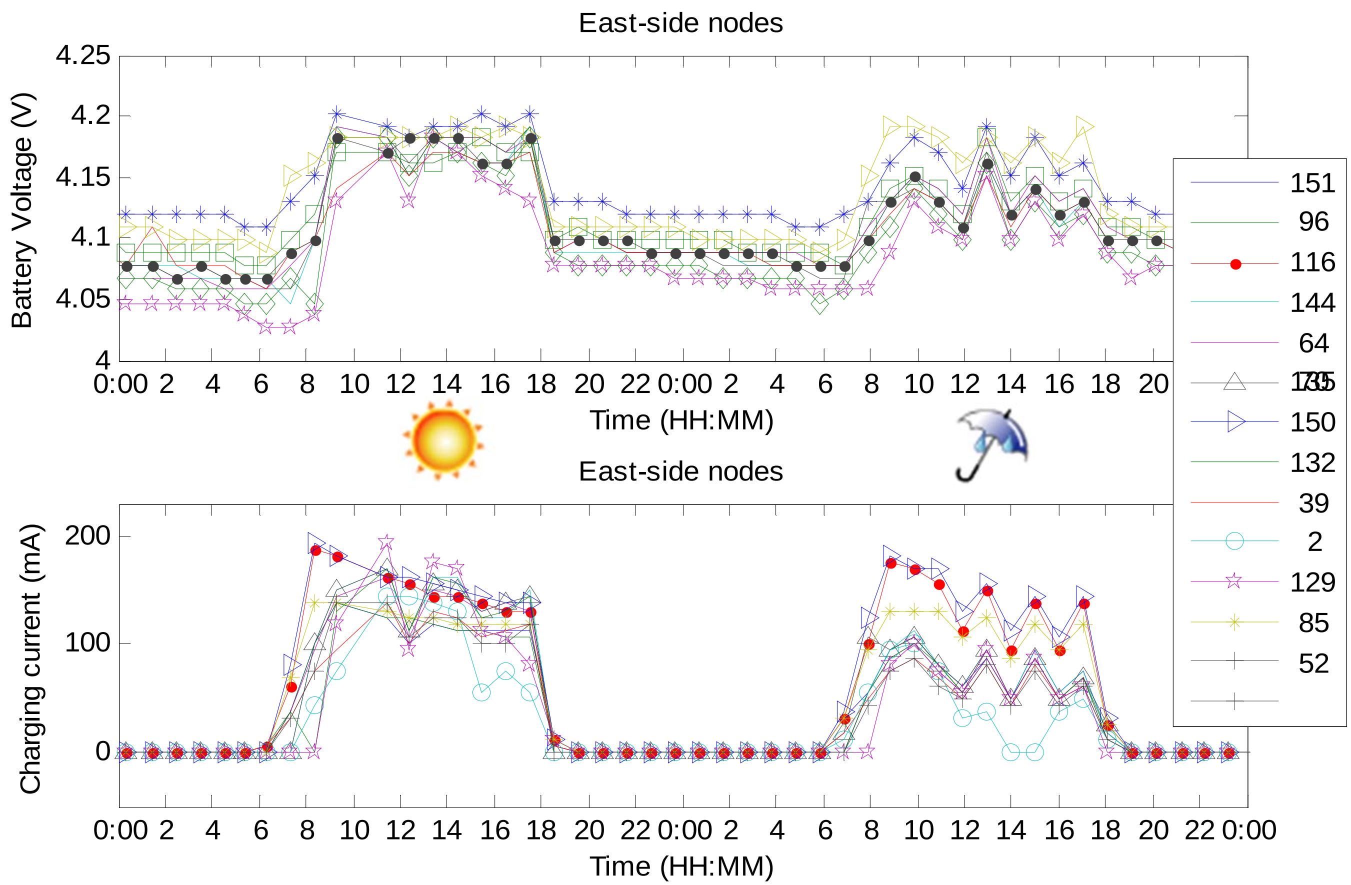






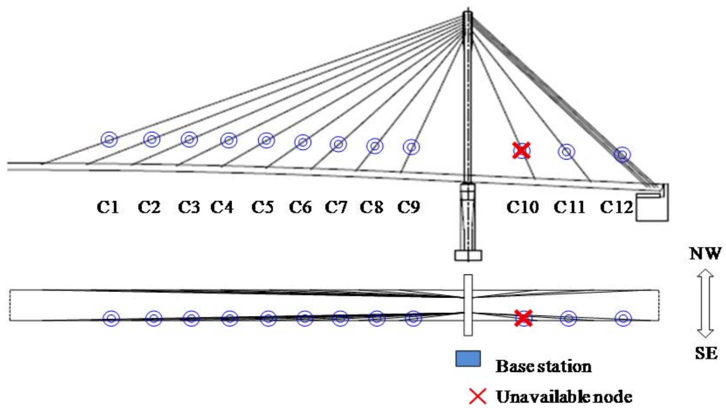
- Double peaks are caused by the double-concaved influence line
- Can be utilized for estimation of vehicle's speed, moving direction, and weight (Bridge Weigh-in-motion, BWIM)

Evaluation: Battery Monitor

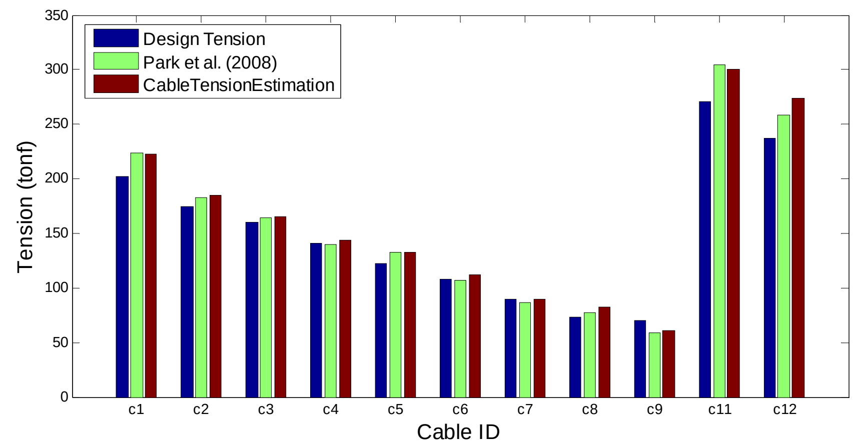


Evaluation: Cable Tension and Temperature

Cable tension estimation

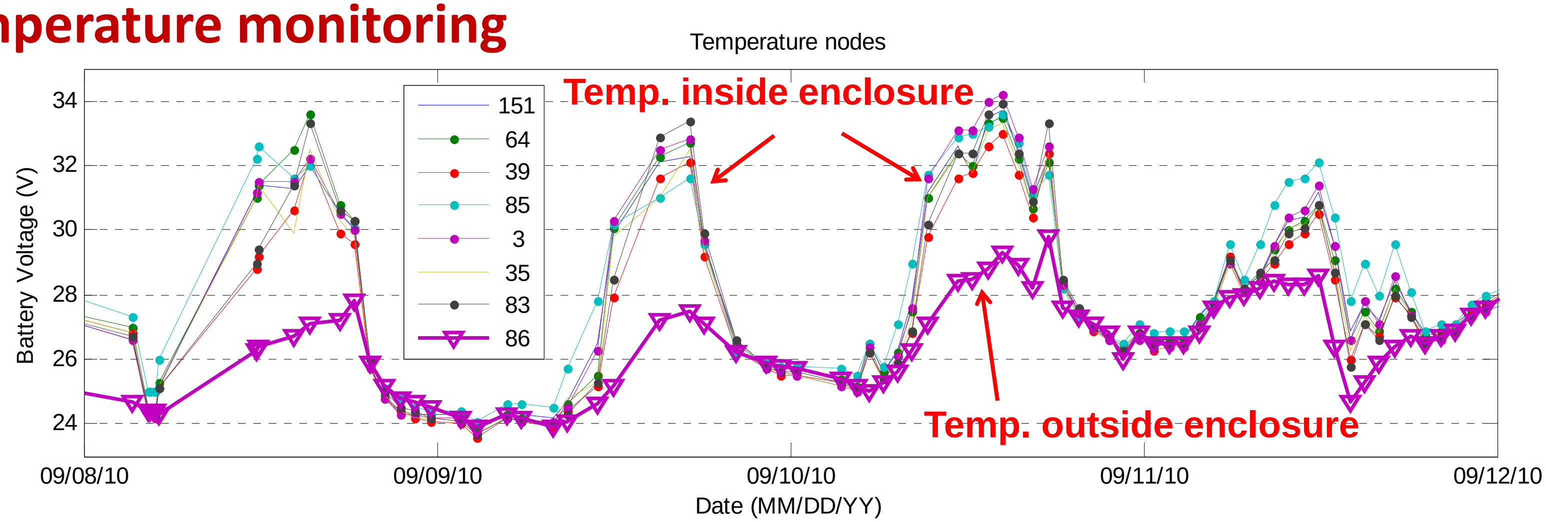


[Cable ID]



[Cable tension comparisons]

Temperature monitoring



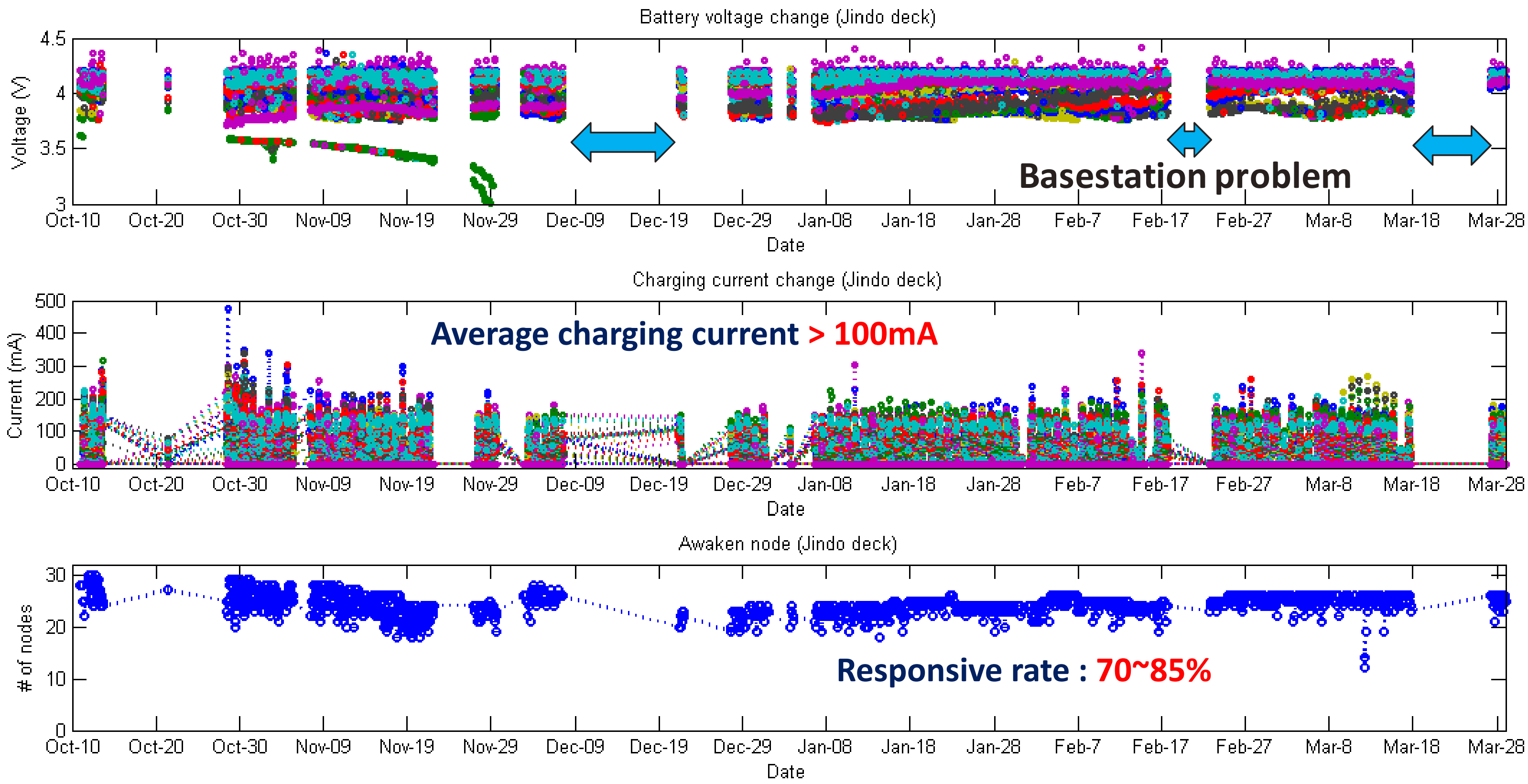
SSTL

Evaluation: Long-term performance of Jindo-side WSSN

Battery voltage (V)

Charging current (mA)

Number of responsive node (out of 31)



SSTL

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.

- A

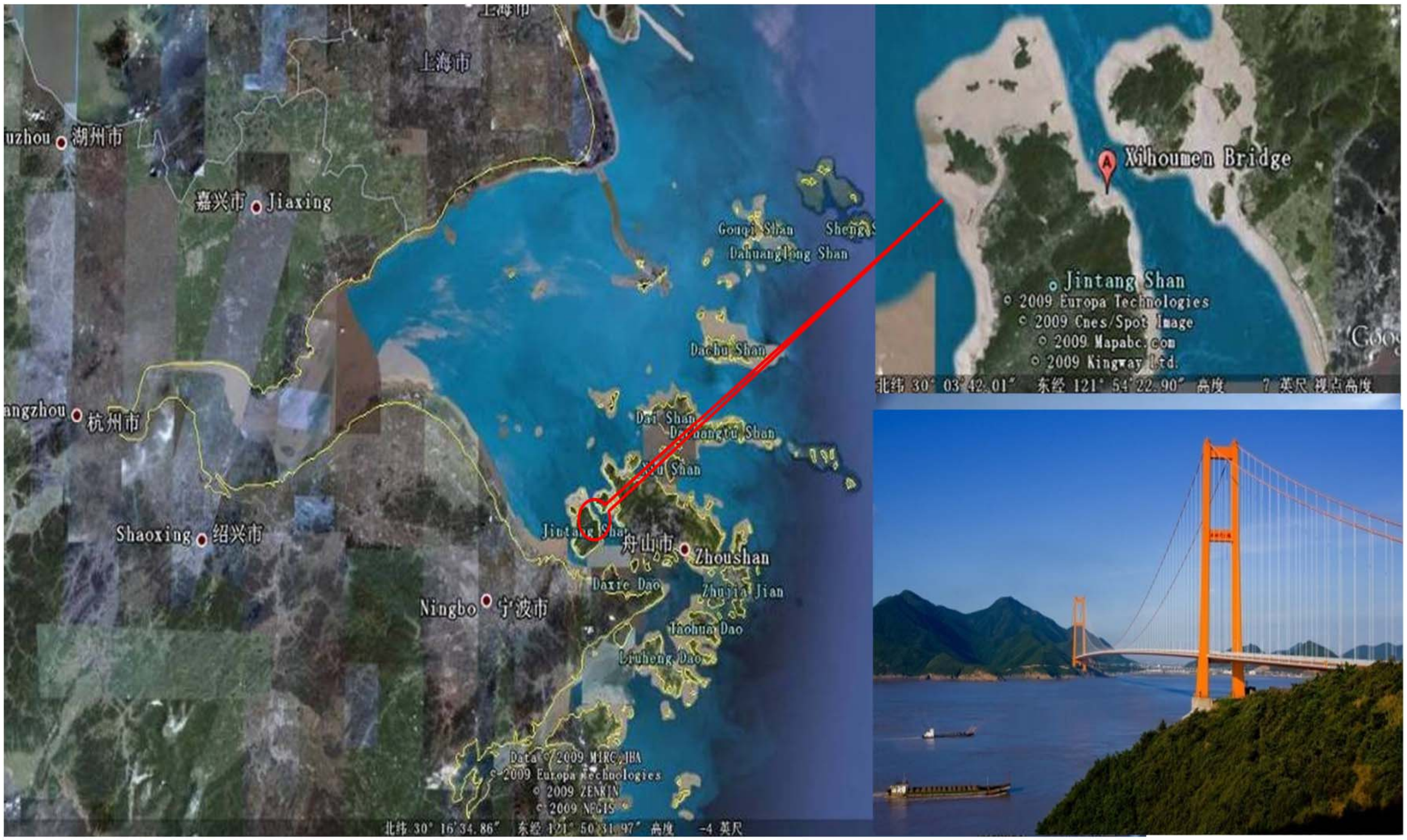
- Modal analysis with system synchronization
- Vibration-based tension estimation
- Multi-scale structural health monitoring (Modal information + Cable tension force)
- Wind-vibration correlation analysis

- International collaboration for test-bed
- Web-based data repository and sharing

Next Steps

Wind Load and Wind Effects on Xihoumen Bridge

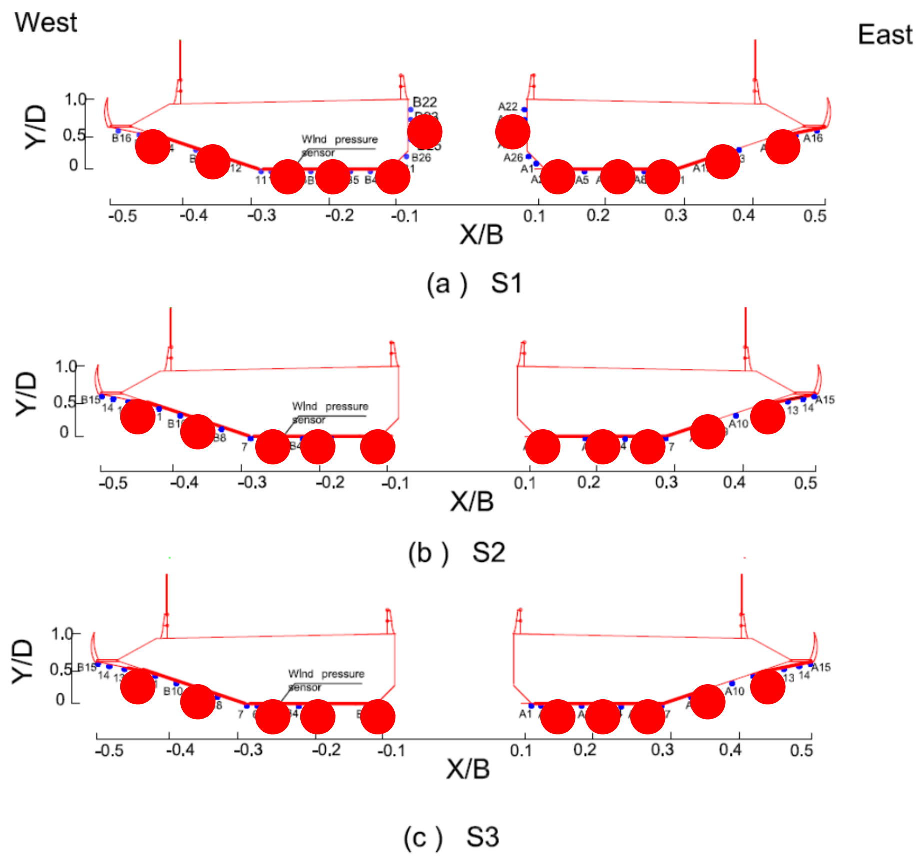
- Hui Li, B.F. Spencer, Yan Yu, Jinping Ou



Wind Load and Wind Effects on Xihoumen Bridge

SHM-DAQ board

KAVLICO P992
Low-level pressure sensor

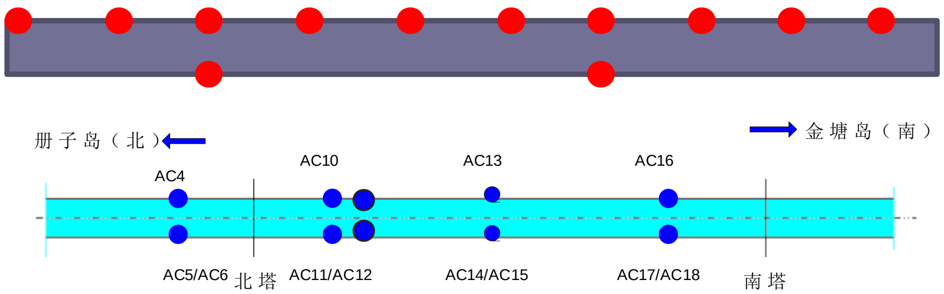


Add 32 wireless pressure modules (P992 connected to SHM-DAQ)

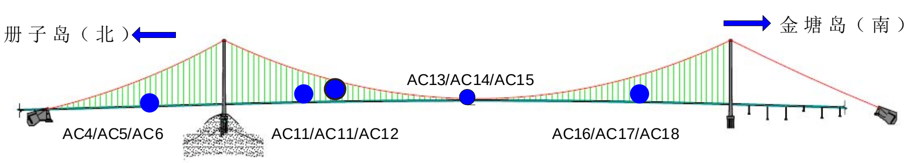
Range: ± 250-500Pa

Accuracy: ≤ 0.5% of full span

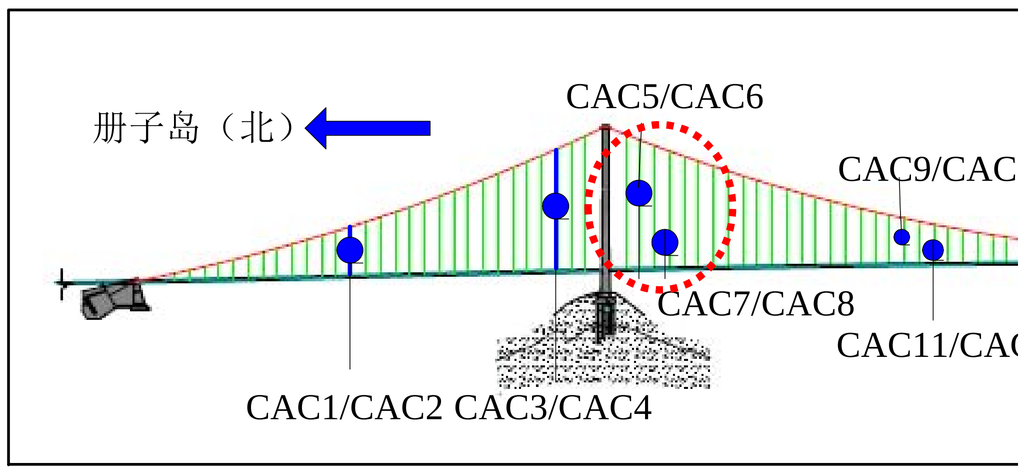
Wind Load and Wind Effects on Xihoumen Bridge



Add 12 bidirectional wireless accelerometers in ten sections



Add 10 bidirectional wireless accelerometers



Campaign Monitoring for Management of Railroad Assets

The Future

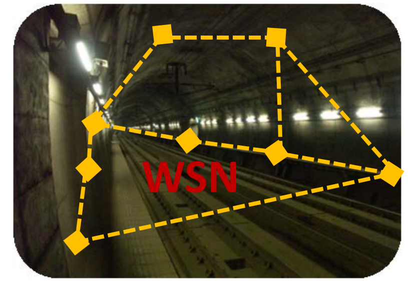
Cyberinfrastructure for Smart Structures

Bridges

- Structure Monitoring
- Hurricane & Earthquake Monitoring
- Traffic Monitoring
- Emergency Respons

Tunnels

- Deflection Monitoring
- Leakage Detection
- Fire Detection
- Traffic Monitoring
- rgency Response



Cloud Services

Dams

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

The Other Infrastructure

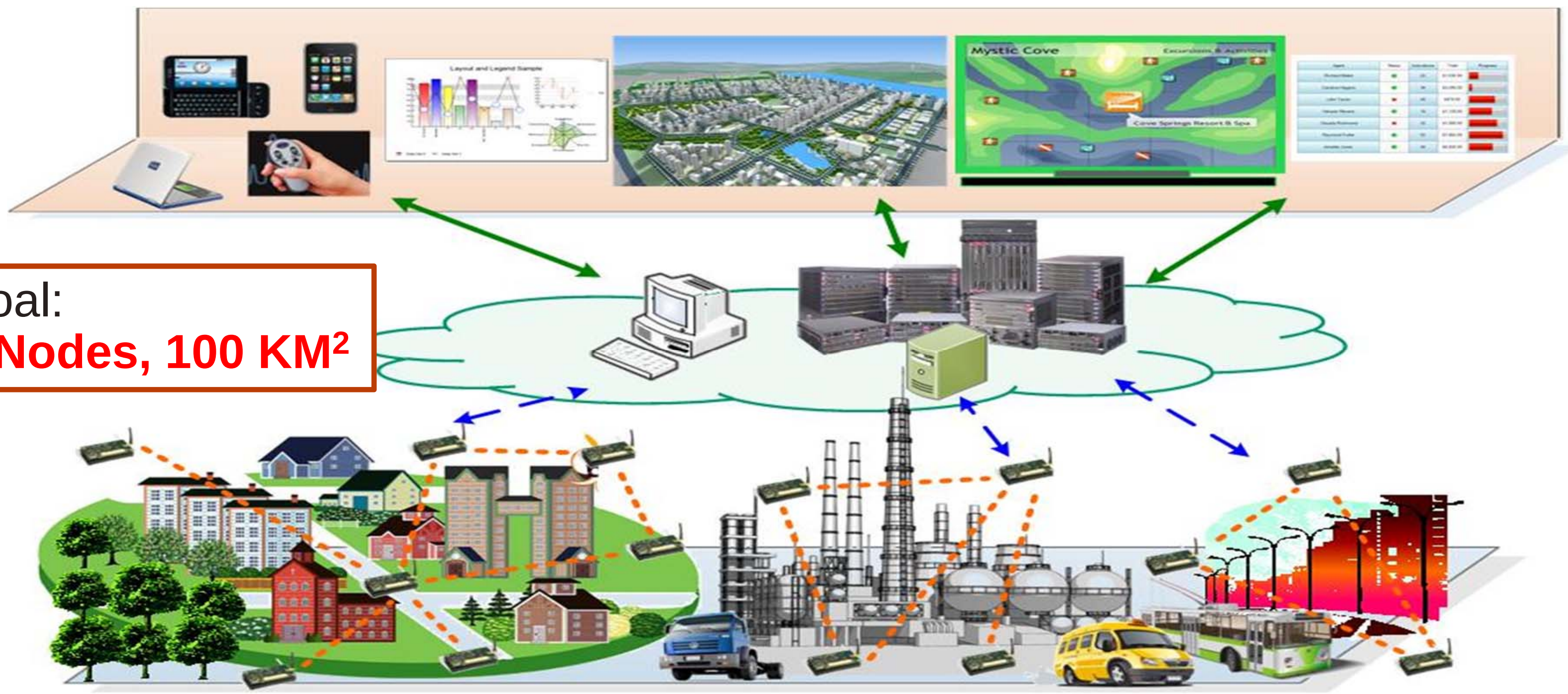
- Structure Monitoring
- Hurricane & Earthquake Monitoring
- Load Rating
- Emergency Response

- **WSN applications for structural monitoring**
- **Repository of structure data and monitoring algorithms**
- **Repository of models**

CitySee: City-wide Urban Sensing

*(Courtesy of **Prof. Yunhao Liu** of Tsinghua U.)*

- ◇ Objective: 20 KM^2 urban area in Wuxi
  - ☐ 4000+ sensor nodes with temperature/humidity and light sensors
  - ☐ 500+ nodes with CO_2 sensor

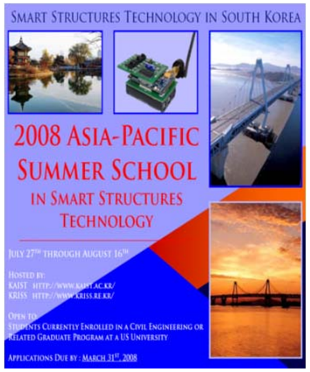


Final Goal:
10,000 Nodes, 100 KM^2

Asia-Pacific Summer School on Smart Structure Technology

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

Concluding Remarks

- ◇ 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!