Corridor-based Highway Bridge Monitoring and Control using Cyber Physical System Architectures

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Cyber-Physical System Program Grant ECCS-1446521

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*

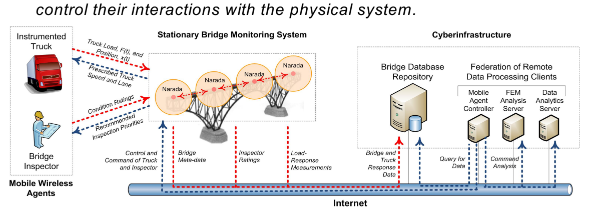
Silver Bridge Collapse (1967, West Virginia)

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 heavy trucks that interact and load infrastructure (e.g., bridges) along a highway corridor;*
- *Wireless sensors installed in bridges and trucks along with a network of traffic cameras are deployed to stream data to the cloud;*
- *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.*

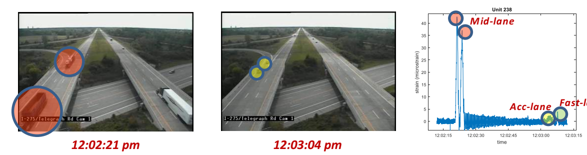


Cyber-Physical System (CPS) Framework for Structural Health Monitoring

CPS Applications for Asset Management

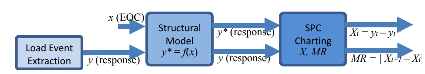
1. Identification of Truck Load Events

- Only truck events are of interest due to their direct impact on long-term bridge deterioration.
- Two scalable analytical approach are developed to extract bridge response data pertaining to trucks loads:
  - Support vector machine (SVM) classification using bridge data to identify truck events in real-time
  - Haar classification using traffic images to identify trucks in near real-time based on extensive training at each bridge site



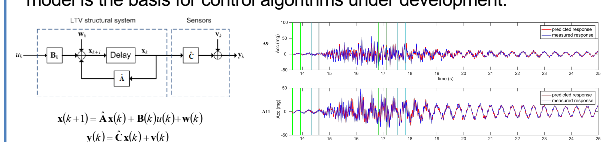
2. Bridge Health Assessment

- Extract structurally significant response events (truck load events)
- Nonlinear regression by Gaussian Process Regression (GPR) between environmental and operational condition (EOC) parameters and bridge responses
- Apply statistical process control (SPC) on response compared to baseline regression model of normal behavior
- Performed autonomously in the cloud using data stored in the project database system.



3. Control of 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. A linear but time varying state-space model is formulated using the measured vehicle-bridge response data with a varying form of the input matrix, $\mathbf{B}(k)$, used. The state-space model is the basis for control algorithms under development.



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

Testing Environment: I-275 Highway Corridor

A CPS testing environment has been set-up on the northbound I-275 corridor between I-94 (Romulus, Michigan) and I-75 (Monroe, Michigan). Three major data sources are used in this project: four bridges with complete wireless monitoring systems installed, one weigh-in-motion system (WIMS) station measuring truck traffic, and a network of traffic cameras. Data is collected and pushed to a NoSQL databases in the cloud for analytics.

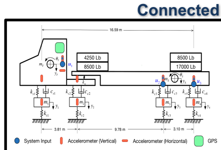
Weigh-in-Motion System (WIMS) Station

Most bridge owners have WIMS stations in their networks. These systems measure the curb weight of trucks on an per axle basis; they also record the speed of traffic and the lanes in which vehicles travel. The accuracy of WIMS stations range from 5-10% in the measurement of vehicle weights.

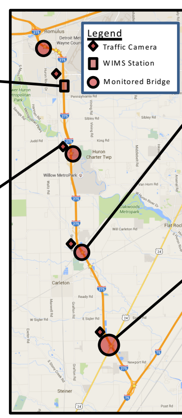
Traffic Camera System

A dense network of traffic cameras have been installed along the I-275 corridor providing a real-time stream of traffic conditions. Camera feeds from the instrumented bridges are recorded at 1 Hz rates to acquire information on truck loading. OpenCV used to segment images and extract truck events.

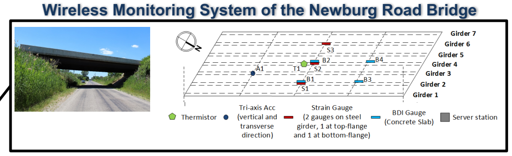
Connected Vehicle: Test Truck



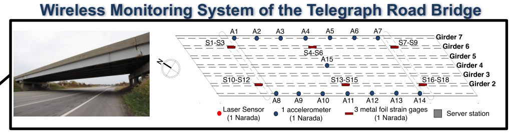
A mobile wireless sensor network of 20 accelerometers is installed in a four-axle tractor-trailer truck with a GPS module recording truck speed and position: two vertical accelerometers are at each wheel location (with one on the axle and another above the axle on the chassis) and two accelerometers are installed in the tractor to measure vertical and horizontal motion.



Wireless Monitoring System of the Newburg Road Bridge



Wireless Monitoring System of the Telegraph Road Bridge



Wireless monitoring systems are currently installed on the Telegraph Road Bridge and Newburg Road Bridge. Both systems consisting of accelerometers, strain gages, and thermistors used to record response of bridge to truck loads. Data is collected at each bridge by a wireless sensor network of *Narada* wireless sensors. Data is locally stored and pushed from a base station to a NoSQL database server at the University of Michigan.

Acknowledgements:

This research is supported by the National Science Foundation Grant Number ECCS-1446521 (Program Manager: Dr. Radhakisan S. Baheti). The authors would also like to express their gratitude to Peter Jansson (Michigan Department of Transportation) and Mark Gilbert (University of Michigan Transportation Research Institute) for their research support.