Decision support system for integrating remote sensing in bridge condition assessment and preservation

Arthur Endsley[*a], Colin Brooks[a], Devin Harris[b], Tess Ahlborn[b], Khatereh Vaghefi[b]
[a]Michigan Tech Research Institute (MTRI), 3600 Green Ct, Suite 100, Ann Arbor, MI, USA 48104
[b]Michigan Technological University (MTU), 1400 Townsend Drive, Houghton, MI, USA, 49931

ABSTRACT

Since the National Bridge Inventory (NBI) was first conducted, structural health monitoring (SHM) of U.S. bridge infrastructure has consisted largely of time and labor-intensive surveys with subjective results. In-situ and embedded sensors, while more reliable and accurate, can be costly and in many cases infeasible for SHM because they require installation in hard-to-reach places or during construction. Remote sensing (RS) technologies such as radar, electro-optical imaging and laser scanning may offer an innovative, cost-effective method of monitoring the dynamic conditions of U.S. bridges in real-time. While some RS techniques may be costly for state agencies to deploy on their own, RS imagery is available through government agencies or commercial vendors for moderate or no cost. How can disparate RS datasets be integrated with one another and with inventory data in a way that is meaningful to bridge asset management decision makers? This paper discusses the development and functionality of the Bridge Condition Decision Support System (DSS), a web-based asset management tool for bridge managers and inspectors. The DSS seamlessly merges bridge metrics from RS data with NBI inventory data allowing decision makers to compare up-to-date bridge condition metrics from multiple inputs as a time series. It enables analysis of RS and inventory data available through user-friendly web services which can also expose virtually unlimited server-side data processing. Using open-source software, the authors developed a scalable, spatially-aware bridge condition database with a fast and flexible server application programming interface (API) and a cross-browser compatible web mapping application written in Javascript.

Keywords: bridge, asset management, remote sensing, decision support, structural health monitoring

1. INTRODUCTION AND PROJECT OVERVIEW

According to the American Society of Civil Engineers (ASCE), more than 26% of the nation's bridges in 2009 were classified as either structurally deficient or functionally obsolete. The average American bridge is now 43 years old. The ASCE estimates that the total investment needed to bring the nation's bridge infrastructure up to code over 5 years is $930 billion, but in that time only $549.5 billion is being spent[1]. Funding is limited but its allocation may make up the difference in the long run. Rehabilitation, for instance, is far cheaper than replacement when damage is minor. Better management of funds used to inspect and maintain existing bridge infrastructure could reduce costs. A report by the Federal Highway Administration indicates that, given more time and funding to complete bridge inspections, the use of non-destructive evaluation (NDE) methods would increase among state and county transportation agencies[2]. NDE promises a way to improve the allocation of funding by improving the information these decisions are based on—by improving the assessment of existing bridge conditions. Coupled with asset management practices, the greatest return on investment can be achieved.

Asset management for structural health monitoring is analogous to human health management. It emphasizes regular evaluation of health indicators that may lead to an early diagnosis which, in turn, triggers preventive measures that save money over the longer term. For state transportation agencies that have already adopted asset management

[*] kaendsle@mtu.edu; phone 1 734 913-6874; fax 1 734 913-6880; mtri.org

practices, the goal is to maintain their infrastructure at its current condition, making improvements where necessary as indicated by regular assessments in a cost-effective manner. Infrastructure managers also model the performance of a structure over time to predict when maintenance, repair or rehabilitation will be necessary. Bridge deterioration curves are an example of such and Pontis, the most popular bridge management system used among state transportation agencies, uses a Markov chain model in its prediction of bridge deterioration[3].

The advent of intelligent transportation systems (ITS) has created the potential to integrate transportation infrastructure with information technology systems such as Pontis; to "merge the transportation and information superhighways[4]." Current structural health monitoring for bridges, however, has not yet caught up to this advanced goal. In the United States, current bridge inspection practices are characterized by traditional, labor-intensive techniques such as chain dragging and the tap test as well as largely subjective visual assessment methods. The standard evaluations used by the Federal Highway Administration (FHWA) have been limited to such auditory tests and visual inspection since the National Bridge Inventory (NBI) was first conducted almost 40 years ago[5]. Qualitative expressions of damage are used, such as classifying rust as “minor,” “moderate,” or “considerable.” Alternatives to these slow and subjective methods are taking hold, however. As of 2005, about 40 long-span (100 m or longer) bridges worldwide have been equipped with “array[s] of inexpensive, spatially distributed, wirelessly powered, wirelessly networked, embedded sensing devices supporting frequent and on-demand acquisition of real-time information about the loading and environmental effects, structural characteristics, and responses[6].” Despite these advantages, permanent, in-situ sensor networks are costly and can be difficult to install on some bridges or bridge elements, particularly when they were not considered during the construction phase. For these reasons, such networks may also be totally inappropriate for the far more common concrete overpass bridges that make up the bulk of bridge infrastructure in this country.

In situ sensor networks paved the way for modern bridge monitoring practices, including electronic data collection and distribution. Bridge inspection officials have indicated that the best way to improve the performance of bridge inspections is to allow for electronic data to be uploaded directly to a Bridge Management System; many have also cited the establishment of such a system as a major accomplishment for their team[2]. Ideally, SHM for bridges should incorporate remote sensing techniques that provide the same capability for remote collection of high-resolution (both spatial and temporal), real-time structural data without the costly disadvantages of *in situ* networks.

This paper details the applicability of remote sensing technologies to assess and monitor bridge performance while providing state and local engineers with additional information that can be used to prioritize critical maintenance and repair of the nation’s bridges. Remote sensing technologies are defined as those that collect information at a distance from the feature being measured or assessed. Selected technologies are defined and their relationships to communicating bridge needs to bridge engineers and inspectors are discussed. Integration of these technologies into the bridge inspection industry can benefit the management of bridge assets, especially considering the large number of bridges in the United States that require inspection and the challenging funding environment for inspection, maintenance and rehabilitation. Furthermore, a decision support system (DSS) has been developed to assist bridge management teams in prioritizing needs by combining information from available inventory and inspection data with new inspection technologies, making the task of communicating decisions simpler as decisions are based on sound quantifiable measures rather than mostly on subjective visual inspections. The DSS is intended to be a decision-making framework for asset management where the asset is the bridge itself.

2. BRIDGE CONDITION ASSESSMENT AND PHENOMENOLOGY

State transportation agencies have a daunting task of maintaining and preserving extensive networks with shrinking workforces and budgets. Critical to their success is an effective methodology for assessing condition state for elements of a bridge and the bridge system as a whole. These condition states, along with historical practice and experience, form the basis of essential decisions and strategies related to maintenance, rehabilitation, and replacement priorities of the transportation agencies.

However, primary methods for assessing condition state are heavily dependent on visual inspection, which can be subjective[7]. In addition to the subjectivity, routine visual inspections are typically conducted at "arm's length" and at times under traffic, preventing the inspector from truly evaluating conditions, especially subsurface conditions. For more detailed scopings, refined techniques are available such as ground penetrating radar, infrared thermography, and impact echo, but in some cases these techniques require expert training for application and interpretation. More commonly, inspections utilize sounding techniques such as chain drag or sounding with a hammer or rod. A list of the commonly used techniques is presented in Table 1 along with a summary of each.

Table 1: Common assessment methods for bridge defects (Adapted from FHWA, 2002; Yehia, et al. 2007)[8, 9]

Method	Uses	Advantages	Limitations
Visual inspection	• Cracks • Geometry • Surface roughness	• Accessibility • Oldest known technique • Well established	• Subjective • Time consuming • Qualitative results
Liquid penetrant dye	• Surface flaws • Detection of irregularities	• Portable • Easy interpretation	• Surface preparation • Exhausting for inspector • Time consuming
Chain drag	• Flaw detection inside decks • Delaminations	• Simple • Portable • Good for delaminations	• Time consuming • Tedious • Subjective • Not good with overlays
Half-cell potential	• Detect corrosion state in concrete reinforcement • Corrosion rate	• Simple • Portable • Good for corrosion	• Deck needs preparation • Time consuming • Not good for delaminations • Lane closure • Not very accurate
Acoustic emission	• Cracks • Delaminations • Corrosion	• Real-time response • No lane closures	• Qualitative results only • Not good with overlays • Interpretation • Costly • Not reliable
Ultrasonic pulse velocity	• Homogeneity of concrete cracks, voids • Strength determination	• Portable • Easy test procedure at relatively low cost • Relatively easy to interpret	• Not very reliable for concrete • Attenuation negatively affects results • Does not give information about the shape of defect
Ground penetrating radar	• Concrete mapping, mining, geotechnical, road, and bridge • Forensics • Detection of voids, honeycombing, • Delaminations • Moisture content	• Versatility • Portability • Effectiveness • Low cost • Good with overlays • Minimum traffic control • Prediction of repair quantities in roads	• Interpretation • Complexity of results • Interpretation of results sometimes requires destructive testing

Method	Uses	Advantages	Limitations
Impact echo	• Detection of voids, cracks, delaminations, unconsolidated concrete, and debonding • Determining thickness	• Requires one surface of the tested material to be exposed, independent of the geometry of the structure • Less susceptible to steel reinforcement • High accuracy	• Size of detected flaws is highly dependent on the impact duration • Less reliable in the presence of asphalt overlays • Interpretation of the results is difficult
Thermography	• Detection of thermal differences, delaminations, cracks, voids	• Portable • Simple, easy interpretation • Minimum traffic interference	• No information about depth of defects • Dependent on environmental conditions

For many transportation agencies, much of the effort related to condition assessment relates to concrete bridge decks, which represent that vast majority of decks in-service in the United States. A sound and well-maintained bridge deck typically correlates well with a good condition superstructure, as the deck system serves not only as the riding surface, but also as a protective barrier for the primary load-carrying members. As a result, many assessment techniques for condition assessment are catered to the bridge deck. However, it should be noted that to date there does not appear to be a single method that is capable of providing a comprehensive condition assessment of a concrete bridge deck. This becomes increasingly evident when comparing technologies capable of observing surface features (e.g. spalls and cracking) and technologies more suited for subsurface features (e.g. delamination and corrosion). The real solution to this challenge is the data fusion of multiple technologies aimed at providing an overall condition signature based on multiple technologies. This concept has been adopted in this research program using a variety of remote sensing technologies and is highlighted in the following sections.

3. REMOTE SENSING TECHNOLOGIES

Remote sensing technologies are innovative technologies that can enhance the current bridge inspection process as well as provide useful metrics for the decision-making procedure of transportation agencies. Faster data collection, quantifiable measures, and advanced data visualizations are some of the characteristics of these technologies. Commercially available remote sensors, which are the focus of this paper, have the ability to monitor the dynamic condition of the nation's bridges and the capacity to enable user-friendly presentation of data. The technologies have been evaluated for their ability to measure associated high-priority health issues in bridge superstructure areas. Several of these technologies have been selected for further development in the assessment of bridges. Primary performance criteria for this commercial remote sensor evaluation included whether a technology is currently commercially available and whether it is sensitive to each measurable health indicator[10].

Remote sensing technologies found to be the most promising by the authors for applicability to bridge inspection were infrared thermography, digital image correlation, 2D and 3D radar including synthetic aperture radar and interferometric synthetic aperture radar, Street-View style photography, satellite imagery, and a 3D optical bridge-evaluation system (3DOBS) including photogrammetric assessment. Useful measures that can be obtained from each technology can be integrated into the web-based based DSS in order to enhance both bridge inspection and bridge management practices. Refer again to Table 2 for an overview of the technologies and the associated useful measures.

3.1 3DOBS (3D Optical Bridge Evaluation System)

The 3D Optical Bridge evaluation System (3DOBS) is a low-cost, rapid, close-range photogrammetric technology that can create a stereographic map of deck surface condition by taking images with sixty percent longitudinal overlap. This technology can help in detecting spalls and scaling on the bridge by creating a Digital Elevation Model (DEM) of the bridge deck surface for analysis in a Geographic Information System (GIS). A vehicle-mounted system using a digital single-lens reflex (SLR) camera has been developed to capture stereographic photos (Figure 1). One lane-width per pass is captured in the image swath. These photos are then processed into a 3D model of the bridge deck using close-range photogrammetric modeling software tools. The DEM is analyzed within ESRI ArcGIS to determine percent spall, spall volume, and surface roughness using 3D analysis and raster calculation tools (Figure 2) and a custom analysis algorithm (Figure 3). Note that the bridge was found to be 6.99% spalled that totaled 37.98 square meters (408.8 square feet) using the 3DOBS technology. Current methods are capable of resolving features as small as 5x5 mm in size and 2 mm depth; smaller features can be resolved using higher resolution digital cameras.

Table 2: Remote sensing technologies and the useful measures of bridge condition they produce

Remote Sensing Technologies	**Useful measures**
3DOBS (3D Optical Bridge-evaluation System)	% Spalled, volume and area of spalls, and International Roughness Index (IRI), crack patterns and density
Infrared Thermography	% Delaminated area, location of delaminations
Digital Image Correlation	Deflection, vibration
Radar	% Delaminated area, location of delaminations
Street-View Style Photography (BridgeViewer RCS)	High-resolution, location-tagged photo inventory
LiDAR	% Spalled, volume and area of spalls, and crack pattern
Satellite Imagery and Aerial Photography	Overall deck condition

Figure 1: Deployment of 3DOBS to assess bridge deck surface condition from a moving vehicle

3.2 Infrared Thermography

Infrared thermography is a technology based on measuring the radiant temperature of the concrete bridge deck and converting that temperature measurement to a digital image (visual image). Thermal anomalies on the thermal infrared image can be associated with material or structural defects, such as subsurface delaminations that are not visible to the bridge inspector, especially in areas up to approximately 8 cm (3 inches) deep. Many factors can influence this technique including the environment (humidity, ambient temperature, wind speed, time of day), surface materials and overlays, and element location (deck, girder, soffit, piers). Figure 4 shows the delamination map that was created based on thermal infrared images taken from the bridge and total area and percent delaminations were calculated from these data. This bridge was found to be 0.76% delaminated using the thermal infrared assessment.

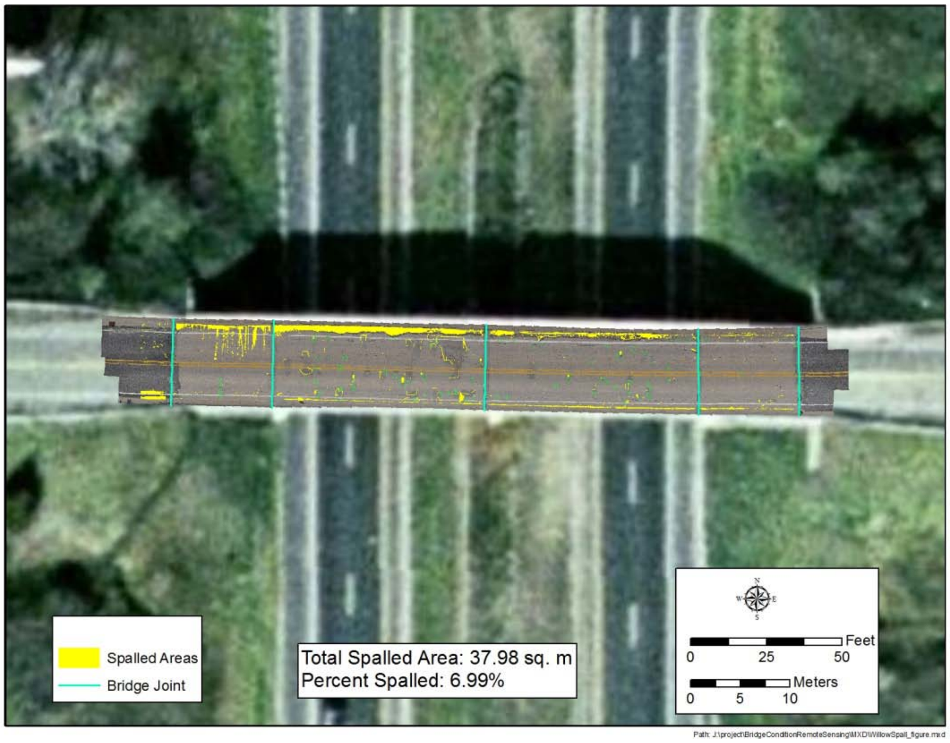

Figure 2: Visualizing spalled area analysis results from 3DOBS in ArcGIS

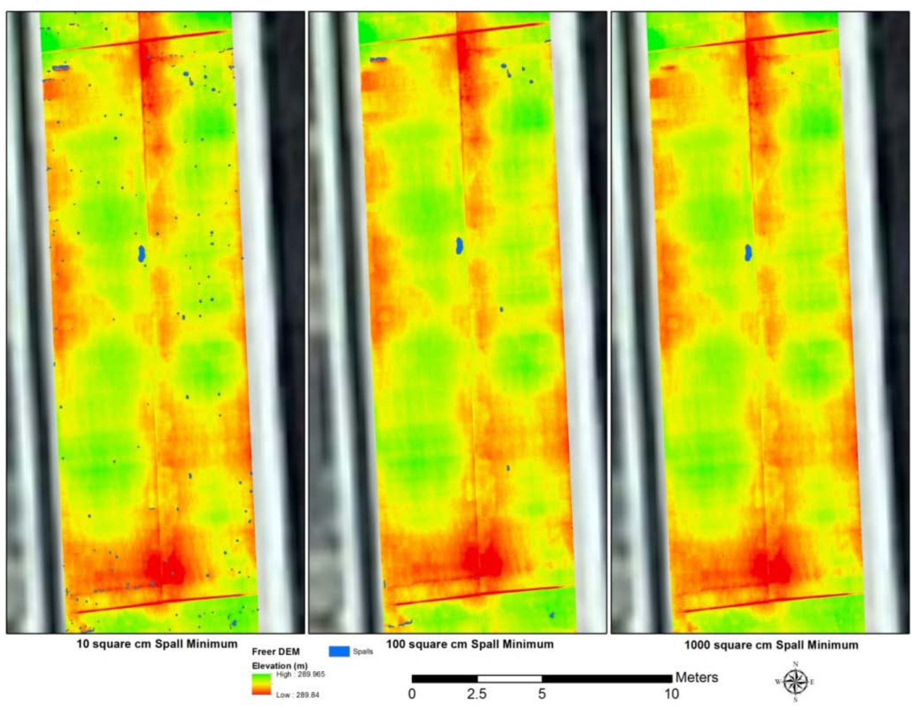

Figure 3: An example of the spall algorithm's results

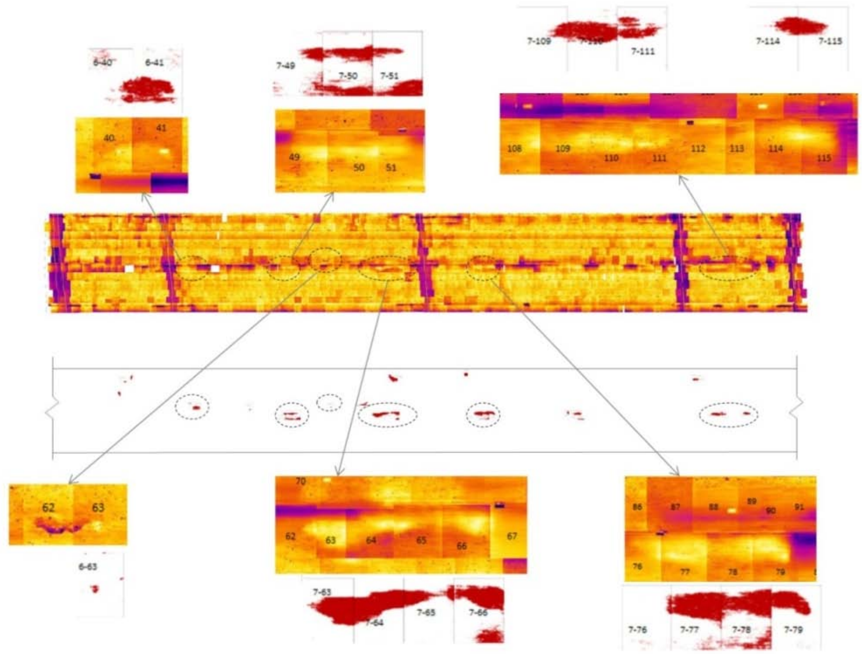

Figure 4: Bridge deck delamination map created by thermal IR images

3.3 Digital Image Correlation (DIC)

Digital Image Correlation (DIC) is an optical technology to measure the deflection and settlement of the bridge based on the variation of pixels (speckle patterns) between several images. Using a readily available digital SLR camera along with image processing software such as MATLAB, images are used to determine changes in location due to high-load hits, flooding, settlement or other factors. Capturing data with this technology is highly sensitive to several environmental conditions, such as wind and passing by traffic. Figure 5 shows a displacement field calculated from DIC applied to a steel I-beam in the laboratory. Analysis so far indicates this method is best suited for vibration and deflection measurements in a lab setting, although research is continuing with DIC bridge applications.

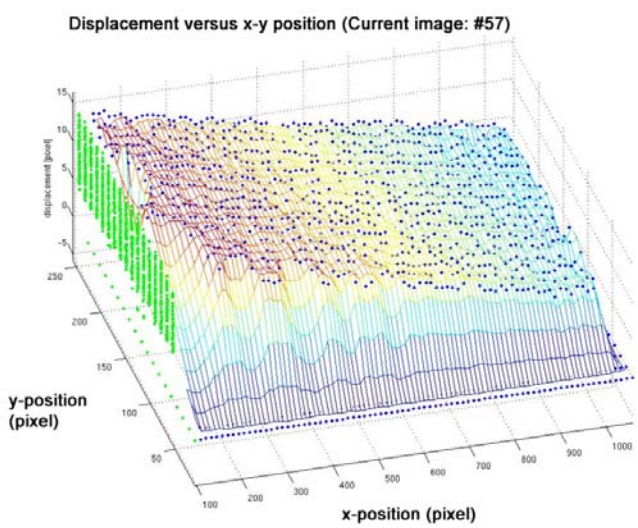

Figure 5: Example of a displacement field calculated from digital image correlation on a laboratory I-beam

3.4 Radar including SAR and InSAR

Most commercially-available ground-penetrating radar (GPR) systems for bridge deck assessment use arrays of antennas pointed perpendicular to the deck to probe the subsurface. As noted in Vaghefi et al. 2011, these systems can sense subsurface defects, but can require substantial time to survey an entire bridge deck. These commercial systems can provide output products for use in the DSS, such as the location of delaminations. To potentially improve data collection efficiency, the current project has been investigating the idea of using side-looking, low-cost ultra-wide band imaging GPR, now referred to as UWBIRS (see Figure 6). This type of collection is consistent with a concept of operation that has a radar system mounted on a moving vehicle to produce maps of deck radar reflectivity that identify areas of concern. This type of collection could also be performed by a standoff airborne sensor. An issue with this approach is whether or not the subsurface deck defects will be uniquely indicated when the deck is illuminated obliquely by the radar. In results so far, the side looking GPR images show variation that is likely due to variation in the bridge structure, an initial qualitative comparison of the side looking GPR images with the delamination ground truth suggests that the high return areas in the radar images do not uniquely identify the delamination areas. Based on the vendors' descriptions, the project team anticipates that data from commercial systems, such as Roadscanners, could provide the needed delamination data for inclusion in a Bridge Condition DSS.

Figure 6: An example of the ultra-wide band imaging radar system being developed to locate bridge deck delaminations

3.5 StreetView-style photography

Described here are two types of systems the project team developed: 1) the BridgeViewer Remote Camera System (BridgeViewer RCS) and 2) a bridge-focused application of the existing GigaPan system. The BridgeViewer RCS includes collecting contiguous location-tagged photos, typically taken from a moving vehicle, where the photographs have been projected into a continuous 360-degree viewing environment (like Google StreetView), elements of bridge condition can be "virtually" assessed and "re-inspected" over time by collection of multiple location-tagged and time-stamped photo inventories. This is a low-cost method of creating GPS-tagged photos that could help create a high-resolution photo inventory for inspecting missing or torn expansion joint seals, cracked or broken plating, map cracking, scaling, spalling, or other surface issues. A low-cost, two-camera BridgeViewer Remote Camera System (RCS) that can be mounted to a car has been developed for this research project (Figure 7). The cameras were positioned to capture a full lane width and were taken in quick succession so there was photo overlap as the vehicle drives across the bridge.

Using GPS, the photos are location-tagged where they were captured on the bridge to produce a photo inventory of the bridge deck surface (Figure 8).

An ultra-high resolution inventory can also be created through a “GigaPan” collection mode. This technology, when combined with automated data analysis software, can monitor changes in crack density, percent of spall areas, or other deterioration indicators that benefit from early detection and preventative maintenance. Figure 9 demonstrates the application of this technology and high resolution bridge photo that was created from the photo inventory.

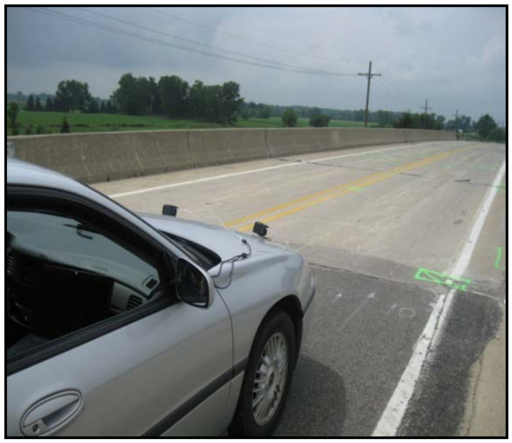

Figure 7: Deployment of the BridgeViewer Remote Camera System to collect a time and location-tagged inventory of bridge condition for comparison over time

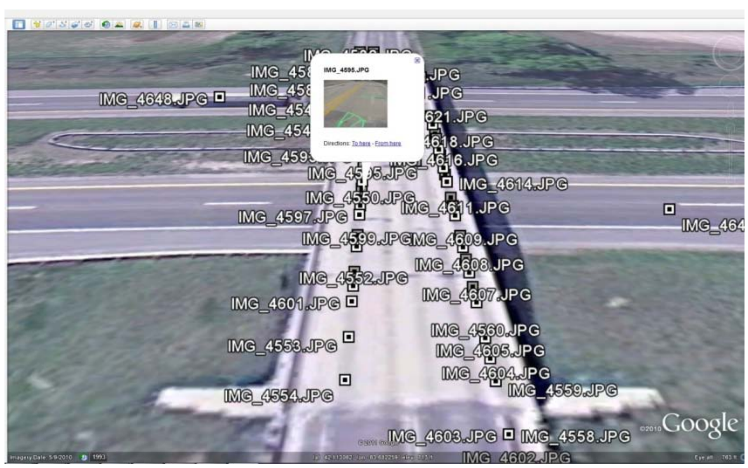

Figure 8: The location-tagged bridge images displayed in Google Earth

3.6 Satellite imagery and aerial photography

Any satellite imagery or aerial photography in the visible and infrared ranges of the spectrum that has sufficient resolution has the potential to be used to remotely assess the section loss or surface condition (e.g. large cracks) of a bridge, or global metrics including changes in bridge length. These techniques are more appropriate for special inspections as high-resolution satellite imagery can be costly for routine bridge inspections. However, small-format aerial photography using small aircraft or unmanned aerial vehicles to capture images may be better suited for bridge applications. In an earlier study, members of the project team were able to match road Sufficiency Ratings for concrete surface roads with 80.5% accuracy and with 88.1% accuracy for asphalt surface roads using multispectral imagery[11].

Figure 10 shows an example of a bridge deck with an NBI rating of 5 (fair condition) using WorldView-2 imagery, which has resolution of up to 50 cm (20 inches). While some of the surface features affecting the bridge deck are apparent, the overall idea of using satellite imagery is that there is a composite signature of the entire deck that helps in rating the overall bridge deck condition. Thus, assessment of a deck's condition is not limited to just the resolution of the pixel size. Additionally, very high-resolution small-format aerial photography has been shown to be useful to supplement current visual inspection methods[12].

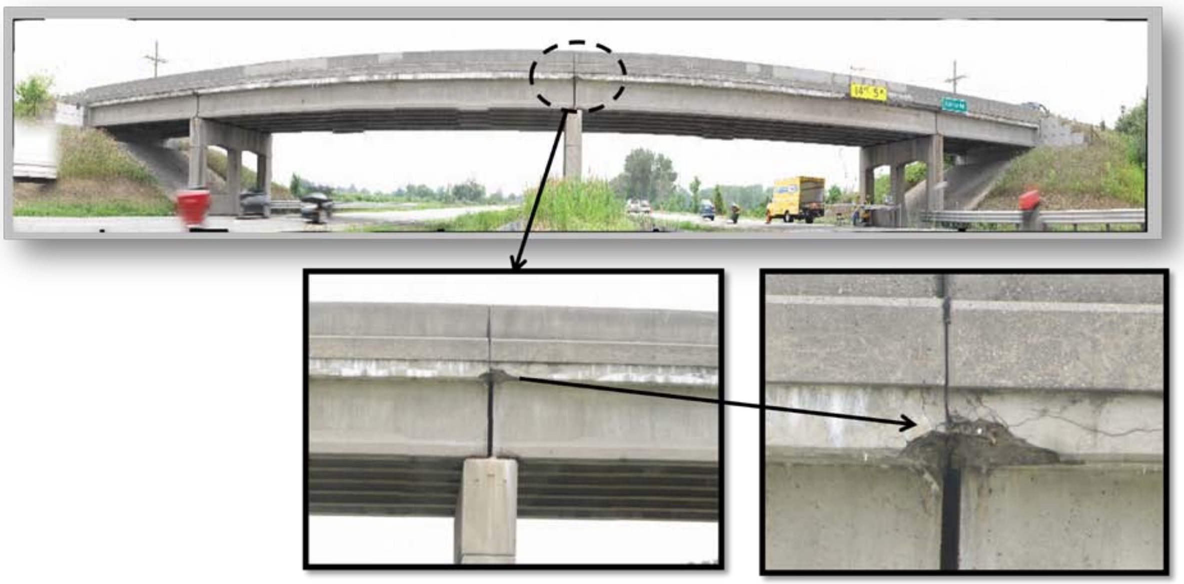

Figure 9: Profile view of Willow Road bridge from a GigaPan image

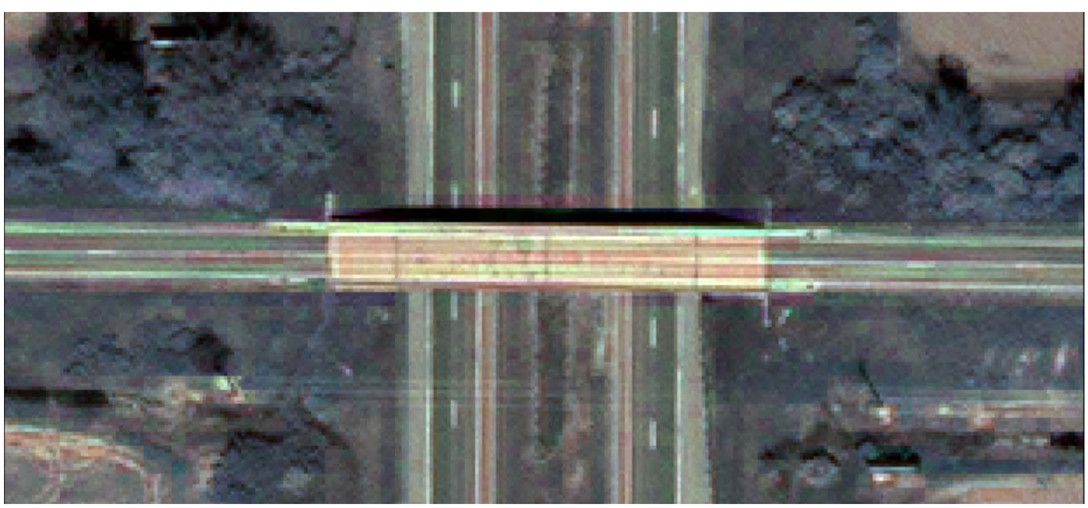

Figure 10: Example of satellite imagery of a bridge deck; the overall spectral reflection of the bridge deck can help indicate its condition

3.7 Light Detection and Ranging (LiDAR)

LiDAR is a technology that can measure distance to a target based on timed light pulses. The utilized light spectrum for LiDAR data collection is typically infrared or near infrared, which eliminates issues associated with either an excess or shortage of lighting. A high-resolution 3D model of a bridge deck surface can provide information on expansion joints, map cracking, scaling and spalling. On a more global scale, LiDAR can be used to detect changes in location due to settlement, clearance issues, and transverse movements due to man-made or natural hazards. Based on the parameters of the LiDAR data collection, it can be used to locate areas of bridge deterioration such as spalls in bridge decks (Figure 11) and support structures.

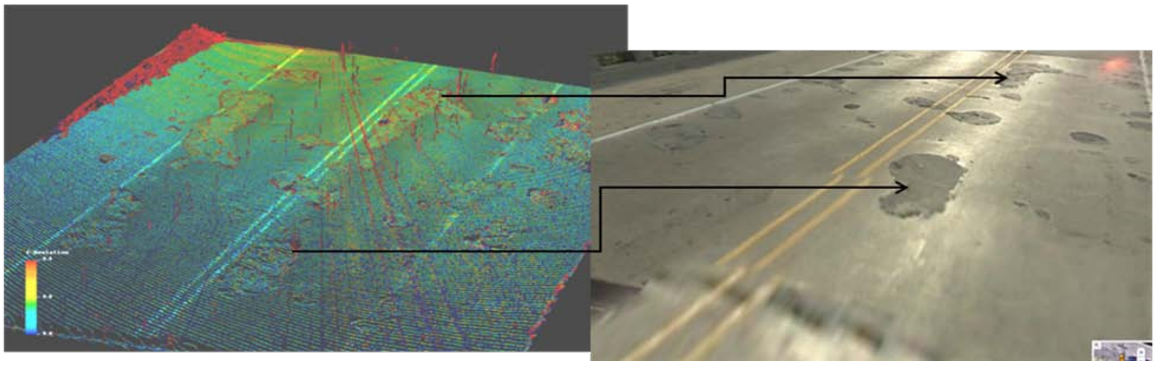

Figure 11: LiDAR point cloud of the deck surface

4. DECISION SUPPORT SYSTEM DEVELOPMENT

The Bridge Condition Decision Support System (DSS) was initially conceived of as a web-accessible database application for exploring inventory, inspection and remote sensing metrics of bridge condition. Early on, distinctions were made between established bridge metadata (inventory data), new condition information from routine NBI inspections (inspection data) and condition information derived from remote sensors (remote sensing data). Inventory data consist of bridge metrics such as deck width, total length, the number of lanes, the latitude and longitude of the bridge, the facility it carries, the feature(s) it intersects and many other items that do not change often and sometimes never change in a bridge's lifetime. Inspection data include items required by routine NBI inspections such as the NBI deck, superstructure, substructure and culvert ratings. One of the goals of the DSS is to provide a comprehensive bridge condition signature. To achieve this goal the DSS must synthesize measures of bridge condition from the disparate remote sensing, inspection and inventory datasets.

4.1 Integrating the existing decision support infrastructure

The project's partner and representative state transportation agency, the Michigan Department of Transportation (MDOT), currently manages bridge inventory, inspection and work records using the Bridge Management System (BMS), one of six management tools available in their Transportation Management System (TMS). Employees usually interface with the BMS through Pontis, an FHWA-contracted software program first released in 1992[13]. Pontis thus represents a *de facto* standard for nationwide bridge management. For this reason, the DSS was designed to incorporate the same data structures used by Pontis and found in the BMS.

There were some challenges to implementing a relational database-driven framework that uses data from Pontis. The BMS, based on what Pontis requires, implies the use of foreign key relationships which simply do not exist in the database. According to BMS metadata, the bridge key is the "primary structure identifier in Pontis" and is described as such for each of the multiple tables that use it. To maximize the expressive power of the database framework, the authors made new foreign key relationships to the Pontis bridge table on the bridge key. Another challenge stems from the fact that the Pontis schema was not designed to support an object-oriented web framework. This problem is referred to as *object-relational impedance mismatch*. The premier example from this project is the result of a query to visualize the latest bridge condition information for every one of the thousands of bridges in Michigan along with their geographic location. This query is easily executed in a relational context; however, to utilize the results of the query in the DSS, the query would need to be executed anytime the user wishes to page through the 12,000 unique bridge records returned. The solution employed in the DSS is to store the results of this query in an intermediate table. This enables faster access through the web-based DSS tool for users, such as transportation agency bridge operations staff.

4.2 Client-server architecture

The DSS can be described in terms of two major dichotomies, the client and the server (both are computers) or the application layer and the service layer. The client computer is used by a decision maker who loads the DSS application into his or her web browser. There can be multiple client computers with simultaneous connections to the server, which is a computer or network of computers that handles requests for data that come from the client computer(s). The DSS application, multimedia and the data themselves are hosted on the server, though the database might be physically or virtually separate from the web server, as depicted in Figure 12. Also depicted in the figure is the dichotomy between the application layer, which comprises the web application loaded into the client computer's browser, and the service layer, which comprises the various web services that respond to requests for data.

Developed entirely with open-source software, the DSS exposes bridge data for decision support through a series of web services hosted on an Apache server. The web services are programmed in Python using the Django web framework, a database application programming interface (API) that allows (among other things) for database queries to be parameterized and executed programmatically. The parameterization of queries is done in the application layer, on the client, by decision makers who, for instance, wish to look at the first 50 bridge records in the inventory sorted by structure number. Such a request is handled by the web server which delegates Django to construct a database query and return the desired results, encoded in Javascript Object Notation (JSON, a more compact alternative to XML), through one of the web services. These requests are made *asynchronously*, which means the web browser executes them in the background so as to minimize the decision-maker's wait time. The client application responsible for making these requests is a Javascript program, utilizing the ExtJS framework, which contains all the logic necessary to provide the decision-maker with an informative, user-friendly experience allowing data manipulation all on its own until more data are needed. The application also retains *state*; it remembers what the user has done in the same session so that, after filtering a table of bridge records, a subsequent sort operation returns only the filtered records.

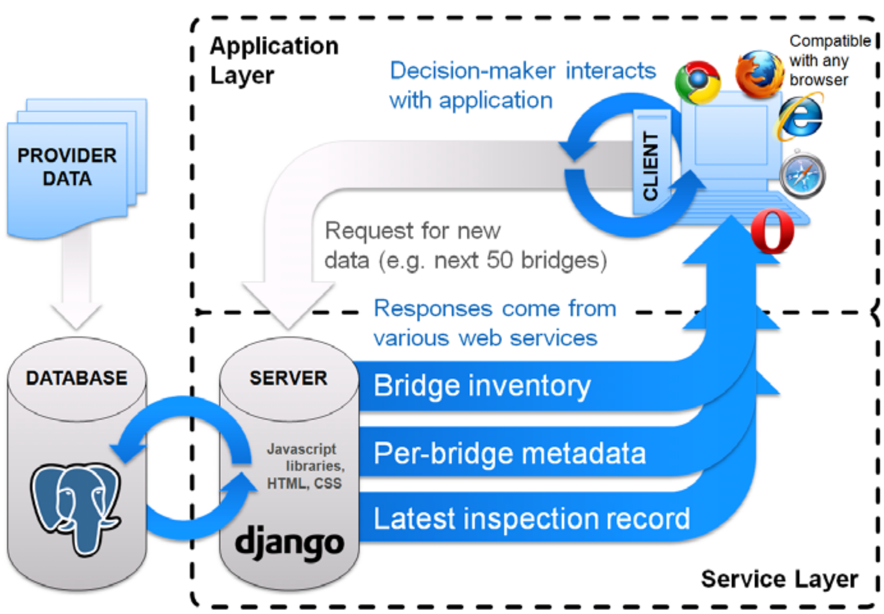

Figure 12: Conceptual diagram illustrating the technological components of the DSS and their interactions

5. REMOTE SENSING INTEGRATION AND DECISION SUPPORT

The integration of remote sensing data is perhaps the most important feature of the Bridge Condition DSS and one that is still in development at the time of this writing. A version for evaluation use by the project's MDOT partners is expected in the spring of 2012. Remote sensing data from disparate sensors must not only be integrated with and compared to inventory and inspection data but with each other. The approach the project team has taken is to identify the products that can be derived from remote sensing data which are of interest to bridge asset management and the commonalities between the derived products of different remote sensing datasets.

It is a primary motivation for the use of remote sensing and NDE in general that the existing protocols for bridge condition assessment describe subjective indicators (e.g. "excessive" cracking or "shallow" spalling). However, some quantifiable metrics of bridge condition are available that could be used to fit remote sensing observations to existing rating schemes such as the NBI[14, 15]. The quantifiable metrics of bridge condition that are derived from remote sensors, listed in Table 2, can thus be correlated to an NBI or IRI rating. Furthermore, these metrics could be used to synthesize user-defined, comprehensive indicators of bridge condition, exemplified by the following example equation for what the authors call the *bridge deck surface rating* (B_D) where a, b, c, and d are user-defined weights:

$$B_D = a*[\%\ \text{spalled}] + b*[\%\ \text{delamination}] + c*[\text{roughness index}] + d*[\text{crack density}] \qquad \textit{(Equation 1)}$$

The architecture of the DSS facilitates rapid and easy user experimentation with the bridge deck surface rating and other custom indicators by manipulation of the weights. These weights might be chosen so that the expected range of observations fits the range of scores (Figure 13). The underlying data can be pulled on-demand from a central database that is updated in real time with the latest bridge inspection information, which means that individual bridge managers' and inspectors' custom indicators are updated in real time as well. The DSS offers many different ways to visualize bridge condition at the inventory scale or the scale of individual bridges; many are pictured in the screenshot of the demonstration DSS (Figure 14).

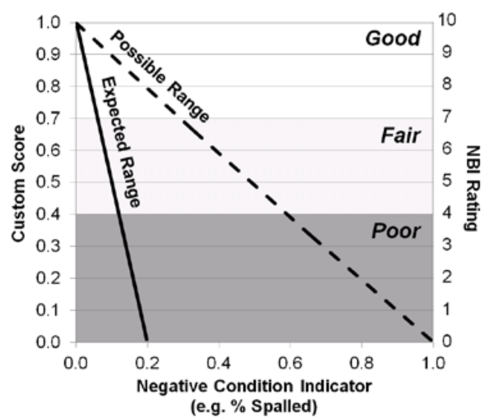

Figure 13: Example of fitting the metrics of a bridge condition indicator to a custom score

Some visualizations to aid in asset management can be quite simple but nevertheless a tremendous improvement over existing decision-making workflows, often simply because they are an automated and quickly reproducible visualization already in use. The DSS offers pie charts, for instance, drawing from up-to-date inspection records, showing the distribution of NBI ratings in the inventory, in a given region, or in a given county. The "Bridge GIS" panel, an interactive map based on the Google Maps API, is the centerpiece of most inventory-level asset management visualizations. Here, bridge decision-makers can get a sense of the spatial distribution of bridge condition, defined by various NBI ratings or Sufficiency Rating, along corridors, within user-defined areas-of-interest hand-drawn on the map, or within pre-defined areas-of-interest such as counties or the state transportation agency's regions. The latest inspection record, field inspection report, photographs and metadata can also be accessed on-demand for individual bridges.

More importantly, visualizations of remote sensing data complete the asset management picture of a bridge by linking the quantifiable metrics of bridge condition to the traditionally more intuitive, visual inspection that is commonplace today in bridge inspection. As bridge decision-makers become more familiar with using remote sensing data in asset management, the ability to view a thermal infrared image, for instance, or a high-resolution DEM in the map plane and virtually walk the bridge, orienting themselves with oblique photographs from the Bridge Viewer RCS affords them a more thorough understanding of a bridge's condition. At the inventory scale, being able to compare the delamination or spall area of multiple bridges in a corridor or of a given type to one another, rather than the NBI ratings, will afford the bridge manager or inspector a more accurate and comprehensive view of bridge condition.

Figure 14: Screenshot of the Bridge Condition DSS showing visualizations, arbitrary query construction for power users and ancillary services such as a driving directions tool

6. CONCLUSIONS

Remote sensing technologies are capable of producing useful, quantitative metrics of bridge condition (e.g. percent spalled from 3DOBS; location and extent of shallow delaminations from thermal infrared). The information thus obtained can be integrated into a user-friendly, web-based DSS built on open-source tools that integrate with Pontis data structures, offering a framework any state transportation agency can adopt. The DSS can integrate existing NBI data and remote sensing data to make these available for transportation agency use, querying, mapping, and custom reporting in an asset management context. Overall bridge health signatures such as the bridge deck health signature devised by the authors as an example can be generated using remote sensing data. This, too, can be integrated with existing bridge condition data in existing asset management workflows. Work is continuing into research of the remote sensing technologies to make them faster, cheaper, and more accessible to end users with the inevitable goal of commerciallyviable, operational adoption. The DSS described in this paper is intended to be an example of a next-generation bridge condition assessment tool for asset management.

ACKNOWLEDGEMENTS

This work is supported as part of a larger program (Bridge Condition Assessment Using Remote Sensors) sponsored by the Commercial Remote Sensing and Spatial Information program of the Research and Innovative Technology Administration (RITA), U.S. Department of Transportation (USDOT), Cooperative Agreement # DTOS59-10-H-00001, with additional support provided by the Michigan Department of Transportation, the Michigan Tech Transportation Institute, the Michigan Tech Research Institute, and the Center for Automotive Research. The views, opinions, findings, and conclusions reflected in this paper are the responsibility of the authors only and do not represent the official policy or position of the USDOT/RITA, or any state or other entity. Further information regarding remote sensing technologies and the decision support system for bridge condition assessment and about this project can be found at www.mtti.mtu.edu/bridgecondition.

REFERENCES

1. ASCE, A.S.o.C.E. *Bridges | report card for America's infrastructure*. 2009 [cited 2010 February 22, 2010]; Available from: http://www.infrastructurereportcard.org/fact-sheet/bridges.
2. USDOT, *Highway Bridge Inspection: State-of-the-Practice Survey*, T.-F.H.R. Center, Editor. 2001, U.S. Department of Transportation, Federal Highway Administration: Mclean, VA, U.S.A.
3. Fu, G. and D. Devaraj, *Methodology of homogeneous and non-homogeneous Markov chains for modeling bridge element deterioration*. 2008, Wayne State University.
4. Aktan, A.E., et al., *Issues in infrastructure health monitoring for management.* Journal of Engineering Mechanics, 2000. **126**(7111): p. 14.
5. Chong, K.P., N.J. Carino, and G. Washer, *Health monitoring of civil infrastructures.* Smart Materials and Structures, 2003. **12**(3): p. 483.
6. Ko, J.M. and Y.Q. Ni, *Technology developments in structural health monitoring of large-scale bridges.* Engineering Structures, 2005. **27**(12): p. 1715-1725.
7. Washer, G., *Long-term remote sensing system for bridge piers and abutments*, in *Innovations Deserving Exploratory Analysis (IDEA)*, T.R. Board, Editor. 2010.
8. FHWA, *Bridge Inspector's Reference Manual*, N.B. Institute, Editor. 2002, Federal Highway Administration: Arlington, VA.
9. Yehia, S., et al., *Detection of common defects in concrete bridge decks using nondestructive evaluation techniques.* Journal of Bridge Engineering, 2007. **12**(2).
10. Vaghefi, K., et al., *Evaluation of commercially available remote sensors for highway bridge condition assessment.* Journal of Bridge Engineering, 2011.
11. Brooks, C., et al., *TARUT pilot studies technical details report*, in *Deliverable 5.3-B*, M.D.o. Transportation, Editor. 2007, Michigan Tech Research Institute.
12. Chen, S.-E., et al., *Small-format aerial photography for highway-bridge monitoring.* Journal of Performance of Constructed Facilities, 2011. **25**(2).
13. FHWA. *More about Pontis - Bridge Management - Asset Management - FHWA*. Asset Management 2011 April 7, 2011 [cited 2012 January 31, 2012]; Available from: http://www.fhwa.dot.gov/infrastructure/asstmgmt/pontmore.cfm.
14. FHWA, *Recording and coding guide for the structure inventory and appraisal of the nation's bridges*, U.S.D.o. Transportation, Editor. 1995.
15. MDOT, *Michigan Structure Inventory and Appraisal Guide*, M.D.o. Transportation, Editor. 2009.