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Remote Sensing Technologies for Detecting Bridge Deterioration and Condition Assessment

Theresa (Tess) M. Ahlborn, Ph.D., P.E.¹, Devin K. Harris, Ph.D.¹, Colin N. Brooks²,
K. Arthur Endsley², Darrin C. Evans¹ and Renee C. Oats¹

¹Department of Civil and Environmental Engineering
Michigan Tech Transportation Institute
Michigan Technological University
1400 Townsend Drive
Houghton, Michigan USA 49931
(906) 487-2625; fax (906) 487-1620; email: tess@mtu.edu

²Michigan Tech Research Institute
Michigan Technological University
3600 Green Court, Suite 100
Ann Arbor, Michigan USA 48105
(734) 913-6840; fax (734) 913-6880; email: cnbrooks@mtu.edu

INTRODUCTION

The condition of transportation infrastructure, specifically bridges, has received a great deal of attention in recent years as a result of catastrophic failures, deteriorating conditions, and even political pressure. However, the challenges of a deteriorating infrastructure have been at the forefront of transportation authorities' attention for many years as they attempt to establish maintenance priorities for an aging infrastructure with decreasing funds. The U.S. is home to nearly 600,000 highway bridges. Structural deficiency, which describes the condition of significant load-carrying elements and adequacy of waterway openings, typically relates directly to the age of a bridge¹. The number of bridges listed as structurally deficient as of 2007 was 72,520 (12% of U.S. highway bridges), clearly demonstrating the need for a uniform rating system to make sure the correct bridges receive the necessary and needed funding².

The objective of structural health monitoring is to observe infrastructure condition, assess in-service performance, detect deterioration, and estimate remaining service life. Current practices for condition assessment include: visual evaluation, measurement of bridge response to known loading, and the use of specialized sensor technologies for specific effects. However, to date, no single solution exists that is capable of completely determining structural condition, with the true likely solution being a combination of multiple techniques. This paper explores the feasibility of using commercial remote sensing technologies for bridge condition assessment. Included is a review of available technologies that have potential applications in bridge condition assessment and the advantages and shortcomings of these techniques. An assessment is underway by our team to explore how these techniques could be combined with current practices to assess current bridge condition and health.

STRUCTURAL HEALTH MONITORING

Structural health monitoring (SHM) is the practice of monitoring a structure to ensure that its structural integrity and safety remain intact. Given the information about structural condition, preventative measures can be performed to maintain a longer life span and prevent catastrophic failure of the structures³. The period of time between monitoring is related to the type of monitoring that is underway.

In recent years, SHM for bridges has adopted the "Level IV" approach with a primary focus of accurately monitoring in-situ behavior to assess in-service performance, detect damage, and determine condition of a structure⁴.

Most research efforts have focused on the subsystems of a structural health monitoring system including: 1) static field testing, 2) dynamic field testing, 3) periodic monitoring, and 4) continuous monitoring, but a complete SHM system also requires routine inspection, data management, data interpretation, and decision support. Current assessment methods provide critical information about the condition of a bridge element, but the data obtained must often be interpreted by a skilled professional and are typically limited to local metrics, such as stress, strain, temperature, deflection, moisture, cracking, and delamination. Recent advances in SHM have included novel sensing technologies and assessment methods such as: fiber optic sensors, wireless sensors, strain sensing films and local damage identification. SHM is further complicated by the wide degree of variability in bridge types, materials, operating environments, and structural configurations.

Remote sensing technologies, which enables non-contact data collection at great distances, offer the ability to combine several methods to obtain a more complete assessment. Currently, these methods exhibit a divide between metrics for structural response at the global level and material distress at the local level. The combination of these metrics should provide a better picture of overall bridge condition.

No single SHM method exists that is capable of completely determining the condition of a bridge. Figure 1 depicts the overall project concept of combining several types of monitoring with historical bridge inspection data and maintenance records. The information would then analyzed by a computer decision support system to develop unique signatures of bridge condition. Monitoring how these signatures change over time is expected to provide state and local engineers with additional information used to prioritize critical maintenance and repair of our nation's bridges.

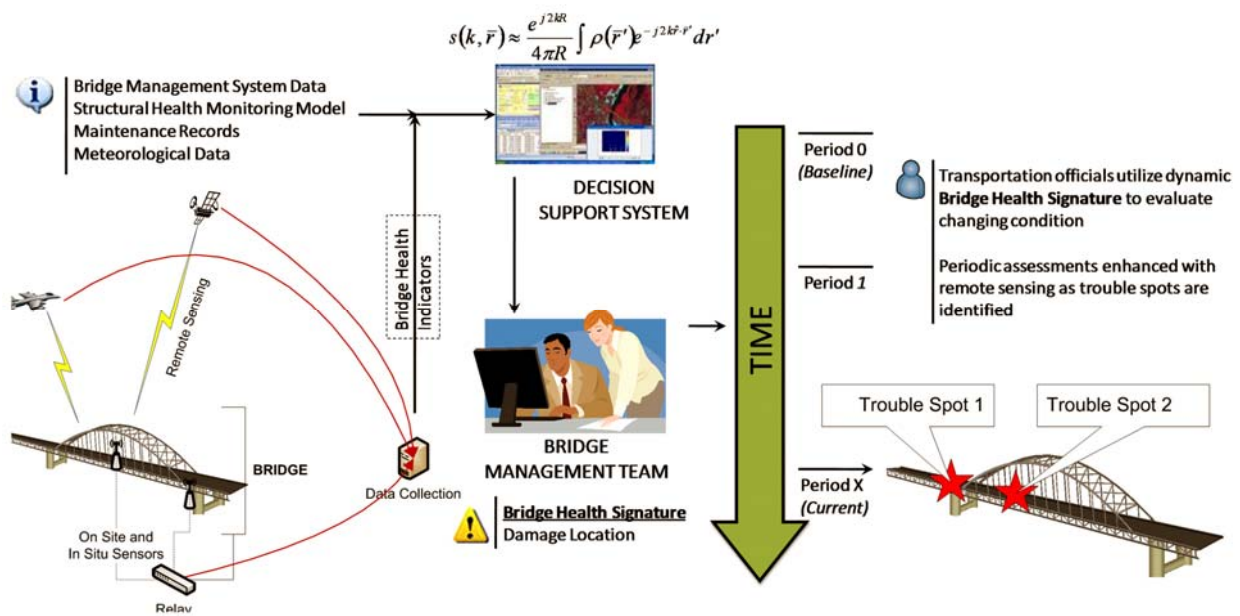


Figure 1: Bridge Health Monitoring Concept

INSPECTING BRIDGES IN THE U.S.

A variety of methods are used when conducting the inspection of a bridge, but all inspections are completed in accordance with the National Bridge Inspection Standards (NBIS)⁵. The Bridge Inspector's Reference Manual (BIRM)⁶ is available to help the bridge inspector with programs, procedures, and techniques for inspecting and

evaluating a variety of in-service highway bridges. The BIRM is sponsored by the National Highway Institute through the Federal Highway Administration (FHWA). All inspectors must be certified through a NBI comprehensive training program and are required to keep this certification current through refresher courses.

According to NBIS, publicly-owned bridges in the U.S. must be inspected at least every two years. Some bridges with problem areas need to be inspected more frequently than the two year minimum requirement. Any structure that has a span length greater than twenty feet is required to be rated for National Bridge Inventory (NBI). The condition of a bridge can also be used in the load rating process for a bridge, which in some cases results in a reduced load rating capacity for bridges in poor condition. From a transportation agency perspective, bridge condition affects maintenance and repair schedules, but it also influences allowable load limits for vehicle traffic, all of which significantly impact the public's experience with the current state of the U.S. bridge infrastructure.

Defects

Though bridges are designed with a variety of materials, they are chiefly constructed of concrete and steel. Each of these materials has its own properties that determine what types of defects an inspector must evaluate to confirm the material still has adequate structural capacity and durability. When inspecting reinforced and prestressed concrete systems, the inspector must look for multiple defects including: cracking, scaling, delamination, spalling, chloride contamination, efflorescence, ettringite formation, honeycombs, pop-outs, wear, collision damage, abrasion, overload damage, and reinforcing and prestressing steel corrosion. Similarly for steel members the defects include: corrosion, fatigue cracking, overloads, collision damage, heat damage and paint failures. Additionally, there are several defects that can be observed when considering the overall condition of the structure which include unevenness between members, settlement, excessive vibration and/or deflection.

Inspection Tools

The typical routine inspection performed for the bridge would be a review of previous inspection details and a visual inspection of all elements of the bridge including the superstructure and substructure. The second type of visual inspection is an in-depth inspection of one or more members from less than an arm's length from the inspector. The inspector typically carries several tools to help in an accurate condition assessment of the bridge. One tool is a chipping hammer that can be used for sounding concrete, to check for sheared or loose connections and to loosen dirt and debris. Another tool used by inspectors is the chain drag apparatus which can be used to determine the location of delaminations often located in the concrete bridge deck. While these techniques may appear to be simple, they have proven very effective over years; however, they can be time consuming and subjective.

More advanced inspections are typically performed when it is determined that the defect needs to be further analyzed or to assist with the routine inspection. Advanced techniques can be categorized as either destructive or nondestructive. Nondestructive tests include a variety of techniques such as: acoustic emissions testing, delamination detection, ground-penetrating radar, electromagnetic methods, pulse velocity, flat jack testing, impact-echo testing, infrared thermography, laser ultrasonic testing, magnetic field disturbance, nuclear methods, pachometer, rebound and penetration methods, ultrasonic testing, Lamb wave monitoring, corrosion sensors, smart paints, dye penetrant, magnetic particles, magneto-elastic testing, radiographic testing, computer tomography, ultrasonic testing and eddy current; all of which do not affect the integrity of the structure under evaluation. Destructive tests typically relate to material performance and include concrete coring, the Brinell hardness test, the Charpy impact test and tensile tests, which can affect the integrity of the structure, so the amount of tests done would typically be limited. Destructive tests are often used to confirm the findings of a nondestructive test. An inspector typically has discretion as to what tests should be appropriately used for the given situation.

REMOTE SENSING TECHNOLOGIES FOR BRIDGE CONDITION ASSESSMENT

For the typical bridge engineer the concept of remote sensing is often associated with satellite imagery and aerial photography for applications in the earth sciences; however, additional remote sensing techniques have been used in infrastructure applications without being specifically labeled as such. A general definition of remote sensing can be summarized as the collection and measurement of spatial information at a distance from the data source, without direct contact^{7,8}. This approach or grouping of techniques makes remote sensing potentially valuable in the field of bridge inspection and monitoring, especially considering the sheer number of bridges in the United States transportation infrastructure system and the challenging funding environment for inspection, maintenance and rehabilitation. The formal integration of remote sensing techniques into the bridge monitoring and condition assessment scheme has the potential to enhance inspection practices and also provide temporal assessments between inspection cycles, without traffic disruptions.

Typical remote sensing techniques that may be applicable to bridges include: electro-optical imagery including photogrammetric assessment, spectral signature assessment, speckle photography and speckle pattern interferometry, infrared thermography, laser scanning or LiDAR, GPS and geodetic survey, infrared thermography and spectroscopy, radar and interferometric synthetic aperture radar, and ground penetrating radar. A general summary of these remote sensing techniques is presented in Table 1. 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).

Table 1: Summary of Remote Sensing Techniques

Remote Sensing Technique	Measurement Detail	Typical Application	Active or Passive	Potential Infrastructure Assessment	Considered in Study
Electro-optical imagery	Commercial aerial and satellite typically up to 8 cm spatial resolution; digital photogrammetry capable of millimeter-level resolution	Mapping and characterization of bridge and landscape features for aerial and satellite imagery; creation of 3-D bridge deck surface of photogrammetry for spalling assessment	Passive	Deck condition	Yes
Speckle Photography and Speckle Pattern Interferometry	Millimeter-range displacement possible depending on setup; adjustable	Vibration and strain assessment	Passive and active systems	Bridge stiffness and load rating, others	Yes
Radar and Interferometric Synthetic Aperture Radar	Depends on instrument; millimeter level displacement and vibration possible	Vibration and strain assessment	Active	Bridge stiffness and load rating, others	Yes

Ground Penetrating Radar	Depends on wavelength; 3-4 cm typical object resolution for shorter wavelengths	Presence of subsurface problems (e.g., delamination, voids)	Active	Sub-surface deck assessment	Yes
Laser Scanning or LiDAR	Centimeter-level possible; 15-cm typical Z (elevation) accuracy	Detection and ranging, structural size, or measurement of displacement and velocity	Active	Structure shape, size, movement	Not planned
GPS and Geodetic Measurements	Centimeter-level	Absolute displacement measurements of structures and structural elements using GPS satellite information	Passive	Structural geometry and displacement	Not planned
Infrared Thermography and Spectroscopy	0.05 C (0.1 F) in commercial systems	Assessment of delamination areas	Passive	Sub-surface deck assessment	Under consideration for inclusion

While some of these techniques have potential applications for infrastructure monitoring and condition assessment, a representative set are discussed further herein. The technologies include electro-optical imagery, speckle photography and speckle pattern interferometry, infrared thermography, radar and interferometric synthetic aperture radar, and ground penetrating radar. In this work the remote (non-contact) sensors are further classified as on-site, where the instrument is brought to the bridge, and remote, where the sensors are used far from the bridge (such as satellite imagery and aerial photography).

Electro-optical imagery (Remote)

Electro-optical (EO) sensors are those electronic sensors which are sensitive to electromagnetic radiation in the visible and near-infrared parts of the spectrum. Charge-coupled devices (CCDs) are the most common electro-optical sensors and may consider the contribution of even simple digital camera components to structural health monitoring of bridges. Photogrammetry refers to the practice of making measurements from photographs, usually stereographic pairs of overlapping imagery, and would currently include measurements made from both film photography and digital photography. The two most common sources of EO imagery are from aerial photography and satellite imagery such as Quickbird, Worldview, and Landsat.

Proposed Applications for Condition Assessment

These technologies might be useful for the characterization of bridge deck surface condition including spalling, cracking and crack density, and surface ride quality, as well as paint condition assessment for steel structures.

Speckle Photography and Speckle Pattern Interferometry (On-site)

Speckle is a deterministic, seemingly random, interference pattern formed when coherent light is reflected from a surface. Speckle patterns are high-contrast, fine-scale, granular patterns with a random intensity⁹ that are produced

by light reflected from most rough surfaces, with roughness corresponding to microscopic imperfections on the scale of optical wavelengths. Although two different surfaces may appear to be identical on the macroscopic scale, their optical roughness is always unique on the microscopic scale to the effect that the two can be distinguished by their speckle patterns. Furthermore, speckle can be used to identify deformations or displacements by comparing speckle patterns of the same surface. Speckle can be used to measure a displacement gradient (strain) or local rotation, rigid translation of the surface, or a morphological change under which the initial and final states are totally unrelated.

Proposed Applications for Condition Assessment

This technology might be useful in displacement and strain measurements (both static and dynamic).

Radar and Interferometric Synthetic Aperture Radar (IfSAR) (Remote and On-Site Systems)

Radio detection and ranging (RADAR, now commonly written as radar) is a well-established technique for measuring the range, altitude, direction, and speed of moving or stationary objects. This is achieved through the illumination and, commonly, the reflection off of an object with electromagnetic (EM) waves. Inspection techniques typically operate at frequencies ranging from 300 MHz to 300 GHz in dielectric (electrically insulating) material¹⁰. To achieve 3D displacement measurements, radar measurements from independent directions must be made, as radar can only measure displacement in the range direction, parallel to transmission¹¹.

A further extension of radar is interferometric synthetic aperture radar (IfSAR, also referred to as InSAR) which compares pixel-by-pixel differences in phase between two synthetic aperture radar (SAR) images in order to determine changes in surface deformation or ground topography during the time interval that occurred between the two images. Though sophisticated SAR instrumentation is installed on Earth-orbiting satellites, many of these instruments are not practical for monitoring structures on Earth for despite their sufficient accuracy because they can lack the resolution or imaging time required for SHM. Consequently, the techniques described here are focused on ground-based applications¹¹. IfSAR is capable of operating under all weather conditions, and different wavelengths can be applied to achieve different degrees of penetration.

Proposed Applications for Condition Assessment

These technologies might be useful for measurement of bridge displacements and accelerations for vibration response correlation.

Ground Penetrating Radar (On-site)

GPR is the most commonly used radar technique in structural health monitoring. The technique is based on the emission of a very short time-duration (<1-20 ns) EM pulse in the frequency band of 10 MHz to 2.5 GHz; typically, no less than 500 MHz is used for practical applications. However, as the Earth acts like a low-pass filter, these high-frequency antennae cannot penetrate farther than about 3 m depth. Penetration depth is achieved when the radar amplitude has been attenuated by a factor of e^{-1} , but the degree of penetration varies as a function of the attenuation factor and the medium's electromagnetic properties.

The spatial (plan) resolution of GPR is determined by the antenna frequency, achieved depth, and the electromagnetic properties of the medium. Sensitivity studies have shown that the horizontal resolution of GPR can be as fine as 3-4 cm in a high-velocity medium such as saturated concrete¹². When there is only small spacing between anomalies, it can be difficult to discern buried objects from one another due to interference effects, which become significant at a spacing of less than 10 cm in lower-velocity media.

Advantages of GPR are that it can rapidly and effectively investigate a large swath of one surface, it requires no coupling medium, it is continuous, results have a high potential to be improved through signal processing, 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 features¹³.

Proposed Applications for Condition Assessment

Some potential applications of GPR for structural concrete include: thickness estimation from one surface, the location of reinforcing bars or other metallic objects, estimation of the depth of buried objects, location of moisture variations, location of voids, the dimensions of such voids, location of honeycombing or cracking, and an estimation of the size of reinforcing bars. For this project, GPR might be useful for bridge deck sub-surface condition including delamination, location and condition of reinforcement, as well as anomaly detection.

Infrared Thermography (On-site and Remote)

Infrared thermography is the detection of electromagnetic waves in the mid-infrared "thermal" part of the spectrum. More specifically, it is the detection of the strength and location of thermal anomalies and in the context of SHM these anomalies are (ideally) associated with structural defects. This technique is commonly applied directly to concrete and asphalt decks for the detection of thermal variances that are given by radiation, conduction, and convection¹⁴, which may be a sign of delamination.

Proposed Applications for Condition Assessment

This technology might be useful for the evaluation of deck delaminations at highway speeds, thus eliminating the need for lane closures.

CLOSURE

Remote sensing technologies, while available for several industries, have not traditionally been used in the bridge industry. Bringing these technologies together into an understandable and usable environment to support the work of bridge inspectors is a goal of our larger project. While individual assessment of technologies have been made, this study will evaluate them as part of an integrated decision support environment to move them towards practical use. Overall, remote sensing technologies aim to advance bridge condition assessment beyond that of other traditional methods.

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