FEASIBILITY STUDY OF A BUS-DATA-DRIVEN APPROACH FOR ASSESSING DAMAGE IN BRIDGE STRUCTURES USING MULTIRESOLUTION SIGNAL PROCESSING TECHNIQUES

Project summary

This project aims at using pseudo data from idealized vehicle-bridge systems, available data from a moving bus, and data acquired in the future from a new vehicle and bridge, to study the feasibility of a new approach for bridge structural health monitoring. The approach has the potential of causing a transformative change in the way bridges are monitored, based on the combination of two special features: 1) The bridge monitoring data is obtained from moving vehicles, and, is therefore, considered as an *indirect* bridge instrumentation; 2) The proposed structural classification mechanism makes use of highly accurate signal processing techniques used currently for biomedical imaging applications, such as multiresolution classification and wavelets analysis.

The broad problem addressed is the current deteriorated structural state of bridges and the need for more cost effective, objective structural interrogation techniques. Today, structural evaluation is based primarily on subjective, biennial visual inspections. There are approximately 600,000 highway bridges in the U.S., 25% of which the Federal Highway Administration in 2007 rated as structurally deficient or functionally obsolete. The initial investment cost of monitoring bridges by placing sensors directly into the structure, is estimated at roughly $22.5 billion for the structurally deficient bridges, and $90 billion for all 600,000. The *indirect* monitoring approach, if successful, would reduce this cost drastically. This fleet-based approach will allow for much broader coverage of the entire bridge population, where only a fraction of the bridges are sensed directly today due to initial and long-term maintenance costs.

This project provides a perfect match with the research problems envisioned by Traffic21 in terms of reducing the cost of sensing infrastructure and assisting bridge inspections with physics-based evaluation. This approach can be considered as creating a sensed system (the bridge) by using mobile sensing systems (vehicles or buses) that are continuously transmitting information. These data can be of further use for other Traffic21 challenges, such as changing traffic patterns in real time, learning about driver pattern behavior, and in the development of smart vehicles.

Pittsburgh is known as the city of bridges and offers a great setting for using the already built infrastructure as a test bed that could serve to validate the approach. This project considers interaction with the Pennsylvania Department of Transportation (PennDOT) and the Port Authority of Allegheny County. It also has the potential of greater impact as it is put into service and is potentially expanded nationally and abroad.

This project also is multidisciplinary by nature, due to its complexity and the needed input from experts from different disciplines. Data will be processed by image processing experts from the Department of Biomedical Engineering; it is a civil engineering application that requires expertise in structural dynamics and numerical modeling; and it is highly technological in terms of sensing equipment required for data acquisition, storage, and management. These last tasks will be assisted by the NAVLAB (The Robotics Institute) members of the team. For future large-scale applications we have already been offered the use of necessary computational resources by the Pittsburgh Supercomputing Center (PSC). One of the Co-PIs is already a regular user of the PSC facilities.

Initial research, in which the response analysis of a simple oscillator-beam interaction model was examined, has produced preliminary results that show the potential of the approach. It was able to accurately detect very slight changes in the oscillator response due to different levels of damage conditions in the beam (reduction of moment of inertia), and to differentiate between a damaged and an undamaged state with an average of *88.4% accuracy*. This project would enable us to extend the approach to more realistic vehicle-bridge models, and to analyze already acquired acceleration data collected by the NAVLAB, and, thus, step up the validation of this approach with real case data.

1. Problem definition and main objectives.

The cost and challenges of bridge monitoring. The United-States faces the problem of having one of every four bridges categorized as structurally deficient or functionally obsolete (SD/FO). The entire national bridge population consists of approximately 600,000 highway bridges. In the Pittsburgh area there are over 2500 bridges over 8 feet in length (http://pghbridges.com/). Nationally, the evaluation of the condition of bridges is based on visual inspections conducted every two years. This monitoring approach has the disadvantage of being partly subjective, not always able to detect hidden damage (internal cracks, or closed cracks), having a long periodicity, and not being scalable at reduced cost.

It is important, therefore to have a reliable physics-based evaluation of bridge infrastructure. This would enable extending the life expectancy of current bridges still in good condition and make authorities aware of structural decay so they can schedule maintenance actions before they become critical and more expensive.

The current instrumentation approach for performing structural health monitoring (SHM) is based on data acquisition of bridges in a *direct* form, i.e., by putting sensing devices in specific locations on the structure. This direct form, while extremely useful, poses a number of practical challenges, such as vandalism or involuntary damage of installed equipment, the need for a power source or complex energy harvesting devices, together with the high-cost equipment maintenance and sensor reliability over the structure's life time. The estimated cost of an average bridge monitoring system is about $150,000 in initial costs alone (the life-cycle costs of maintaining this system on an annual basis is not given) (Web reference Lifespan technologies, whitepaper, 2008). That translates into a first-cost estimate for these 150,000 SD/FO bridges that need to be monitored of $22.5 billion. For the 600,000 bridges in the U.S., we would need $90 billion dollars.

The need for alternative bridge monitoring systems. Thus, there is an urgent need to explore alternative, more cost-effective means to monitor our complete stock of bridges on a regular basis. Our proposed approach is consistent with international experience that considers different levels of inspection depending on the structural condition and importance of the bridge. Superficial inspections are done on a regular short-term basis, while a more detailed thorough inspection is done periodically, usually every two years, or as required by the bridge condition. Such an approach is based on the need to detect drastic unexpected changes, and at the same time keep track of the normal degradation of the structure.

Preliminary findings. The research group has already started to work on this approach by developing a simple numerical model of an oscillator moving over a beam. The dynamic responses of different oscillators traveling at different speeds over the beam were analyzed with multiresolution image pattern recognition techniques. Preliminary results show that the proposed approach has the ability to detect damage with an average 84% accuracy. As this accuracy is improved with more research effort, this initial identification of damage would be sufficient to serve as a trigger for further more detailed inspection. A previous project executed by the Navlab at Carnegie Mellon gathered data from an instrumented bus for a period of over a year (see Figure 2 for a description of this data). We propose to explore whether this collected data can be used to develop a bus-data-driven structural assessment approach able to locate and determine severity of damage. Our approach stresses the use of signal processing techniques to characterize data obtained from moving vehicles over the use of intensive deployments of sensors directly on the bridges for monitoring purposes. It must be stressed that the proposed approach is envisioned to be complementary to the current visual and direct sensing approaches to monitoring structures. This proposed approach would be able to use other collected data for calibration and will be able to provide early indications of structures needing more visual inspection and/or direct sensing. We now give a brief description of the multiresolution algorithm that has been applied to our preliminary results.

Application of multiresolution techniques. The task of classification is a standard signal processing task. It involves assigning one of the possible labels (in this case five different labels) to a given input. This is typically done by computing, through signal processing methods, certain numerical descriptors, called *features*, on the given input, in the hope that these descriptors will be sufficient to discriminate among classes. Thus, a generic classification system has a *feature extraction* block followed by a *classifier* block (see Figure 1). This is, in a rough sense, the basic idea that enables us to apply the new multiresolution classifier developed by Kovacevic's team to our problem.

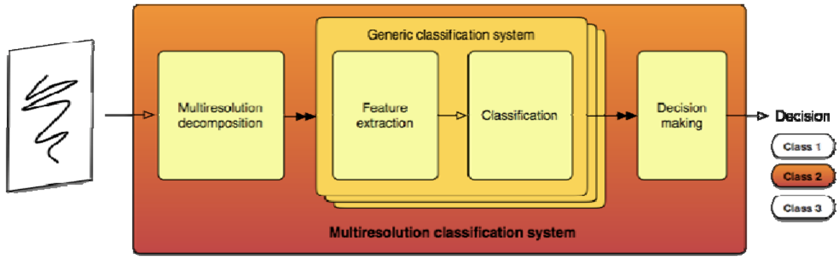

Figure 1. Multiresolution classification system.

Objectives. This project considers the application of the proposed approach to mathematical and computational vehicle-bridge models, as well as to data gathered during a NavLab project where data was gathered from an instrumented bus for a period of over a year for the purpose of creating a collision avoidance system (see Figure 2). Because of the proposed use of this bus data, we refer to this specific approach as a *bus-data-driven* approach. This data could serve as the first exploration of this approach with real sensed data. During the execution of this project, significant effort would be applied for data cleansing, mining, and management. We will then analyze this dynamic response data with multiresolution algorithms for pattern recognition and correlate them with environmental and atmospheric conditions.

Our *main objective* for this project is to find out whether, based on our model simulations and on the real-sensed bus-data provided, we are able to detect changes in the condition of bridges, and to perform a rough classification of undamaged versus damaged bridges, as well as determining the extent of damage.

The *secondary objectives* for this project are:

- Develop comprehensive models of bus-bridge interaction based on what we have done to date with an Oscillator Bridge Interaction (OBI) model and the data that has been collected from PAT buses to date.
- Develop a bus data processing scheme for structural evaluation of bridges. The acquired acceleration data is going to have to be normalized in terms of position with respect to the bridge, velocity at which the bus was driven (not constant in most cases), and variations with respect to the number of passengers (dynamic characteristics of the bus would be modified), and instrumentation noise among others. Before processing the data with the multiresolution algorithms, we will have to take into account these various factors into an automated preprocessing scheme.
- Modify existing multiresolution signal analysis approaches used in other engineering branches and adapt them to our bridge damage detection problem
- Create synthetic damage scenarios in the bus-bridge interaction model and produce response signals
- Evaluate capability of algorithms for damage detection by acquiring data from damaged and undamaged scenarios. This can be performed by collecting data from bridge with scheduled maintenance before and after the execution of the repair actions.

2. Major tasks and approximate timetable.

The project considers three major tasks. Numerical modeling, signal acquisition and extraction, and damage classification with advanced signal processing. These tasks are broken into subtasks over an 18 month span.

Year 1 Semester 1

- 2D Numerical Simulation of Bus-Bridge interaction system.
- Analysis of simulated data using multiresolution algorithm (MR) as is.

- Pre-process, visualize and analyze collected bus data, including data cleansing, data normalization, data fusion, and data comprehension.

Year 1 Semester 2

- Analysis of simulated data using MR algorithm as is.
- Analysis of real bus data using MR algorithm as is.
- Collection of new data from instrumented bus-fleet.

Year 2 Semester 1

- Analysis of additional real bus data using MR algorithm as is.
- Application and assessment of MR techniques for detecting the simulated damage data inserted into the bus-bridge interaction system.

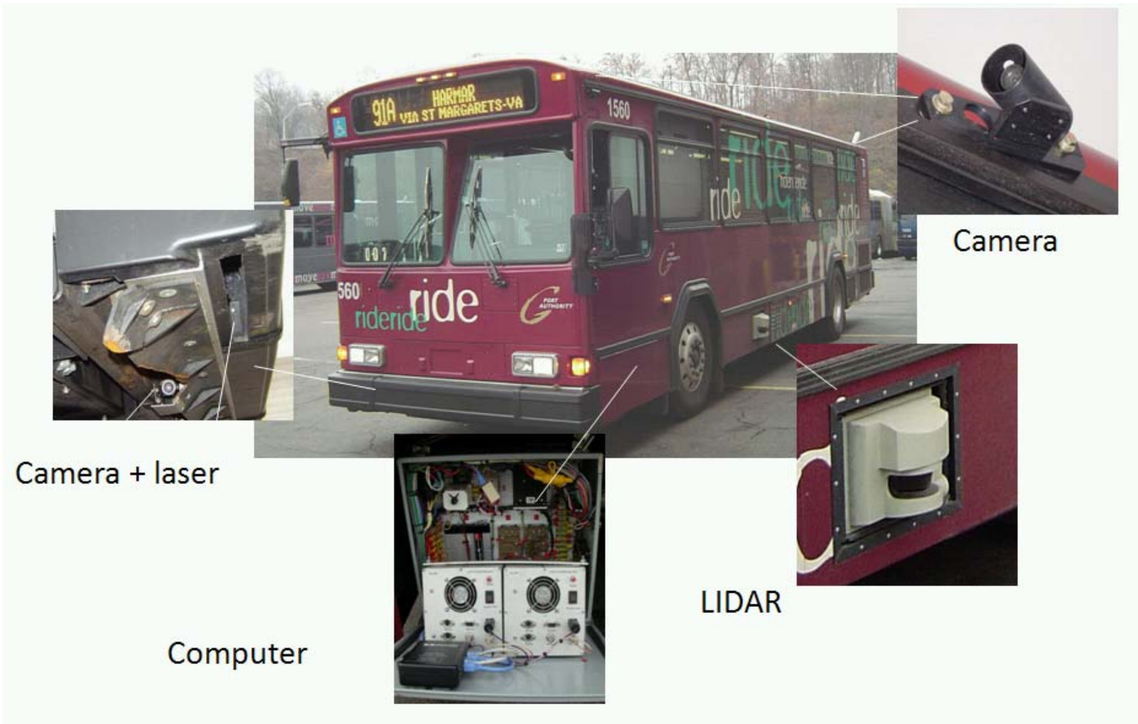

Figure 2. Equipped bus with various sensing devices.

3. CMU project team.

This project requires an interdisciplinary team of faculty and students. The initial phase is being conducted by a team from the Advanced Infrastructure Systems and Mechanics, Materials and Computing groups in the Civil and Environmental Engineering (CEE) Department, and from the Bioimage Informatics group from the Electrical and Computer Engineering (ECE) and Biomedical Engineering Departments. More recently, we have initiated activities with members from the Navigation Laboratory (NAVLAB) at the Robotics Institute. The CEE group will coordinate the entire effort and focus on the numerical models, the sensing implementation of real case studies, and damage identification; the bioinformatics group will be focused on the signal processing and damage identification algorithms; and the NAVLAB group will provide and help organize and interpret the sensed data obtained during a previous project, as well as instrument and conduct future bus instrumentations. The NAVLAB group has a fully instumented Jeep Wrangler (Navlab 11) which can be utilized by this project, e.g. to systematically measure the vibration of a bridge at different vehicle speeds or measure the vibration before and after the repair of a bridge. The Pittsburgh Super Computing Center (PSC) will also be involved in the project by providing access to supercomputing systems and services for data storage and processing, together with data visualization tools and services.

The project team consists of:

PI: James H Garrett (CEE)

CO-PIs: Jacobo Bielak (CEE), Jelena Kovacevic, (BME, Director of the Center for Bioimage Informatics), Christoph Mertz and Aaron Steinfeld (SCS, Robotics Institute, NAVLAB Navigation Laboratory).

Students involved in the project: Fernando Cerda (CEE PhD student), Ramu Bhagavatula (ECE PhD student, Center for Bioimage Informatics) , Russel Tutt IV (CEE Undergraduate Student).

4. Actual need for or potential for involvement of public/private partners.

PennDOT. We will ask PennDOT to be involved in identifying a bridge being monitored in District 11 that we could use as a test bridge for collecting vehicle data. They will provide access to the sensor data collected from the sensors installed on the bridge that could then be compared to the data taken from the vehicles traveling over the bridge at the same time. They will also be signaling a bridge that would be under repair over the execution period of this project.

Port Authority of Allegheny County. We will seek the participation of PAT to help provide access to their bus fleet to deploy further sensing equipment for collecting the bus accelerations, time and location data. There is already some indirect involvement since the data already available was taken from one bus on their fleet.

Osmos Technology. We will ask OSMOS to provide access to bridge sensing information.

PSC. We will ask PSC to provide hardware and services and visualization of data as needed.

5. Cost estimate.

The direct costs anticipated for this project and the associate PITA project are:

Category	**Traffic21**	**PITA**
Graduate Student Stipends	$55,630	
Graduate Student Tuition	$91,137	
1 month of Research Staff		$12,367 (includes fringe)
Capital Equipment		$10,000
Operating Expenses	$5,000	$1,000
Total	**$152,567**	**$23,367**

6. Other potential sources of financial support.

NSF: Civil Infrastructure Systems (CIS)

A proposal was submitted to this NFS program and we are waiting to hear the results. This project is complementary and parallel to the work that would be done in case the NSF proposal is granted. (http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=13352)

Pennsylvania Infrastructure Technology Alliance (PITA) program. We will submit another complementary proposal to this program, with the budget indicated in the table above.

7. Groundwork for future R&D funding.

This work will provide a significant and preliminary scientific basis for further research related to this vehicle-based structural damage detection capability of this approach. Having this initial project funding for these 18 months will provide a significant advantage for applying to NSF and other federal funding agencies, such as the FHWA.

Web references:
http://pghbridges.com/
http://www.historicbridges.org/b_c_pa_allegheny.htm (signaled bridges near demolition)
LifeSpan Technologies :. http://www.lifespantechnologies.com/contactus.asp