Enhanced Structural Health Monitoring of Civil Infrastructure by Observing and Controlling Loads using Cyber-Physical Systems

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The Problem: Deteriorating Infrastructure

Restoring urban infrastructure is one of the major grand challenges for the 21st century as named by the National Academy of Engineering. Highway bridges remain a poignant example of the dire need to improve how critical civil infrastructure systems are managed:

- *The U.S. spends roughly $350 million annually just to inspect bridges*
- *20% of the nation's bridges exceed their design lives (50 years)*
- *From 1989 to 2000 over 130 bridges in the U.S. collapsed*
- *ASCE estimates that "$17 billion annual investment is needed to substantially improve current bridge conditions"*
- *Population growth is adding higher load demand on bridges*

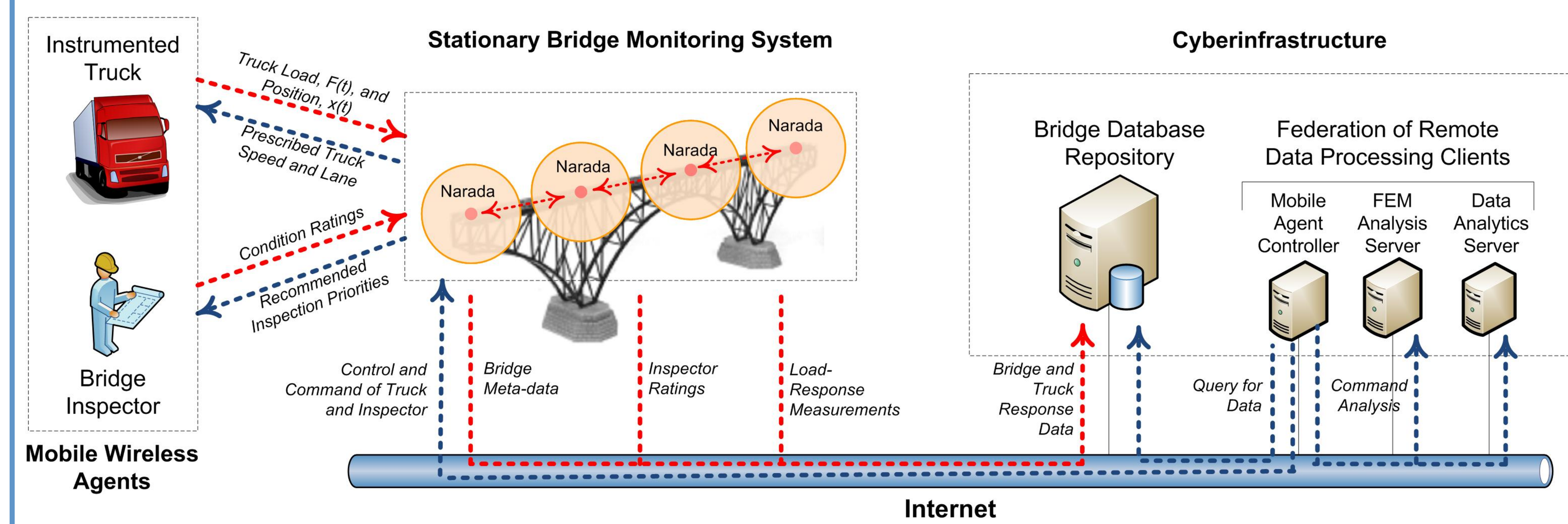
Silver Bridge Collapse (1967, West Virginia)

Mianus Bridge Collapse (1983, Connecticut)

The Solution: Cyber-Physical Systems

This project offers innovative solutions to resolve the existing limitations associated with current asset management strategies. A cyber-physical system (CPS) approach is taken with:

- *Wireless telemetry used to observe and control mobile agents (e.g., trucks, inspectors) that interact and load infrastructure systems (e.g., bridges) in which stationary wireless monitoring systems are installed;*
- *Advance database systems designed for secure storage, curation and automated interrogation of sensed data to determine infrastructure health and to formulate mobile agent control actions in real-time;*
- *Automated registration of mobile agents within the CPS framework to control their interactions with the physical system.*



Cyber-Physical System (CPS) Framework for Structural Health Monitoring

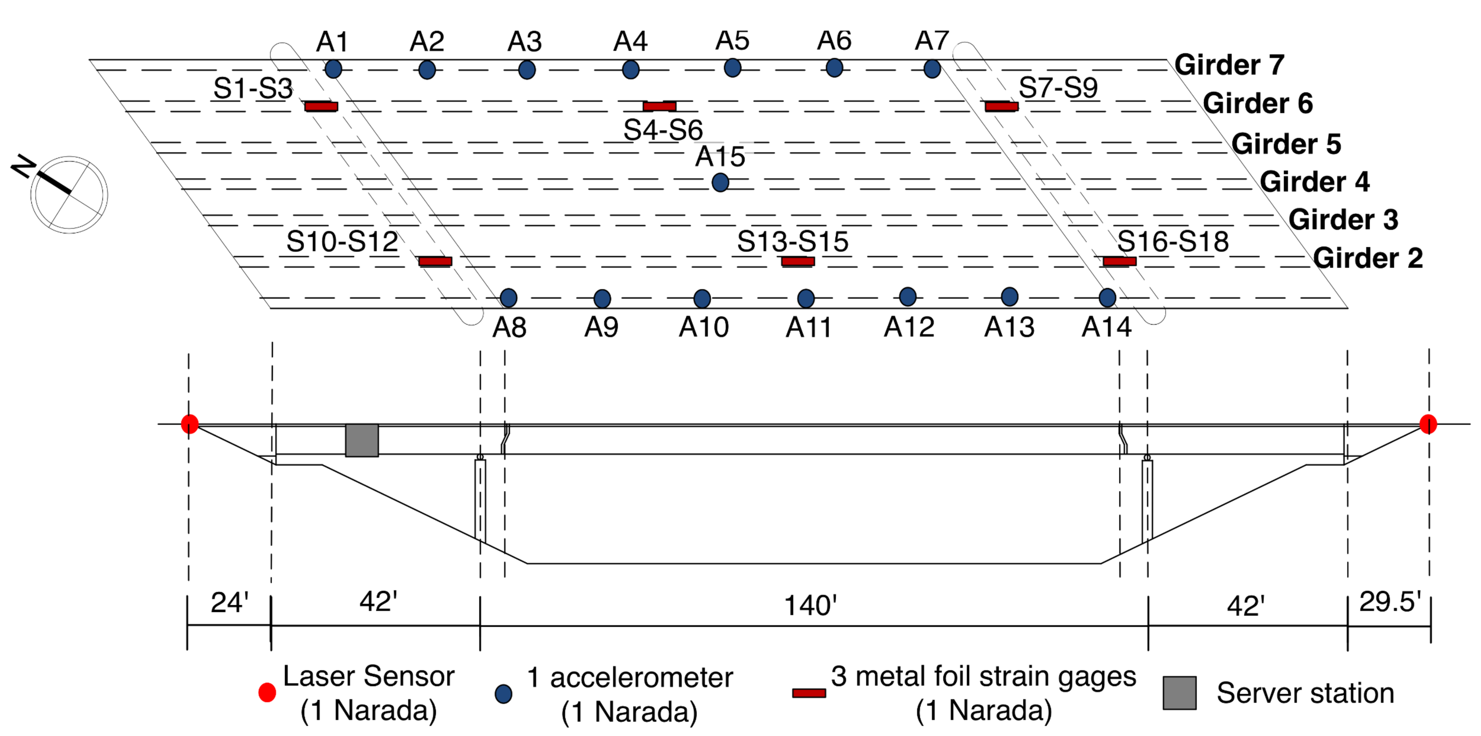
Year 1 Project Accomplishments

The project spans from January 2015 to December 2017. Year 1 research accomplishments include:

- *Designed a scalable Internet-based database system using NoSQL architectural elements for data storage with high-speed query capacity;*
- *Designed and deployed a dense stationary wireless sensor network on an operational highway bridge (Telegraph Road Bridge);*
- *Automated data interrogation schemes for time-series analysis of bridge behavior under extreme environmental and operational condition (EOC) variation based on Gaussian Process Regression (GPR) and Statistical Process Control (SPC);*
- *Designed and deployed a mobile wireless sensor network on a heavy truck to load the bridge;*
- *Developed an automated registration scheme for registering mobile truck-based wireless sensors within the bridge stationary wireless monitoring system;*
- *Field tested the highway bridge with the wirelessly sensed truck imposing controlled vehicular loading;*
- *Analyzed vehicle-bridge interaction using two-stage system identification methodology based on subspace system identification;*
- *Outreach conducted with the Detroit-Area Pre-College Engineering Program to enrich Detroit middle school students with sensors and data.*

CPS Testbed: Telegraph Road Bridge

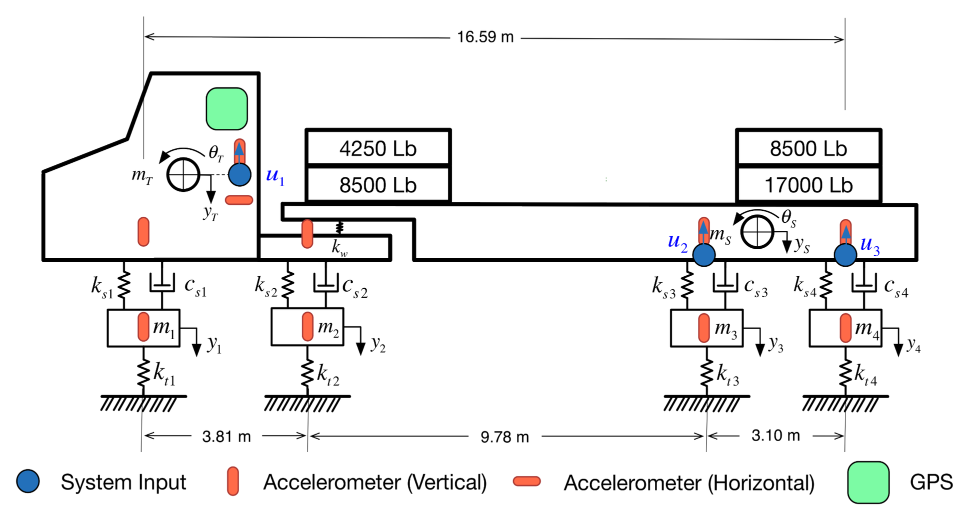
Telegraph Road Bridge (TRB) located in Monroe, MI is used as the project testbed. The 224 foot long bridge consists of seven steel girders supporting a reinforced concrete deck over three spans. The center span is fully suspended from two cantilever abutment spans using pin-and-hanger connections. A network of *Narada* wireless sensor nodes has been deployed to collect data from a total of 15 accelerometers and 24 strain gages. Data is written to a secure data server hosted at the University of Michigan using a cellular connection to the Internet installed at the bridge.



Wireless Monitoring System of the Telegraph Road Bridge

Monitoring and Modeling of Vehicular Loads on the Telegraph Road Bridge

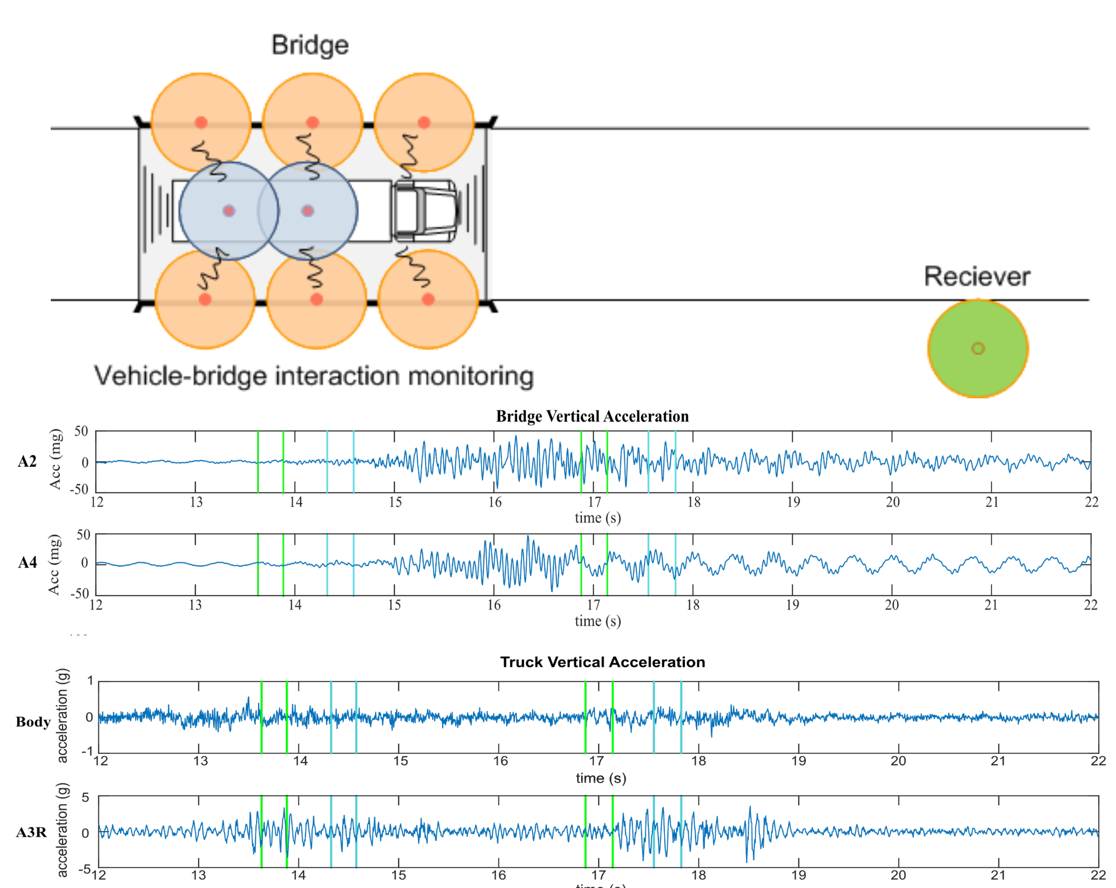
1. Mobile WSN on Heavy Truck



A mobile wireless sensor network of 20 accelerometers is installed in a four-axle tractor-trailer truck with a GPS module recording truck speed and position: two vertical accelerometers are at each wheel location (with one on the axle and another above the axle on the chassis) and two accelerometers are installed in the tractor to measure vertical and horizontal motion. *Narada* wireless nodes, the same as those installed on the Telegraph Road Bridge, are used to monitor the truck dynamics when crossing the bridge.

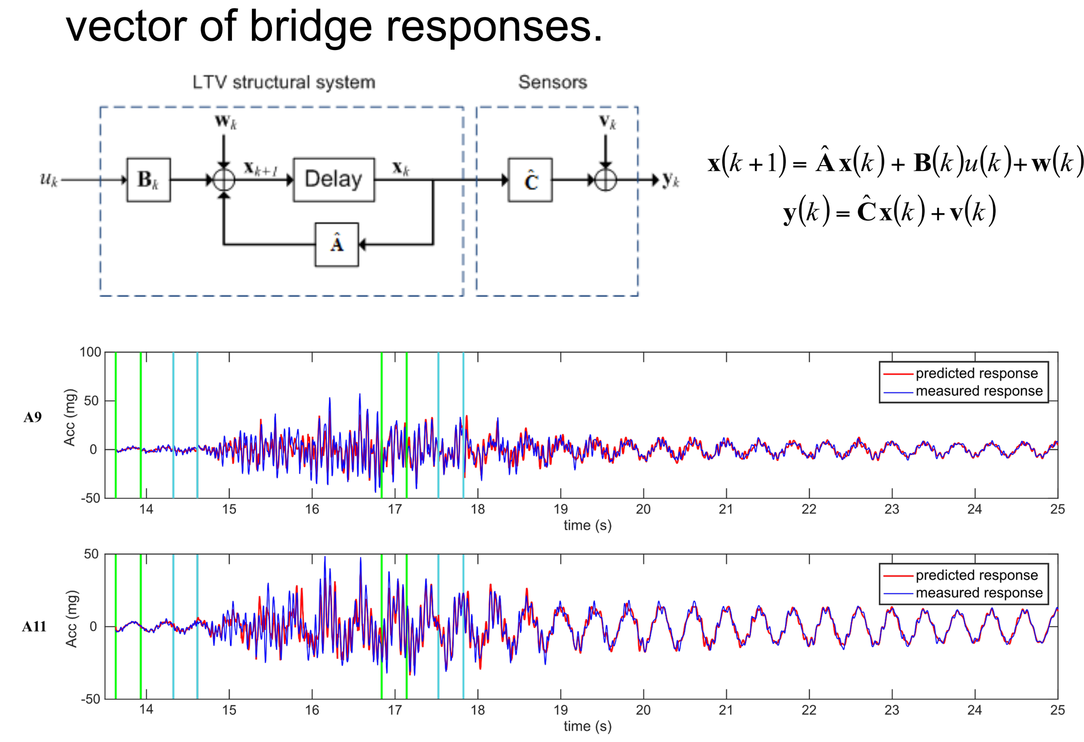
2. Vehicle-Bridge Response

Tests were conducted on the Telegraph Road Bridge with the truck mobile sensors registering with the bridge wireless sensor network. Time is synchronized between the mobile and stationary networks and data is communicated from the truck to the bridge. The truck is driven at various speeds with the tests repeated.



3. Vehicle-Bridge Interaction Model

A state-space model is formulated using the measured vehicle-bridge response data. In the first stage, the time-invariant system matrices $\mathbf{A}$ and $\mathbf{C}$ are estimated through stochastic subspace system identification using free vibration data (post-load responses). The time-varying system matrix $\mathbf{B}(k)$, which depends on the truck trajectory, is estimated by least square methods. The system input is the truck vertical vibration, u, and the output, $\boldsymbol{y}$, is the vector of bridge responses.



$$\mathbf{x}(k+1) = \hat{\mathbf{A}}\mathbf{x}(k) + \mathbf{B}(k)u(k) + \mathbf{w}(k)$$
$$\mathbf{y}(k) = \hat{\mathbf{C}}\mathbf{x}(k) + \mathbf{v}(k)$$

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