Technology Innovation Program

The Challenges of Structural Health Monitoring Technologies in Civil Infrastructure

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8th International Workshop on Structural Health Monitoring
Stanford, California

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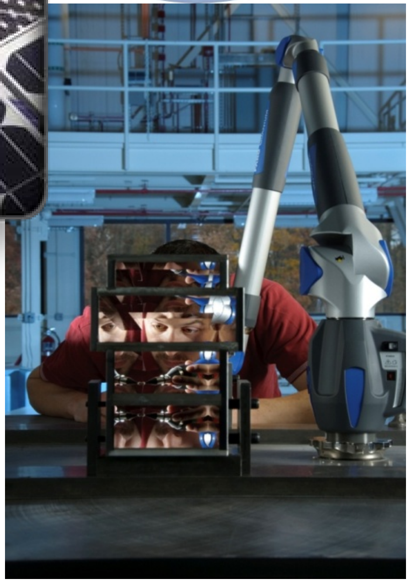
National Institute of Standards and Technology
U.S. Department of Commerce

Laboratories and Major Programs



Scientific & Technical Research Services - NIST Laboratories

- Engineering Laboratory
- Physical Measurement Laboratory
- Information Technology Laboratory
- Material Measurement Laboratory
- Center for Nanoscale Science and Technology
- NIST Center for Neutron Research

Innovation and Industry Services Programs

- Hollings Manufacturing Extension Partnership (MEP)
- Technology Innovation Program (TIP)
- Baldrige Performance Excellence Program
- Technology Partnerships Office

Technology Innovation Program (TIP)

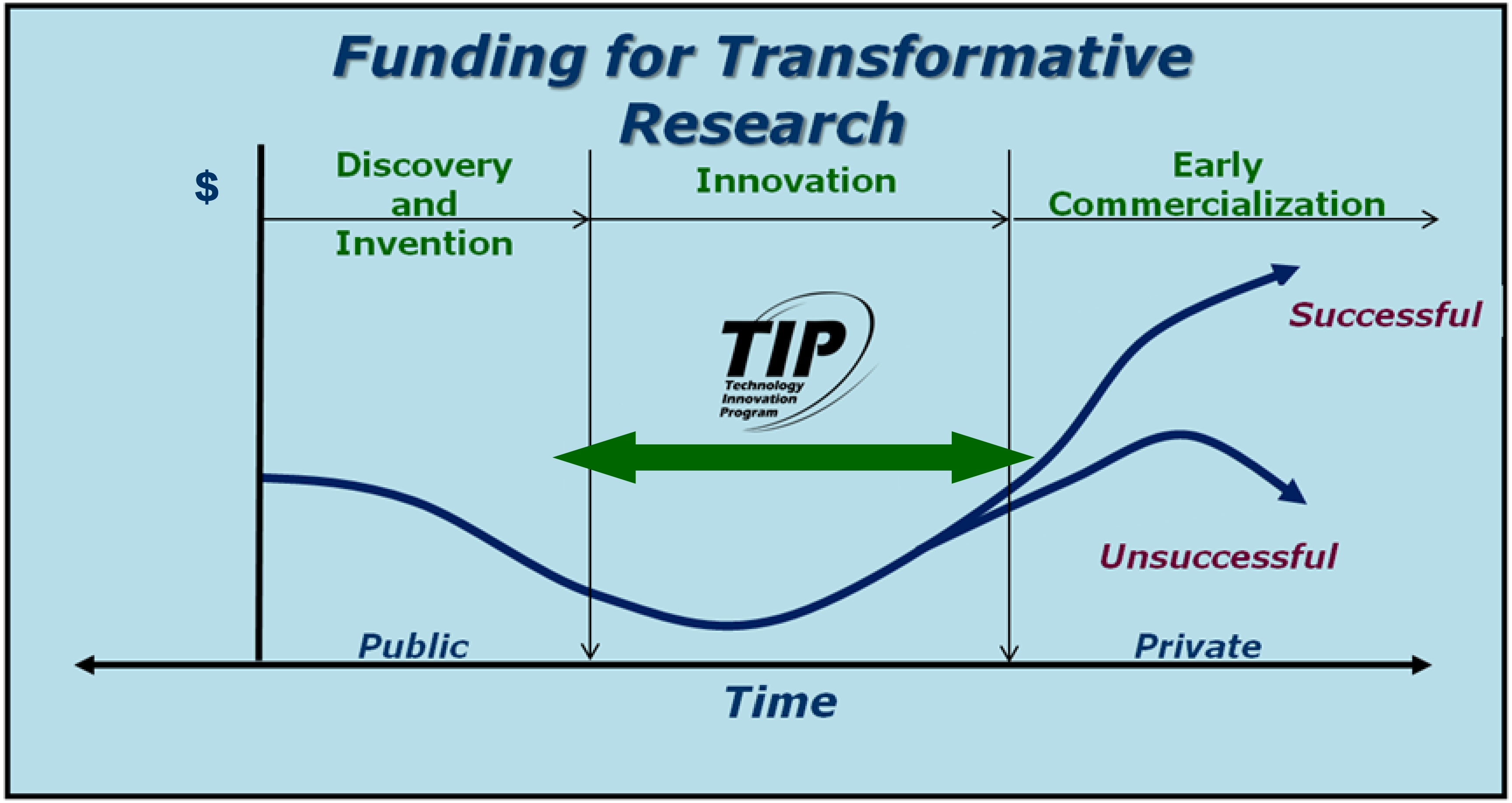
TIP's Mission

- **Assist United States businesses and institutions of higher education or other organizations, such as national laboratories and nonprofit research institutions**
- **Support, promote, and accelerate innovation in the United States through <u>high-risk</u>, <u>high-reward</u> research**
- **In areas of <u>critical national need</u>**

America COMPETES Act (PL 110-69)
August 9, 2007

Funding Transformational Research for Critical National Needs

Provide Funding Not Possible by Others



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TIP
Technology Innovation Program

INNOVATION AND INDUSTRY SERVICES

Failures of Civil Infrastructure







Courtesy of Internet sources on images of bridge collapsed, potholes, and underground pipe rupture

NIST
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National Zoo Animals Sensed Early on 8/23/11 in Washington, D.C. 5.8 Magnitude Earthquake


Red ruffed lemur


Orangutan - Iris

But not…


Giant Panda


Rheas


Flamingos

Hooded mergansers

Courtesy of http://news.discovery.com/animals/earthquake-how-animals-reacted-110825.html?print=true

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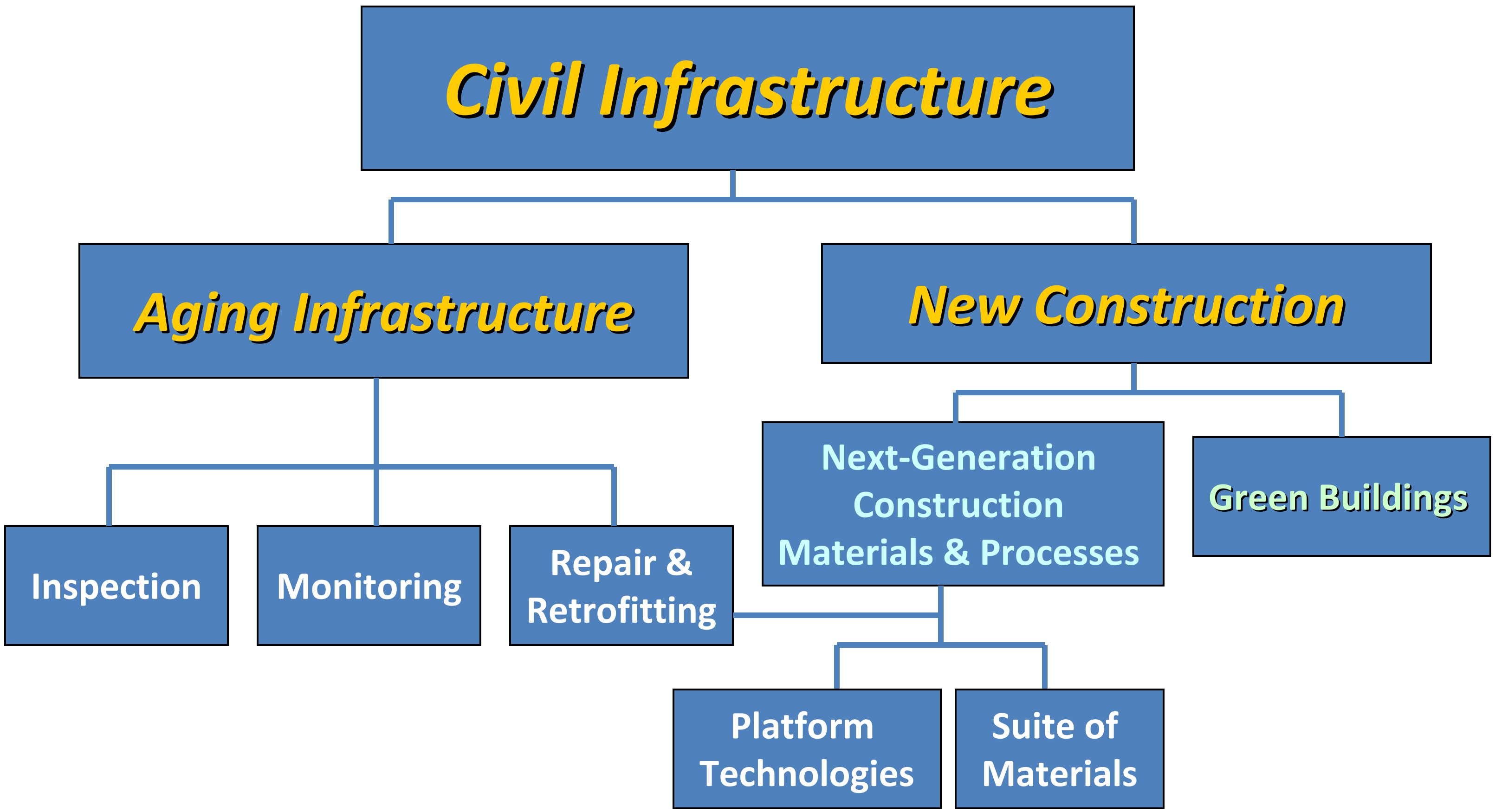
Proposed Vision



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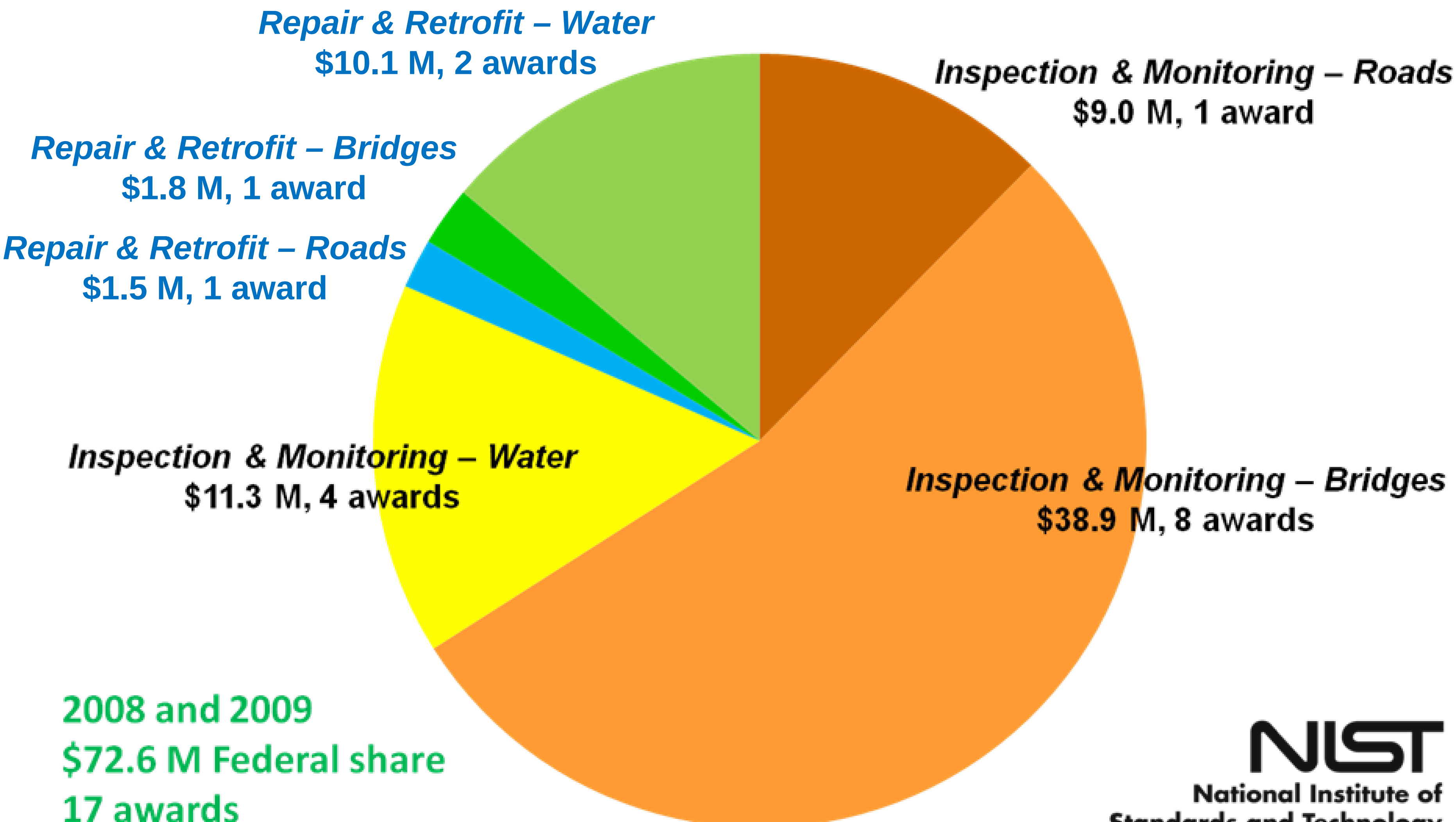
Civil Infrastructure: TIP Funding and Awards



2008 and 2009
$72.6 M Federal share
17 awards

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TIP Civil Infrastructure Project Portfolio

Civil Infrastructure:

- 2008 and 2009
- 17 awards
  - 5 single company awards
  - 12 joint ventures
- $149.9 million
  - $72.6 million Federal share
- 69 participating organizations

(includes subrecipients and contractors)

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U.S. Department of Commerce

Civil Infrastructure: Inspection & Monitoring (Highways)

VOTERS: Versatile Onboard Traffic Embedded Roaming Sensors

Northeastern University, Boston, Massachusetts
Other Joint Venture Participants: University of Massachusetts Lowell, Lowell, MA; University of Vermont and State Agricultural College, Burlington, VT; Trillion Quality Systems LLC , Plymouth Meeting, PA; Earth Science Systems LLC, Golden, CO

March 1, 2009 to February 28, 2014
Total Project Budget: $18,802k
TIP Cost Share: $9,000k

Project

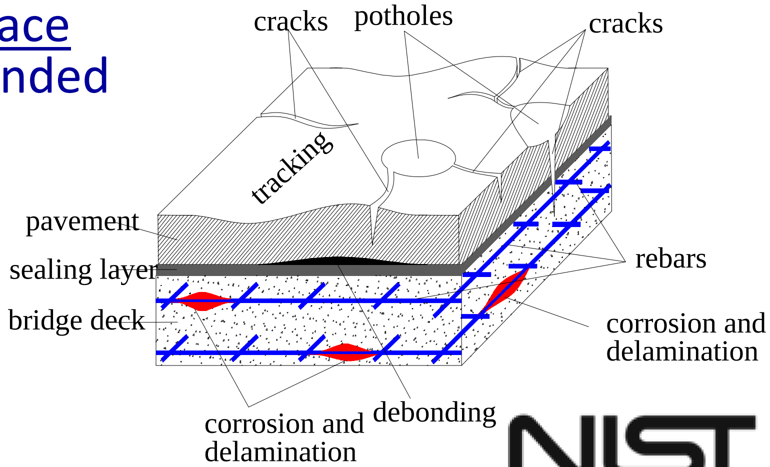
Develop a novel system that can be installed on a wide variety of private and public vehicles to assess bridge and roadway conditions while driving at regular speeds during the course of ordinary vehicle use

Potential Impacts

- Eliminates need for hazardous and congestion-prone highway work zones to conduct roadway inspections;
- Provides constant information stream on road and bridge deck conditions gathered under real, daily driving conditions at operational speeds; and
- Allows planners to schedule needed repairs at the right place and at the right time

VOTERS develop new technology and adapt existing state of the art systems into an integrated, vehicle-based system to completely classify pavement condition while traveling at traffic speeds.

- **Ground Penetrating Radar (GPR)**: Subsurface defects such as corroded rebar up to one foot below surface. Also, map subsurface moisture.
- **Novel Acoustic Technology**: Using tire-induced vibration and sound waves to determine surface texture, and subsurface defects such as debonded asphalt layers.
- **Optical Profilometry**: surface defects and sub-base damage prediction.
- **High-Frequency Radar**: Moisture content and Ice at surface and in the top 1-2 mm of pavement.



Courtesy of Northeastern University

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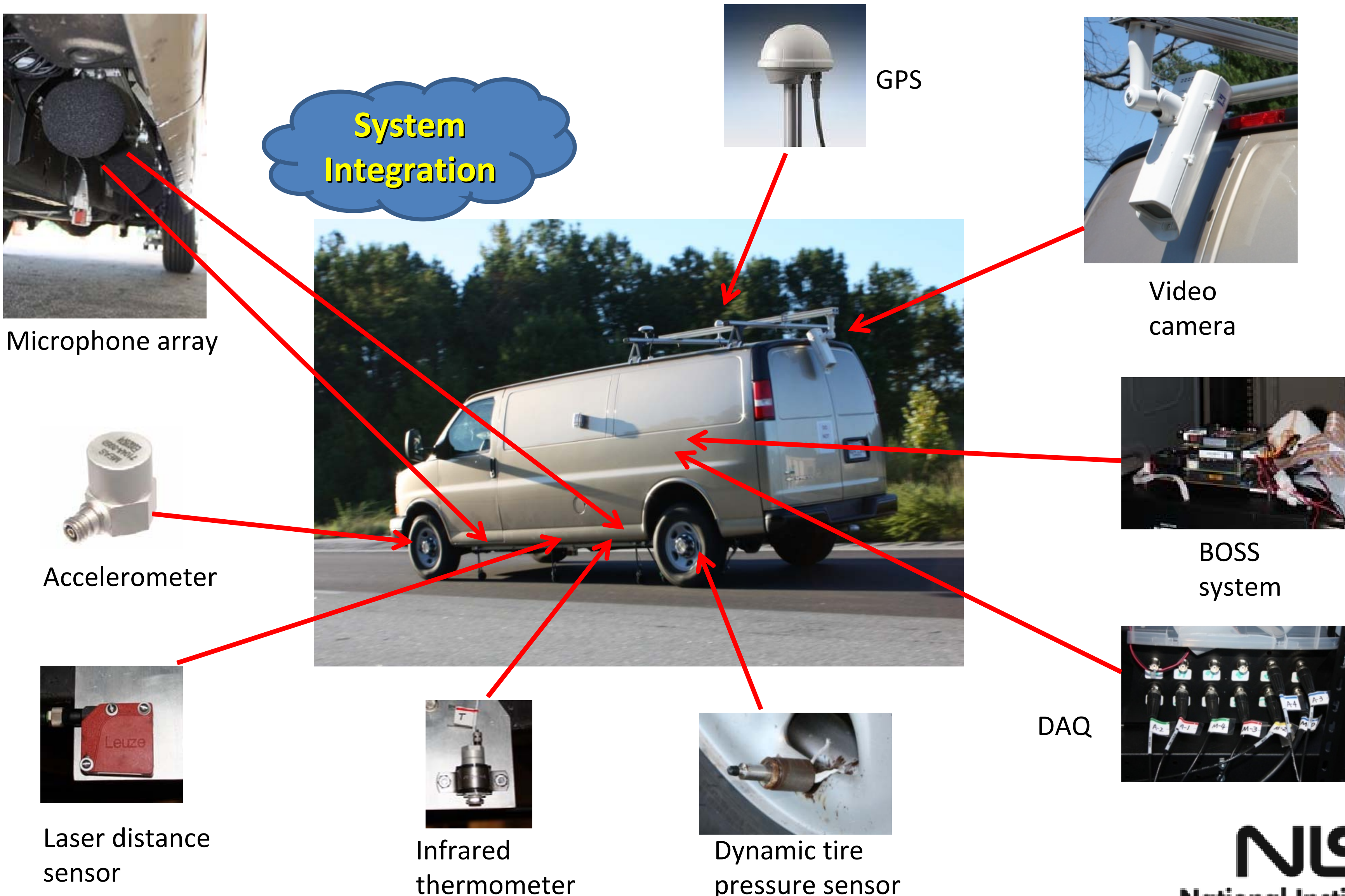
VOTERS VEHICLE



Courtesy of Northeastern University

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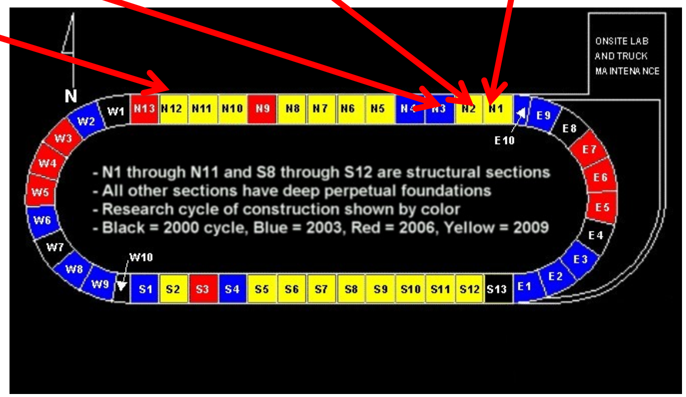
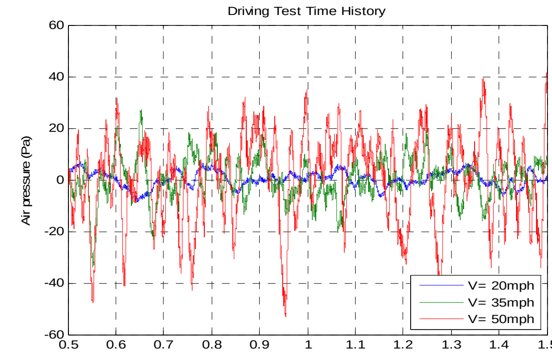
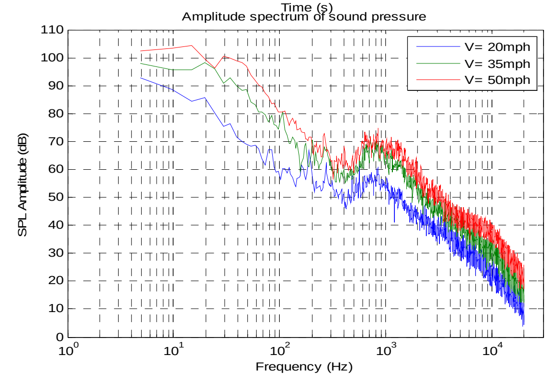
NCAT* Test

- 46 sections
- 5 configurations
- 200 runs
- 50 GB data







Team Work

*National Center of Asphalt Technology

Courtesy of Northeastern University

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Energy correlates to MTD (Mean Texture Depth)

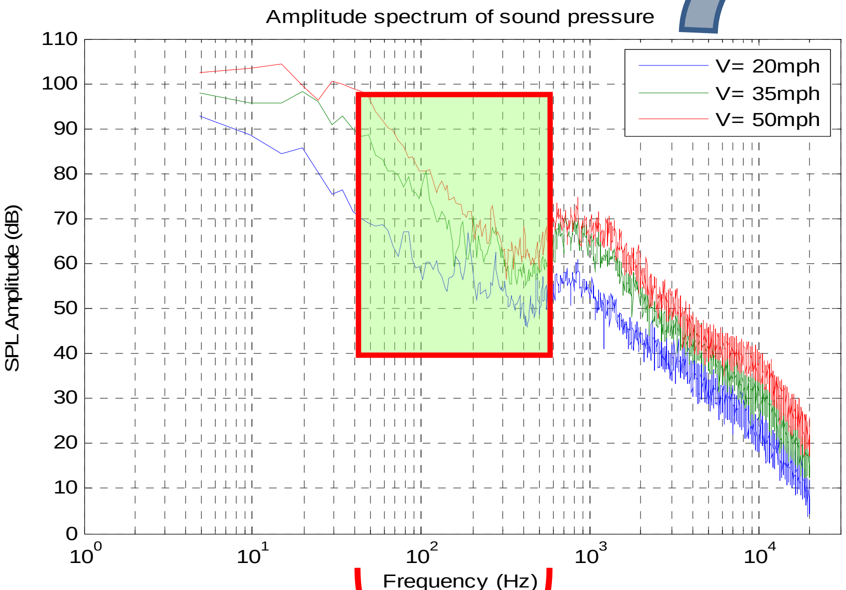
Advantages

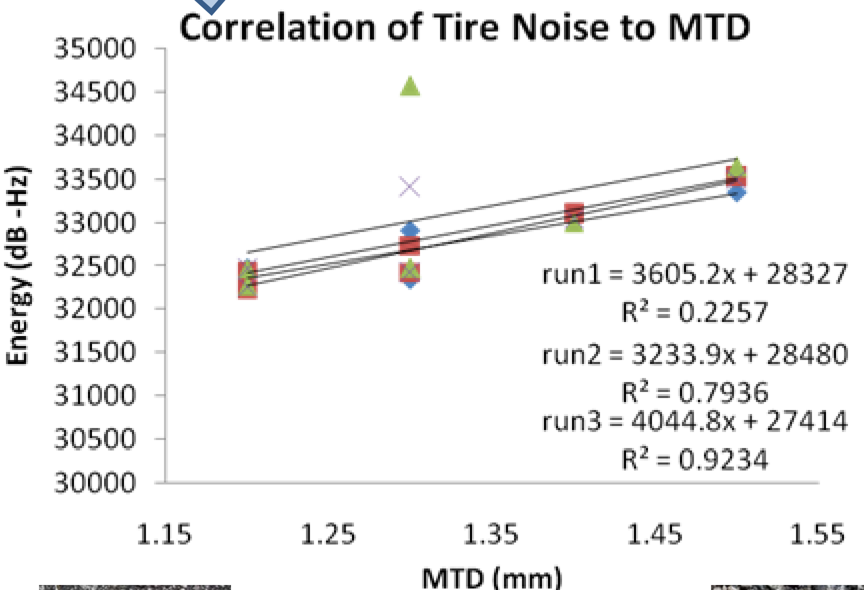
- Real-time
- Continuous
- Automatic
- Safe
- Reliable
- Accurate

Disadvantages

- Time consuming
- Dangerous
- Creates Traffic
- People dependent

0.8-0.9 Correlation





50-600 Hz

Optimal Spectrum Energy Range for MTD Measurement

smoother ⟷ **coarser**

Courtesy of Northeastern University

Major Achievements

VOTERS, a vehicle-based system, can completely classify pavement condition while traveling at traffic speeds

1. Created several sensor subsystem prototypes
   a) Tire-excited acoustic sensor (TEASe), Wireless dynamic tire pressure (DTP) sensor, Mobile air-coupled subsurface sensing (MASS)
   b) ESS-GPR, UVM-GPR, SLiMR
   c) Optical profilometer, BOSS, MAP, DGPS

2. Six provisional patent applications

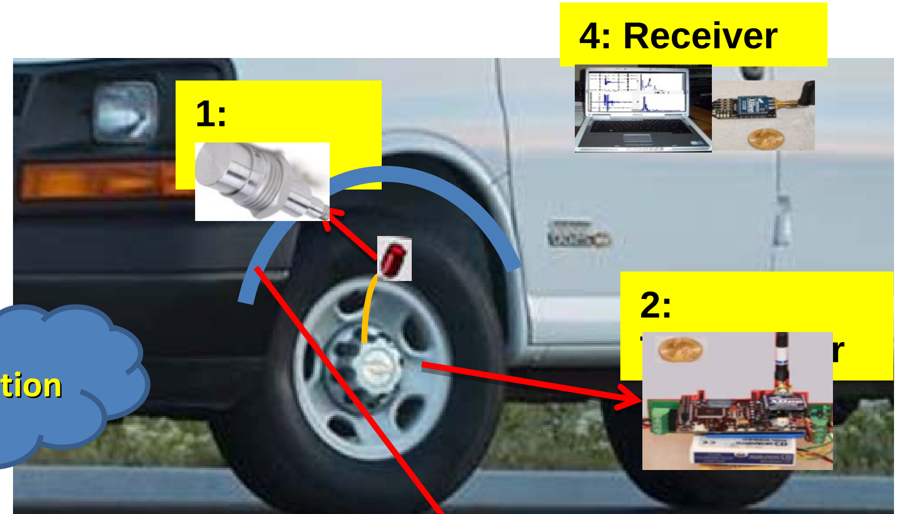
Courtesy of Northeastern University

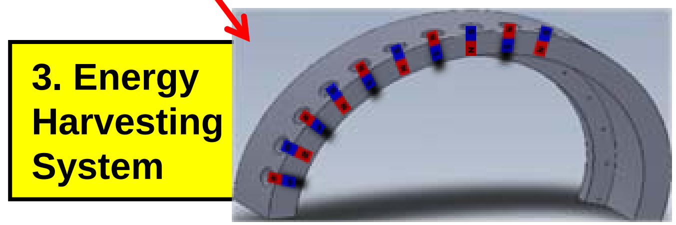
Wireless Dynamic Tire Pressure (DTP) Sensor

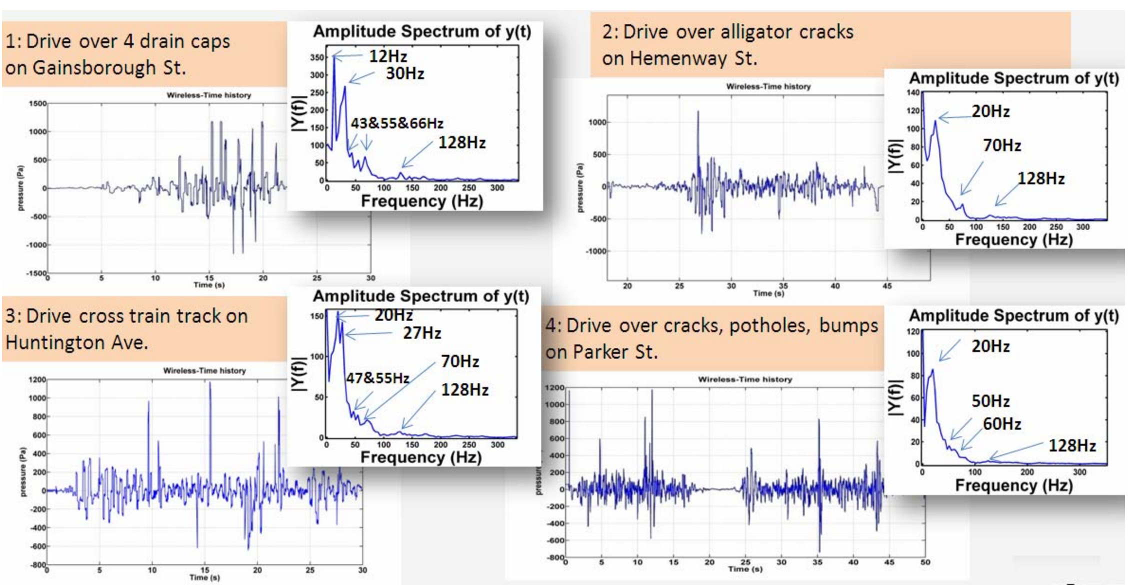
Features

- Tire isolates outside noise
- Tire amplifies ground vibration
- Tire protects sensors from environment

Innovation







Application

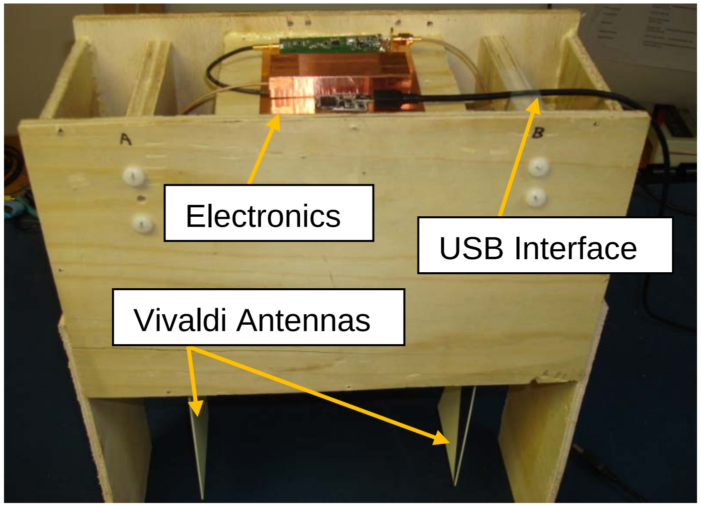
- Surface condition
- Subsurface condition
- Debonding

Courtesy of Northeastern University

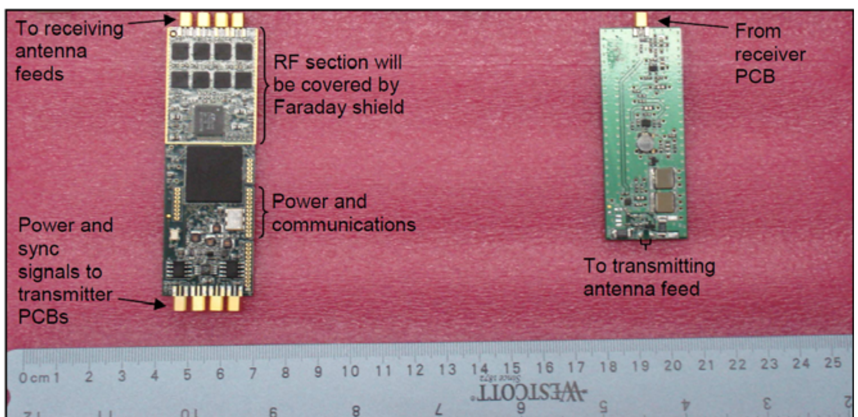
Earth Science Systems -GPR Array System

ESSential Underground Information

First Prototype



Electronic building blocks



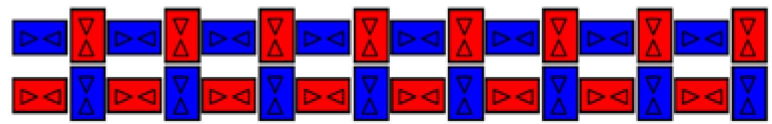
Key Features

•Fully polarimetric multi-offset array for geometric, frequency, and polarization diversity

•Antenna array with up to 16 transmitting and 16 simultaneous receiving antennas

•Low cost and fast digitizers provide

- **30 times faster data collection OR**
- **Better penetration of signals**



Plannaed Antenna Array Configuration

Major Accomplishment

•Created 1st generation integrated ESS-GPR prototype ready for more testing

Outlook

•Testing of 2nd generation simultaneous array system is underway and will be build up to an array in the third year of VOTERS (2011)

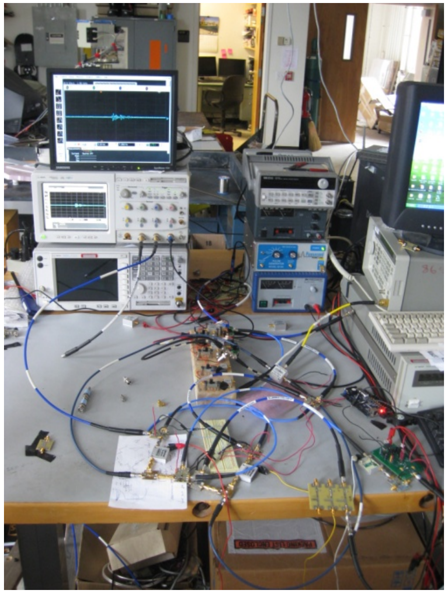
•Development of matching antenna underway

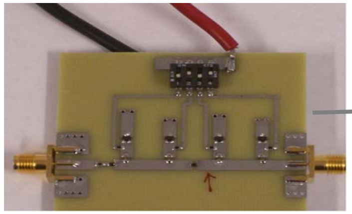
Impact

•ESS-GPR array will be faster, less expensive, and smaller than currently available COTS GPR arrays setting a new bar for the industry

Courtesy of Northeastern University

UVM-GPR Array System

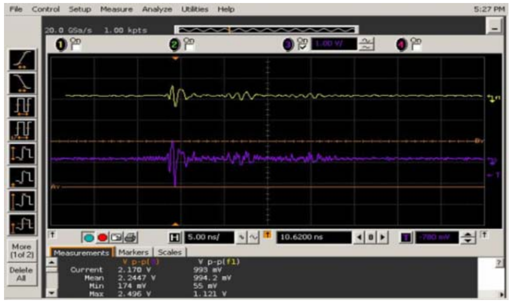


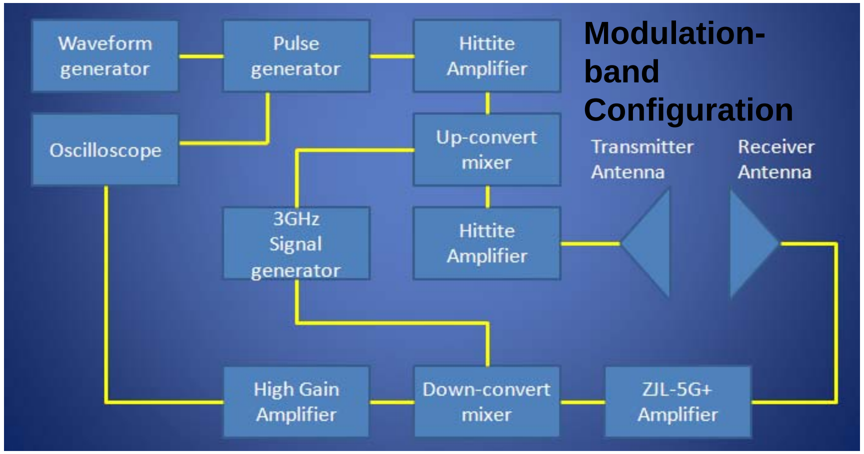


Key Features

- **Modular multi-channel architecture**
- **Low cost transmitter**
- **Full waveform digitization suitable for dense spatial coverage and high speed moving**

Benchtop dual-channel prototype



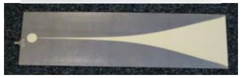


Major Accomplishment

- **Benchtop dual-channel UVM-GPR operational**
- **Working on suitable antennas, EBG backed Spiral**

Outlook

- **Final integration of dual channel UVM-GPR components and testing**
- **Continue development of matching antenna**



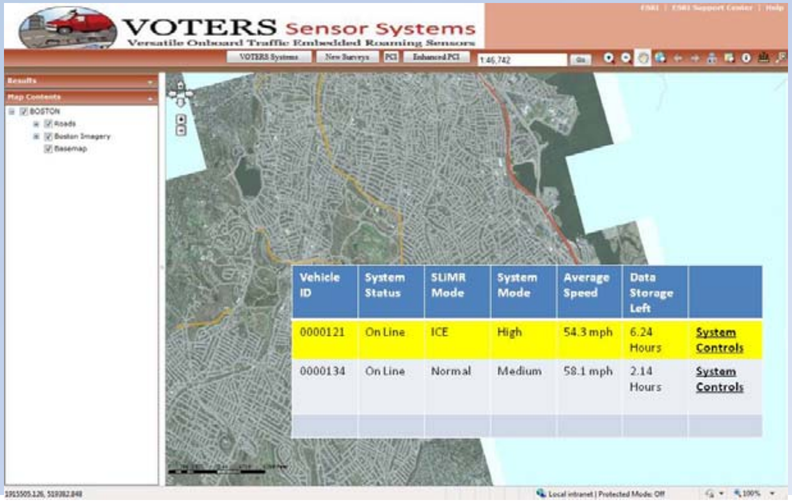
Impact

- **UVM-GPR will demonstrate "single-shoot" high-frequency capability, which will be the future of GPR array systems, currently still a matter of affordability of fast ADCs**

Courtesy of Northeastern University

MAP (Management And Prognosis) System

Prototype Display

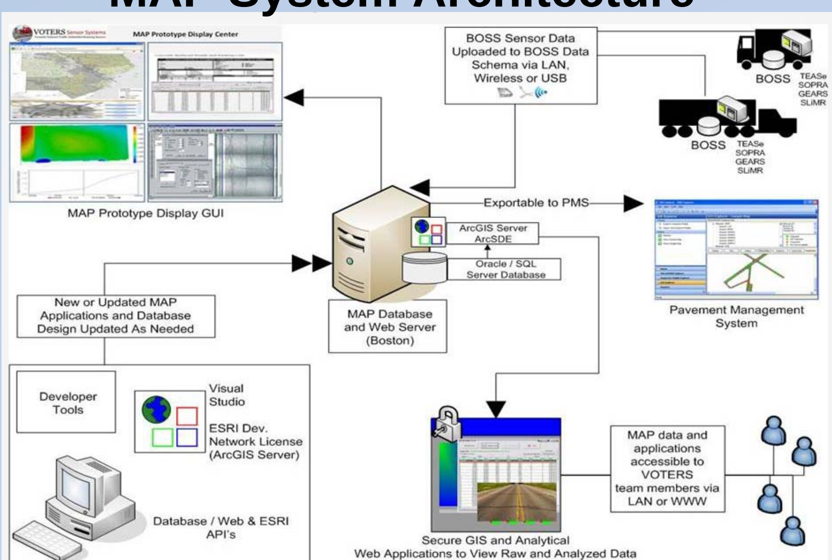


Geospatial database system to store, analyze, and report VOTERS sensor data

Major functions include:

•Sensor data QA and registration
•Tabular data query and reporting
•Graphical data query and presentation of roadway condition information via GIS (Geographic Information System) maps
•Interface to Pavement Management Systems
•Real-time wireless tracking and command of mobile VOTERS systems

MAP System Architecture



Features:

•Manages terabytes of sensor data
•Synchronizes all sensor data to same geographic coordinate system for multi-dimensional analysis
•Performs roadway classification analysis
•Access via browser for authorized users
•Based on ESRI ArcGIS geospatial products

Development plans:

•Implement data registration strategy
•Complete real-time vehicle tracking software
•Support researchers in analyzing multi-sensor data fusion, especially using sub-surface data

Courtesy of Northeastern University

Civil Infrastructure: Inspection & Monitoring (Bridges)

Cyber-enabled Wireless Monitoring Systems for the Protection of Deteriorating National Infrastructure Systems

University of Michigan, Ann Arbor, Michigan
Other Joint Venture Participants: Li, Fischer, Lepech & Assoc. LLC, Ann Arbor, MI; Weidlinger Assoc., Inc., New York, NY; Monarch Antenna, Inc., Ann Arbor, MI; SC Solutions, Sunnyvale, CA; Prospect Solutions, LLC, Loudonville, NY

February 1, 2009 to January 31, 2014
Total Project Budget: $19,162k
TIP Cost Share: $8,998k

Project

Novel system including self-sensing materials, ultra low power wireless nodes using only harvested power, embedded data processing for automated data interrogation, vehicle-infrastructure integration, grid-based FEM analyses, and cyber-enabled inspection

Potential Impacts

- Offers a next-generation structural health monitoring architecture for a comprehensive decision making;
- Proposes a new paradigm to structural sensing based on multifunctional materials; and
- Allows for embedment of sophisticated data processing algorithms directly into the wireless sensor network

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INNOVATION AND INDUSTRY SERVICES

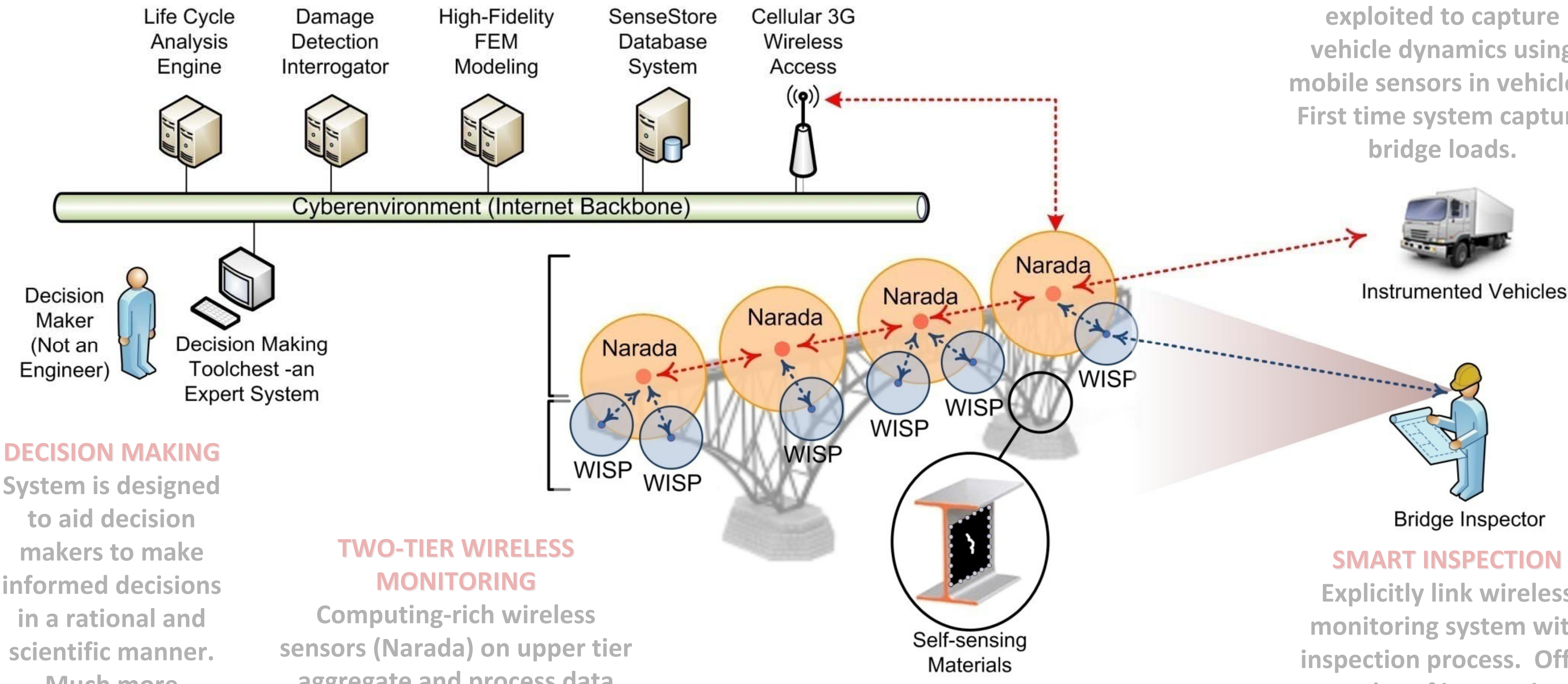
Project Overview

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.

Courtesy of University of Michigan

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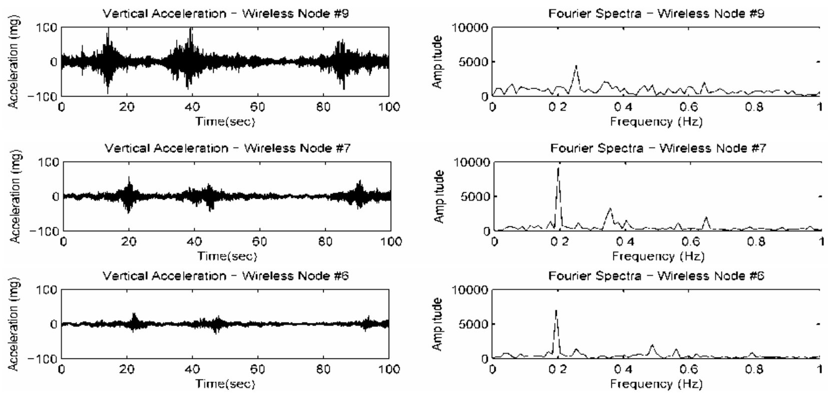
New Carquinez Suspension Bridge

- Team is utilizing the New Carquinez Bridge (Vallejo, CA) as a realistic testing environment for all project technologies:
  - 1056 m long suspension bridge opened in 2003
  - Currently have permanently installed 25 *Narada* wireless sensing units collecting over 70 channels of data



Data and results obtained from a field test using Narada wireless sensors are in good agreement with the existing wired sensors built into the bridge.

Courtesy of University of Michigan

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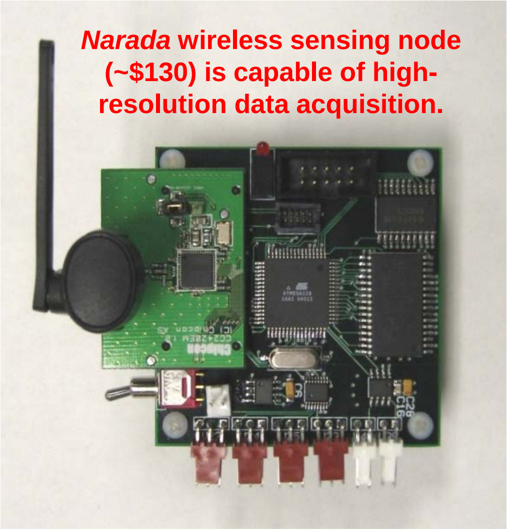
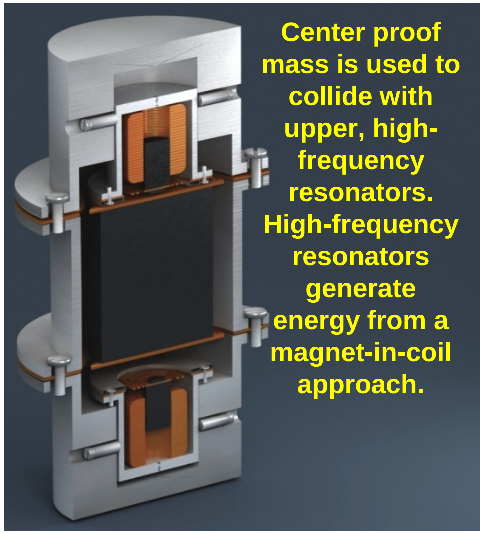
System Building Blocks

- **Wireless sensor network for data collection:**
  - Dense network of *Narada* wireless sensors installed on the bridge
  - Augmented with vibration based power harvesting (PFIG device)
  - Using self-structuring antenna for improved wireless communications
  - In-network data interrogation includes mode shape estimation



Narada wireless sensor



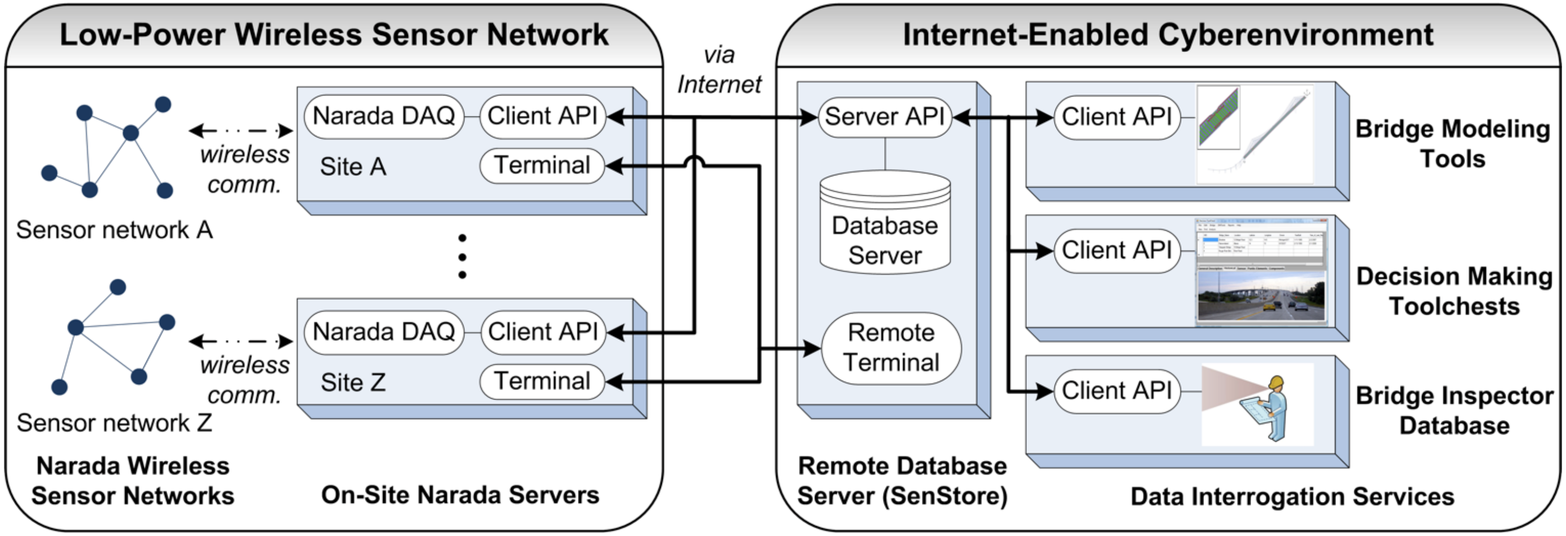
PFIG harvester

Self-structuring antenna

Courtesy of University of Michigan

System Integration

- **Cyberinfrastructure:**
  - Sensor technology has outpaced data management tools creating more data than can be manually processed
  - Technology bottleneck can be resolved by combining database of sensor data with powerful analytical tools

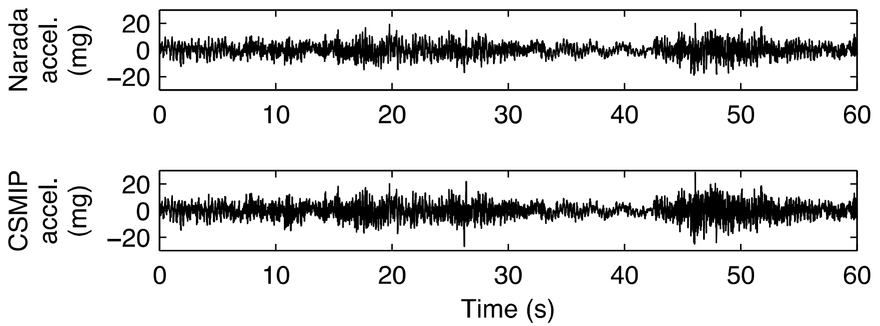


Proposed cyberinfrastructure framework for bridge SHM

Courtesy of University of Michigan

INNOVATION AND INDUSTRY SERVICES

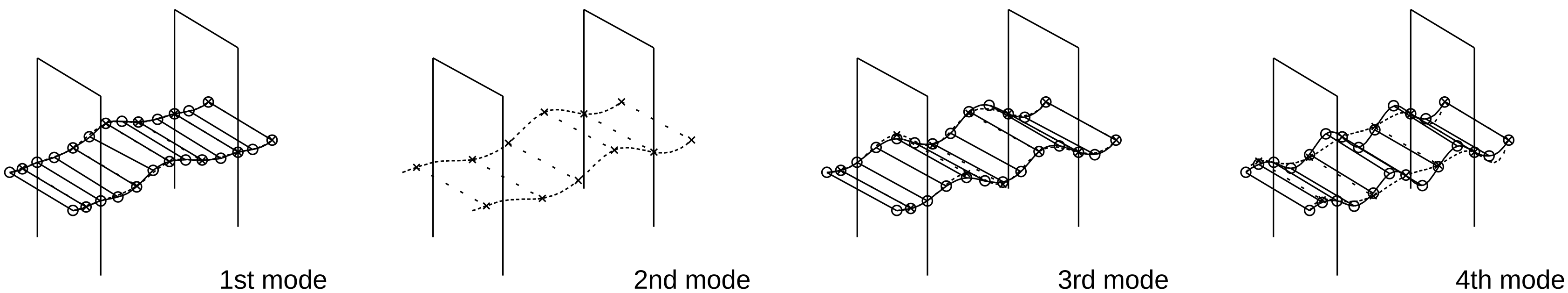
Bridge Monitoring Results



***Narada* wireless sensor**

***Traditional* wired sensor**

1) Wireless sensor data compares well to wired sensor data



2) Extraction of bridge mode shapes for model updating conducted in cyberinfrastructure autonomously

Courtesy of University of Michigan

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Major Accomplishments

- **Revolutionary approach to structural health monitoring:**
  - First use of self-sensing cement-based materials for direct damage sensing
  - Ultra low-power wireless sensor nodes two orders of magnitude lower power than existing commercial nodes
  - Broad-band vibration-based power harvester based on MEMS technology
  - Scalable cyberinfrastructure system seamlessly combines data with data interrogation technologies for automated data mining
  - Internet-enabled bridge inspectors can interact directly with the wireless monitoring system when on-site inspecting the bridge
  - Powerful decision-making toolbox translates data and processing results into information for the bridge owner
- **The impacts of this system are enormous:**
  - Provide end-users with information to make more informed decisions
  - Timely and reliable detection of structural and environmental problems
  - Accurate assessment of design characteristics
  - Reduction of construction, inspection, and business interruption costs

Courtesy of University of Michigan

Broader Impacts

- **Cyber-enabled wireless monitoring system:**
  - Bridge structures are safer for the public
  - Lower-cost to manage and maintain
  - System technology applicable to other infrastructure systems
- **Close collaboration with Caltrans and MDOT:**
  - Key stakeholders vetting the technology lead to wide-spread adoption
- **University as the project lead engages graduate students:**
  - Tooling of the future workforce in cutting-edge technologies
  - Prolific publications including 20 conference and 5 journal papers
- **Project is generating new businesses:**
  - Ambiq Micro (Austin, TX): $2 million in VC funding for ultra low-power microprocessor technology
  - Civionics LLC (Ann Arbor, MI): marketing wireless sensors to SHM market including bridges and other infrastructure systems

Courtesy of University of Michigan

Civil Infrastructure: Inspection & Monitoring (Water Systems)

Next Generation SCADA for Prevention and Mitigation of Water System Infrastructure Disaster

The Regents of the University of California (UCI), Irvine, California

Other Joint Venture Participants: Earth Mechanics, Inc., Fountain Valley, CA; Irvine Ranch Water District, Irvine, CA; Orange County Sanitation District, Fountain Valley, CA; Santa Ana Watershed Project Authority, Riverside, CA

A 108-year-old water main ruptured just after 1 p.m., Oct. 16, 03, NYC

April 1, 2009 to March 31, 2012
Total Project Budget: $5,685k
TIP Cost Share: $2,800k

Project

Develop a non-invasive inspection and monitoring system for pipe networks in drinking water and wastewater infrastructure using wireless sensor nodes incorporated in an advanced Supervisory Control and Data Acquisition (SCADA) system

Potential Impacts

- Results in significant reduction of water loss and reduced number of contaminated spill events
- Enables infrastructure agencies to monitor and identify physical and chemical deterioration of pipe network in real-time and provides effective maintenance schedules
- Extends the useful life and reliability of the water infrastructure
- Impacts ecosystem to ensure good quality of life

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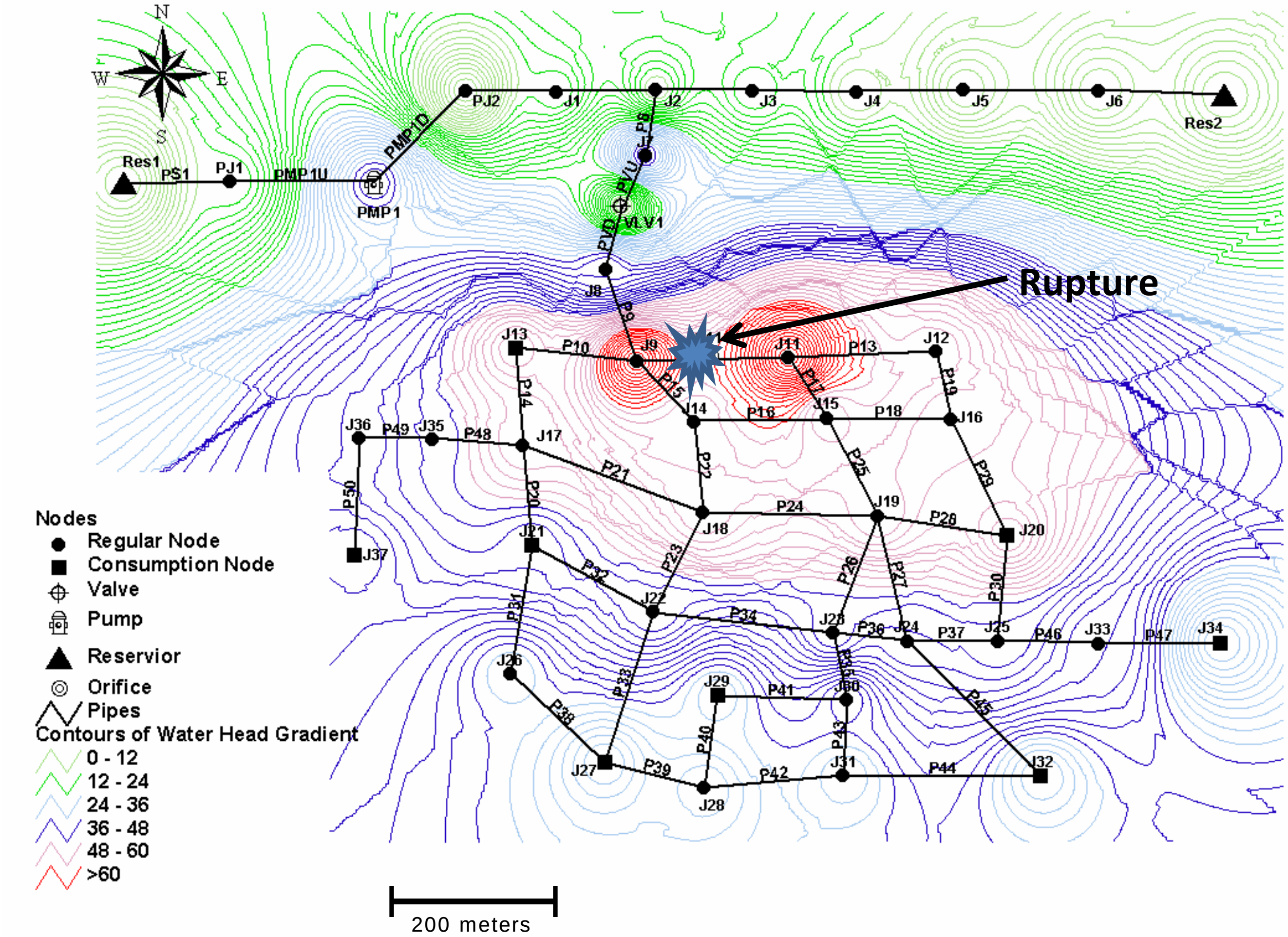
Broader Impacts

- Monitoring pipeline networks in real time, detecting and localizing ruptures/leaks rapidly, and scheduling maintenance more rationally will result from the next generation **SCADA** system (Supervisory Control And Data Acquisition system).
- Preparing for emergencies from the development of response strategies for each predicted disaster scenario through using simulations.
- Implementing a response strategy developed from the most similar simulated disaster may minimize the response time and the consequences. The next generation SCADA system will provide information of the damage in real time.

Courtesy of University of California at Irvine

Contour of Water Head Gradient



$$D = \left| \frac{H_2 - H_1}{t_2 - t_1} \right|$$

Where:
H_2 and H_1 are the water head of a node at the time t_2 and t_1

D reveals the rapidness of water pressure head drop

Computer Simulation by HAMMER

Courtesy of University of California at Irvine

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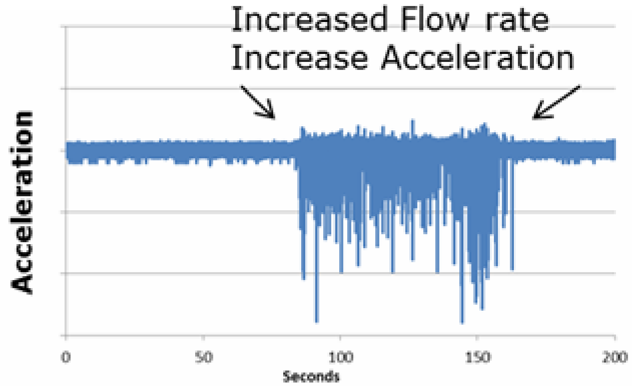
Experimental Work (Field Tests)

PACE* (Subawardee)


14" Diameter Pipe



Irvine Water Ranch District (IRWD)


4" Diameter Pipe

***PACE - Pacific Advanced Civil Engineering**

Courtesy of University of California at Irvine

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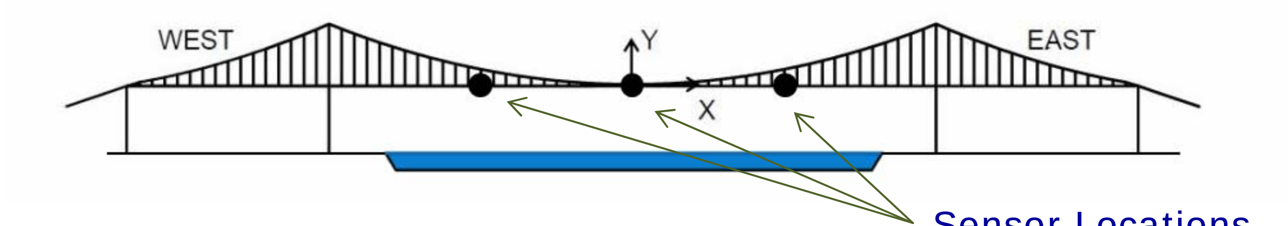
Field Test (Vincent Thomas Bridge)



Sensor Locations

- 1847 m long suspension large steel structure
- Sensors on structure and pipe
- Communication in a steel environment with radio interference

Structure

Pipe

Vibration Results: They Were in Agreement With Previous USGS Studies

Vibration Periods (s):

Mode	PipeTECT	USGS
No.1:	.228	.231
No.2:	.372	.364
No.3:	.478	.452
No.4:	.818	.808

The PipeTECT sensors have proven themselves to be very reliable.

Courtesy of University of California at Irvine

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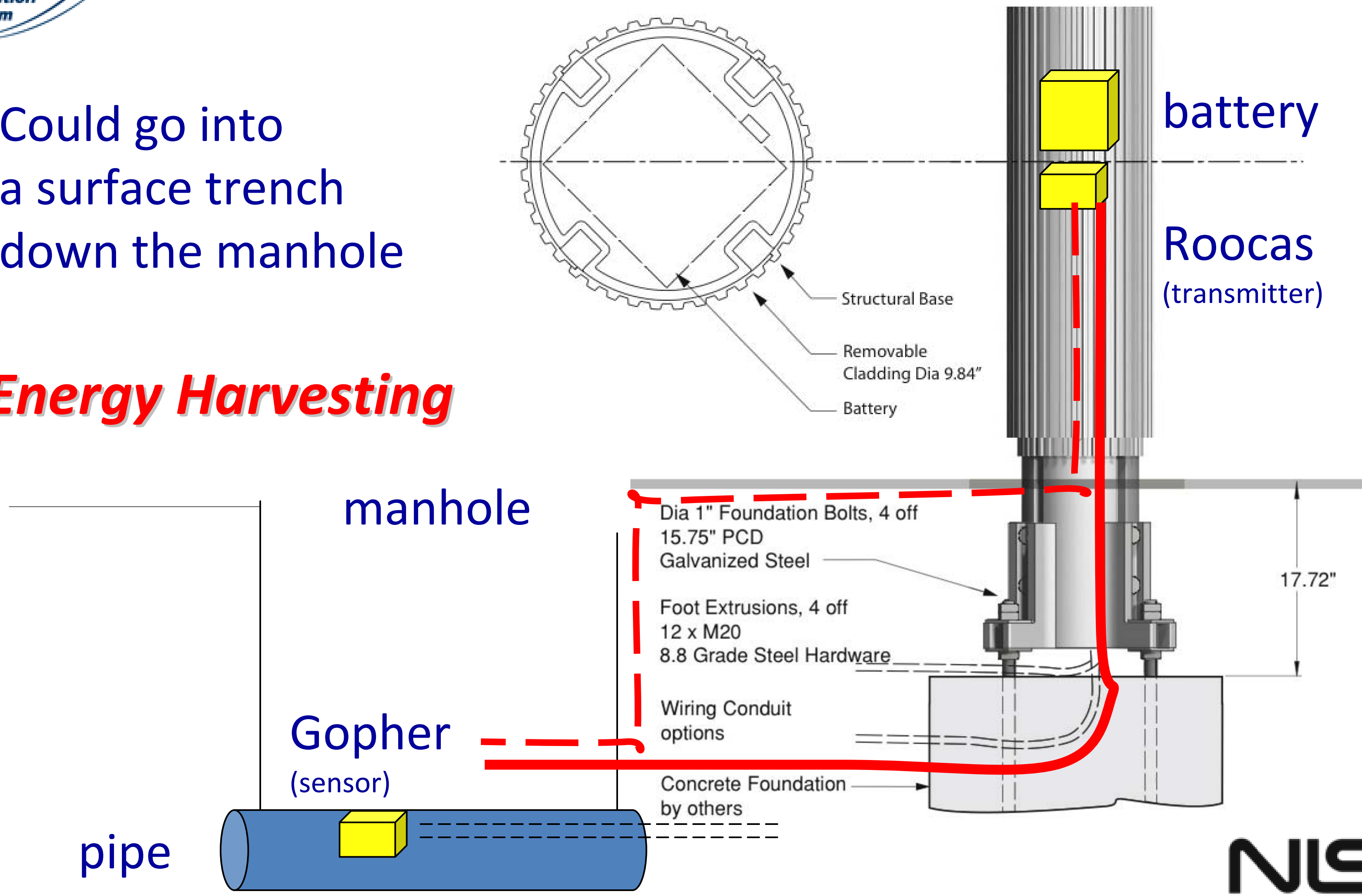
INNOVATION AND INDUSTRY SERVICES

Manhole Modifications with SAWPA*

Could go into
a surface trench
down the manhole

Energy Harvesting



***SAWPA - Santa Ana Watershed Project Authority**

Courtesy of University of California at Irvine

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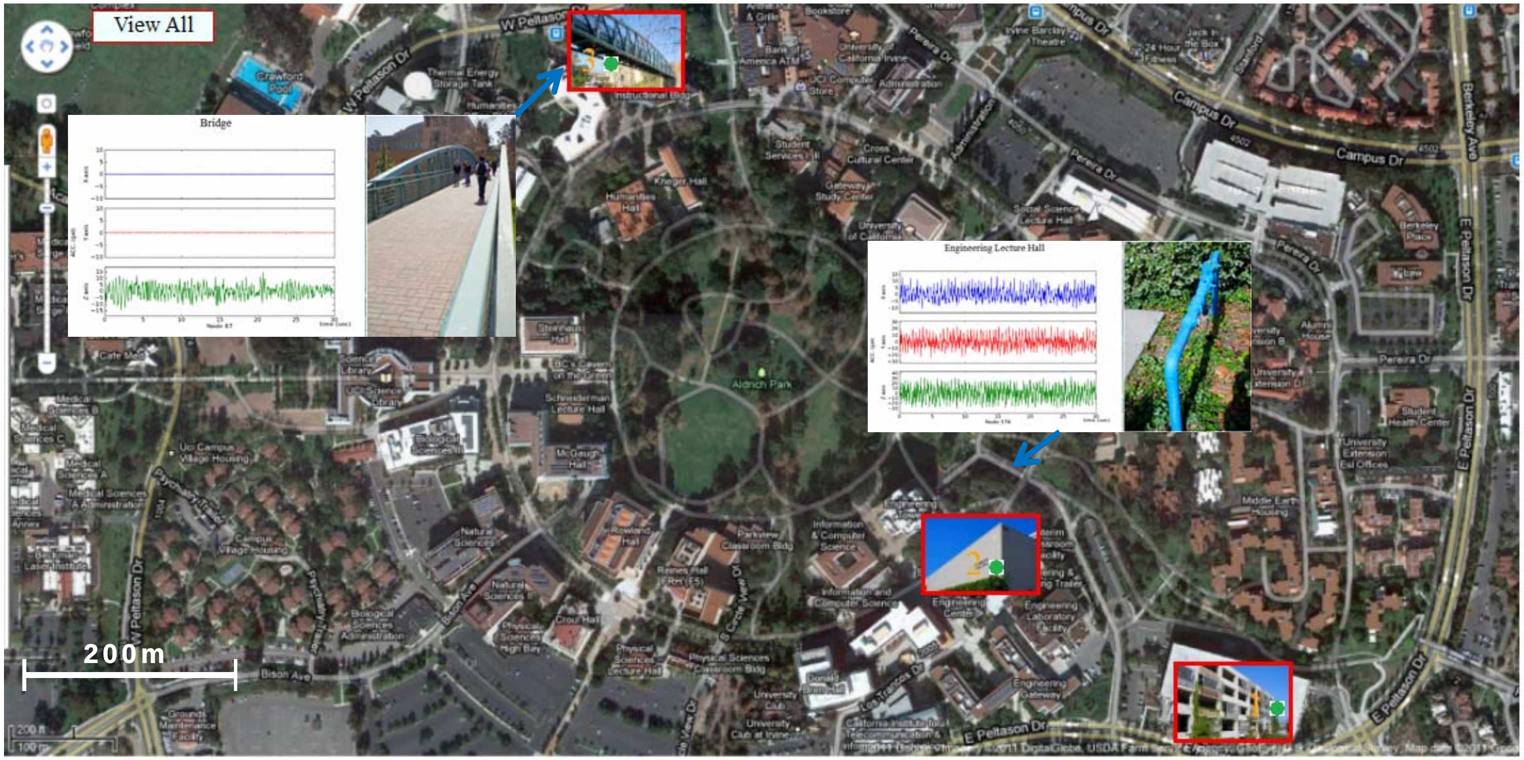
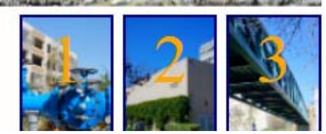
U.S. Department of Commerce

Prototype Next Generation SCADA for UCI Infrastructure Systems



Location 1: Utility pipes located behind the parking structure
Location 2: Utility pipes of Engineering Lecture Hall
Location 3: Bridge between main campus and art school



Currently two sites:

tchien.eng.uci.edu/PipeTect/campus.html

tchien.eng.uci.edu/PipeTect/OCSD.html

Courtesy of University of California at Irvine

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Future Challenges:

Platform Technology Areas & A Suite of Materials

- Engineered Nano/Micro-Structures
- Multi-functional Materials & Systems
- Nano/Micro-Manufacturing
- Self-healing & Self-monitoring Materials

Next-Generation Construction: Materials, Processes and Green Buildings

- Lower cost (direct/socioeconomic)
- Agile construction
- *In-situ* quality control
- Reduced construction time
- Low/no maintenance
- Managed maintenance
- Extend construction season
- Ultra-high performance materials
- Longer service life of materials

- Concrete
- Polymer
- Fiber
- Steel
- Glass
- Insulation

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