Leveraging Structural Health Monitoring for Bridge Condition Assessment

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ABSTRACT

Highway bridge infrastructure is a key aspect of the US transportation system. Efficient maintenance is important for preserving the integrity and improving the condition of aging national bridge infrastructure. Highway bridge condition is typically assessed using visual inspections and accompanying non-destructive field tests. This paper presents a solution that leverages low-cost Structural Health Monitoring (SHM) sensor data and the cumulative knowledge of bridge inspectors to monitor bridge condition. The developed solution utilizes a central database to store infrastructure inventory, inspection, and SHM information. The paper presents the Bridge Inspection Toolkit (BIT)—an innovative software solution that provides condition assessment decision-making support to bridge inspection documentation. Condition assessment support is provided by integrating the BIT with functionality that allows inspectors access to intelligent interpretation of SHM data. The BIT also allows inspectors access to condition assessment data corresponding to equivalent components, recorded by other responders, thus allowing them to draw on the collective experience and judgment of peers. The implementation of the inspection solution developed in this research introduces a greater degree of objectivity into condition ratings assessed by bridge inspectors. Condition assessment data gathered using the presented methods helps in effectively rating bridge infrastructure capacity and efficiently allocating maintenance resources.

INTRODUCTION

Importance of the research

Bridges are an essential component of a nation's civil infrastructure and transit systems, affecting passenger and commercial traffic on the regional and national scales. In 2010, the US Federal Highway Administration (FHWA) division estimated road passenger vehicles to account for approximately 83% of passenger travel mode choice by number of trips. The FHWA also estimated that commercial track traffic carried over $11 trillion worth of freight in 2008 within the US (FHWA 2013). The FHWA predicts that most highway routes will experience increases in both passenger and commercial traffic over the next 20 years (FHWA 2013). Bridge structures are key components of the US highway system. Therefore, problems with substandard highway bridges not only affect millions of passengers in terms of safety and convenience, but can cause substantial damage to economic activity. The reasons for bridge infrastructure failure are many, including the use of defective materials, deteriorating materials, substandard construction methods, improper design load ratings, natural disaster, man-made events, and long-term wear and tear. There are 605,102 public highway bridges (20 feet in length or longer) in the US, as documented in the National Bridge Inventory (FHWA 2013). Much of this infrastructure is aging, a factor that contributes significantly to the degradation of bridges. The long-term deterioration and rehabilitation of bridges is an important problem that could lead to large-scale disasters, if left unchecked.

Bridge inspection and maintenance

In the US, bridges are subject to the National Bridge Inspection Standards (NBIS), and State Departments of Transportation (DOTs) are generally responsible for the regular inspection and maintenance of the bridges under their jurisdiction. The DOTs are required to inspect, assess, and report the condition of bridge infrastructure to the FHWA. Bridge inspectors regularly evaluate bridges and assign condition ratings using the National Bridge Inspection Rating Scale, ranging from 0 (failed condition – out of service, beyond corrective action) to 9 (excellent condition – like new), based on NBIS. The FHWA classifies bridge infrastructure into three categories based on the reported bridge health: 1) healthy, 2) structurally deficient, and 3) functionally obsolete. Estimates suggest that over 25% of bridges in the US currently fall into the structurally deficient or functionally obsolete categories.

Traditionally, bridge inspections have been documented manually—based on standard rating guidelines and previous inspection reports; the bridge inspector assesses the condition of a bridge through visual inspection and accompanying non-destructive field tests (Farrar 2008). In recent years, the use of bridge inspection reporting software has been explored by several state DOTs as well as by independent asset management software developers. Bridge inspection reporting software solutions incorporate a centralized database and software installed on the inspector's tablet PC to facilitate the inspection process in the field. The bridge inspection software typically consists of interactive forms that retrieve customized inspection guidelines and relevant historic bridge inspection data, capture bridge evaluation data, and automatically associate the captured information with the bridge components making the bridge inspection documentation intuitive.

Structural Health Monitoring (SHM)

Although most jurisdictions in charge of bridges have inspection and maintenance measures in place to ensure that bridges meet minimum safety standards, bridge failures still occur. One reason for the shortcomings of the current measures is that bridges are assessed primarily using visual inspections. Recent studies to quantify the reliability of visual inspection methods have shown significant variability in condition ratings assigned to bridges by professional bridge inspectors (Moore et al 2001). To increase the reliability of condition assessment, state DOTs are adopting alternative, non-destructive evaluation technologies with an increased focus on SHM.

SHM is a non-destructive, in-situ sensing and evaluation technique that uses multiple sensors embedded in a structure to monitor and analyze the structural response in order to estimate deterioration and to evaluate its consequences regarding response, capacity, and service life. In recent years, several SHM systems have been developed and implemented. With the increased availability of wireless data networks, sustainable SHM systems have been developed so that pervasive sensor networks allow for centralized data collection, which allows for more efficient monitoring of multiple bridges and bridge segments across large areas (O'Connor et al 2012).

Objective of the research

Bridge infrastructure asset management emphasizes timely actions—such as infrastructure preservation, rehabilitation, and replacement—through cost-effective planning and resource allocation. Bridge owners are often faced with the task of prioritizing operations to allocate limited resources to in competing bridge infrastructure maintenance operations. The SHM-integrated bridge inspection approach presented in this paper was developed as part of a project to provide bridge owners with actionable information for improved decision-making. The efficiency of allocating maintenance resources can be improved by introducing objectivity from bridge condition assessment rating methods.

The developed solution provides inspectors with objective SHM metrics while assessing bridge component condition. The solution also allows for the concurrent generation of SHM data and corresponding visual condition rating data. This concurrent information generated through the large scale adoption of the presented solution is the first step towards developing algorithms that compute bridge component condition ratings using SHM information.

SHM-INTEGRATED BRIDGE INSPECTION SOLUTION

The architecture of the SHM-integrated bridge inspection solution is shown in Figure 1. The inspection solution developed in this research was deployed using the northbound I-275 highway bridge crossing over Telegraph Road (US-24) in Monroe, Michigan as the case study bridge (CSB). The crossing is a skewed, steel-concrete composite bridge with three spans and the bridge is supported by two abutments at the ends and two sets of concrete piers at the middle. The total length of the bridge is 223 ft, and the middle span—which is also the longest span—is 140 ft in length. The bridge superstructure is comprised of 7 steel girders that support an 8-inch concrete deck slab. The girders are simply supported at the piers and abutments, and each girder is suspended by two pairs of pin and hanger assemblies in the middle span. The middle span deck is connected to the end spans by an expansion joint and a construction joint aligned directly above the pin and hanger assemblies. The developed solution is scalable and extensible to most highway bridges.

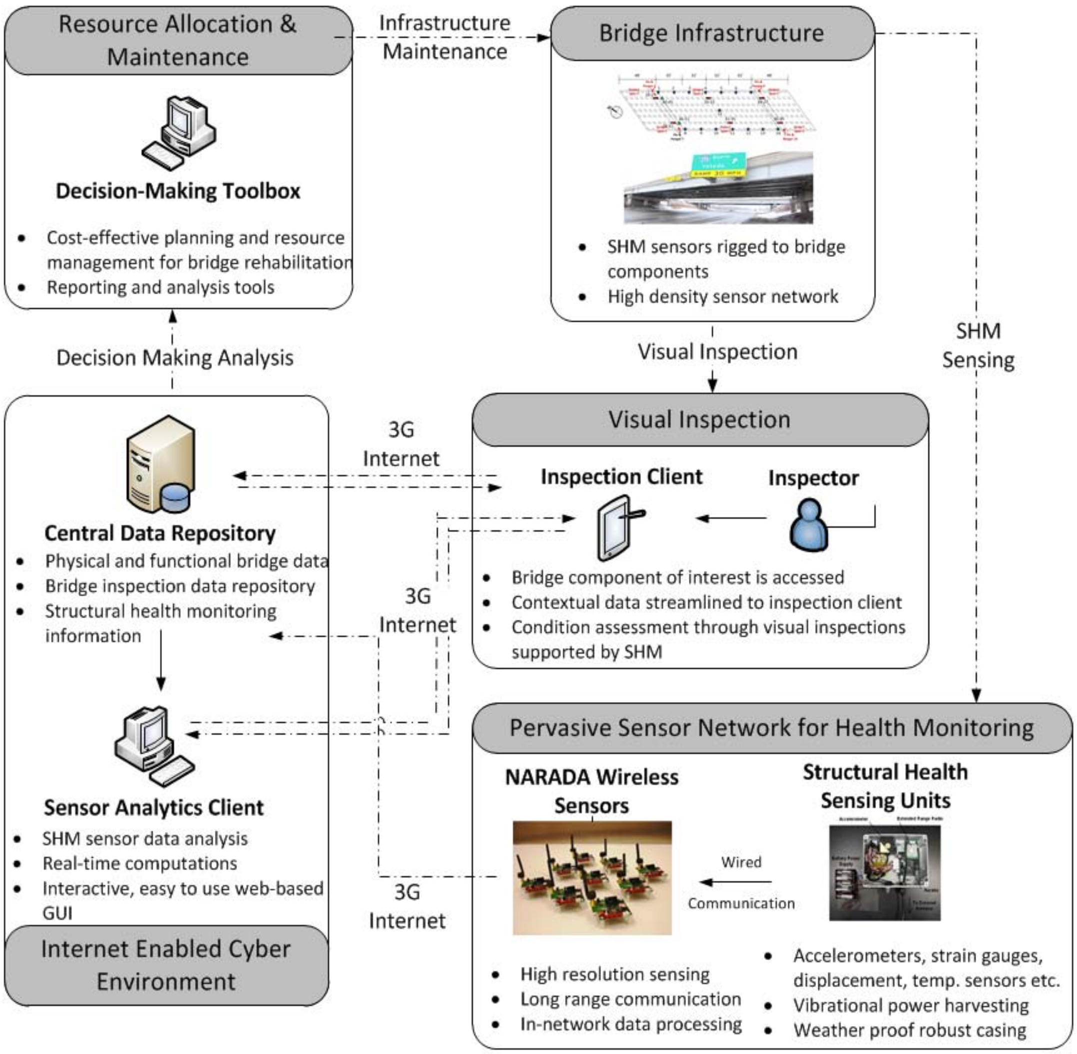


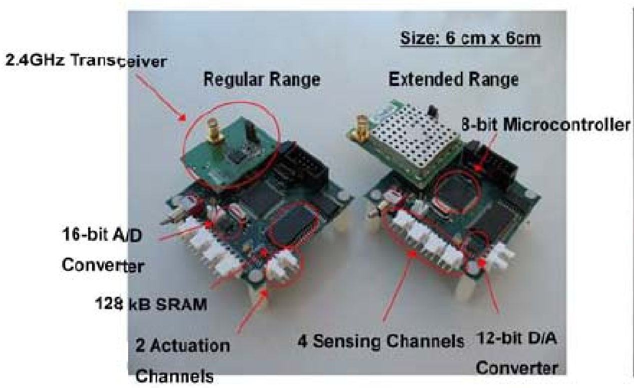
Figure 1. Architecture of the SHM-integrated bridge inspection solution

Central Data Repository (CDR)

The CDR is implemented as a PostgreSQL database with a multi-platform client-server application for storing data. PostgreSQL is an open source object-relational database management system. The multiplatform client-server application is developed using the Internet Communications Engine (Ice) middleware, and can be accessed through a number of development environments, including Python, Java, C++, and C#. The CDR stores three main categories of information for bridge infrastructure fleets: 1) bridge information, 2) sensor information, and 3) inspection information. Bridge design information includes information regarding bridge design (such as identity, location, desired inspection frequency, and structural components), physical characteristics (such as component material and geometry), and functional characteristics (such as finite element models, traffic volume, and load distributions) of the bridges in the database. Sensor information includes metadata (information about where/how sensors are deployed, the types/characteristics of sensors deployed, etc.) and the sensor readings themselves (van der Linden et al 2013). Inspection information includes bridge inspection data along with accompanying digital and multimedia data that supports assessment decisions. Condition assessment based on visual inspections and SHM are conducted using bridge information along with inspection information and sensor information, respectively. A detailed discussion of the database model is beyond the scope of this paper.

Pervasive sensor network for SHM

Automated wireless pervasive sensor networks are used for SHM of bridge infrastructure. The wireless SHM system features access to the internet to facilitate communication with the CDR and the rest of the cyber-infrastructure environment. The pervasive sensor network is designed to be reliable with enhanced communication ranges and long-term power harvesting strategies, and to operate on solar energy. The architecture of the wireless SHM system is designed with system functionality delineated to different hierarchical tiers. Sensors that measure vibration responses, atmospheric profiles, strain hysteresis, etc. are tethered to low-power *Narada* wireless sensor nodes, shown in Figure 2, that collect data and process it in-network to compress the information to be communicated and stored by the system.



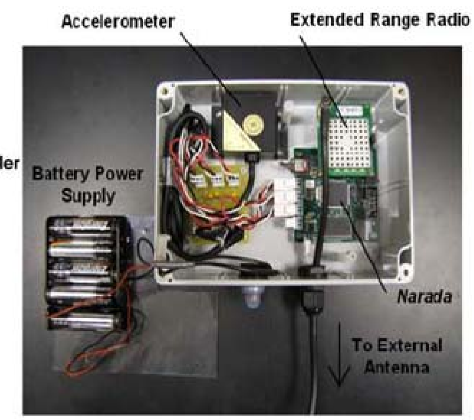


Figure 2: Narada wireless node (left) and a pre-assembled sensing unit (right)

The data logging system installed at the receiver station is an industrial-grade single board computer running Linux. The system accesses the internet (and the cyber-environment) through a 3G mobile phone network. The system is specifically designed for robust continuous operation with automated rebooting. The *Narada* server program automatically starts after the system starts up; at the start, the server initiates data collection from the *Narada* nodes. After data collection, the server program triggers the *Narada* sleep mode and waits for an assigned period (e.g., 1 hour) until the next scheduled data collection step. At every data collection step, the receiver station autonomously transfers data as a client to the CDR. The CDR is accessible through the internet-enabled cyber-environment to a series of data interrogation servers hosting modeling tools, damage-detection tools, and system identification tools (O'Connor et al 2012).

SHM-integrated bridge inspection

The inspector carries a tablet PC, running a Windows operating system, with access to the internet through a 3G mobile network. The tablet PC allows the inspector to navigate using a stylus, recognizes intelligible handwriting input from the touch screen, and has inbuilt features to record audio-visual multimedia. An innovative bridge inspection software known as the Bridge Inspection Toolkit (BIT) is installed on the tablet PC.

The component of interest is selected and passed to the BIT to query for contextually relevant information including component condition history, supporting documentation, rating guidelines, and SHM analysis. The component condition history, supporting documentation, and rating guidelines are retrieved from the CDR whereas the SHM analysis is retrieved by querying the sensor analytics client. The inspector visually inspects the component and reconciles field observations with the retrieved contextually relevant information to assess the condition of the component. The assessed condition is documented in the CDR along with any supporting digital and multimedia documentation by using the BIT functionality.

Sensor analytics client

The BIT allows inspectors to access meaningful information regarding the structural health of bridge components that are of interest. The sensor analytics client processes raw sensor data to generate a meaningful interpretation of structural health that is easily understood by the inspector. The sensor analytics client is hosted on a machine, running Linux, with access to the sensor data stored in the CDR through the internet. Bridge components that are monitored using the pervasive sensor network may have one or more types of SHM analysis that can be performed to assess their condition. The client is comprised of a set of Python scripts, each corresponding to a type of SHM analysis. The appropriate Python scripts are invoked by querying the sensor analytics client with the component of interest and the desired type SHM analysis. Upon being invoked, the Python script connects to the CDR and retrieves the raw sensor data to process the underlying SHM algorithms to generate the requested analysis. The generated analysis is written to a Google Chart object, using the Google Chart API, and is embedded in a webpage that is returned to the BIT.

Decision Making Toolbox (DMT)

The Decision Making Toolbox (DMT) uses the data collected through bridge inspection and SHM to support cost-effective planning and resource allocation decisions for timely bridge maintenance action including preservation, rehabilitation, and replacement (Ettouney and Alampalli 2007). DMT is a coherent, comprehensive set of analysis programs implemented to run on a Windows operating system. DMT also provides a medium to develop rapid application analysis through a visual modeling environment without any programming (Ettouney and Alampalli 2007). DMT uses multiple algorithms including modal identification, parameter identification, and rain flow techniques in conjunction with inspection and SHM data to compute, in real-time, different reliabilities and risk estimates for bridge components. Moreover, capacity, demand, and failure consequences of bridge components are also estimated and summarized in an elegant form for bridge decision-makers to use (Ettouney and Alampalli 2007).

BRIDGE INSPECTION TOOLKIT (BIT)

The BIT is an innovative proprietary software solution that takes a new and unique approach for intelligent condition assessment decision-making. The BIT is a scalable, extensible, and modular software tool written in the C# programming language using the WinForms API included as a part of Microsoft's .NET Framework and is implemented to run under the Windows operating system. The BIT, shown in Figure 3 (a), provides bridge inspectors with the following functionalities:

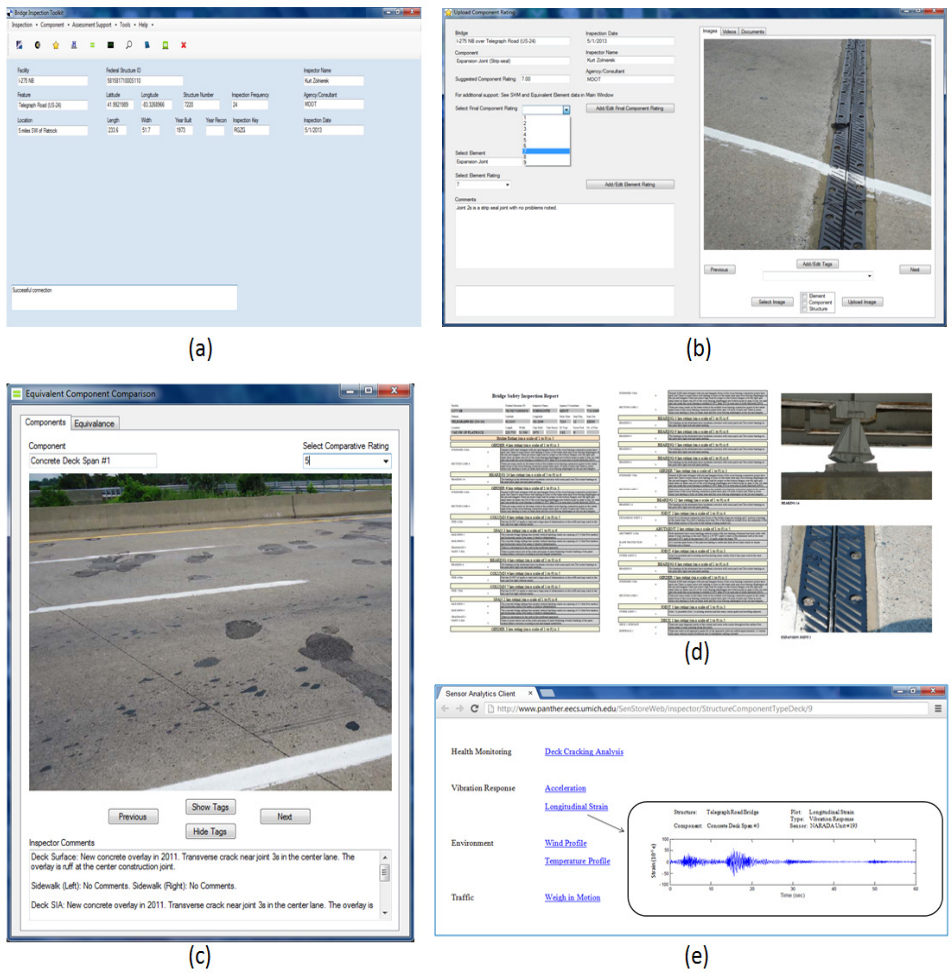


Figure 3. (a) The Graphical user interface of the BIT and the (b) rate component, (c) equivalent component comparison, (d) generate report, and (e) SHM analysis functionality available in the BIT

Rate component: This functionality allows the inspector to rate the condition of the bridge component corresponding on the NBIS scale, as shown in Figure 3 (b). The functionality also provides methods to associate captured multimedia and notes documenting the inspector's observations with the component of interest.

Component history: This functionality allows inspectors to intuitively access and understand the history of condition ratings, inspector notes, supporting multimedia documentation, and assessment metadata associated with the component.

Progress log: The BIT allows the inspector to track the progress of the inspection operation by keeping a log of those components that have been assessed and those that are yet to be assessed.

Equivalent component comparison: This functionality, shown in Figure 3 (c), allows the inspector to draw on the experience and judgment of peers by comparing the condition of the component in context with equivalent components across the rating scale. Upon selecting the condition rating deemed appropriate for the component, the functionality provides methods for the inspector to view captured multimedia, inspection notes, and observations associated with similarly rated equivalent components in the inventory. The inspector then refines the component's condition rating by browsing for condition concurrence among equivalent components. The BIT also allows the inspector to define similarity among bridges based on bridge characteristics and the traffic loads it is subjected to.

Generate report: Upon completing an inspection, the inspector can generate information-rich inspection reports, shown in Figure 3 (d), using this functionality. The inspection reports are formatted based on the NBIS guidelines.

SHM analysis: This functionality presents inspectors with condition assessment decision-making support based on SHM analysis using a web-form based interface, as shown in Figure 3 (e). The inspector then interprets the presented SHM analysis and refines the component's condition rating.

SHM ANALYSIS AND INTEGRATION

The developed solution integrates SHM analysis into the visual inspection process, thus, providing inspectors with objective metrics to support condition assessment. As a proof of concept, SHM analysis algorithms were developed for the following phenomenon: 1) deck cracking, 2) ping and hanger fatigue, 3) pin and hanger lock-up, and 4) deck-girder system composite action. A discussion on the implementation and utility of the deck-girder system composite action is presented in the following paragraphs. A detailed discussion on the implementation and utility for the rest of the developed SHM analysis algorithms is beyond the scope of this paper.

Deck-girder system composite action analysis

The deck and girders are physically connected using bolts, adhesive, and shear connections to behave as a single composite unit when subject to loading. This allows the deck slab to contribute to the girder strength. The composite action of the deck-girder system results in significant improvements in bending strength and stiffness of the bridge, allowing the use of much lighter girders for a particular span and loading.

The effectiveness of composite action is measured by comparing the expected neutral axis with the observed neutral axis of the deck-girder system. The location of the expected mean neutral axis is determined by calculating the neutral axis distribution resulting from the expected traffic load distribution. Strain gauge sensors are attached to the bottom and top flanges of the CSB girders to record strain history. Using strains measured at the bottom flange since the last scheduled inspection, and the time-correspondent strains at the top flange, the location of the neutral axis is estimated as a distribution.

The sensor analytics client presents the inspector with a visualization of the distribution of the neutral axis location from current (shown in blue) and previous (shown in red) inspection periods and compares them to the expected neutral axis, as shown in Figure 4. The inspector assesses the condition of the girder system based on the movement of the neutral axis' location between current and previous inspection periods. Thus, the developed solution integrates objective condition feedback during assessment that would have been absent in simple visual inspections.

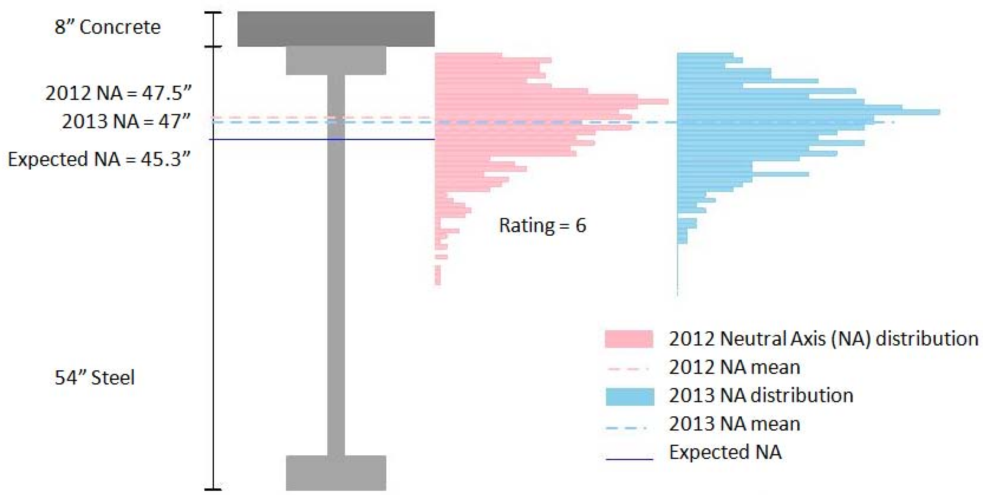


Figure 4. Movement of the composite action neutral axis between 2012 and 2013 as observed in the second girder (from the south-west) of the middle span in the CSB

Long-term strategy for integrating SHM into condition assessment

The authors are currently designing and developing additional SHM sensor suites and analysis algorithms that can be leveraged by inspectors during condition assessment routines. The authors are working with the Michigan DOT towards widespread deployment of low-cost SHM sensor networks for the large-scale monitoring of infrastructure fleet condition. The long-term adoption of the developed inspection solution will result in a statistically significant set of concurrent SHM and visual condition assessment data, thus helping the developing of algorithms that correlate SHM metrics with bridge infrastructure condition assessment.

SUMMARY AND CONCLUSIONS

A bridge inspection solution that integrates visual inspection with SHM analysis has been developed and deployed. The system integrates an automated low-power wireless sensor network with an internet-enabled cyber-infrastructure for ensuring periodic data collection and automated secured data transfer into a remote database server. The client-server model featured by the cyber-infrastructure manages data transfer and storage in the federated relational data repository and enables easy access to the stored data by applications engaged in data processing and mining. The

BIT and the sensor analytics client tools have been developed to allow the integration of objective SHM metrics in the condition assessment process. The team has completed the early application of the system at the I-275 Bridge over Telegraph Road in Monroe, MI. The long-term assessment of the implemented solution is underway with several upgrades and system expansions in the near future.

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DISCLOSURE

Manu Akula and Vineet R. Kamat have a significant financial and leadership interest in Perception Analytics & Robotics LLC (PeARL) and Navvy Robotics LLC, and are the inventors of technology—optioned to PeARL—involved in or enhanced by its use in this research project.

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