Integration of Bridge Damage Detection Concepts and Components

tech transfer summary

This work made significant advances in the development of a structural health monitoring system ready for implementation with improvements to automated data reduction/analysis, data acquisition hardware, sensor types, and communication network architecture.

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RESEARCH PROJECT TITLE
Integration of Bridge Damage Detection Concepts and Components

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Background

Although bridge testing has been an important tool for evaluating structures for several decades, it has only been within the last decade that specific effort has been given to develop systems that are capable of operating in an autonomous fashion. The development of an automatic and low-cost structural health monitoring (SHM) system is in high demand and crucial to reduce the costs associated with manual inspection, effectively monitor the status of bridges, and, therefore, minimize risk associated with bridge infrastructure.

The Iowa State University Bridge Engineering Center (BEC) began a project in 2002 (through the Federal Highway Administration Innovative Bridge Research and Construction program) to evaluate the state's first bridge constructed with high-performance steel. One of the objectives was to further the state's expertise in long-term bridge monitoring.

This project was the first major, concerted effort to handle large amounts of performance data. A great deal was learned during this project. Principally, an algorithm was developed that allowed for the automated removal of temperature effects, which represented a significant step in the development of a long-term monitoring system.

The Iowa Department of Transportation (DOT) started investing in research (through both the Iowa Highway Research Board and the Office of Bridges and Structures) in 2003 to develop an SHM system capable of identifying damage and able to report on the general operational condition of bridges.

In some cases, the precipitous has been a desire to avoid damage that might go unnoticed until the next biennial inspection. Of specific and immediate concern was the state's inventory of fracture-critical structures.

Field tests for this project were conducted on the US 30 Bridge over the South Skunk River in Ames, Iowa

Following on the success of the 2003 project, the BEC embarked on a project to develop an algorithm capable of autonomously detecting damage in the nearly 50 fracture-critical girder bridges in Iowa. That work resulted in the foundation for a complete, turnkey system.

The system operates on the assumption that pairs of data can be assembled from sensors located throughout a bridge and that the relationship between the data from the sensors can be established and is reliable as long as no damage occurs to the bridge. Thus, damage can be detected when the relationships no longer predict the response.

An analytical evaluation of the developed algorithm revealed that variability in truck characteristics (e.g., number of axles, weight, speed) created scatter in the relationships. Further work to refine the system resulted in an algorithm that accounted for truck variability and analyzed the data in a strong statistical manner. A second analytical evaluation gave further evidence that the developed algorithm was likely to be able to detect bridge damage.

A study completed in November 2010 sought to validate the developed algorithms experimentally. During that study, sacrificial specimens (which simulated the likely damage locations) were installed on an in-service bridge. The sacrificial specimens were exposed to real traffic loads and had two types of damage induced: fatigue cracks and thickness loss.

The damage-detection algorithm was able to detect 100% of the damage cases. However, it also had a relatively high false-detection rate, so improvements to the algorithm were further investigated and evaluated.

Also completed in 2010 was a project to develop a damage-detection tool based on vibration-based techniques. This work, completed by the University of Iowa, consisted of testing using numerical simulations, laboratory experiments, and field testing and a great deal was learned about using vibration-based techniques.

Although the techniques were not ready for implementation, there was strong evidence that integration of vibration measurements into the BEC methodology may enhance the overall damage-detection capabilities.

Work completed at the University of Northern Iowa, also in 2010, sought to evaluate the feasibility of using wireless sensor systems for system monitoring. Because a significant cost of any bridge monitoring system lies in the cost of cabling and its installation, this work was of great importance.

Several recommendations were developed as part of the work that may enhance the robustness of the overall systems under development including system modification for the measurement of lower sample rate sensors and development of energy harvesting systems.

Project Scope and Objectives

Through collaboration, the goal of this project was to bring together various components of the completed research at Iowa's Regent Universities with the following specific objectives:

- Final development of the overall SHM system hardware and software
- Integration of vibration-based measurements into current damage-detection algorithms
- Evaluation and development of energy-harvesting techniques suitable for wireless sensor networks

Overall SHM System

The objective of this part of the research was to finalize the development of the overall SHM system including the hardware, software, and strain-based damage-detection methodology.

- New hardware (including sensor, data acquisition, and communication architecture) was configured, installed, and verified operationally on an in-service bridge
- Four strain-based damage-detection methodologies, one-truck event, truck events grouped by ten, cross prediction, and f-test, were investigated and compared using control chart theory
- A complete software package called Bridge Engineering Center Assessment Software (BECAS) was developed to form an integrated SHM system

Vibration-Based Algorithm

Many challenges in detecting damage to bridges are attributed to the complexity of the structures and the presence of noise and environmental effects/interferences. The objective of this part of the project was to validate/integrate a vibration-based damage-detection algorithm with the strain-based methodology formulated by the BEC.

The proposed algorithm was based on localizing sensors around failure-critical joints and establishing transmissibility ratios. The methodology was tested in laboratory experiments and field tests.

Sacrificial specimen with accelerometers and varying levels of damage induced for vibration-based on-site field tests

Energy-Harvesting

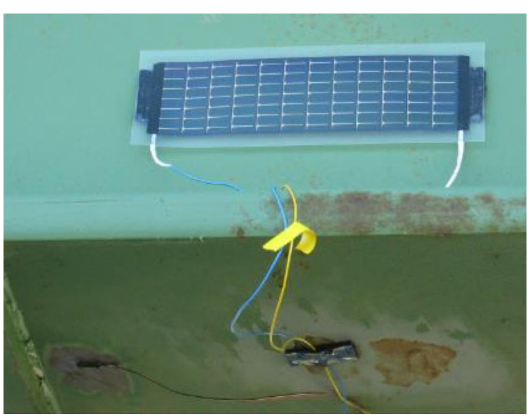
A wireless monitoring system that does not need long cables (for easy and fast installation and improved flexibility) and that can harvest energy from the ambient environment has gained attention in recent years because a self-powered system eliminates the maintenance requirement for battery changes.

Although batteries are still the primary type of energy storage components used in wireless sensor networks and other portable devices to date due to cost, energy density, and flat discharge voltage, they have the disadvantages of limited number of recharge cycles and charging/discharging temperature range.

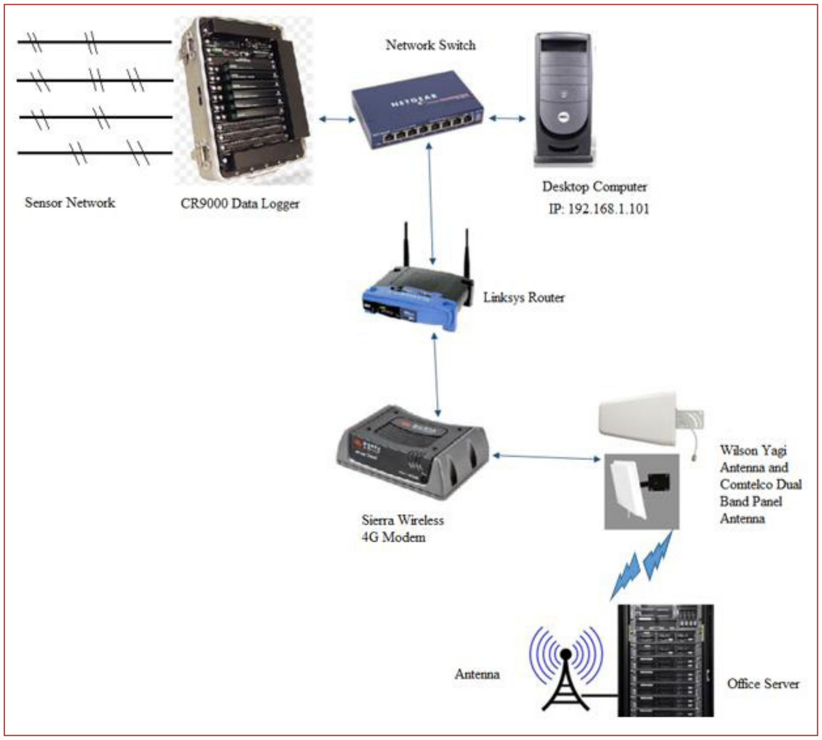
The wireless bridge monitoring system developed was tested to measure the strain data generated by the ambient traffic across the bridge. Four wireless sensing nodes with strain gauges were deployed on the west end of the bridge. The validation of the strain data and raw data process for further data processing were studied.

The self-sustainability of energy harvesting and reliability of the wireless communication in the system were also analyzed. Efficient power management is important to maximize the benefits of the harvested energy in addition to selecting the proper energy source and energy reservoir.

Solar panels were selected as the power source and an energy harvesting circuit (EHSuperCap) with two super-capacitors for energy storage was developed and tested on the bridge. Along with the strain data, the power supply voltage, temperature measurements, and wireless received signal strength indication (RSSI) were collected periodically for analysis.



Each wireless sensor node was connected to a solar panel to harvest energy and a weldable strain gauge to measure strain



SHM system components and architecture

Key Findings

- As with all SHM methods, separating true structural performance data from monitoring system noise is a major challenge and, with this work, progress was made in this direction by:
  - o Implementation of orthogonal linear regression
  - o Evolution of the F_{shm} method to improve true positive damage indications
- The target false-alarm rate of 0.3% was achieved with the one-truck event method; however, the highest true-indication rate was achieved with the F_{shm} method, while its false-alarm rate was over 0.3%
- Possible damage in the cut-back region of one girder in the bridge was detected by multiple damage-detection methods

The vibration-based algorithm was tested and validated as follows:

- Laboratory experiments on a connection specimen using transient loading conditions
  - o Warning percentages detected, quantified, and located damage
  - o Percent warnings had difficulties in quantifying magnitudes of damage (could not exceed 100%)
- Field testing on a sacrificial specimen that was geometrically similar to the laboratory connection specimen
  - o Warning percentages detected damage under normal traffic loading
  - o Environmental effects (temperature, wind, construction, etc.) were believed to cause false-detection results
  - o Damage quantification was unsuccessful due to variations caused by environmental effects
- Field testing of joints near the mid-span and quarter-span of a bridge girder
  - o Warning percentages were utilized on bridge connections directly with substantial significance
  - o Damage was falsely detected when significant changes in temperature occurred and during construction of a trail under the bridge

The demonstrated wireless bridge monitoring system findings included the following:

- Communication throughput could be an issue for a large network with low-cost wireless sensor nodes for application with high sample rate requirements
- Because the wireless bridge monitoring sensors are required to operate in outdoor environments, solar energy is the most promising source
- Overall, energy harvesting-based wireless sensor networks are an attractive option for various bridge monitoring applications

Implementation Readiness and Benefits

The ultimate goal with this work was to ready a system for widespread implementation and BECAS automates all of the components of a full SHM system successfully. The validation and integration of the vibration-based and strain-based damage-detection methodologies will add significant value to Iowa's current and future bridge maintenance, planning, and management.

The transmissibility concept and damage-detection algorithm demonstrate the potential to sense local changes in the dynamic stiffness between points across a joint of a real structure. Because the majority of failures occur at or near a connection, knowing the changes in inertial properties of failure-critical joints on a bridge would greatly improve detection capabilities and could prevent catastrophic failure. This part of the study showed that the presented algorithm is successful in experimental testing and that it has great potential for application in field analysis.

The demonstrated wireless bridge monitoring system using wireless sensor nodes is suitable for implementation. The nodes are very easy to install and the cost of a system is reasonable.

Light energy is the most abundant and feasible for wireless sensors used in bridge structure monitoring and the cost is not expensive compared to other micro-energy generators.

Because of its easy installation and redeployment, the wireless bridge monitoring system is especially attractive when the bridge monitoring system needs to be deployed in multiple bridges and the number of sensor nodes for each site is not very large, or for short-term structure monitoring and testing. After completing tests at one site, the nodes and solar panels, which are attached with heavy-duty Velcro tape, can be simply removed and moved to another site for another short-term monitoring period, such as several days or a couple of weeks.

Recommendations for Future Research

Additional work is required to obtain a damage-detection methodology that achieves the target false-indication rate (i.e., 0.3%) while at the same time ensuring a high true-indication rate.

Preliminary work related to this improvement leads the research team to believe this work should focus on reducing the effect of strain gauge reading uncertainty. This focus fits well in the previously-completed work aimed at decreasing uncertainty associated with selecting live load events meeting specific criteria.

Further investigation is required to expand the understanding of how temperature affects warning percentages. The association between percent warning and temperature changes suggests that for any significant change in temperature between days (or during the same day), a similarly significant change occurs within the warning percentage.

Further investigation is required to better understand the relationship between temperature and damage quantification. Future work could entail temperature compensation within the damage-detection algorithm or provision of supplemental temperature information to add redundancy to the procedure.

Overall, the transmissibility concept and damage-detection algorithm were successful at detecting damage for days in which temperatures remained near stationary; therefore, this algorithm could benefit from supplementary temperature information to negate false warnings.

When a wireless sensor node works in synchronous burst mode, it collects a given number of samples for a given interval. The collected data are not continuous but still provide the strain information resulting from ambient traffic. Given the strain data give more usable information during traffic-dense periods, such as rush hour, the nodes may be set to take more samples during the traffic-dense hours and save energy during other periods. One issue that needs addressed is how to better utilize the information obtained during burst mode sampling and its impact on the performance of the SHM system.

Another area that can be exploited is bridge monitoring applications that do not demand high sample frequency, such as crack or water level monitoring.

Final Project Reports

Volume I: Strain-Based Damage Detection - Iowa State University Bridge Engineering Center

Volume II: Acceleration-Based Damage Detection - University of Iowa Center for Computer-Aided Design

Volume III: Wireless Bridge Monitoring Hardware - University of Northern Iowa Electrical Engineering Technology