Cyber-enabled Wireless Monitoring Systems for Critical Infrastructure Systems: A Retrospective Summary of Technology Development and Field Validation

Abbas Emami-Naeini
Director
SC Solutions, Inc.
Sunnyvale, CA 94085

Jerome P. Lynch
Dept. of Civil and Environmental Engineering
Dept. of Electrical Engineering and Computer Science
University of Michigan, Ann Arbor, MI 48019

NIST Civil Infrastructure Showcase
March 13, 2014

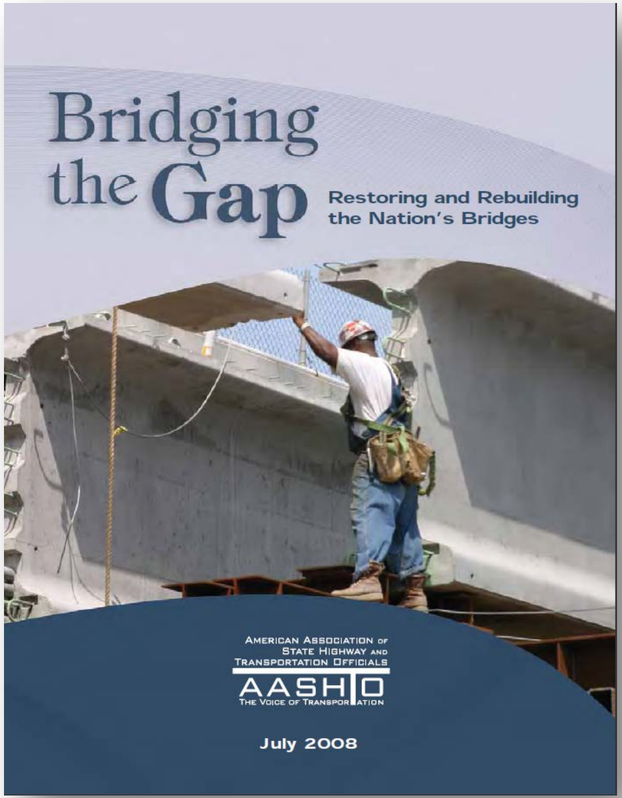
Importance of Critical Infrastructure

- **Civil infrastructure is the backbone for the U.S. economy:**
  - Strategic advantage the U.S. has enjoyed since the mid-1900's
  - Major national investment that is getting on in years

Water & Environment	Grade		Transportation	Grade
Dams	D		Aviation	D
Drinking Water	D		Bridges	C+
Hazardous Waste	D		Inland Waterways	D-
Levees	D-		Ports	C
Solid Waste	B-		Rail	C+
Wastewater	D		Roads	D
			Transit	D

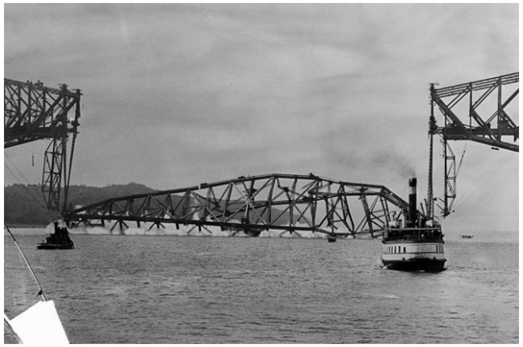
Bridges under Distress

- **5 major problems for US bridges:**
  - Age and deterioration
  - Bridges are chokepoints in the freeway system
  - Soaring construction costs means states must do *less* for *more money*
  - Delay in new bridge construction jeopardize economic growth
  - Unable to maintain bridge safety due to funding shortages



- **Top 2 solutions for bridge systems:**
  - Investment - have to significantly increase transportation investment in the US
  - Research and Innovation - innovations in design, materials, and associated technology are needed to advance a new generation of safe and long-lasting bridges

Notable Bridge Failures



Quebec Bridge, Canada (95 deaths)
September 11, 1916
[Inadequate capacity]

Silver Bridge, OH (46 deaths)
December 15, 1967
[Stress corrosion cracking in eyebar]

Mianus Bridge, CT (3 deaths)
June 28, 1983
[Corrosion induced plate movement]

Songsu Bridge, Korea (31 deaths)
October 21, 1994
[Poor design, construction and upkeep]

Hoan Memorial Bridge, WI
December 13, 2000
[Thermal and traffic loads]

I35 Bridge, MN (13 deaths)
August 1, 2007
[Under-designed gusset plates]

Current Management Strategies

Visual Inspection (VI) Methods

- **Primary management approach for US bridges:**
  - National Bridge Inspection Program mandates bi-annual inspection
  - Leverages expertise and insight of a human inspector
  - Can have some variation but rigorous quality control programs aim to minimize inspector-based variations
  - Offers a wealth of *qualitative* data on bridge health

Non-destructive Evaluation (NDE) Methods

- **Important tool for bridge health assessment:**
  - Inspector-driven measurement approach to collect quantitative data on a facet of bridge health
  - Manually applied techniques
  - Expensive instrumentation requiring technician expertise
  - Often requires *a priori* knowledge of bridge "hot spot" to investigate with NDE method

Structural Monitoring (SM) Methods

- **Increasingly popular approach:**
  - Permanent array of installed sensors measuring bridge behavior continuously or on triggering events
  - Wealth of quantitative data available for health assessment
  - Expensive technology still due in large part to being wired
  - Data inundation remains a major obstacle to unlocking true value of technology (ROI?)

The Monitoring Paradox

- **Age old adage that "information is power":**
  - Tempting to pursue more data regarding asset performance
  - Advanced sensing technologies making this more of a possibility
- **Monitoring data – a double edged sword for owners?**
  - We swim in an ocean of data but remain thirsty for information
  - Scalable data management direly needed to avoid data inundation
  - Physics-based and data-driven tools are needed to extract information

Key Point:

Our ability to collect data using new and fancy sensors has *far outpaced* our ability to analyzed that data – we are not yet empowering the decision-maker!

Who is our "Customer"?

- **Major bridge owners with significant bridge inventories:**
  - *Michigan:* More than 10,000 bridges with an average age of 41 years
  - *California:* More than 24,500 bridges with an average age of 44 years
- **Benefits of SHM are based upon the *decisions* of owners:**
  - Overall risk reduction of their asset inventories
  - Increased public safety and public confidence
  - Discovery of structural reserves after construction
  - Early detection of deterioration and defects = cost effective upkeep
  - Extended service lives = greater amortization of initial cost and energy

MDOT

Caltrans

NIST Technology Innovation Program

- **Comprehensive design of a cyber-enabled monitoring system:**
  - Cyber-environments for SHM-driven decision making
  - Based on wireless telemetry as a core building block of the system
- **We are not advocating getting more data:**
  - We are focused on getting end-users “information,” not just “data”
  - Top-down instead of bottom-up SHM system design
- **NIST TIP Project:**
  - 5 year effort that spanned from February 1, 2009 to January 31, 2014

University of Michigan (LEAD)

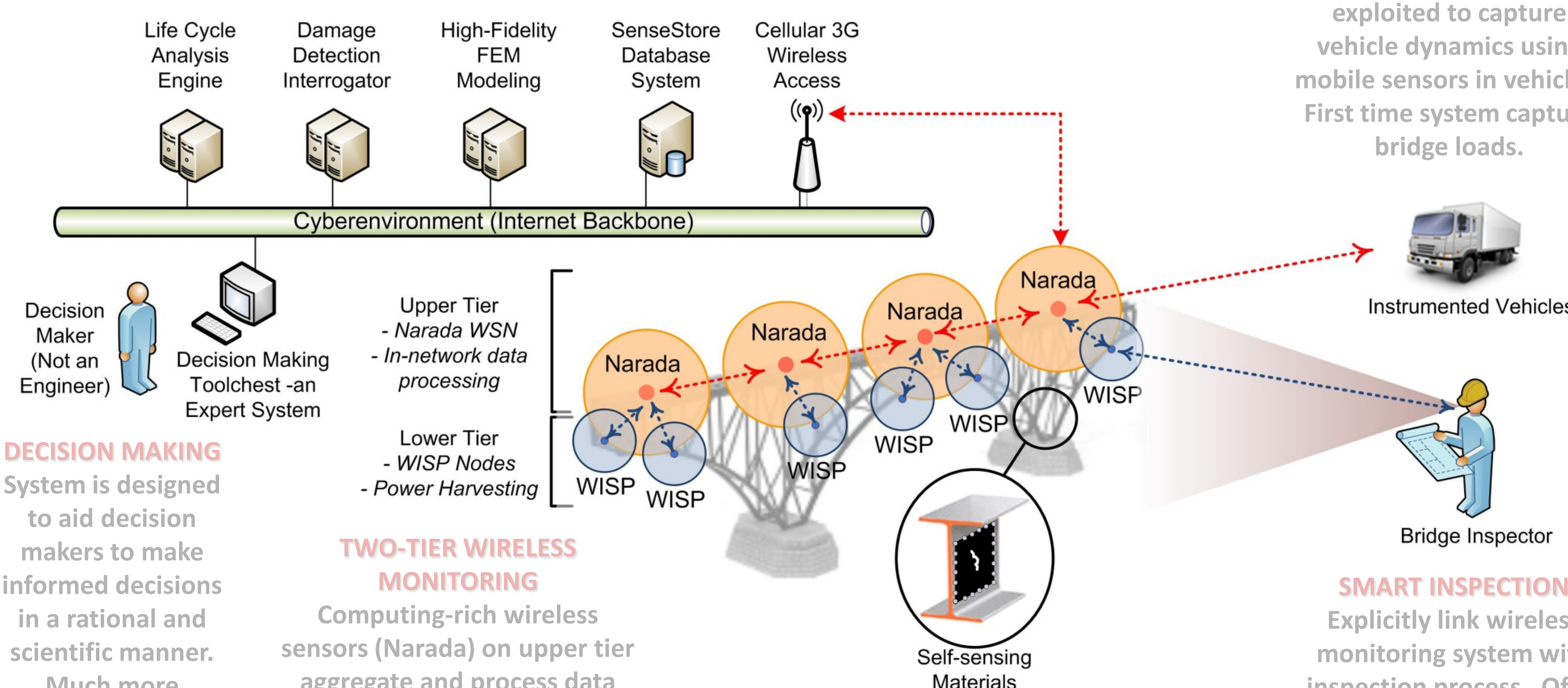
Industrial Partners

Government Partners

NIST TIP Project Roadmap

CYBERINFRASTRUCTURE
Data is passed to the internet by 3G cellular network where it is stored in a database and analyzed using various data mining tools

VEHICLE INTERACTION
Wireless communication exploited to capture vehicle dynamics using mobile sensors in vehicles. First time system capture bridge loads.



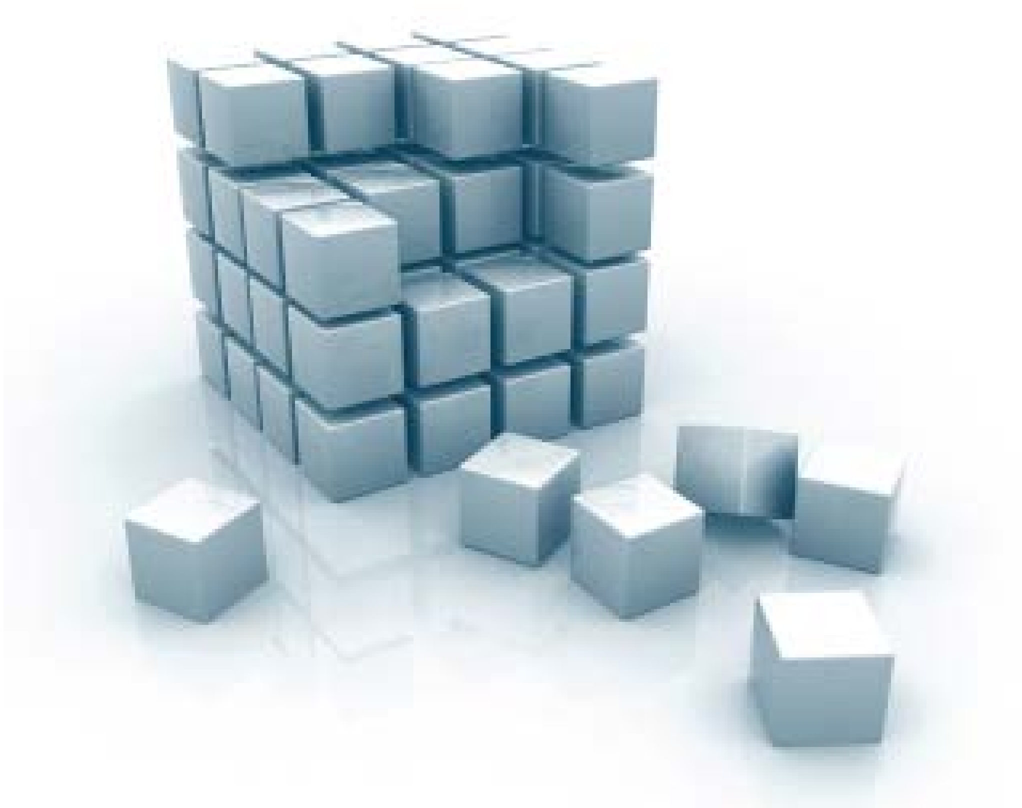
DECISION MAKING
System is designed to aid decision makers to make informed decisions in a rational and scientific manner. Much more effective than inundating owners with raw data

TWO-TIER WIRELESS MONITORING
Computing-rich wireless sensors (Narada) on upper tier aggregate and process data from low-power wireless slaves (WISP) on lower tier. Wireless sensing saves cost by one order of magnitude.

SELF-SENSING MATERIALS
Self-sensing materials including ECC and CNT sensing skins provide detailed, local information on structural damage and degradation *directly*.

SMART INSPECTION
Explicitly link wireless monitoring system with inspection process. Offer modes of interaction between inspector and bridge.

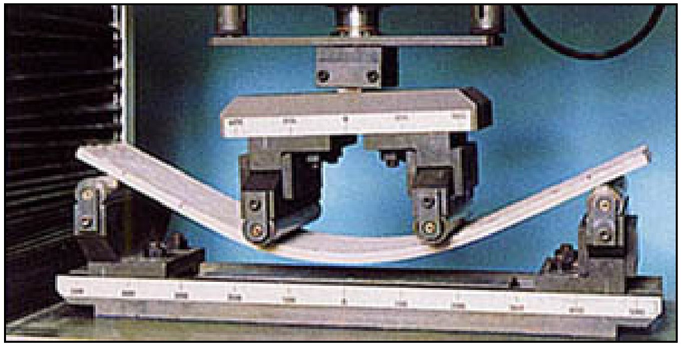
Building Blocks



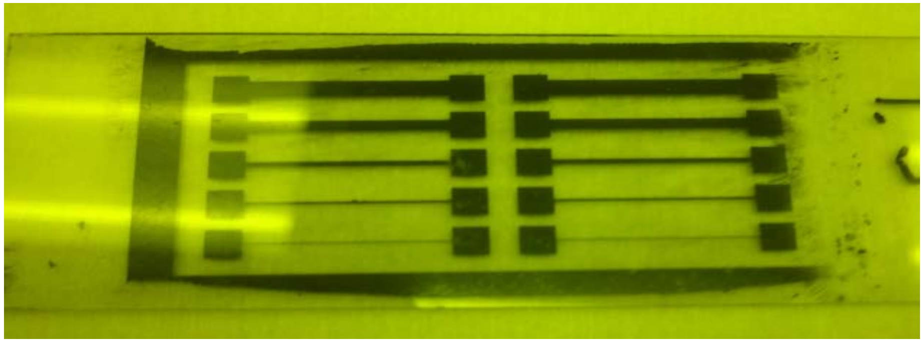
- **Self-sensing Materials**
- **Low-power Wireless Sensing**
- **Self-structuring Antennas**
- **Embedded Data Processing**
- **Power Harvesting**
- **Cyber-infrastructure Tools**
- **Risk and Reliability Assessment**
- **Decision Making Tool-chest**
- **Data-driven Inspection**
- **Vehicle-Bridge Interaction**

Self-Sensing Materials

- **Today's sensing paradigm is based on point sensors:**
  - Point sensors provide measures of localized structural responses
  - Damage is then inferred from inverse modeling which is often ill-posed
- **Distributed damage sensing using multifunctional materials:**
  - Create a new generation of materials tailored at nano-scales
  - Embed strength, ductility *and* sensing capabilities
  - This project focused on self-sensing cement and CNT thin films for *distributed* sensing in civil infrastructure components



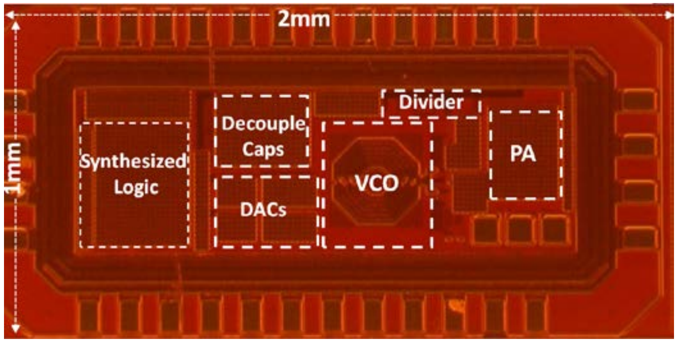
Self-sensing and self-healing ECC
[Utilized self-sensing to identify crack damage]



Patterned Thin-Film Nanoengineered Sensing Skins
[Lithographically assisted CNT film patterning]

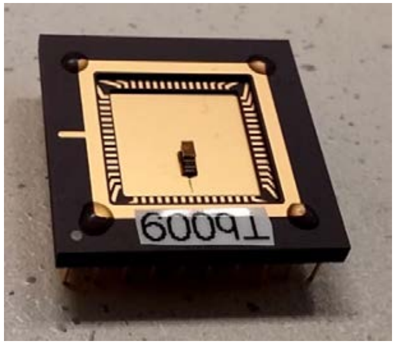
Ultra Low Power Wireless Sensing

- **Current wireless sensors are too power hungry:**
  - Current wireless sensors are too powerful to be truly battery free
  - Powerful new Integrated circuit techniques and VLSI methods
- **Goal of the project was to create an ultra-lower power node:**
  - IEEE802.15.4 transmitter consuming only 12 mW of power
  - Phoenix ARM-based microprocessor with ultra-low power sleep states
  - Demonstration of Phoenix on PCB an in a mm-scale packaging



Ultra low-power IEEE802.15.4 transmitter
[0.13 um CMOS leading to 10-20 mW power]

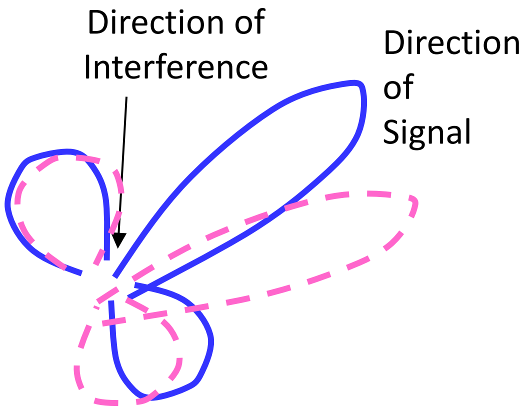
Phoenix Processor WISP Node
[Ultra-lower Phoenix + COT Radio]



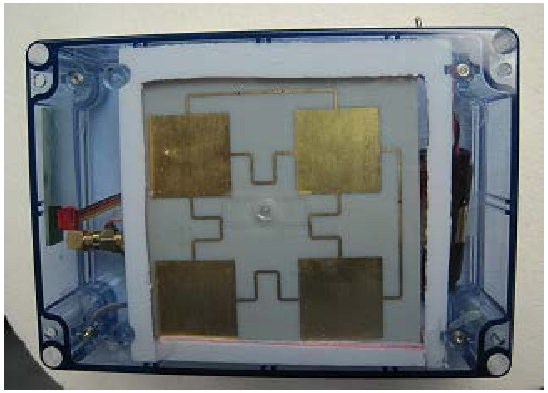
Stacked mm-scale sensor
[~2 mm^3]

Self-Structuring Antenna Technology

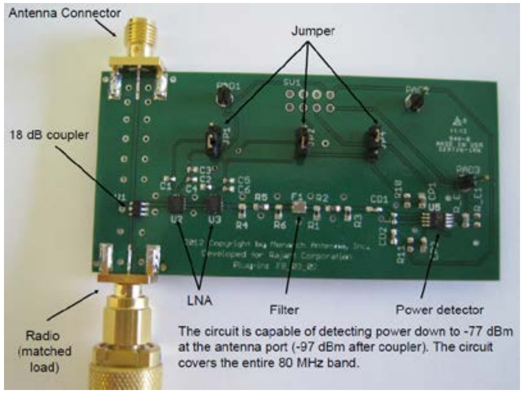
- **Civil infrastructure operate in harsh RF environments:**
  - A key attribute of this harsh environment is its time varying nature
  - As a result, impossible to truly optimize the antenna's performance
- **Self-structuring antenna (SSA) is a major paradigm shift:**
  - Aperture dynamically altered depending on the RF environment
  - Real-time optimization of reception and transmission parameters
  - Beam-steering for concentrated communication pathways



Conceptual Functionality
[Steering the RF beam]



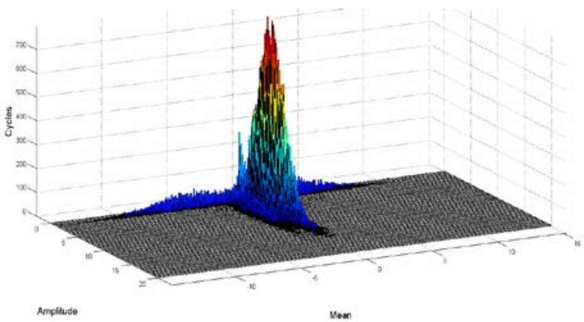
GEN 1X
[Integrated feedback circuit]



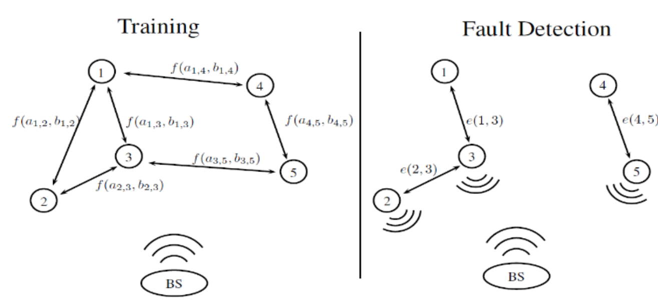
GEN 1X Feedback Circuitry
[RF probe and reconfiguration]

Embedded Data Processing

- **Sensor-based data processing is a game changer:**
  - Major power savings achieved by communicating less data
  - Enhances the scalability of the monitoring system to large node counts
- **This project developed an extensive embedded library:**
  - Fatigue assessment by rain-flow and spectral fatigue methods
  - Distributed modal analysis and system identification
  - Self-diagnosis approach to identifying sensors faults



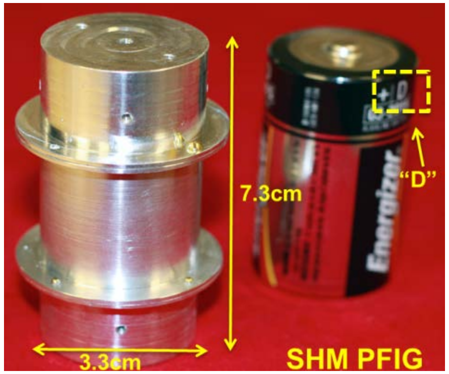
Embedded Fatigue Assessment
[Saves power and limits data glut]



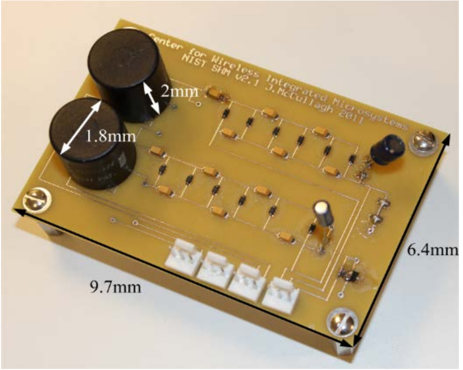
Reference-free Sensor Fault Detection for WSN
[Effective fault diagnosis method for WSN]

Power Harvesting

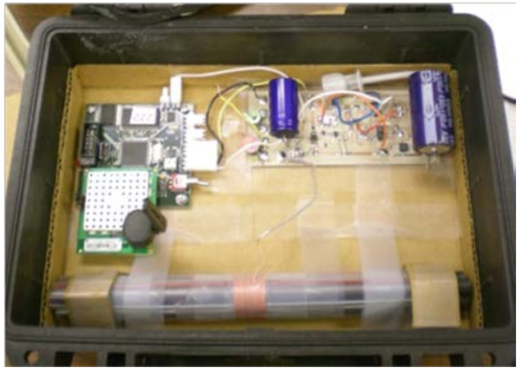
- **Multi-modal power harvesting for bridges:**
  - Don't want wires delivering power to sensor nodes
  - Battery replacement is a non-starter for most technology adopters
  - Power harvesting is still a technology in its infancy
- **Two-prong approach taken in this project:**
  - Develop a multi-modal set of harvesters to maximize energy capture
  - Major focus on power extraction circuits to up their efficiency



Broadband PFIG Harvester
[Optimized to be hardened]



Power Extraction Circuits
[IC-based extraction]

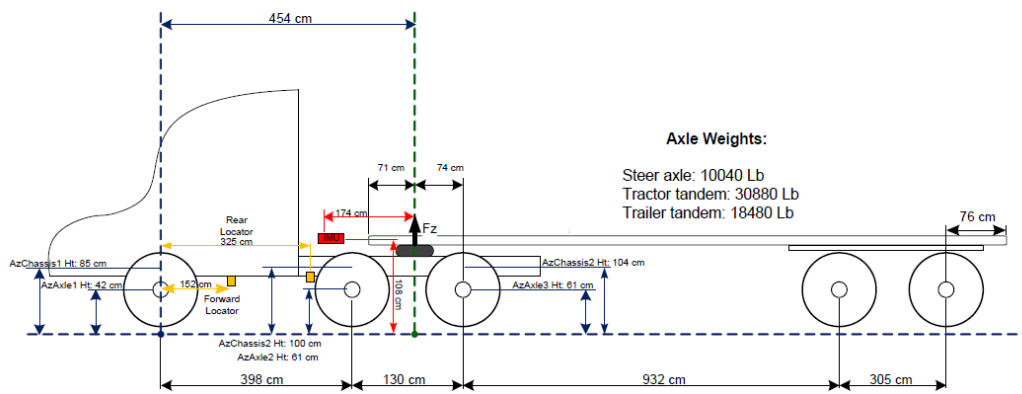


RF Harvester based on AM Radio
[High-efficiency power extraction]

Vehicle-Bridge Interaction

- **SHM algorithms do not explicitly account for the load:**
  - Without a basis for assessing load, SHM becomes further ill-posed
- **This project explores measurements of bridge loads:**
  - Static weight of bridge load accounted for using WIMS
  - Dynamic load factors explored by measuring truck loads and conducting high-fidelity vehicle-bridge interaction modeling
  - Load allows demand on bridge systems to be accounted for

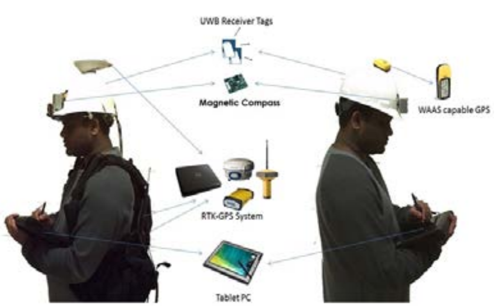
High-speed Weight in Motion
[Michigan has 20+ WIMS Stations]



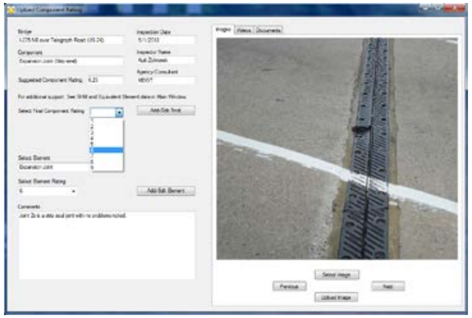
Instrumentation on UMTRI Truck
[First ever monitored and modeled vehicle-bridge interaction]

Data-Driven Inspection

- **Sensing does not free bridge owners from visual inspection:**
  - Anyway, do we really want to eliminate the visual inspector?
  - Our belief is that VI is an incredibly powerful management approach
  - Strive for a synergistic relationship between VI and sensed data
- **Direct inspector communication with the system:**
  - Inspectors access cyber environment on-site for data entry and queries
  - Context aware technology positions inspector on-site



Sensor-based Context Awareness
[Low-cost sensing platform]

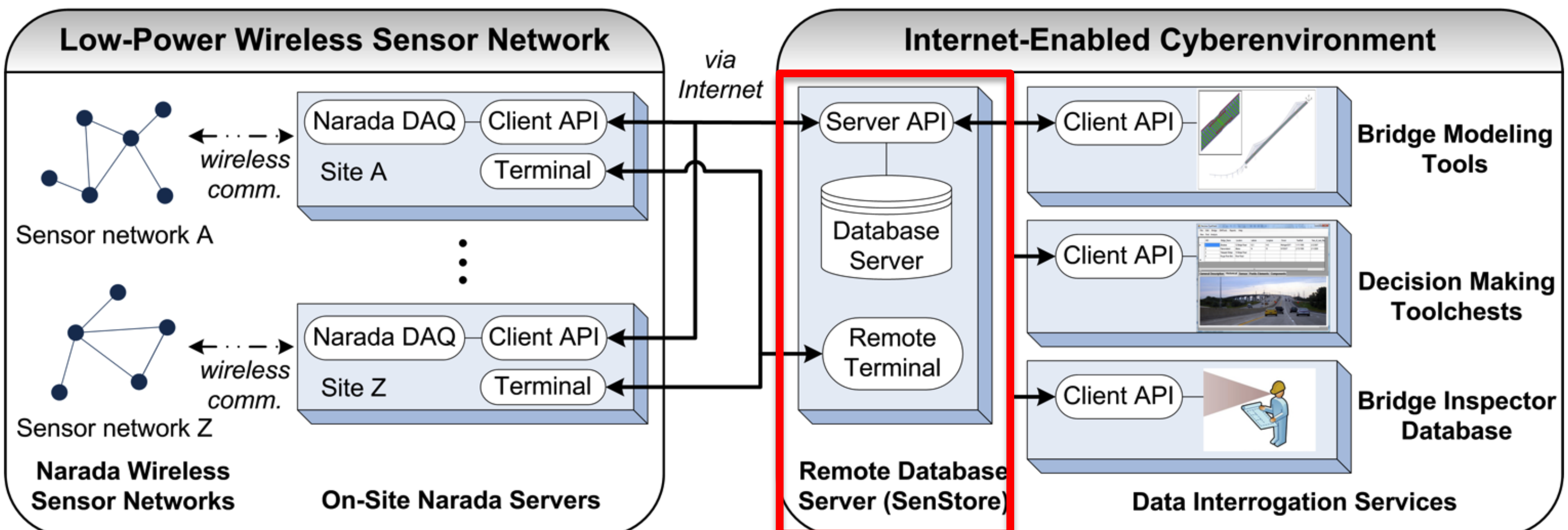


Inspector User Interface
[Optimized to mimic MDOT process]

Inspector User Interface
[Optimized to mimic MDOT process]

Cyber-infrastructure

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



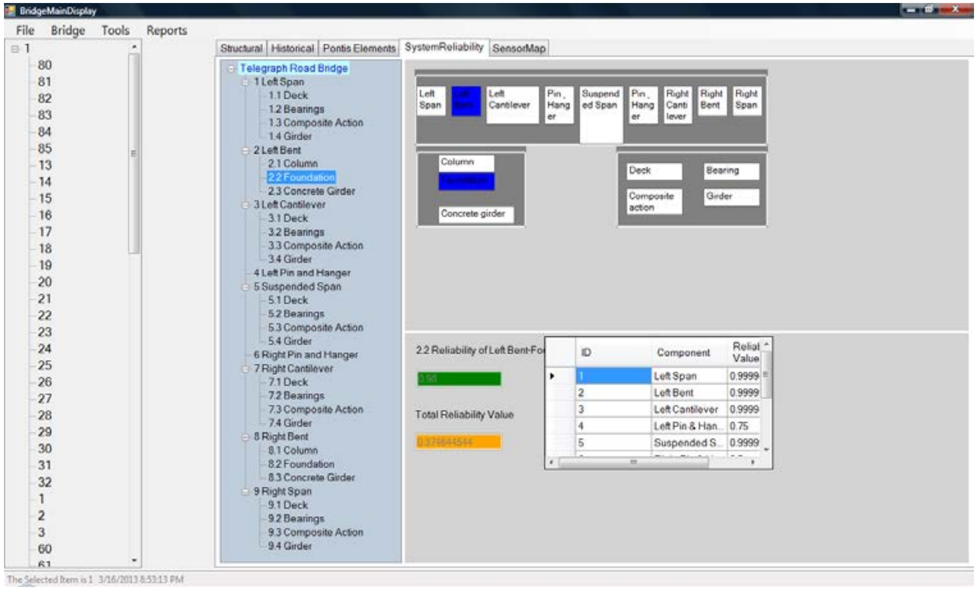
Proposed Cyber-infrastructure Framework for Bridge SHM

SenStore Server

- **SenStore is a database server designed for SHM:**
  - Designed to unlock full potential of data collected over time
  - Allows 3rd party data processing clients to "mine" the database
  - Designed to be compatible with existing databases (*e.g.*, PONTIS)
- **Data types for storage:**
  - Bridge metadata including geometric details
  - Sensor and monitoring system metadata (sensor types, locations)
  - Visual inspection information (reports, pictures)
  - Monitoring system sensor data (sensor time-history data)
  - Load data (WIMS data, environmental factors)
- **Security a critical system requirement:**
  - In post-9/11 world, access to bridge data must remain restricted

Decision Making Toolchest

- **Decision making tool chest for bridge engineers:**
  - Demand estimation using WIMS data
  - Sensor data drives estimation of bridge capacity
  - Reliability methods rationally combine demand and capacity into β
  - Cost and consequences allows for risk management in same tool



Powerful Decision Making Toolchest

[Powerful in its analytical capabilities including damage detection, reliability and LCA]

Field as a Laboratory

- **MDOT and Caltrans offered unfettered access to bridges:**
  - New Carquinez Bridge (Vallejo, CA) – since 2010 (21 GB of data!)
  - Telegraph Road Bridge (Monroe, MI) – since 2011 (6.2 GB of data!)
- **Bridges serve as focal point for technology development:**
  - Illustrate delivery of desired benefits to bridge owners
  - Resolve long-standing cost barriers to monitoring technologies

New Carquinez Bridge (CA)

Telegraph Road Bridge (MI)

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 reinforced concrete towers and pre-stressed link beam

New Carquinez Bridge (NCB)

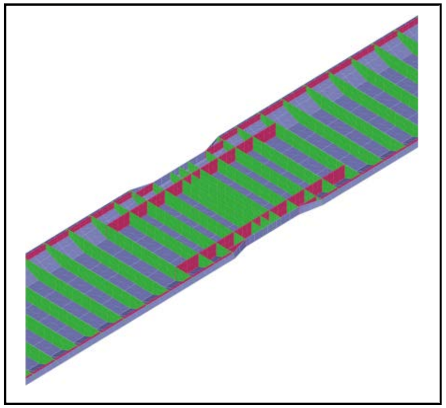
Fault Activity near Vallejo
(Source: USGS)

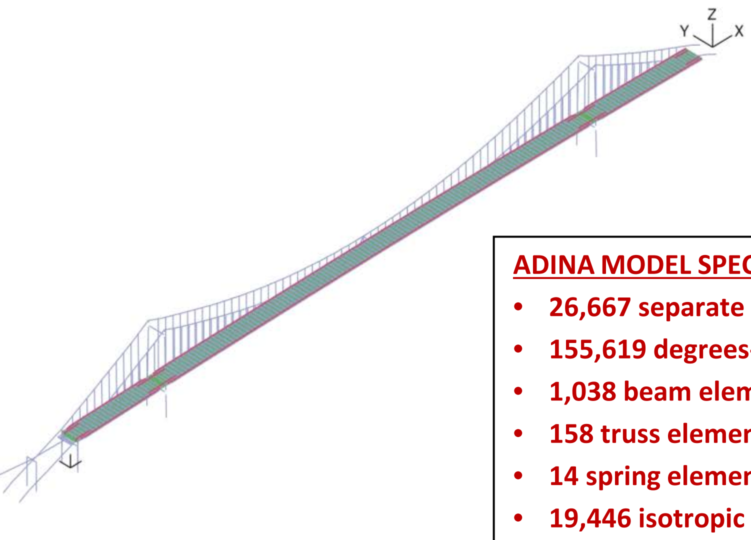
MCE for Vallejo, CA
- **San Andreas (M_w=8)**
- **Hayward (M_w=7.3)**
- **Franklin (M_w=6.5)**

In collaboration with Mr. Patrick Hipely, Caltrans

Monitoring Objectives

- **Owner of bridge (Caltrans) objectives in monitoring:**
  - Validate design assumptions (modal frequency and damping)
  - Update high-fidelity models of the bridge to simulate seismic behavior immediately following an earthquake event to assess structure safety
    - Automated extraction of modal characteristics of structure
  - Not intended to serve as a structural health monitoring system

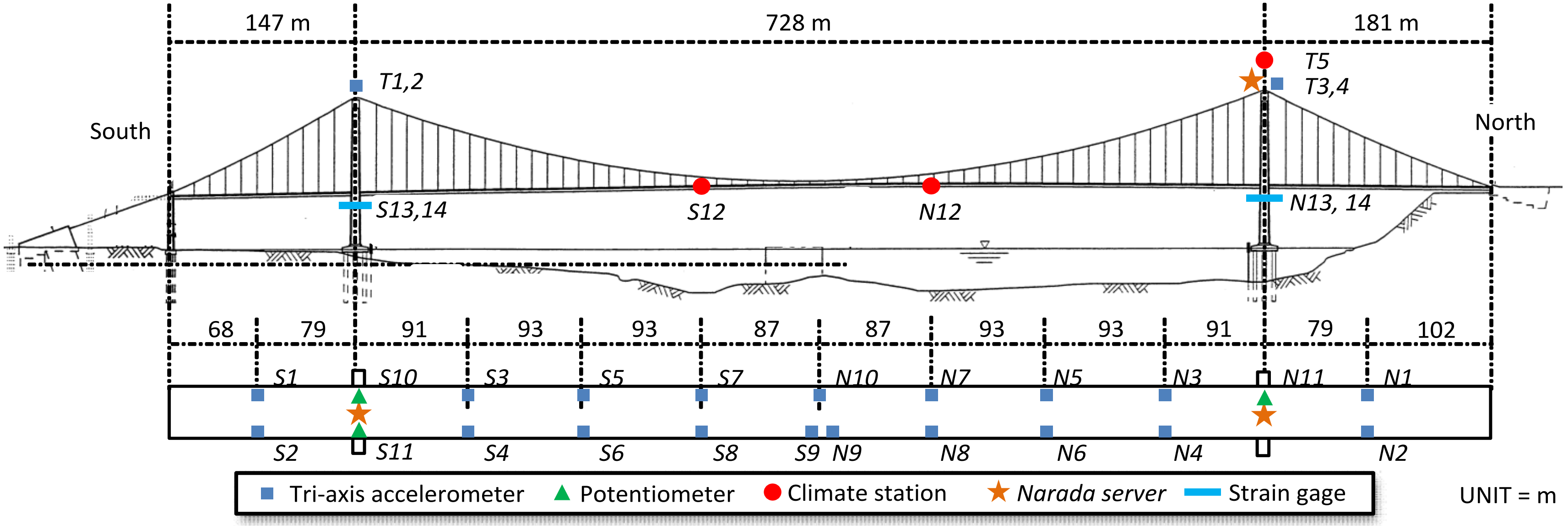




ADINA MODEL SPECIFICATIONS (SC Solutions):
- **26,667 separate nodes**
- **155,619 degrees-of-freedom**
- **1,038 beam elements**
- **158 truss elements**
- **14 spring elements**
- **19,446 isotropic and orthotropic shell elements**

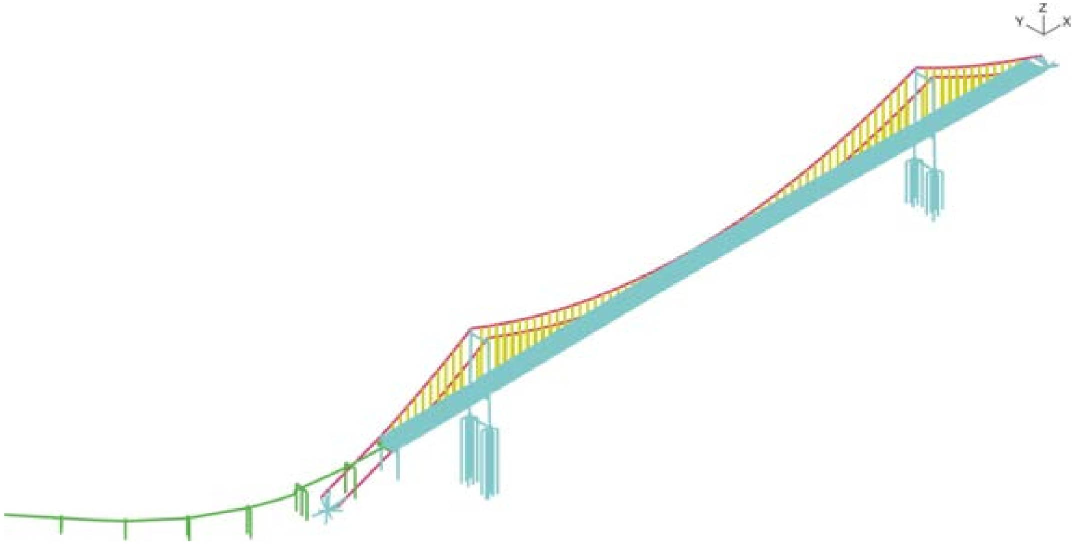
Instrumentation Plan

Sensor Type	Nodes	Channels
Tri-axial accelerometer (girder)	19	57
Tri-axial accelerometer (towers)	4	12
Wind vane, anemometer, temp	3	9
Potentiometer Displacement (girder)	3	3
Strain gages (girder interior)	2	6
TOTAL	**31**	**87**



Modeling Strategy

- **Constructed finite element bridge models in ADINA:**
  - High-fidelity, detailed models based on as-built drawings
- **Calibrated and validated using sensor data:**
  - Model updating based on modal assessment
- **Model is a key tool for post-event decision making:**
  - Recorded ground motions used to simulate bridge response



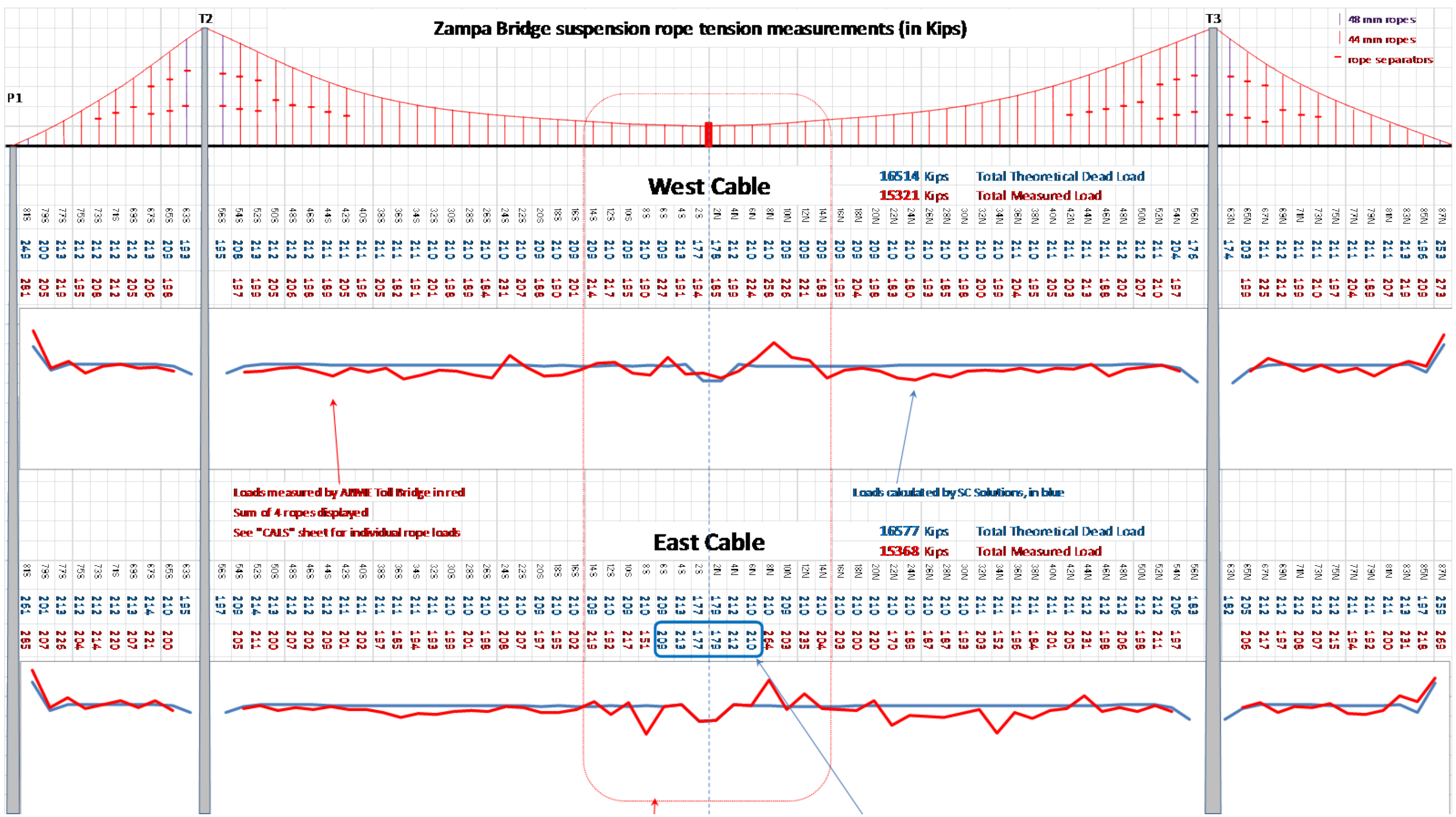
Bridge Model Calibration

- **Results of Model Calibration:**
  - Measured frequencies vs. *un-calibrated* FE frequencies: Max error of 28%
  - Measured frequencies vs. calibrated FE frequencies: Max error of **2.5%**
  - Excellent agreement between measured and calibrated FE frequencies

Mode Number	1 (1V)	2 (2V)	3 (3V)	4 (4V)	5 (5V)	7 (6V)
Nature of mode shape	1st vertical bending	2nd vertical bending	3rd vertical bending	4th vertical bending	5th vertical bending	6th vertical bending
Measured Frequencies	0.193	0.205	0.260	0.350	0.413	0.487
FE Frequencies (Uncalibrated Model)	0.201	0.148	0.262	0.356	0.395	0.464
FE Frequencies (Calibrated Model)	0.196	0.200	0.258	0.349	0.414	0.475
Percent difference (Measured vs. Uncalibrated)	-4.1	27.9	-0.8	-1.7	4.4	4.7
Percent difference (Measured vs. Calibrated)	-1.5	2.5	0.8	0.3	-0.2	2.5

Bridge Model Validation

- **Model validated looking at hanger cable forces predicted:**
  - Total weight error: **0.4%**
  - Average of absolute error per suspender: **10%**



Telegraph Road Bridge

- **Constructed 1973 in Monroe, MI:**
  - Cantilever bridge
  - Steel girders
  - Pin & hanger construction
- **Serious deterioration encountered:**
  - Deck cracking
  - Corrosion of steel girders
  - Failure of bridge abutment structures
  - Fatigue failure

Top-Down SHM Strategy

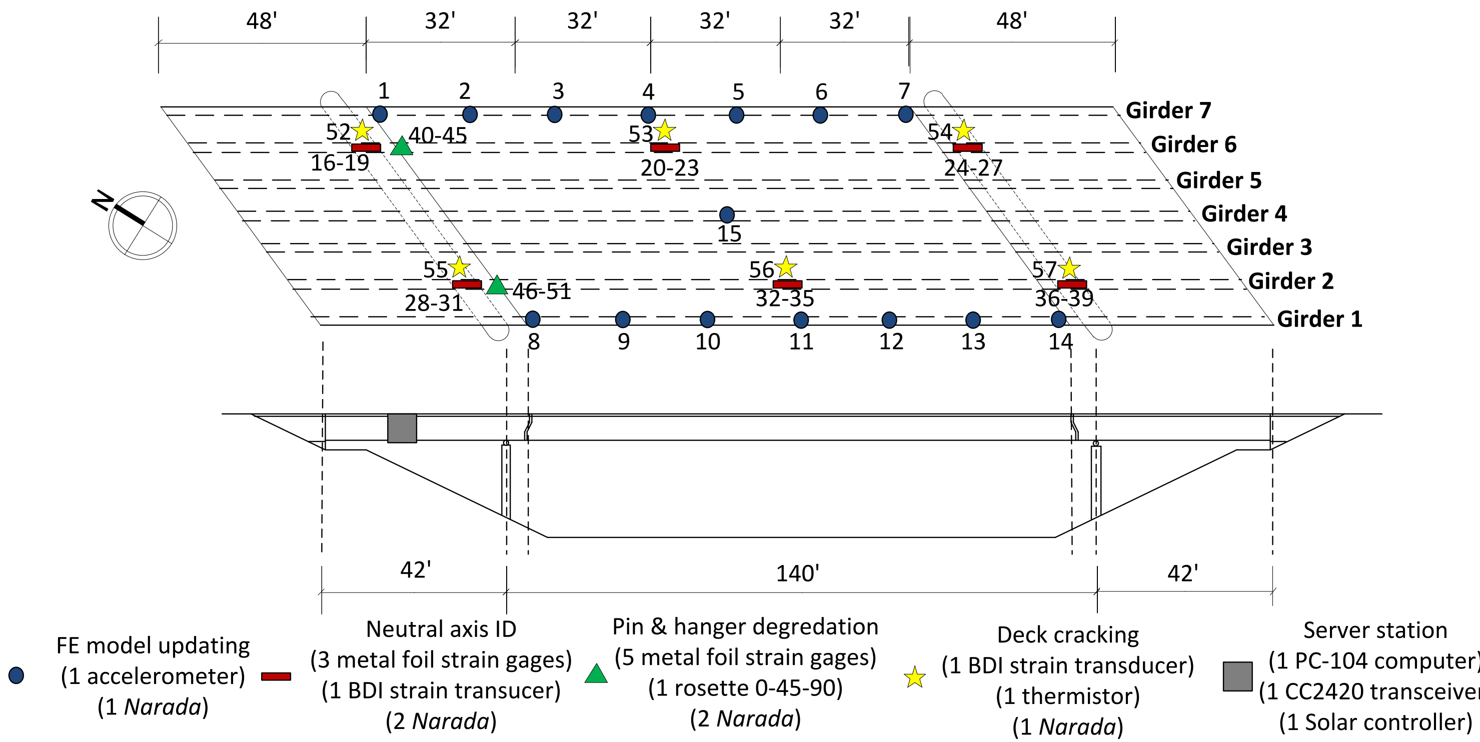
- **Start with the damage processes of primary concern:**
  - Customize sensing to feed data into that decision making process
- **Telegraph Road Bridge damage concerns:**
  - Pin-hanger connections – *heavy instrumentation of link plates*
  - Loss of composite action– *measure dynamic strain through section*
  - Severe deck cracking in wing spans – *measure deck static strains*
  - Calibrate FE model of bridge – *measure accelerations*

Mianus River Bridge (1983)

North Span Severely Cracked

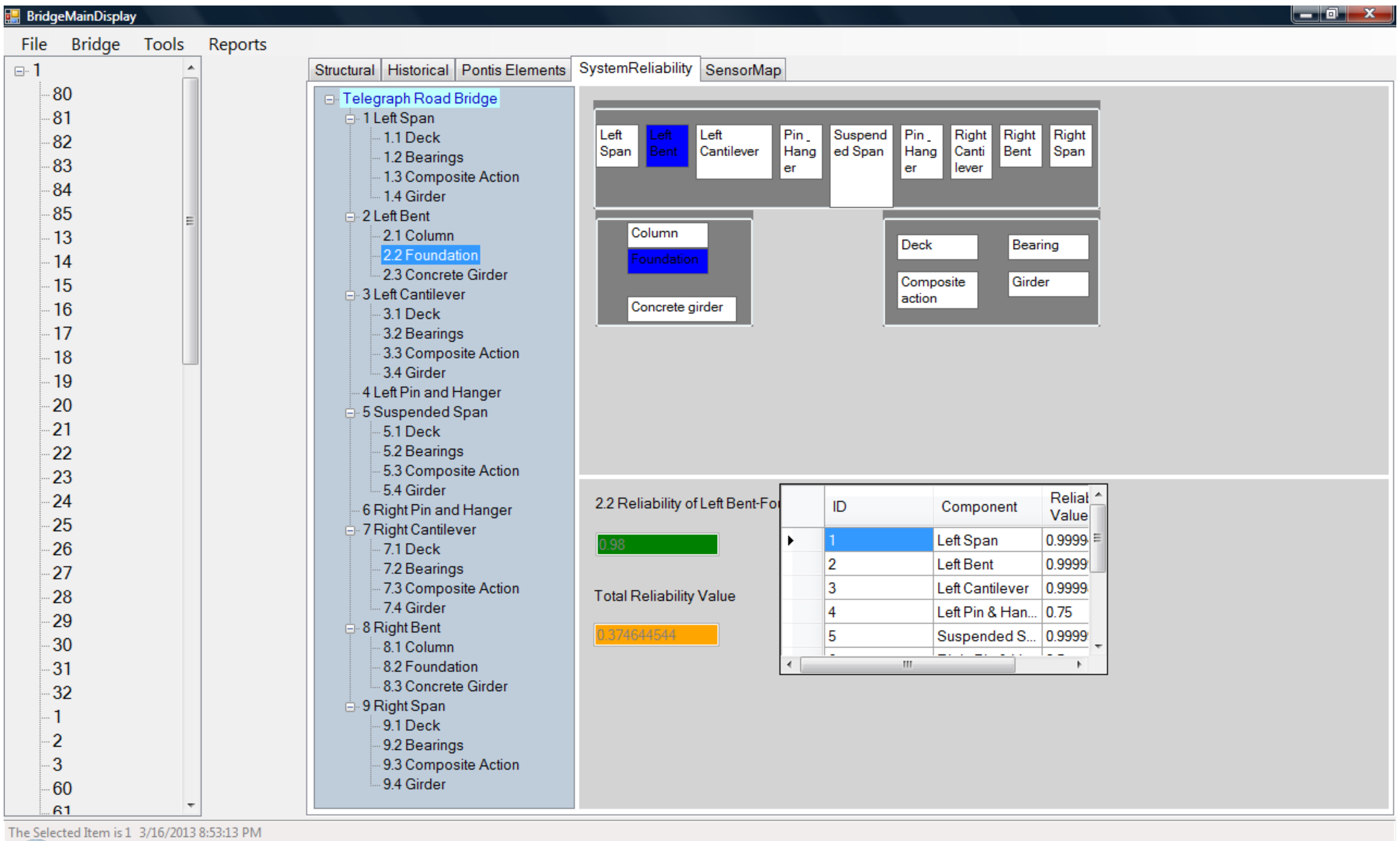
Monitoring System Overview

- **31 *Narada* units installed in 2011 collecting 57 channels:**
  - 15 uni-axial accelerometers for modal analysis and model updating
  - 36 strain gages (24 for beam strain profile and 12 for link plate strain)
  - 6 thermistors to assess temperature load and for thermal corrections



Decision Making Tool-chest

- **Decision making tool-chest now complete:**
  - Telegraph Road Bridge is our validation test case



Summary

- **Project sought to:**
  - Advance sensing capabilities by lowering costs and enhancing function
  - Leverage cyber-infrastructure to transform data into information
  - Create data-driven decision support system to maximize benefits
- **Data is only valuable if it is utilized for asset management:**
  - From a cost-benefit standpoint, cyber-infrastructure is the key!
- **Future efforts of the team aimed at:**
  - Continued use of the New Carquinez and Telegraph Road Bridges
  - Field deploy ultra-low power WISP node with RF power harvesting
  - Explore additional data analysis tools for health assessment
  - Commercialization of project technologies and methodologies

Thank You!

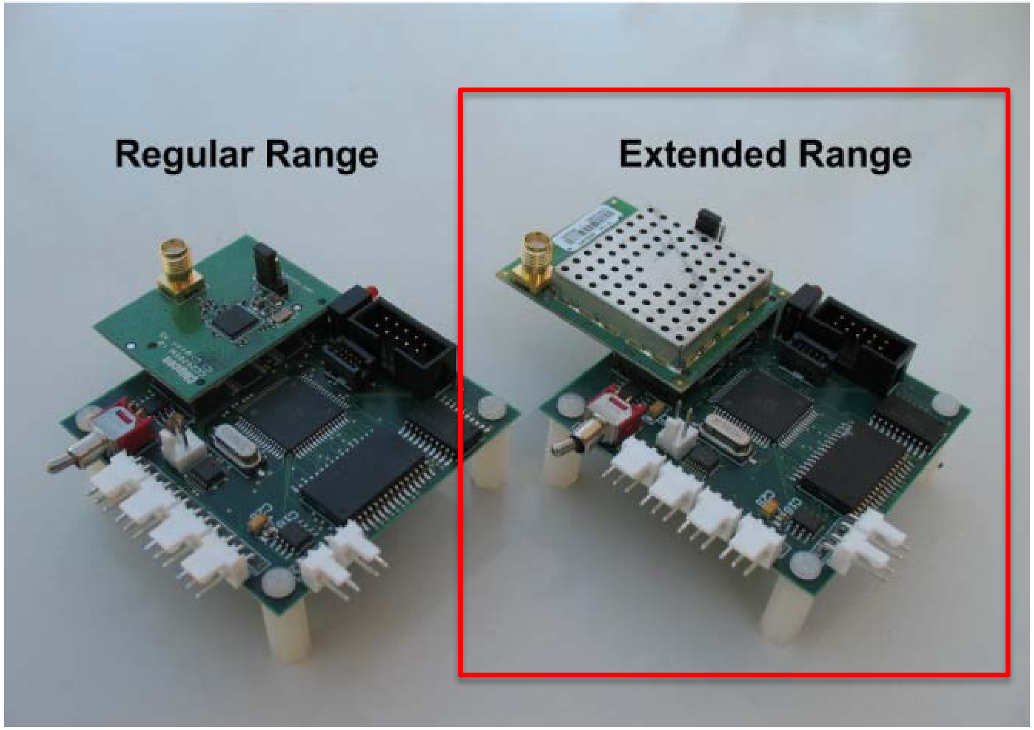
Acknowledgements:

United States Department of Commerce, National Institute of Standards and Technology (NIST), Technology Innovation Program (TIP) managed under the direction of program manager Dr. Jean-Louis Staudenmann.

Additional support was provided by the Michigan Department of Transportation (MDOT), the California Department of Transportation (Caltrans), and the National Science Foundation (NSF).

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
  - Extended range version of IEEE802.15.4 provides 700 m range



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	700 m
Data Rate	250 Kbps
Sample Rate	100 kHz

Vibration Power Harvester

- **Harvest low-acceleration, low-frequency, non-periodic vibration energy from bridge**