INTEGRATION FOR TRADITIONAL AND NON-TRADITIONAL REMOTE SENSING FOR BRIDGE CONDITION ASSESSMENT

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Within the United States, the condition of transportation infrastructure is in a constant state of flux, with a generally negative performance trend due to degradation and the lack of funds to properly repair and rehabilitate this infrastructure. The United States is home to nearly 600,000 highway bridges, with 11.5% classified as structurally deficient, describing the condition of significant load-carrying elements and adequacy of waterway openings, and implicitly relating to the age of a bridge and historical maintenance practices. This level of condition state clearly highlights the need for improved maintenance practices and assessment methodologies that are at the forefront of structural health monitoring.

Much of this observed degradation stems from the inability of transportation agencies to keep up with the perpetual demands of an aging infrastructure, but at the same time typical assessment methodologies do not accurately account for the degree of degradation that exists. For most agencies these assessments are conducted visually, usually at arm's length, and are highly subjective and based on an inspector's experience and judgment. A typical inspector usually balances the challenges of slowly changing condition states (degradation), safety considerations, and limited evaluation tools for a more thorough evaluation. Remote sensing, which can be defined as the collection of data about an object, at a distance and without direct contact, has the potential to address many of these challenges. This paper presents a summary of some of the remote sensing technologies that have the potential to address these challenges, and preliminary results from an ongoing study of using remote sensing for bridge condition assessment. Also included is an overview of a decision support tool being developed for integrating the acquired remote sensing data with bridge performance data for local and system level decision making.

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ABSTRACT:

Within the United States, the condition of transportation infrastructure is in a constant state of flux, with a generally negative performance trend due to degradation and the lack of funds to properly repair and rehabilitate this infrastructure. The United States is home to nearly 600,000 highway bridges, with 11.5% classified as structurally deficient, describing the condition of significant load-carrying elements and adequacy of waterway openings, and implicitly relating to the age of a bridge and historical maintenance practices. This level of condition state clearly highlights the need for improved maintenance practices and assessment methodologies that are at the forefront of structural health monitoring.

Much of this observed degradation stems from the inability of transportation agencies to keep up with the perpetual demands of an aging infrastructure, but at the same time typical assessment methodologies do not accurately account for the degree of degradation that exists. For most agencies these assessments are conducted visually, usually at arm's length, and are highly subjective and based on an inspectors experience and judgment. A typical inspector usually balances the challenges of slowly changing condition states (degradation), safety considerations, and limited evaluation tools for a more thorough evaluation. Remote sensing, which can be defined as the collection of data about an object, at a distance and without direct contact, has the potential to address many of these challenges. This paper presents a summary of some of the remote sensing technologies that have the potential to address these challenges, and preliminary results from an ongoing study of using remote sensing for bridge condition assessment. Also included is an overview of a decision support tool being developed for integrating the acquired remote sensing data with bridge performance data for local and system level decision making.

1 INTRODUCTION

The condition of the infrastructure in the United States is a challenge as it continues to deteriorate and age while transportation authorities' attempt to align maintenance and

replacement priorities with decreasing funds. The U.S. is home to nearly 600,000 highway bridges of which nearly 12% are structurally deficient[1]. FHWA's *Every Day Counts* initiative recognizes the importance to address these challenges and focuses on deploying innovation for enhancing the safety of our roadways by improving the decision making process of prioritizing our aging transportation infrastructure's needs. With a shrinking workforce of experienced bridge inspectors, the use of remote sensing technologies is an efficient solution to enhancing the condition assessment of bridges supporting improved decision making.

For the typical bridge engineer the concept of remote sensing is often associated with satellite imagery and aerial photography for applications in the environmental and earth sciences; however, various remote sensing techniques have been used in infrastructure applications without being specifically labeled as such. Remote sensing is traditionally defined as the collection and measurement of spatial information at a distance from the data source, without direct contact. To the bridge engineer, remote sensing can mean the ability to assess the condition of the bridge at a distance, enhancement of the inspection process, all without traffic disruption.

Structural health monitoring aims to observe infrastructure condition, assess in-service performance, and detect deterioration to estimate remaining service life. Current practices for condition assessment include visual evaluation, measurement of bridge response to known loading, and the use of specialized monitoring technologies for evaluating specific challenges. However, to date, no single solution exists that is capable of determining the complete condition of a bridge. The best solution is a combination of multiple techniques that are integrated with a decision support system.

This paper details the applicability of some traditional and non-traditional remote sensing technologies to assess and monitor the bridge condition while providing state and local engineers with additional information that can be used to prioritize critical maintenance and repair of our nation's bridges. Integration of these technologies into the bridge industry can only benefit the industry, especially considering the sheer number of bridges in the United States that require inspection and the challenging funding environment for inspection, maintenance and rehabilitation.

2 REMOTE SENSING TECHONOLOGIES FOR BRIDGE CONDITION ASSESSMENT

Both traditional and non-traditional remote sensing technologies have been evaluated for their ability to measure associated high priority health issues in bridge superstructure areas (Table 1). Using quantifiable health indicators (e.g. crack width, percent spall area or volume) each technology was ranked based on criteria for its applicability to enhance bridge inspection. 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. Only technologies that met these first two criteria were further evaluated. Cost, ease of operation, complexity of analysis and interpretation, stand-off distance and impact of traffic flow were also factors considered for rating nearly twenty technologies[2].

Remote sensing techniques found to be the most promising for applicability to bridge inspection (in no particular order) were 3D-optical imagery including photogrammetric assessment, infrared thermography, digital image correlation, 2D and 3D radar

including synthetic aperture radar and interferometric synthetic aperture radar, Street-View style photography, and satellite imagery and aerial photography. Most of the sensors used in these techniques can be generally classified as either active sensors, where a signal is emitted from the sensor and a reflected signal is collected (such as radar), or passive sensors which rely on natural reflectance patterns of the sensed object (such as electro-optical imagery collected using reflected visible and infrared light). Traditional remote sensing techniques that have had some previous applications in bridge condition assessment includes infrared thermography, ground penetrating radar (from the radar family) and acoustic emissions (not rated here). Very little had been done for bridge condition assessment using the other noted remote sensing technologies, hence they are considered non-traditional. Integrating these traditional and non-traditional technologies with current assessment methods can provide for an enhanced inspection with quantifiable measures.

Table 1. Priority Health Indicators Used for Assessing RS Technologies

Superstructure Zone	Health Indicators
Deck Surface	Map cracking, Scaling, Spalling, Delaminations (through surface cracks), Expansion Joint External Issues
Deck Subsurface	Scaling, Spalling, Delaminations, Expansion Joint Internal Issues, Corrosion, Chloride Ingress
Girder Surface	Structural Steel and Structural Concrete Cracking, Paint Condition, Steel or Concrete Section Loss
Girder Subsurface	Structural Concrete Cracking, Concrete Section Loss, Chloride Ingress, Prestress Strand Breakage
Global Metric	Bridge Length, Settlement, Transverse Movement, Vibration, Surface Roughness

2.1 3-D Optics including Photogrammetry

Any photograph in the optical, thermal infrared, and near infrared parts of the spectrum is a remote sensing technology that has potential for use in bridge condition assessment. Photogrammetry refers to the practice of making measurements from photographs, usually stereographic pairs of overlapping digital or film-based imagery. This technology is most common in creating digital elevation models (DEM) and mapping relevant features. Using a standard digital SLR camera and modeling software, a 3-D model is generated that can be used to calculate the percent spall volume or assess the roughness of a bridge deck. Positioning of the camera and whether it is hand-held by the inspector or truck mounted and used at highway speed to avoid traffic disruptions can impact image quality. Other measures obtained for the characterization of bridge surface condition including cracking and crack density, concrete and steel section loss, and paint condition assessment for steel structures. Software can turn 3-D models into useful information to quantify several health indicators.

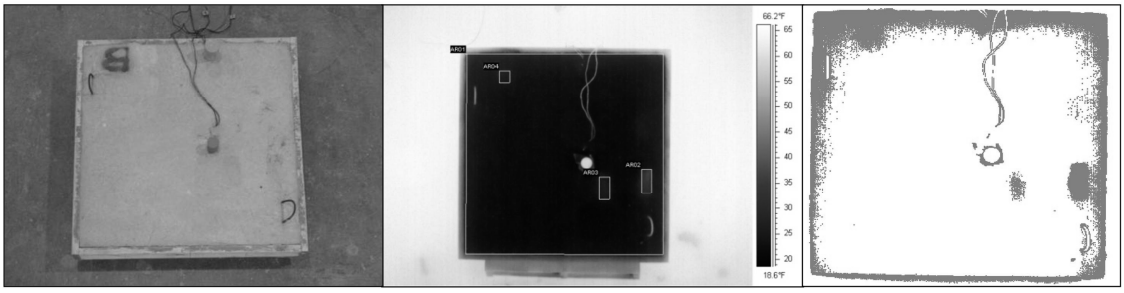
Specifically at Michigan Tech, we have developed a vehicle mounted system using a digital SLR to capture stereographic photos. We have been able to capture one lane

width per pass. These photos are then processed into a 3D model of the bridge deck using close range photogrammetric modeling software tools. The DEM is used within ESRI ArcGIS to determine percent spall, spall volume, and surface roughness using 3D analysis and raster calculation tools.

2.2 Infrared Thermography

Infrared thermography is a technology based on measuring the energy exiting the object in the thermal-infrared part of the electro-magnetic spectrum. More specifically, it involves collecting the surface radiant temperature data (emissivity) of an element and generating a thermal infrared image using a thermal infrared camera. This technology is commonly applied to concrete bridge decks for the detection of thermal variances that are given by radiation, conduction, and convection. Thermal anomalies can be associated with material or structural defects, such as subsurface delaminations that are not visible to the bridge inspector. 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).

This technology is useful for the evaluation of subsurface (near-surface) issues such as delaminations in concrete bridge elements, without the need for lane closure or traffic disruption as no direct contact is required. Delaminations and anomalies manifest as hot or cool areas on thermal infrared image dependent on the time of day. Percentage of delaminated areas can be determined by calculating the ratio of the number of pixels within the hot areas by the total number of pixels within the area of interest. Number of pixels can be measured either by using the thermal infrared camera proprietary software or output data of the radiant temperature data derived from thermal infrared image. Figure 1 shows the optical (visual) and thermal IR image of the concrete slab with simulated defects and associated spreadsheet results using output data. Pixels with higher temperature are highlighted on the spreadsheet. For comparison purposes, the actual percentage of delamination was 1.78%. The proprietary software computed 1.61% and the simplified post-processing using a spreadsheet computed 1.84% of the concrete slab area was delaminated.



a) b) c)

Figure 1. Experimental evaluation of subsurface features using Thermal IR a) Optical (visual), b) thermal IR image of concrete slab and c) post-processed output data results.

2.3 Digital Image Correlation (DIC)

Digital Image Correlation is a non-contact technique consisting of correlating pixels on optical images to determine variations or changes over some finite time. The aerospace, automotive, and mechanical industries rely on DIC. Bridge related applications of DIC

include detecting changes in global bridge metrics such as settlement, vibration, or other movements. Using a readily available digital SLR camera along with image processing through software such as MATLAB, images can be used to determine changes in location due to high load hits, flooding, settlement or other factors. Hazard mitigation for natural and non-natural events can also benefit from this technology being applied in the bridge industry.

2.4 Radar including SAR and InSAR

Radio detection and ranging (commonly referred to as radar) is a well-established technique for measuring the range, altitude, direction, and speed of moving or stationary objects. Synthetic Aperature Radar, SAR, or Ground Penetrating Radar, GPR, are the most commonly used radar techniques in structural health monitoring. Advantages of SAR are that it can rapidly and effectively investigate a large swath of one surface, and there are no special safety precautions required. Disadvantages include the requirement of highly specialized equipment, the need for calibration or 'ground truth' corroboration, user ability to interpret the results, the expense of equipment and signal processing, and the inability to penetrate metal features. Potential applications of SAR for concrete bridges are related to subsurface condition assessment, including thickness estimation from one surface, the location, size and condition of reinforcing bars or prestressing strands, location of moisture variations, and location and dimensions of delamination indicators such as voids, honeycombing or cracking. Integration of collected and reduced data with a decision support system is expected to reduce the need for data interpretation experts.

A further extension of radar is interferometric synthetic aperture radar (InSAR) which compares pixel-by-pixel differences in phase between two synthetic aperture radar (SAR) images to determine changes in surface deformation or ground topography during the time interval that occurred between the two images. Sophisticated SAR instrumentation is installed on Earth-orbiting satellites. InSAR has potential applications for detecting bridge settlement, and vibration and stiffness changes. InSAR is also capable of operating under all weather conditions, and different wavelengths can be applied to achieve different degrees of penetration.

For Michigan Tech's research, applied methods have been developed to detect areas of delamination in a bridge deck surface, assess internal condition indicators for concrete box beams (both using SAR), and measure the amount of settlement in example bridges (using InSAR-based radar imagery).

2.5 Street-view Style Photography

Using a contiguous collection of geo-located photographs taken from the ground, especially 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 photo inventories. This can be a low cost method of creating GPS-tagged photos that 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 related issues. An ultra-high resolution inventory can also be created through a "Gigapan" 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.

At Michigan Tech, a low-cost two camera "BridgeViewer Remote Camera System" (RCS) that can mount to a car has been developed. The cameras are then positioned to capture a full lane width and are taken in quick succession so there is photo overlap as the vehicle drives across the bridge. The photos are location-tagged using GPS data to where they were captured on the bridge to produce a photo inventory of the bridge deck surface. A version of the BridgeViewer RCS also enables more rapid photo collection, with illumination, so that the underside of a deck can be photographed while driving underneath a bridge. Both versions of the BridgeViewer RCS are intended to build from the capability demonstrated by systems such as Google's StreetView, but enable a DOT to deploy a low-cost system *whenever needed* to rapidly create a location-tagged photo inventory of bridges that can be easily updated over time.

2.6 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 vehicle aircraft to capture images may be better suited for bridge applications.

Our program is focusing on using satellite imagery to detect indicators of deck surface condition rather than the cracks themselves. In an earlier study, Brooks et al. (2007) was 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. We are building from these methods to adapt them for bridge deck surfaces.

2.7 Light Detection and Ranging (LiDAR)

LiDAR is the use of timed light pulses to measure the distance to a target. It is most often used to generate high-density 3D models of target surfaces and structures. 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. Commercially available systems have shown promise for locating specific elements, although crack quantification can be overestimated.

3 DECISION SUPPORT SYSTEM

A decision support system (DSS) tool is being developed to help bridge inspectors and managers to make informed and cost-effective decisions about bridge maintenance. The tool will have flexibility to work with multiple types of data generated by the remote sensing technologies discussed above. The relational database is capable of working with different data sets, including geospatial data and bridge condition information from a historical perspective such as year built, year reconstructed or painted or overlaid,

deck rating, superstructure rating, substructure rating, sufficiency rating, number of lanes and spans, and more. The DSS will incorporate multiple heuristics to support bridge managers in evaluating the bridge condition at an inventory level through a modular, web-based interface. Decision criteria will be presented in one of four ways: in a geographic information system (GIS), in an interactive chart, in a table or in a custom "remote sensing" view for photographs and other custom remote sensing data (e.g. interpreted radar images). Trend lines or pie charts can be reviewed by a field inspector to enhance monitoring of changes. Initial development on the desktop is being moved to a mobile device for ease of use in the field and elsewhere. Integrating historical data, remote sensing data, and typical inspection data, the DSS can provide a condition assessment of a bridge that can be monitored over time and used as a baseline for prioritizing maintenance and repair needs.

4 CLOSURE

Remote sensing is a new approach in the field of bridge inspection and monitoring. This valuable family of technologies can enhance inspections by integrating traditional and no-traditional remote sensing techniques. The formal integration of non-traditional remote sensing techniques into the bridge monitoring and condition assessment scheme has the potential to enhance inspection practices and provide temporal assessments between inspection cycles, without traffic disruptions. Bringing these technologies together into an understandable and usable environment to support the work of bridge inspectors is paramount. By combining the results of individual technologies with a decision support system that is implementable and user-friendly, monitoring and assessing superstructure condition is enhanced and our decision-making process for critical repair and replacement can be simplified.

Overall, remote sensing technologies have the potential to transform our current state of bridge condition assessment by helping to take the "guess-work" out of the inspector's toolbox and replacing it with reliable and quantifiable tools to measure several health indicators. When combined with historical data and maintenance records, a unique bridge signature (based on condition) can be established and monitored over time. Ultimately, integrating new technologies, such as remote sensing, with proven tools will enhance the way we decide to prioritize critical and dwindling resources to ensure that our nation's bridges are safe.

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