Long-Term Wireless Monitoring Systems for the Monitoring of Long-span Bridges

Prof. Jerome P. Lynch
Department of Civil and Environmental Engineering
Department of Electrical Engineering and Computer Science
University of Michigan

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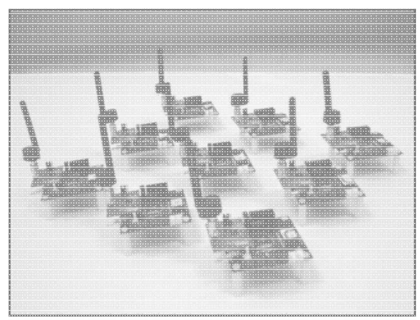
Outline

Safe and Sustainable Infrastructure

1. Motivation and Challenges



2. Wireless Sensor Networks

3. New Carquinez Bridge Field Study

Critical National Resource: Bridges

George Washington Bridge, New York

- **In the United States, there are more than 600,000 bridges:**
  - These bridges fall within federal, state and local jurisdiction
  - 90% of U.S. truck traffic travels over state-owned bridges
- **Post-WWII construction period:**
  - Major expansion of bridge inventory mirrors post-WWII economic growth
  - Within the next 15 years, 50% of the nation's bridges will exceed 50 years
    - "Baby boomer" problem for the US
    - With age comes deterioration ($$)

Michigan Transportation Network

- **Michigan plays a vital role in the national economy:**
  - In 2009, $389 billion in goods are shipped out of Michigan
  - Another $407 billion in goods are shipped into the state
  - By 2020, estimated 50% increase in commercial trucking traffic

Problem: In coming years, we will be required to do more with less

Solution: *Innovative solutions are direly needed* to maintain an aging road and bridge system in the face of inadequate levels of funding

  - 25% of state bridges rated as "structurally deficient" or "obsolete"

- **Perfect storm has emerged nationally in the U.S.:**
  - Aging infrastructure translates into mounting maintenance costs
  - Reduction is availability of funding (federal, state, local)
  - ASCE estimates state requires $6.1 billion annually (2x current level)

What is at Stake?

134 partial or total bridge collapses in the U.S. (1989-2001)

I-35W Bridge, August 1, 2007
Design error – under designed gusset plates

Schoharie Creek Bridge, April 5, 1987
Scour induced collapse

De la Concorde Overpass, September 30, 2006
Long-term deterioration caused collapse

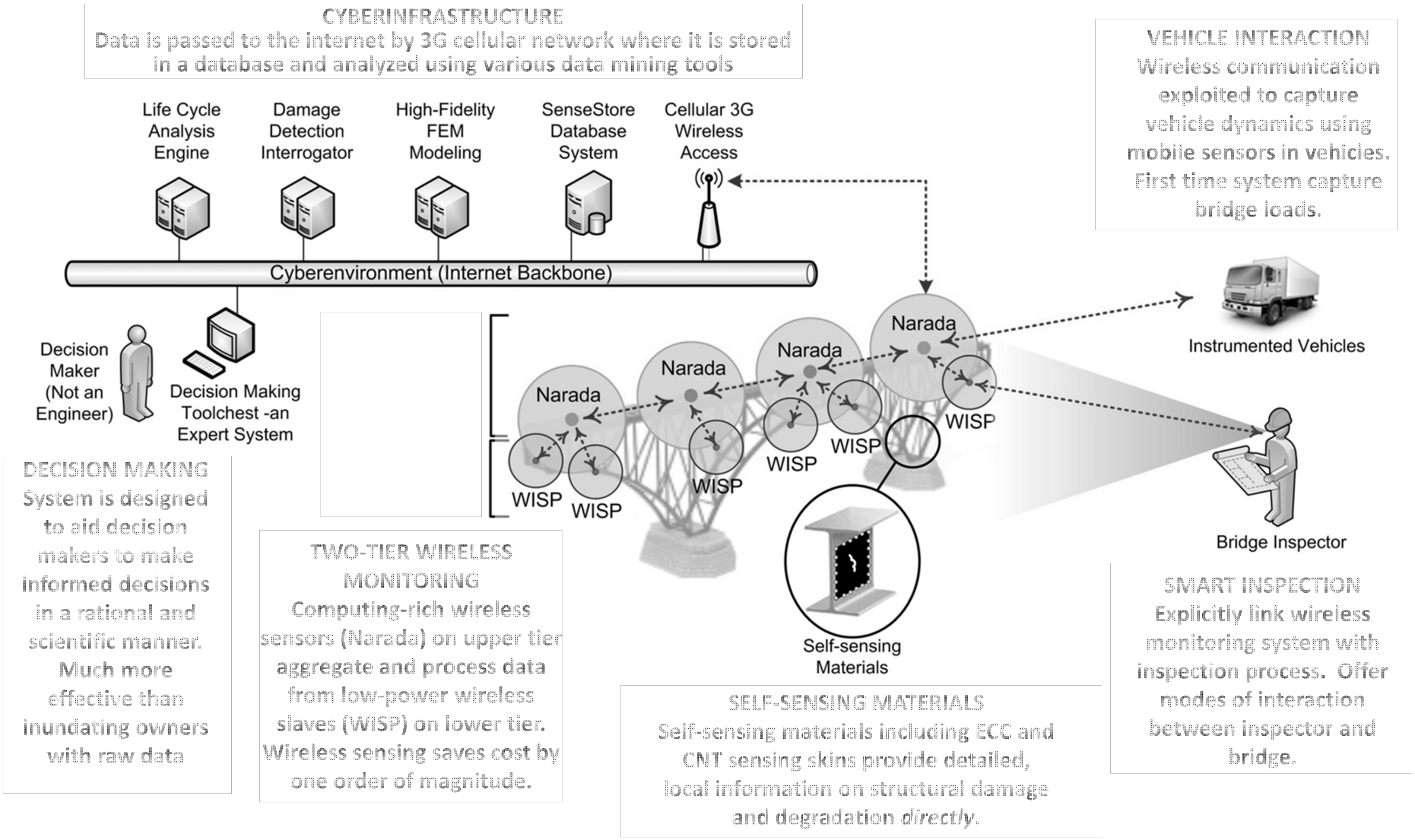
I-95 Overpass Collapse, June 28, 1983
Corrosion beneath pin hanger leads to fatigue

NIST Technology Innovation Program

- **National Institute of Standards and Technology (NIST) Technology Innovation Program (TIP):**
  - 5-year project focused on advancing SHM systems for bridges
  - Address the aforementioned limitations of existing SHM systems
- **Comprehensive re-design of bridge SHM systems:**
  - Based on wireless telemetry as a core building block of the system
  - Researchers have emphasized sensors aimed at getting better data
  - We are focused on getting end-users “information,” not just “data”

University of Michigan (LEAD) | Industrial Partners | Government Partners

NIST TIP Project Overview



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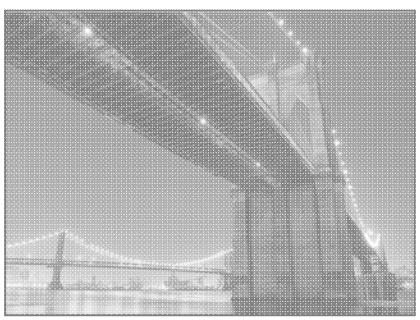

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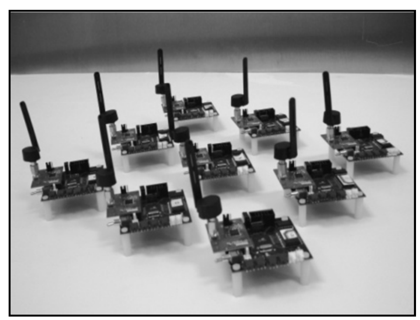

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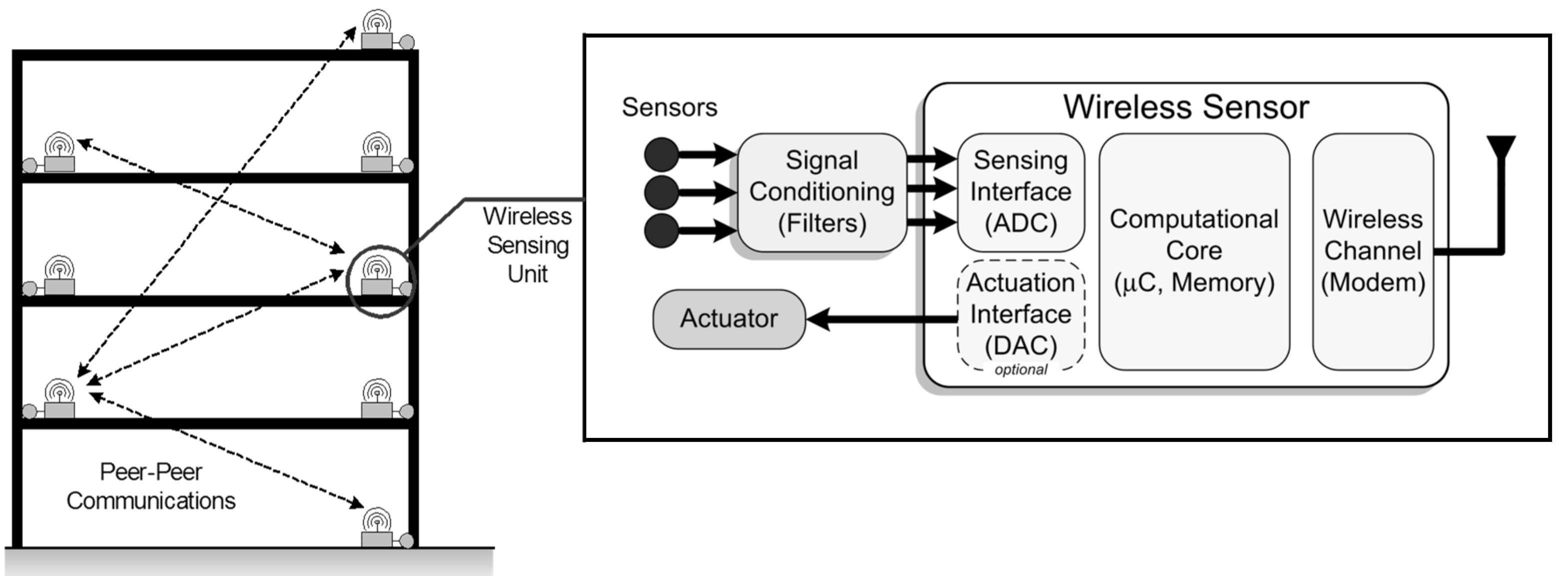
Wireless Structural Monitoring

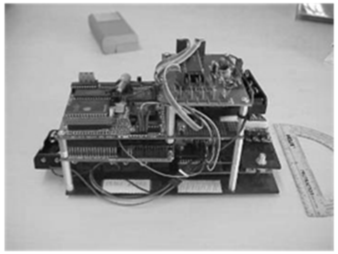
- **Wireless sensing proposed by Straser & Kiremidjian (1996)**
- **Wireless sensor networks are today viable substitutes:**
  - System constructed from low-cost wireless sensors (~$100 per node)
  - Low cost drives *high-density installation* targeting local damage
  - Computational power is coupled with sensors for data interrogation



Architectural design of wireless structural monitoring systems

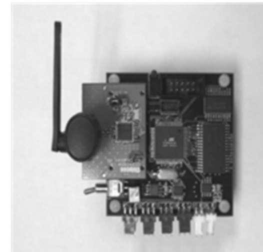
Wireless Sensor Families

Academic wireless sensor prototypes for SHM

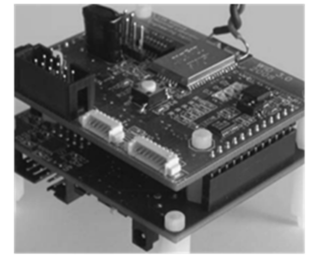


Stanford WiMMS (1996)

Stanford WiMMS-II (2003)

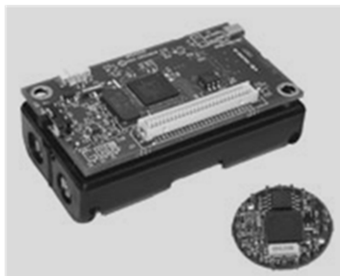


Michigan Narada (2005)

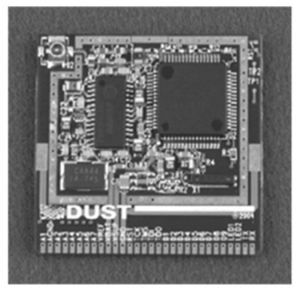


LANL WiDAQ (2008)

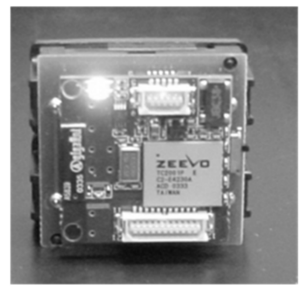
UC Berkeley "Mote" wireless sensor family for generic applications



Crossbow MoteZ (2002)



Dust Inc Mote (2006)



Intel iMote (Gen1) (2004)

Crossbow iMote (Gen2) (2009)

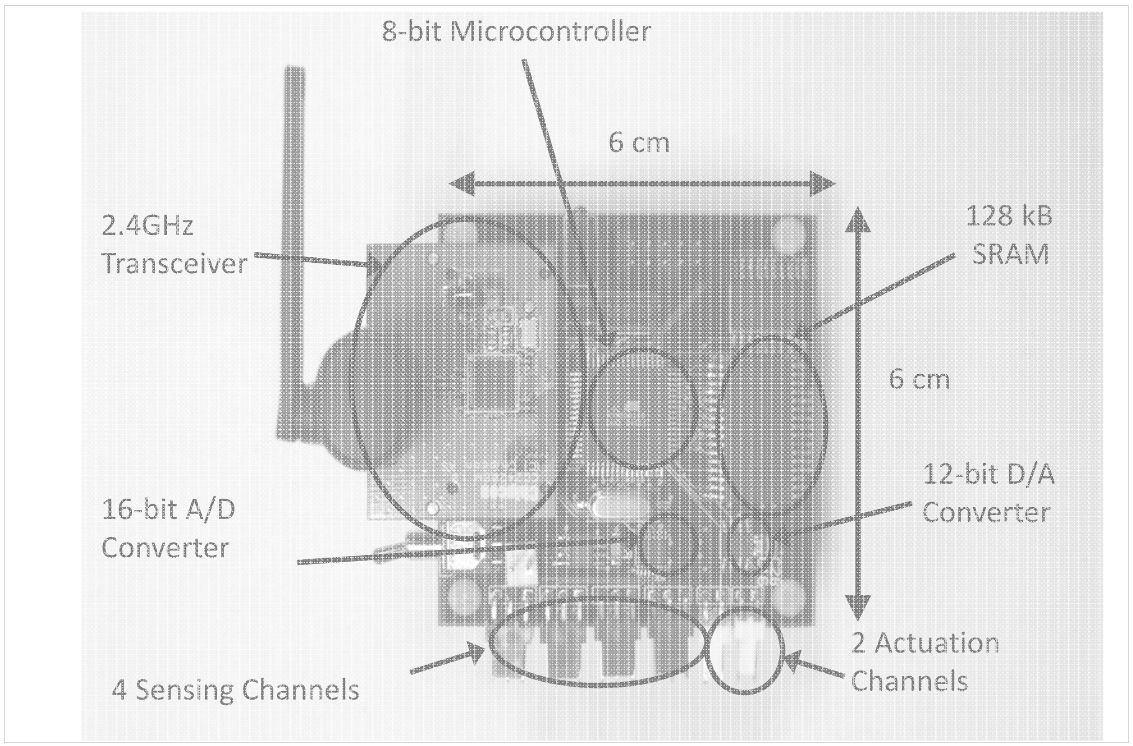
Other commercial wireless sensors for general purpose data acquisition

Microstrain G-Link (2005)

National Instruments (2010)

Narada Wireless Sensor

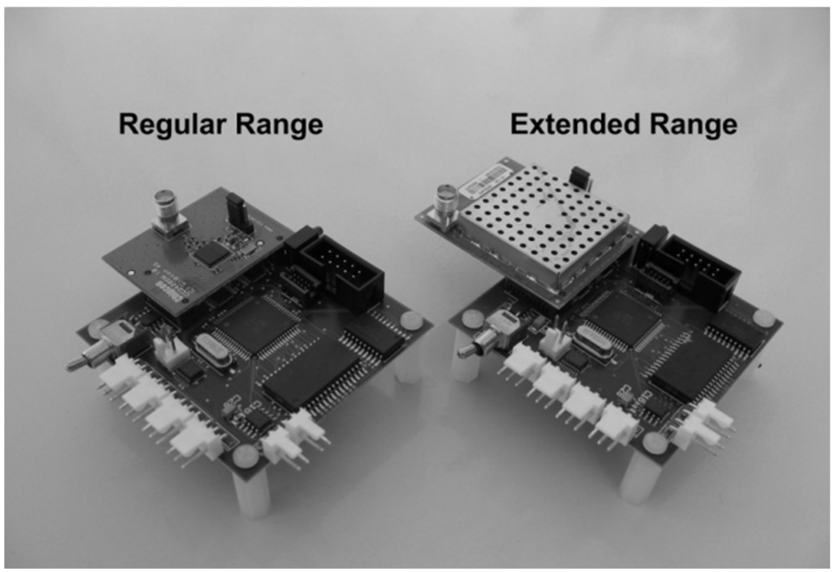
- **Wireless sensor for SHM application (Swartz et al. 2005):**
  - 16-bit ADC resolution on 4 channels capable of high rates (100 kHz)
  - IEEE802.15.4 radio offers interoperability with other sensors
  - Rich embedded processor for sensor-based data interrogation



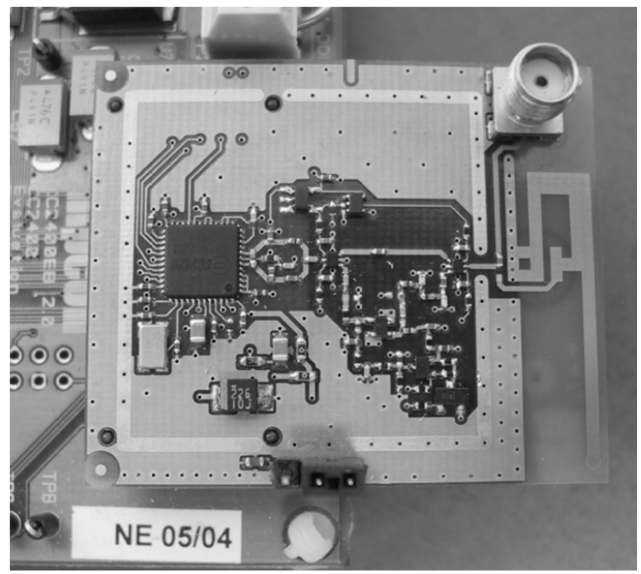
SPECIFICATIONS	
Cost	$175 per unit
Form Factor	5 cm x 6 cm x 2 cm
Energy Source	5 AA Batteries
Active Power	200 mW
Sleep Power	20 mW
Range	100 m
Data Rate	250 Kbps
Sample Rate	100 kHz

Power Amplified Telemetry

- **Large-scale structures require long-range communication**
  - Civil structures, such as bridges, defined by 100’s and 1000’s meters
- **To achieve greater range, *Narada* amplifies its output:**
  - Power amplifier circuit designed to achieve 10 dBm output gain
  - Communication range (line-of-sight) is over 700 meters



Narada with regular and extended range radios



Power amplifier circuit for CC2420

Power Challenges

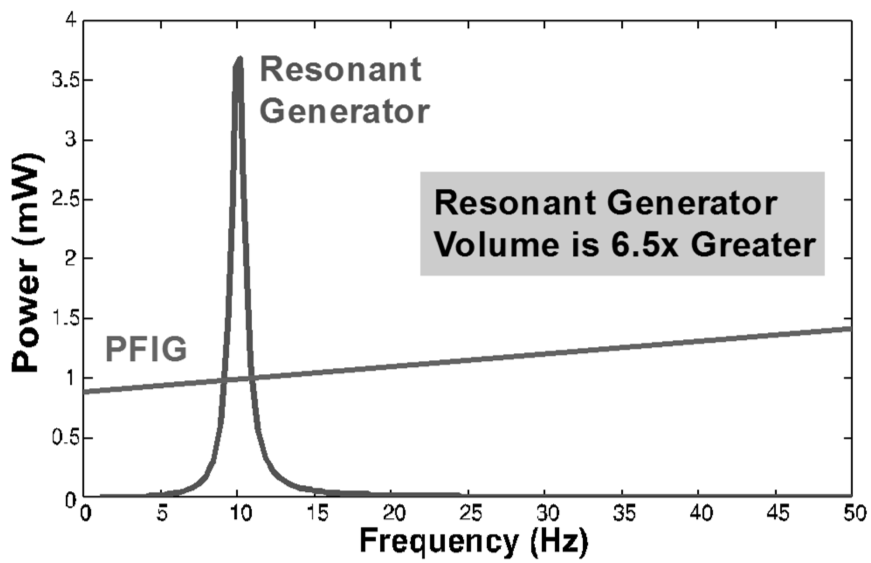
- **Power remains the #1 Achilles heel of wireless sensors:**
  - Solution #1 – Embedded data processing in-network:
    - For most applications, more power-efficient to process data at the sensor node than to transmit raw sensor data
  - Solution #2 - Power harvesting:
    - Solar panels used to keep *Narada* battery pack charged
    - Ambient vibrations targeting powering wireless sensor nodes

Battery replacement a management headache and environmental challenge

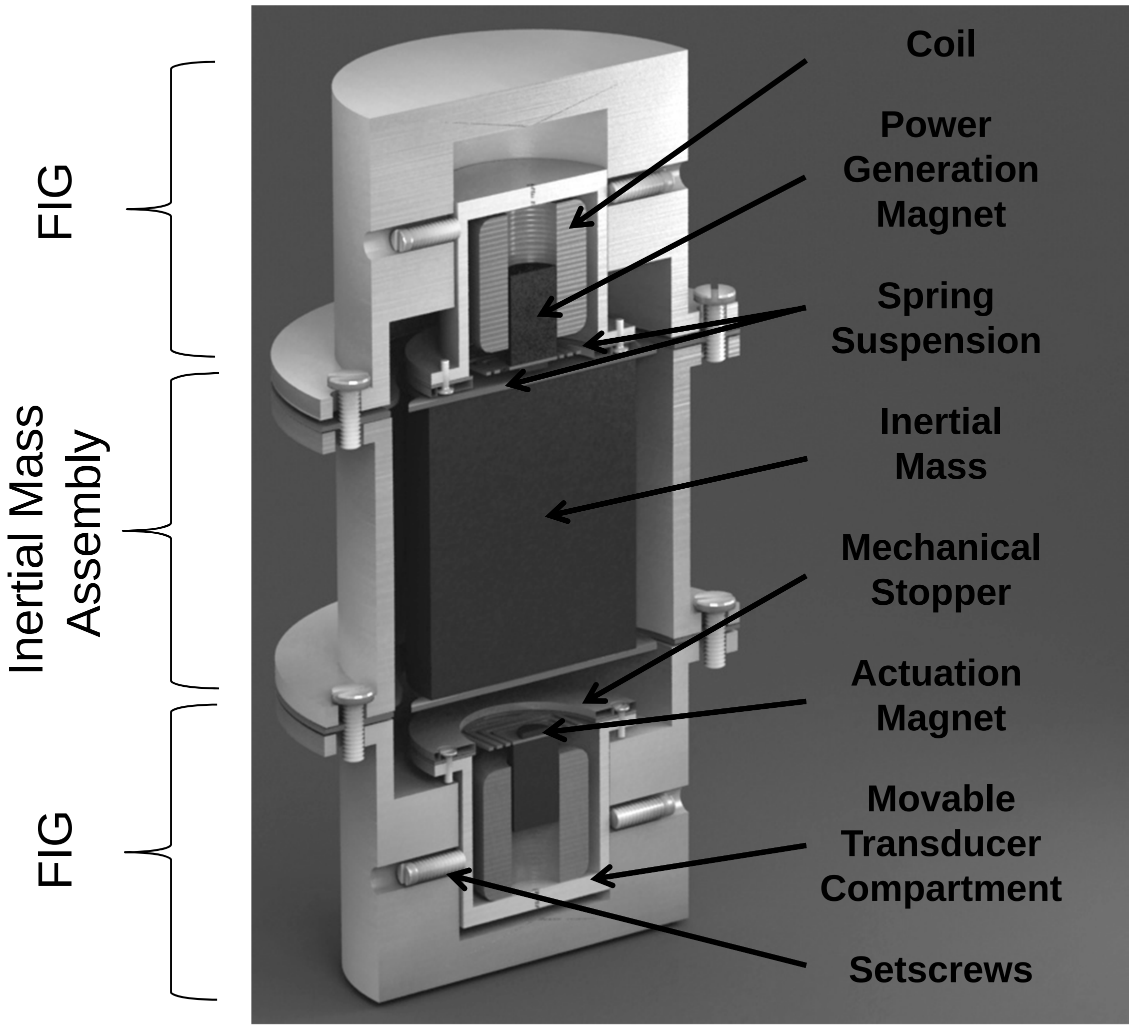
Harvesting Power from Vibrations

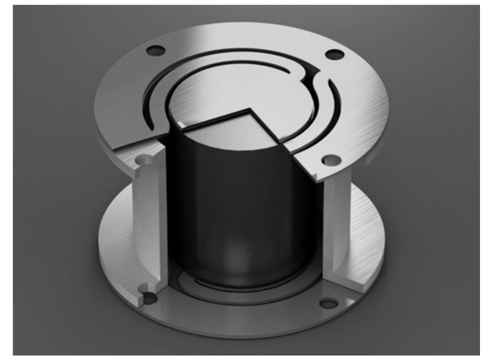
- **Challenges with mechanical harvesting on bridges:**
  - Low frequency (<10 Hz) non-periodic vibrations
  - Low forces available (< 0.1 g of response acceleration) requiring mass
- **Parametric Frequency-Increased Generator (PFIG):**
  - Offers large bandwidth (22 Hz)
  - Requires minimum input acceleration for actuation

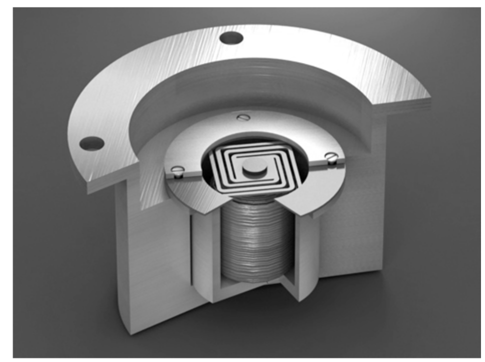
In collaboration with Prof. Khalil Najafi and Dr. Becky Peterson (Michigan)

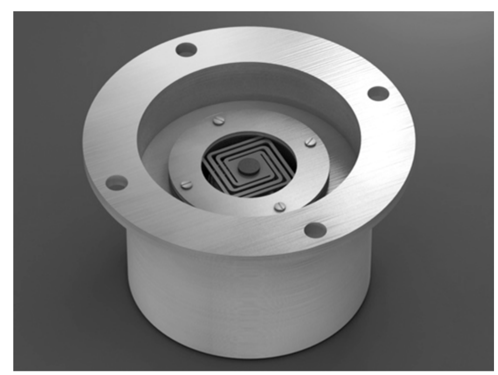


4^{th} Generation PFIG Design





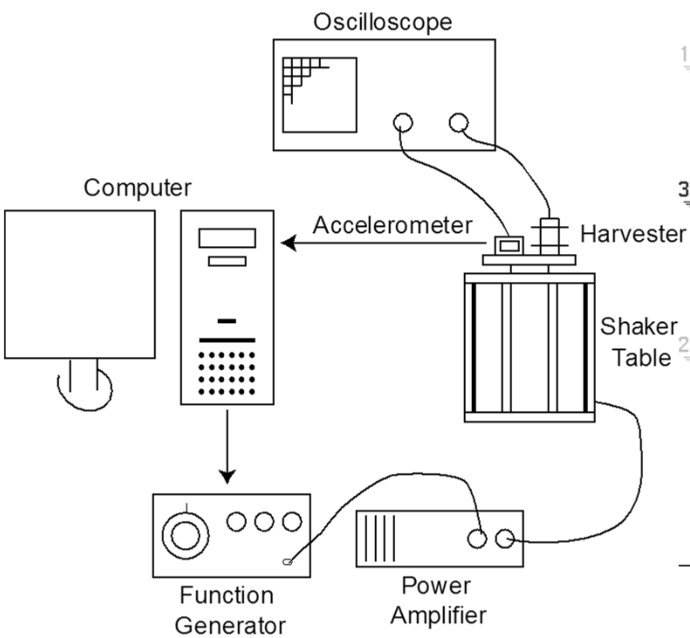


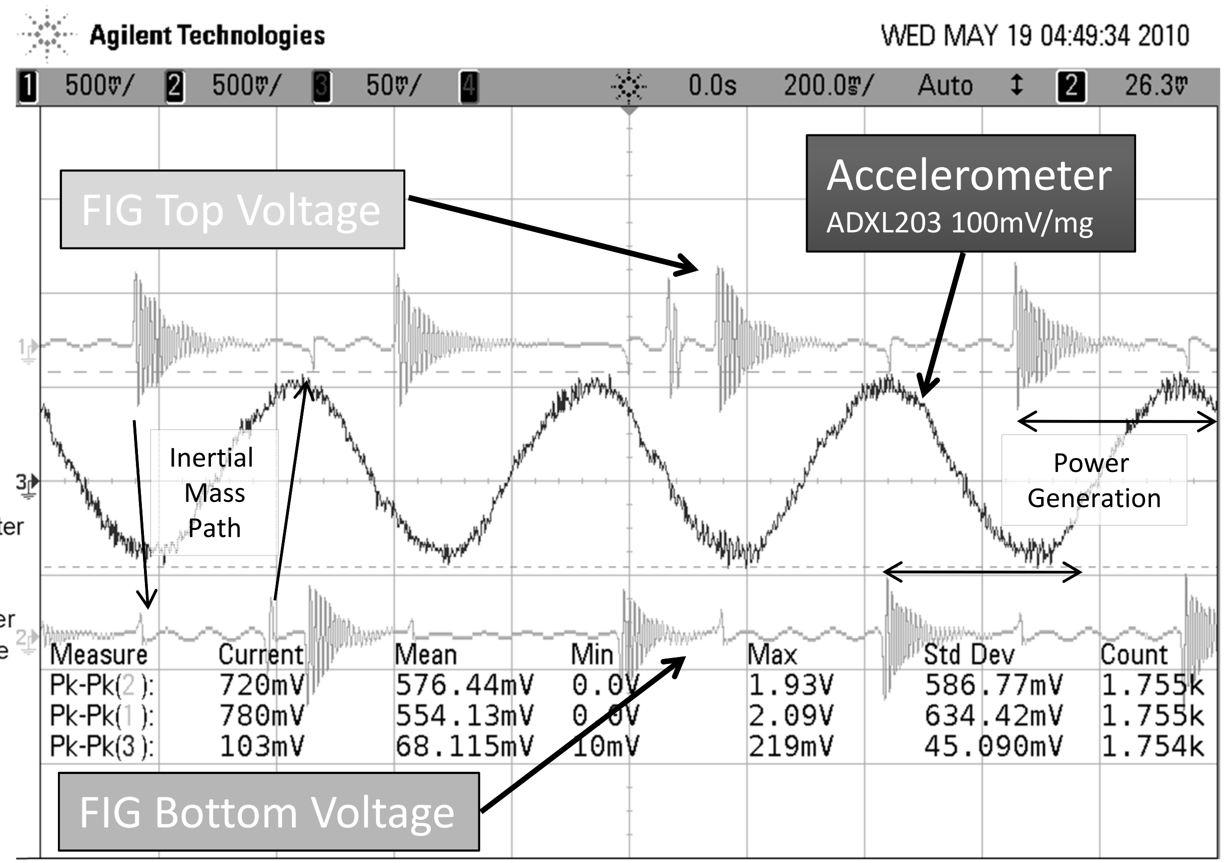


PFIG Performance

Input Vibration

0.055 g @ 2Hz





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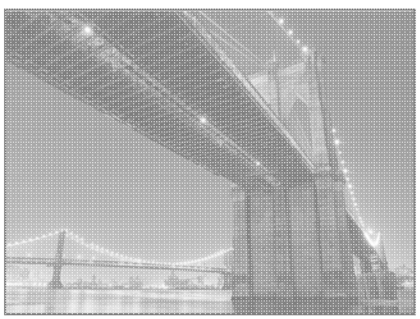

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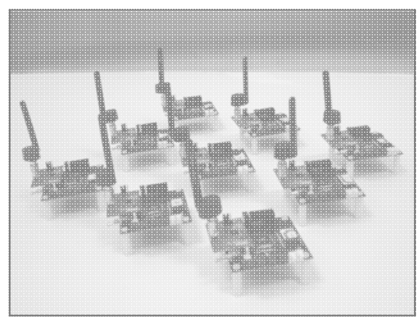

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3. New Carquinez Bridge Field Study

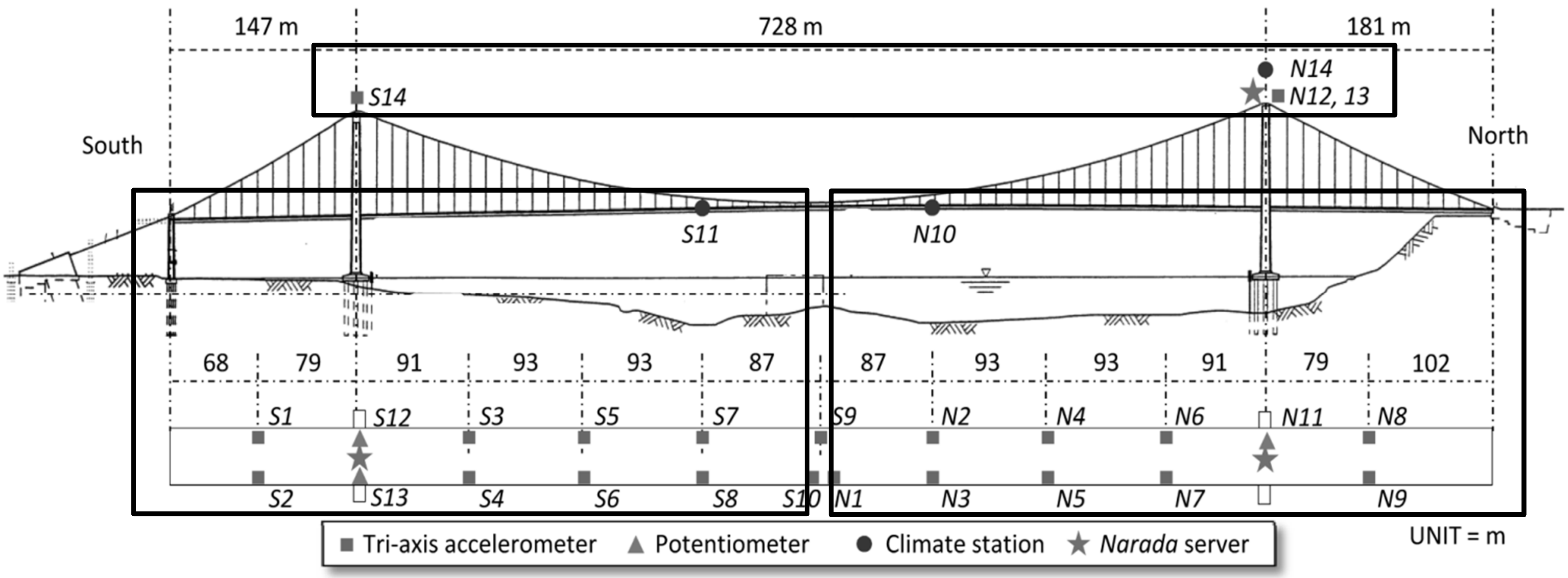
New Carquinez Bridge

- **New Carquinez Bridge (constructed 2003):**
  - Located in the San Francisco Bay Area (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

New Carquinez Bridge, California

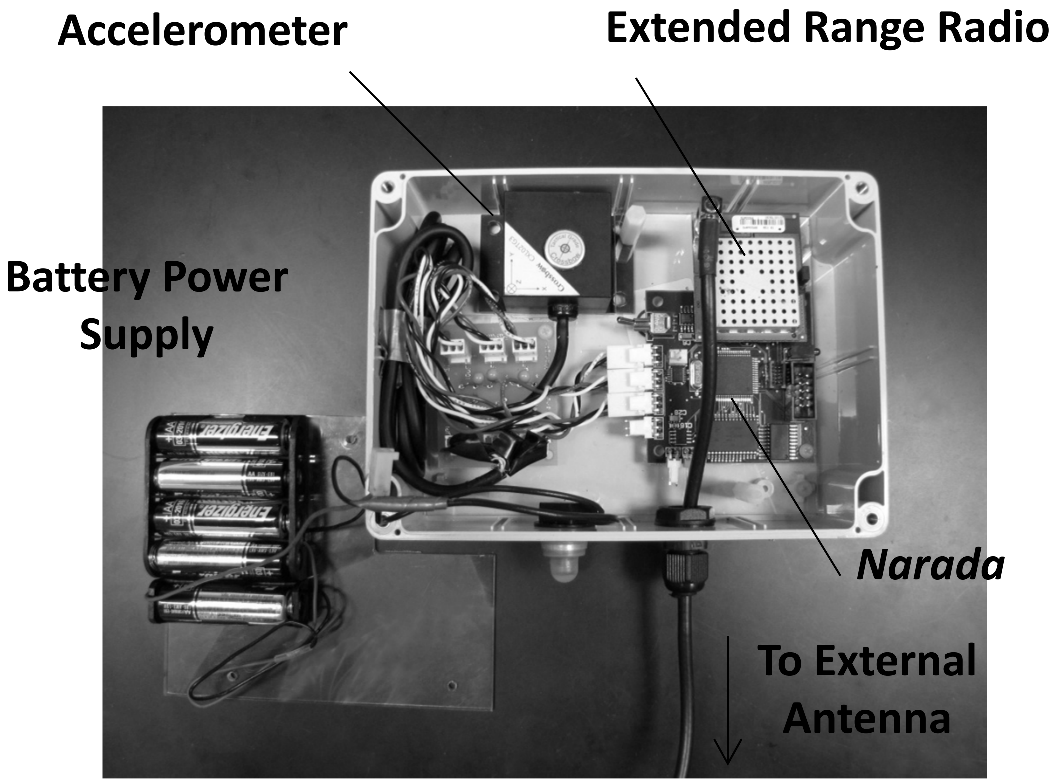
Phase 1 Instrumentation

- **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

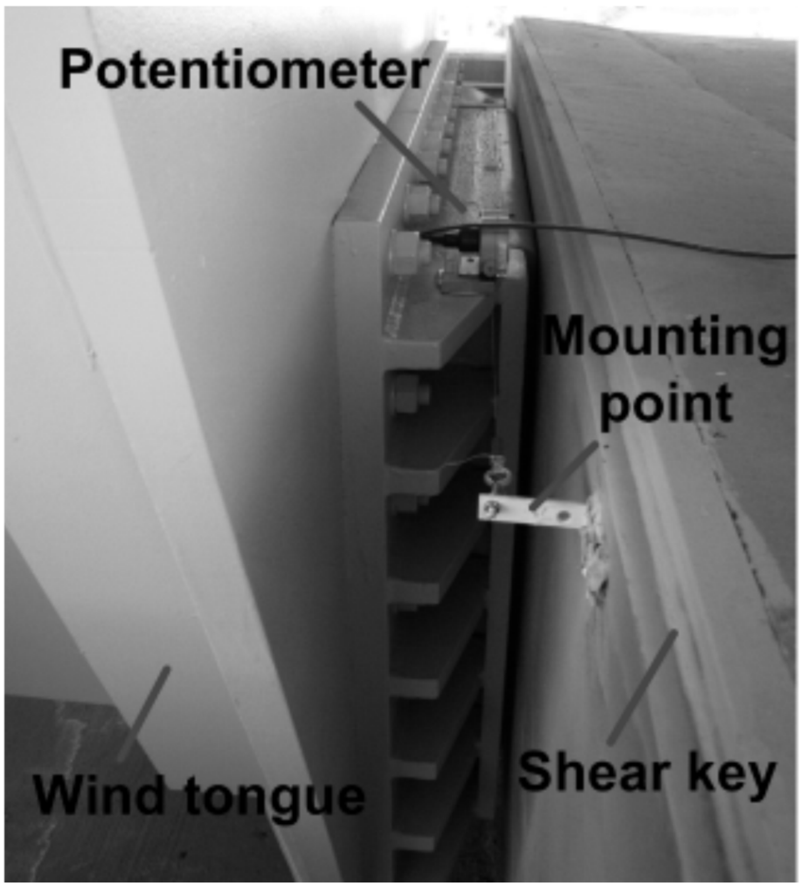


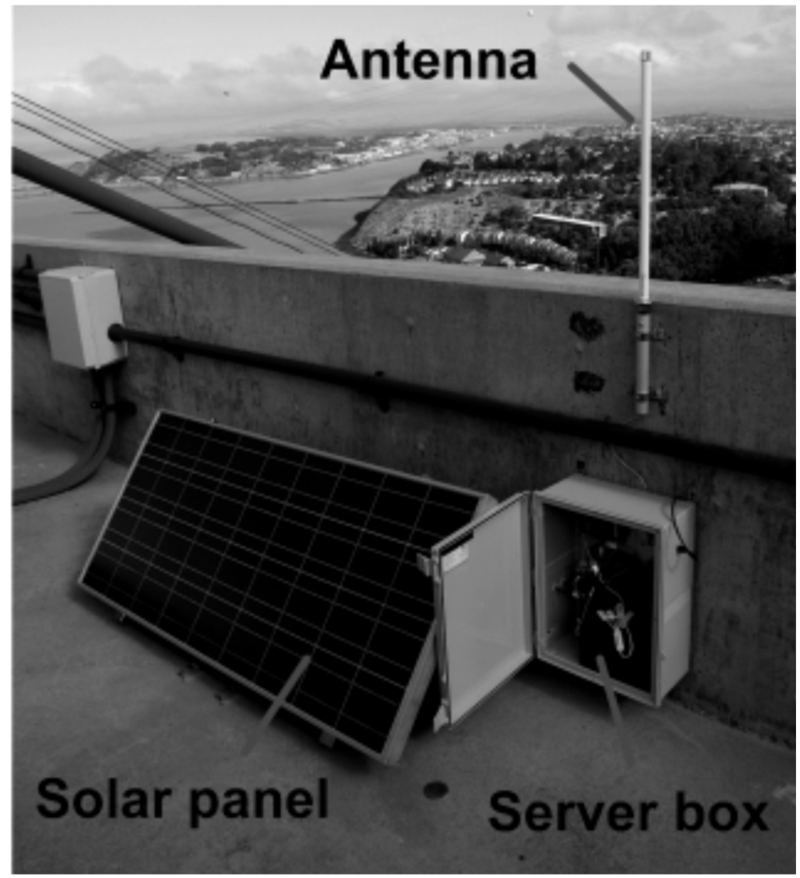
Packaged *Narada* Units

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



Installation Details





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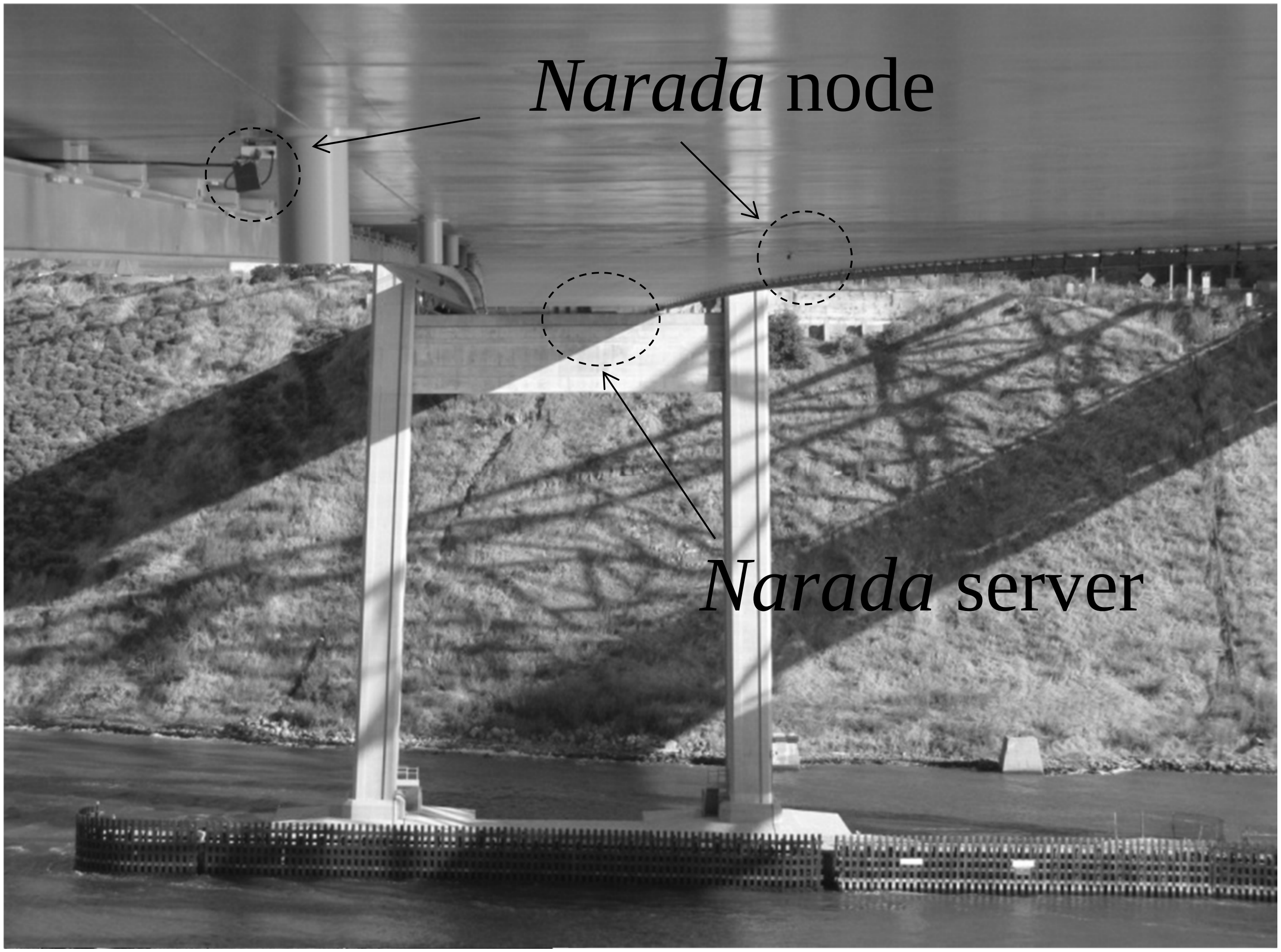
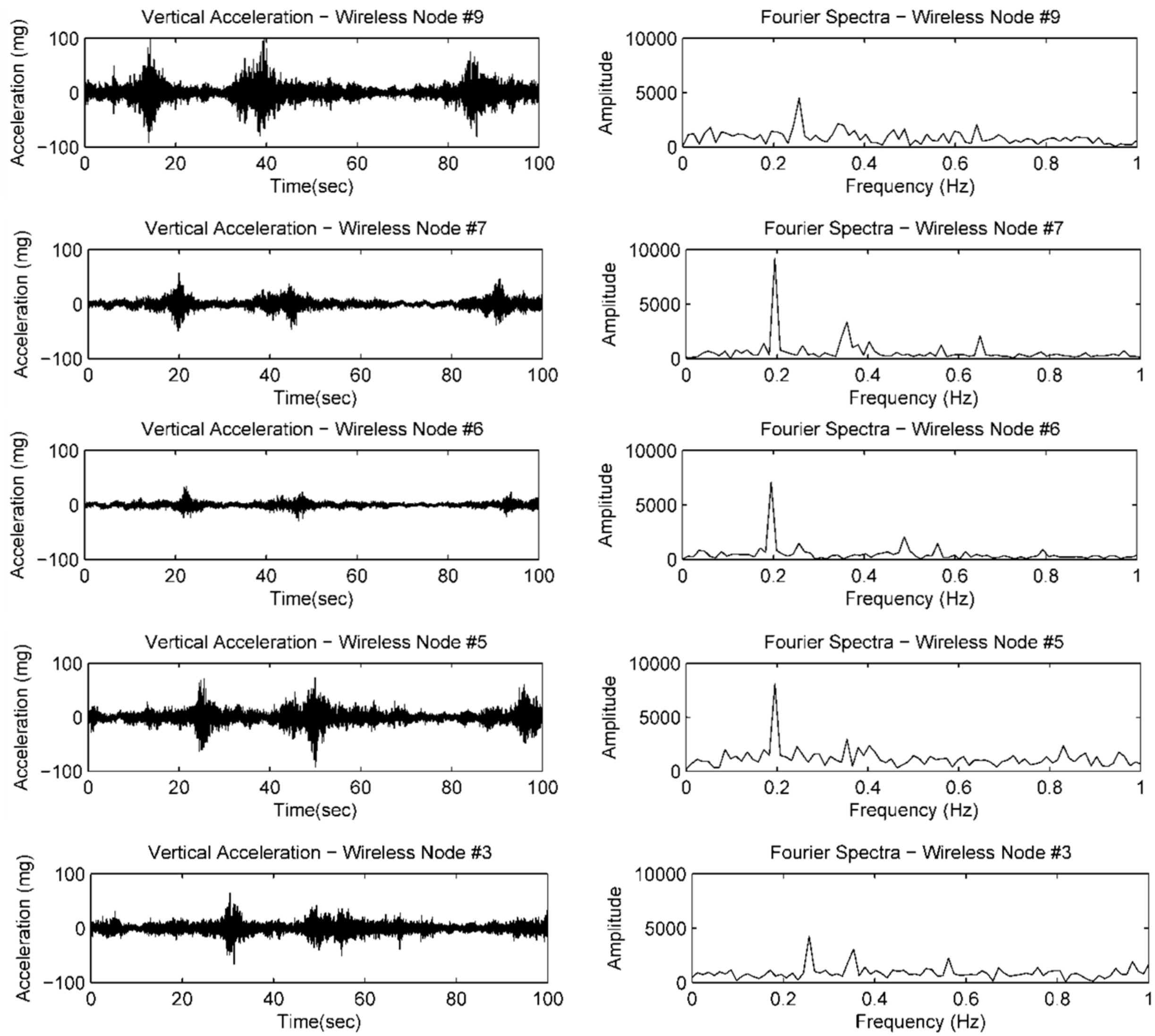
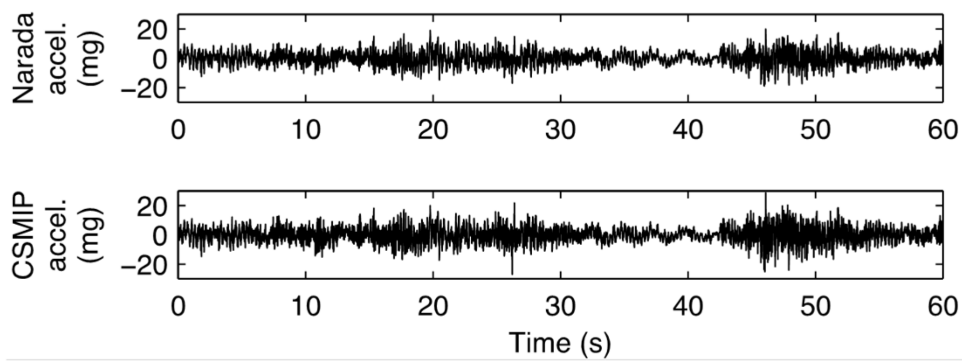


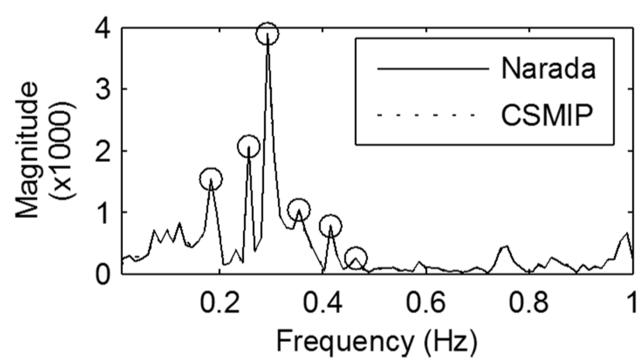
Ambient Vibrations



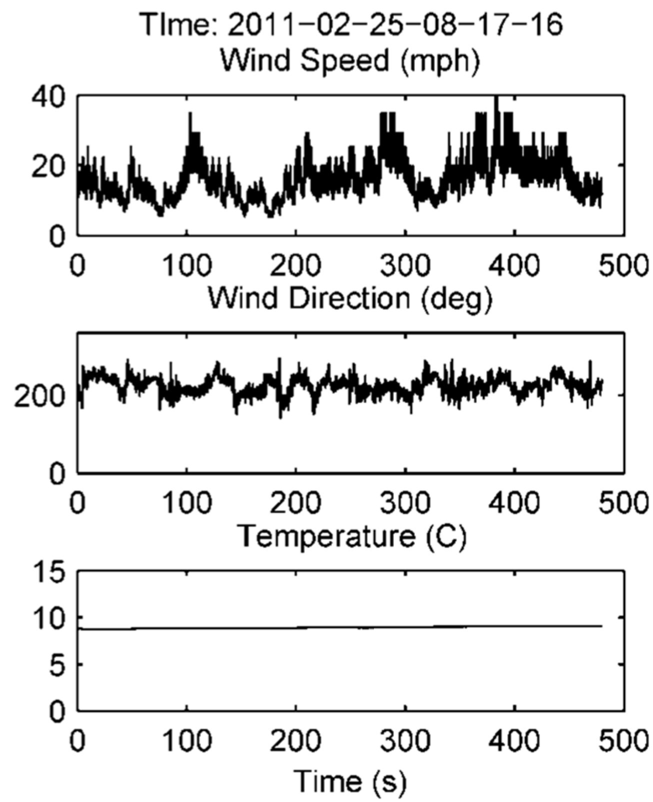
Comparison to CSMIP Data

- **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)



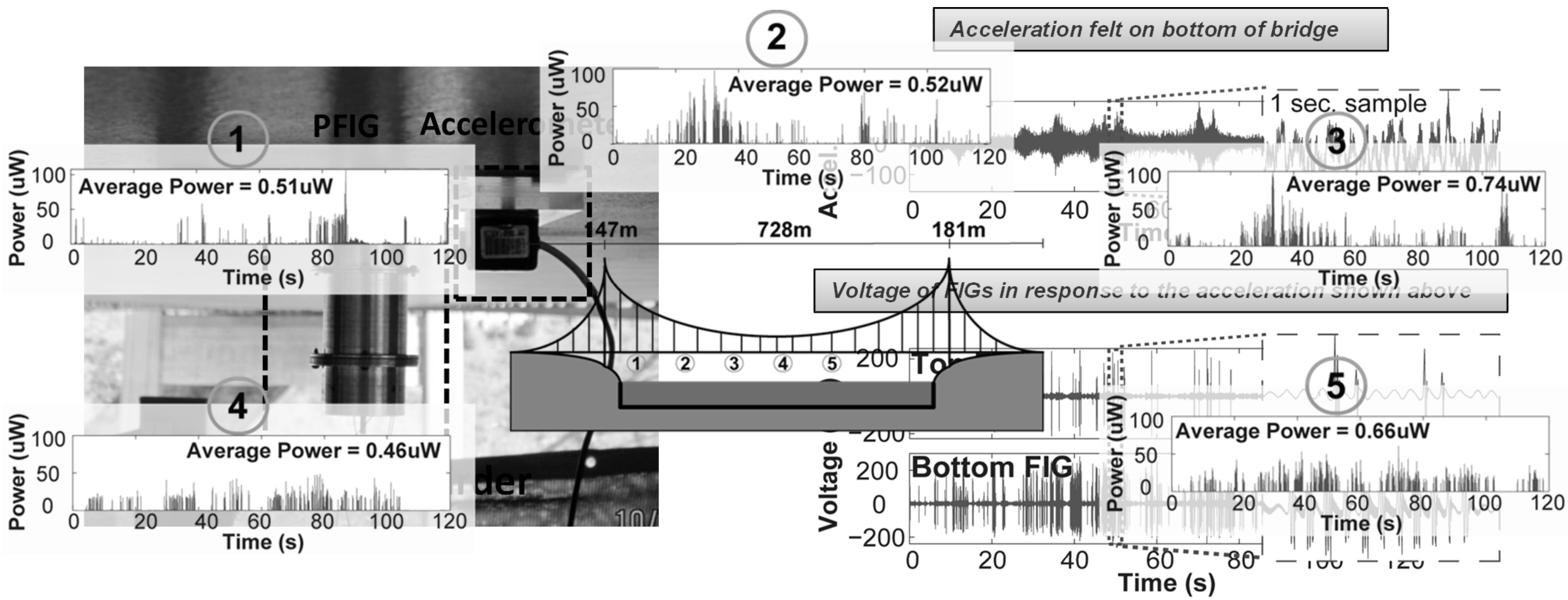


Environmental Data



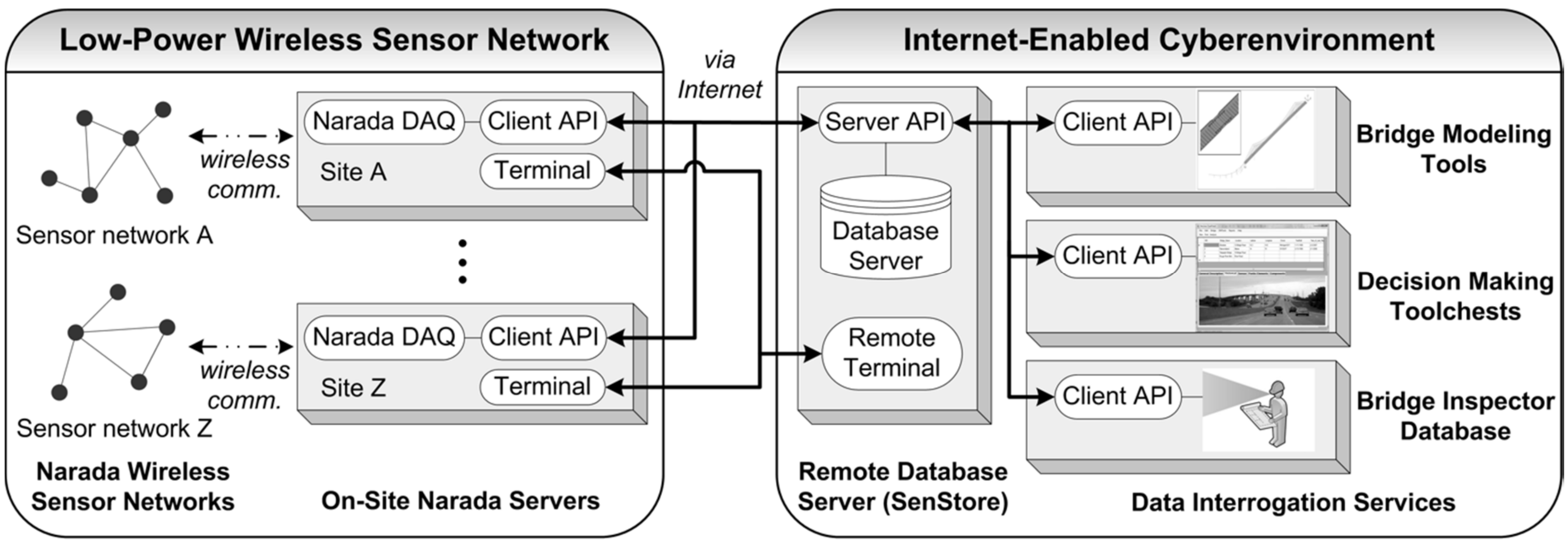
Power Harvesting on NCB

- **PFIG validated on the NCB during ambient vibrations:**
  - PFIG closely monitored using a LabView DAQ system
  - Accelerations in the 30 - 100mg range experienced
  - 0.5-0.75uW constant (average) supply capability verfieid



Cyberinfrastructure

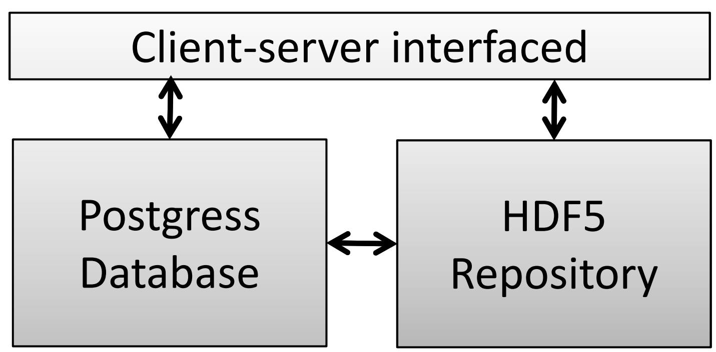
- **What do you do with data from hundreds of channels?**
  - Sensor technology has outpaced data management tools
- **Cyberinfrastructure tools offer enormous potential:**
  - Data combined with powerful analytical tools
  - Physics- and statistics-based information discovery



Proposed Cyberinfrastructure Framework for Bridge SHM

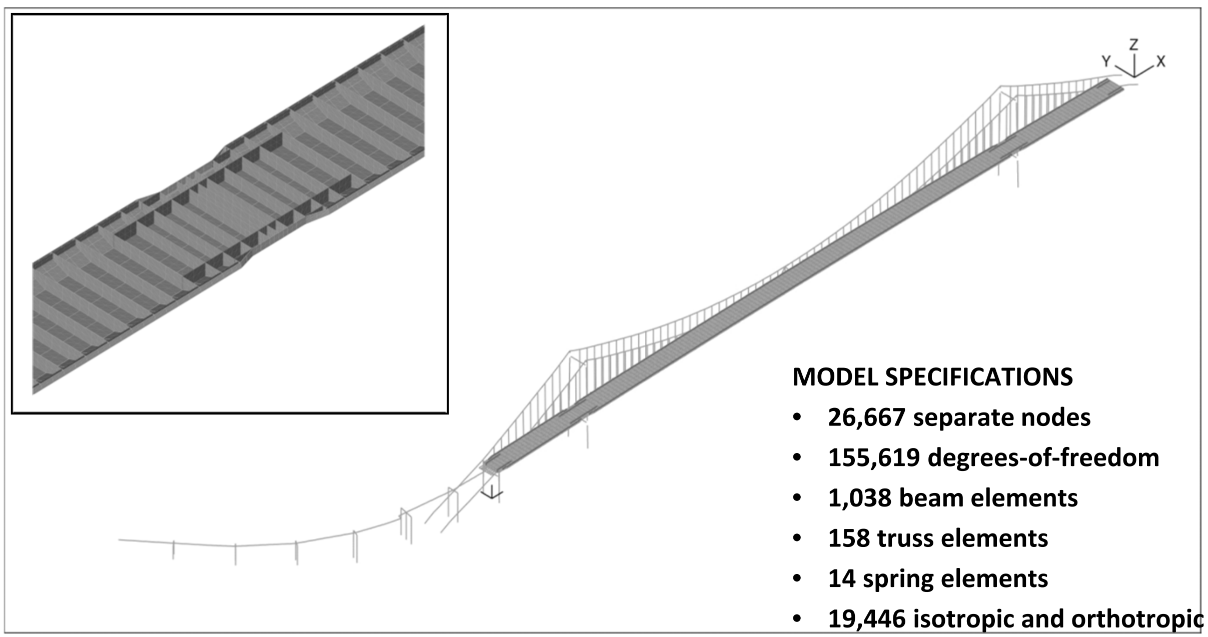
SenStore Database Architecture

- **Relational Database:**
  - Relational database to store all non-sensor bridge information
  - Full description of bridge for automated finite element modeling
  - Bridge management information (inspector reports, etc)
- **HDF5 Repository:**
  - Relational database not an efficient means of storing sensor data
  - Natural means of storing large tracks of time history data
- **Client-server interfaces exposed for data extraction**



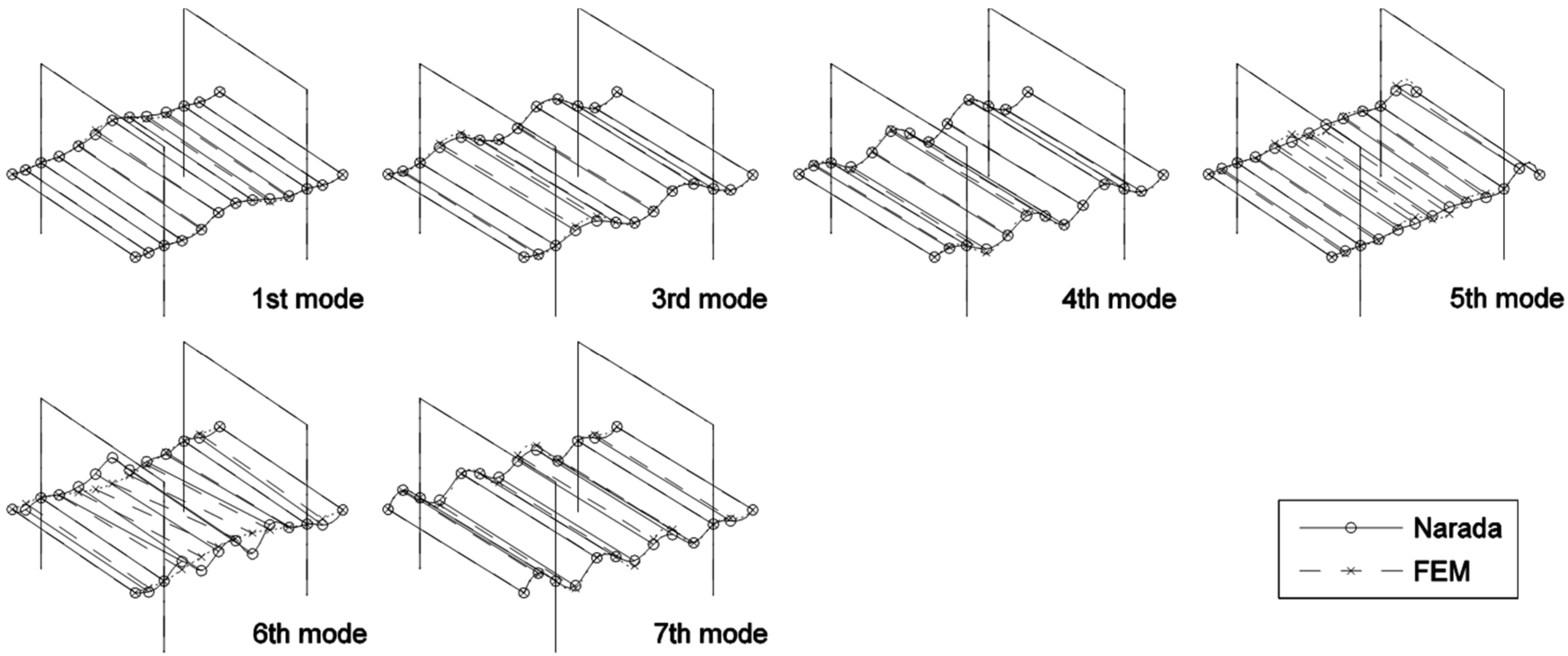
Automated Mode Extraction

- **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

- **In-network 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



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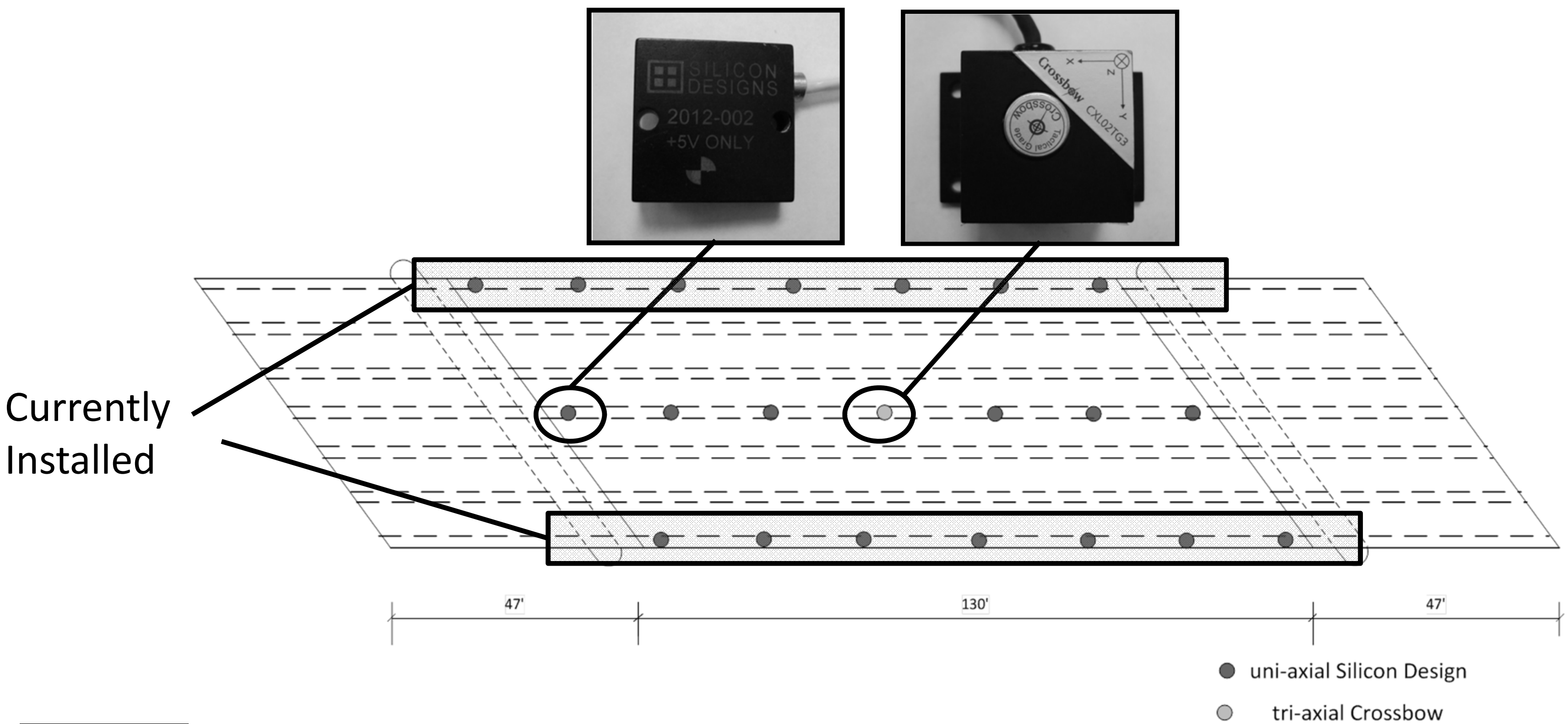
Mode	Frequency (Hz)			Mode shape MAC	
	Narada	CSMIP	FEM	*Narada* vs CSMIP	*Narada* vs FEM
1	0.193	0.194	0.212	0.996	0.956
2	N/A	0.205	N/A	N/A	N/A
3	0.260	0.261	0.271	0.960	0.969
4	0.350	0.351	0.365	0.937	0.973
5	0.407	0.413	0.412	0.843	0.525
6	0.465	0.455	0.492	0.101	0.085
7	0.487	0.484	0.502	0.889	0.913

Telegraph Road Bridge

- **I-275 in Monroe, MI**
- **Cantilever bridge design:**
  - 223 feet long
  - 7 steel girders
  - Pin/hanger construction
- **Observed deterioration:**
  - Deteriorated roadway
  - Fatigue in girder webs
  - Failed abutment
  - Pin-hanger connections

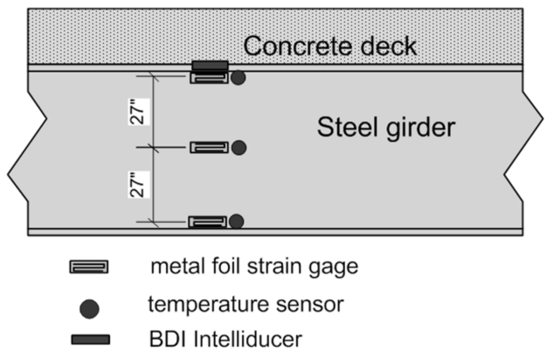
Wireless Monitoring System

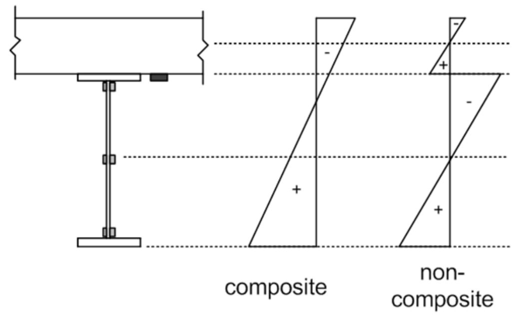
- **System deployed in 2011 and currently being expanded:**
  - Accelerometers currently used to measure vibrations due to traffic loads and wind load (vertical and horizontal, respectively)
  - Used in automated updating of finite element model of bridge



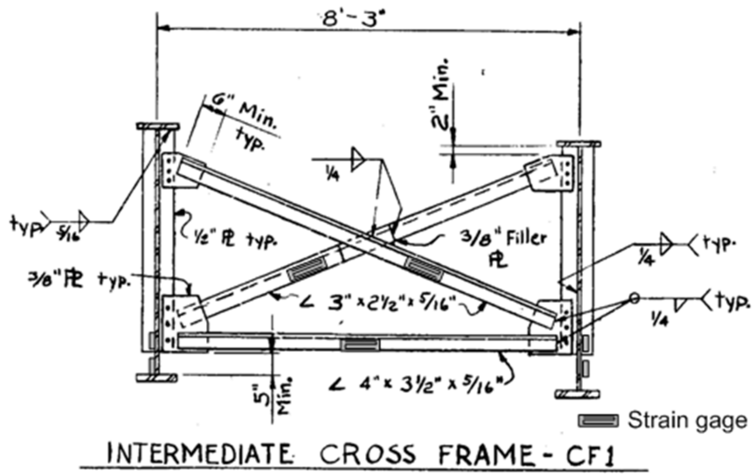
Wireless Sensors Deployed

Installation of Strain Gages

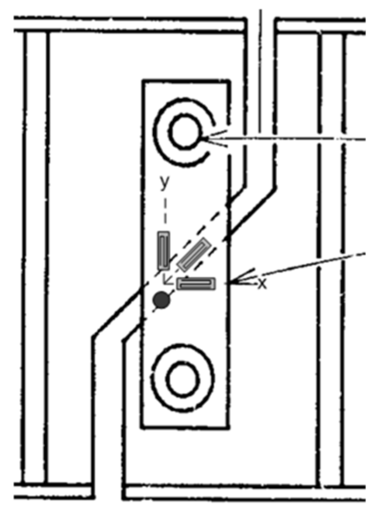




Composite Action Monitoring to Understand Span Flexural Behavior



Monitoring Bracing to Identify Fatigue



Monitoring Hangers to Identify Fatigue

Summary

- **Powerful new technologies proposed for SHM systems:**
  - Ultra low-power wireless sensors with embedded data processing
  - Broadband vibration-based power harvesting
  - Powerful cyberenvironment for asset managers for physics-based and data-driven data mining
- **Validation of all monitoring technologies underway:**
  - New Carquinez Bridge has been an invaluable testbed for validation
    - Phase I deployment of the wireless monitoring system complete
    - Currently using 28 wireless sensor nodes collecting 81 channels
  - Telegraph Road Bridge also being instrumented:
    - Phase I deployment of 14 wireless accelerometers completed
    - Phase II about to initiate with installation of 30+ strain gages

Thank You!

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