An Evaluation of Commercially Available Remote Sensors for Assessing Highway Bridge Condition

T. M. Ahlborn, Ph.D., P.E.[1], R. Shuchman Ph.D[2], L. L. Sutter Ph.D.[1], C. N. Brooks[2], D. K. Harris, Ph.D.[1], J. W. Burns Ph.D[2], K. A. Endsley[2], D. C. Evans[1], K. Vaghefi[1], R. C. Oats[1]

[1]Department 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

[2]Michigan 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

October 2010

Table of Contents

List of Tables

List of Figures

Executive Summary

The nation's bridge program faces some daunting challenges as our transportation infrastructure continues to age. Current bridge inspection techniques consist largely of labor-intensive subjective measures for quantifying deterioration of various bridge elements. Some advanced non-destructive testing techniques such as ground penetrating radar are being implemented, however little attention has been given to remote sensing technologies.

Remote sensing technologies can be used to assess and monitor the condition of bridge infrastructure and improve the efficiency of inspection, repair, and rehabilitation efforts. Most important, monitoring the condition of a bridge using remote sensors can eliminate the need for traffic disruption or total lane closure as remote sensors do not come in direct contact with the structure.

The challenges of understanding deterioration common to bridges throughout our nation have been grouped into five broad areas: deck surface, deck subsurface, girder surface, girder subsurface, and global response. Each area has specific indicators that identify condition or deterioration (e.g. map cracking, delamination, and excessive vibration). A number of remote sensing technologies have been reviewed to evaluate potential applicability for monitoring bridge condition and structural health.

This report focuses on evaluating twelve forms of remote sensing that are potentially valuable to assessing bridge condition. The techniques are: ground penetrating radar (GPR), spectra, 3-D optics (including photogrammetry), electro-optical satellite and airborne imagery, optical interferometry, LiDAR, thermal infrared, acoustics, digital image correlation (DIC), radar (including backscatter and speckle), interferometric synthetic aperture radar (InSAR), and high-resolution "StreetView-style" digital photography.

Using a rating methodology developed specifically for assessing the applicability of these remote sensing technologies, each technique was rated for accuracy, commercial availability, cost of measurement, pre-collection preparation, complexity of analysis and interpretation, ease of data collection, stand-off distance, and traffic disruption. Key findings from the evaluation are that 3-D optics and "StreetView-style" photography appear to have the greatest potential for assessing surface condition of the deck and structural elements, while radar technologies including GPR and higher frequency radar, as well as thermal/infrared imaging demonstrate promise for subsurface challenges. Global behavior can likely be best monitored through electro-optical satellite and airborne imagery, optical interferometry, and LiDAR.

Monitoring how damage or deterioration changes over time will provide state and local engineers with additional information used to prioritize critical maintenance and repair of our nation's bridges. The ability to acquire this information remotely from many bridges without the expense of a dense sensor network will provide more accurate and temporal assessments of bridge condition. Improved assessments allow for limited resources to be better allocated in repair and maintenance efforts, thereby extending the service life and safety of bridge assets, and minimizing costs of service-life extension.

Acknowledgements

This work is supported 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. Additional information regarding this project can be found at www.mtti.mtu.edu/bridgecondition.

1.0 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 correlates directly to the age of a bridge (AASHTO 2008). The number of bridges listed as structurally deficient as of 2009 was 71,179 (11.8% 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 funding (FHWA 2009).

The concept of structural health monitoring (SHM) presents a broad generic framework that is well suited to help address the challenges that pertain to the deteriorating bridge infrastructure in the United States. SHM is the practice of monitoring a structure to ensure that its structural integrity and safety remain intact. In a more general sense, the objective of SHM is to observe infrastructure condition, assess in-service performance, detect deterioration, and estimate remaining service life.

1.1 Current Approach to Condition Assessment

Included within the scope of SHM for bridges is condition assessment, which serves as the basis for determining safety, remaining service life, and maintenance, repair and rehabilitation schedules for state and local transportation agencies. Current practices used for condition assessment are a function of the level of inspection which can include initial, routine, hands-on, fracture-critical, underwater, in-depth or scoping, damage, or special inspections (NCHRP 2007), with routine/hands-on type inspections serving as the primary mechanism for long-term condition assessment and performance evaluation.

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) (FHWA 2004). The Bridge Inspector's Reference Manual (BIRM) is available to help the bridge inspector with programs, procedures, and techniques for inspecting and evaluating a variety of in-service highway bridges (FHWA 2006). 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 and perception of the current state of the U.S. bridge infrastructure.

Within the scope of current practices for bridge inspection and condition assessment include: visual evaluation serves as the primary tool for used by inspectors. Other techniques for assessment can be employed such as specialized sensor technologies to evaluate specific challenges or measurement of bridge response to known loading; however, these techniques are often reserved for inspections beyond the routine and hands-on type. As a result, routine inspections are highly subjective and rely on experience-based expertise that must be developed over the years with practice. At first pass this may appear ineffective, but when considering the volume of bridges in service, available resources, and most importantly the lack of an all-encompassing solution for evaluating structural condition, few alternative approaches exist.

1.2 Remote Sensing Approaches to Condition Assessment

The use of remote sensing technologies presents a potential alternative to the above challenge and has the potential to augment current practices by providing both qualitative and quantitative measures of a bridge's condition. This report synthesizes the findings of an investigation of commercial remote sensing technologies with potential applications for bridge condition assessment. Presented herein are summaries of the challenges that may be addressed with remote sensing technologies and a description and ranking of the appropriateness of these technologies.

2.0 Remote Sensing Techniques and Terminology for Transportation Infrastructure

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 is the collection and measurement of spatial information about an object, area, or phenomenon at a distance from the data source, without direct contact (Falkner 1995; Aronoff 2005). Classic examples that may be familiar to the bridge engineer or inspector include satellite imagery, aerial photography, laser scanning (such as LiDAR, light detection and ranging) and ground penetrating radar (GPR). Remote sensing can also be understood as a form of "stand-off" structural health monitoring (SHM), and a form of non-destructive evaluation (NDE) and non-destructive testing (NDT), where the device gathering data is not touching the object or feature being measured. Remote sensing does not include emplaced sensors such as strain gauges or temperature sensors, which are in direct contact with the feature whose characteristic is being measured, even if these data are being transmitted from the bridge to another location for remote monitoring. Those are "in situ" sensors, which can be valuable in combination with remote sensing data, but this report stems from a USDOT/RITA project that is focused on understanding the value and practicality of applying remote sensing techniques to assessing bridge condition. Being able to apply remote sensing techniques to the field of bridge inspection and monitoring has large potential value, especially considering the sheer number of bridges in the United States transportation infrastructure system and appropriate challenging funding environment for inspection, maintenance and rehabilitation (Ahlborn et al. 2010 a). 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.

This assessment report focuses on twelve forms of remote sensing that are potentially valuable to assessing bridge condition. Those techniques are described in following sections, and are: GPR, spectra, 3-D optics (including photogrammetry), electro-optical satellite and airborne imagery, optical interferometry, LiDAR, thermal infrared, remote acoustics, digital image correlation (DIC), radar (including backscatter and speckle), interferometric synthetic aperture radar (InSAR), and high-resolution "StreetView-style" digital photography. More specific details on the remote sensing technologies are included in the project state of the practice report (Ahlborn et al. 2010 b).

Before discussing these technologies and the bridge condition challenges that can be measured and monitored, it is useful to describe the terms and principles frequently encountered when reading about or applying remote sensing methods. One such area is the use of active versus passive sensors. Active sensors emit a signal from the sensor and a reflected signal is collected off the feature of interest (such as a radar signal or actively emitted light used in

LiDAR). Passive sensors collect only the reflected ambient visible and infrared wavelengths that "bounce" (reflect) off an object. These ambient wavelengths are typically visible and infrared sunlight, which produce spectral reflectance patterns from the object. Aerial photography and Landsat satellite imagery are examples of passive sensors.

The concept of the electro-magnetic (EM) spectrum and the different wavelengths it consists of are important to understanding remote sensing. Figure 1 shows two example diagrams of the EM spectrum from short to long wavelengths. Noteworthy is that visible light is only a small part of the spectrum, between approximately 400 nanometers (nm) and 700 nm. Infrared light includes both the "near infrared" and thermal infrared that is used to record temperature. Visible and near-infrared light are often referred to as electro-optical (EO), while radar (Radio Detection and Ranging) uses radio-wavelength parts of the spectrum, typically with an active emitter and sensor. In general remote sensing can be done with wavelengths at any part of the spectrum; most common in transportation applications are visible, infrared, and radio-range wavelengths.

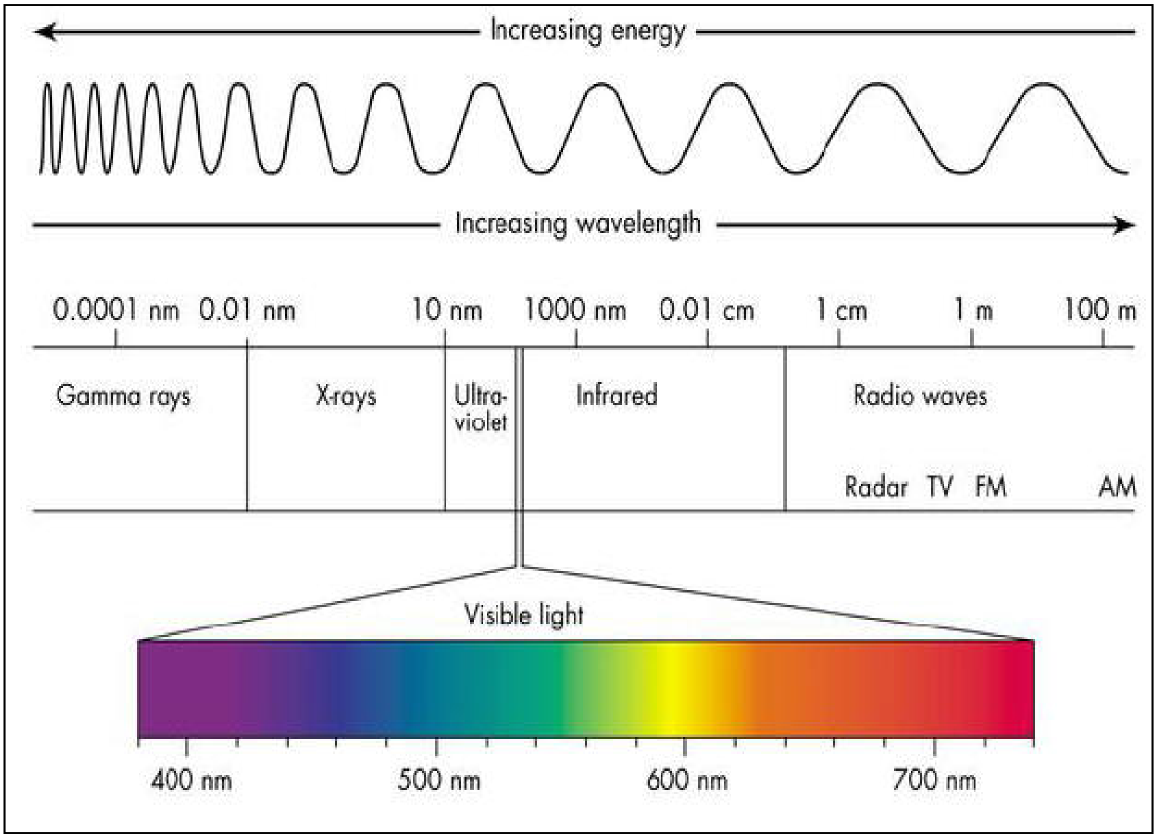


Figure 1: An example of the electro-magnetic spectrum and its relationship to wavelength

Resolution is another important concept. Resolution is most frequently used to refer to spatial resolution, which can be understood as the area on the ground that an image's pixel (picture element) covers, the smallest feature that can be resolved or identified in an image, or the "ground-sample distance" (GSD) between measurements. Spatial resolution usually affects a term known as “swath width” – this is the size of an area that is collected on the ground, usually as a continuous strip of imagery. Higher spatial resolution satellites usually have smaller swaths, meaning smaller areas on the ground are collected. Lower spatial resolution usually means larger areas are collected.

Other types of resolution are temporal, spectral, and radiometric. Temporal resolution refers to frequency in time in which a site or feature can be sensed by an instrument. For example, the Landsat 5 Thematic Mapper satellite gathers an image of the same area on the ground once every 16 days as it circles the earth. A remote sensing technology mounted on a vehicle, such as a terrestrial LiDAR system, would have a temporal resolution of however often it was chosen to be deployed to a location depending on budget and need. Spectral resolution most typically refers to size and number of divisions of the EM spectrum that a sensor can collect. Landsat 5 collects seven spectral bands ranging from the visible (blue, green, and red) to the near infrared and thermal. Digital Globe's Quickbird satellite collects four spectral bands (blue, green, red, and one band of near infrared). A typical consumer digital camera collects the three visible bands of blue, green, and red. Radiometric resolution refers to the number of "bits" used to collect a remotely sensed piece of data. For example, 8-bit color records information on a scale of 0-255 (or 256 values); 24-bit color is recorded with 16,777,216 values, meaning that many finer gradations in a color can be recorded about a feature and displayed later on in software tools and printed products.

Resolution needs impact the type of remote sensing device or platform that should be used to measure a particular indicator of interest, such as the amount of spalling on a bridge. Figure 2 shows an example, adapted from (Luhmann et al. 2006), that MTRI researchers used to define the remote sensing platform needed for an unpaved road condition study. The smaller the object area and the smaller the feature of interest (such as rutting), the higher accuracy is needed, which defines the platform used to collect the data. In the case of this study, the requirements to evaluate unpaved road conditions helped define than an unmanned aerial vehicle (UAV) platform for photogrammetry was needed and suitable for this remote sensing study. Photogrammetry is the science of making reliable geometric measurements from photographs (such as elevation or height data), most often from aerial photographs and satellite images (Falkner 1995).

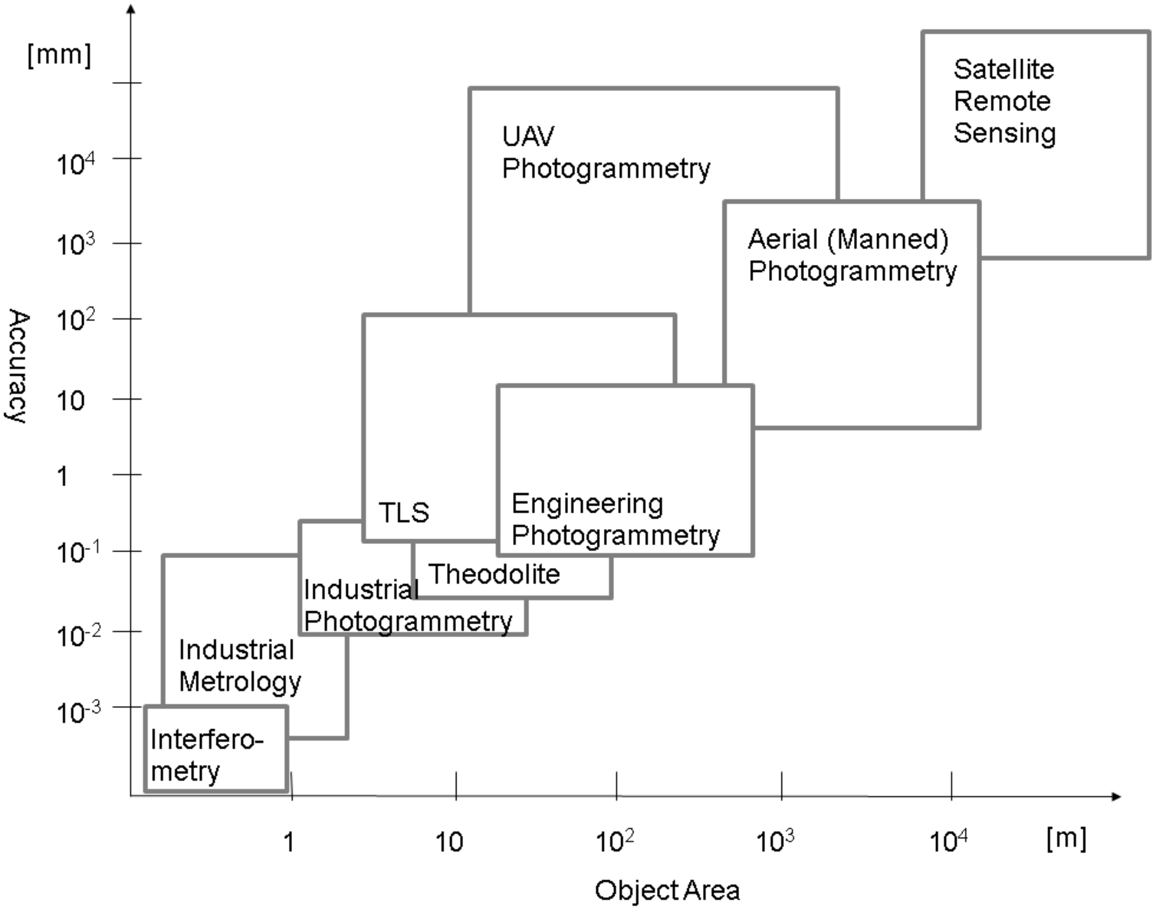


Figure 2: An example of the trade-offs of spatial resolution in terms of accuracy needs and the size of an object or part of an area on the ground that needs to analyzed via remote sensing (Luhmann et al. 2006)

When discussing remote sensing, the terms “multispectral”, “hyperspectral”, and panchromatic are often used when referring to remotely sensed data, especially satellite imagery and aerial photography. Multispectral and hyperspectral both mean remote sensing data that has been collected with many “bands” to capture parts of the electromagnetic spectrum. For example, the commercial WorldView-2 satellite captures data in eight parts of the EM spectrum (8 bands), which are shown in Figure 3. The importance of capturing multiple parts of the spectrum is that features can reflect parts of the EM spectrum differently depending on the type or condition of a surface being imaged by a remote sensing device. For example, this means that a bridge surface in different condition could look different in certain parts of the EM spectrum. In the case of a multispectral sensor (such as WorldView-2, or a typical aerial photography professional digital camera), only a few bands or “slices” of the EM spectrum are collected by the remote sensing platform (typically from three to approximately 30). Hyperspectral sensors are typically 100 to 200 or more bands of the EM spectrum, typically with narrow bandwidths of the spectrum being collected. Panchromatic means a single band of information of information was collected by the remote sensing platform – this typically takes the form a black and white (or grayscale) image. Panchromatic data is limited in color information but takes up relatively little storage space, making it suitable to some transportation applications.

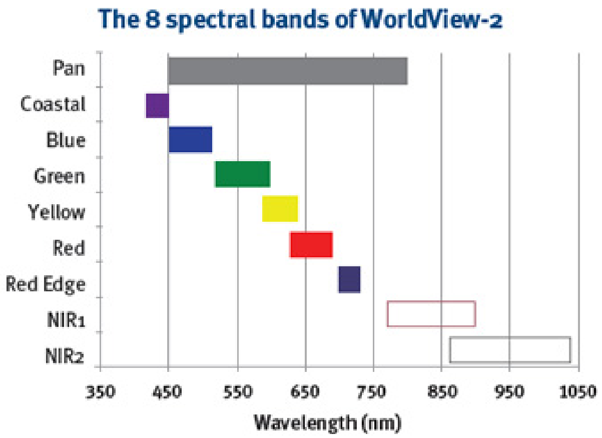


Figure 3: An example of the parts of the electro-magnetic spectrum captured by Digital Globe's WorldView-2 satellite and available as digital images (Digital Globe Webpage 2009)

Radar remote sensing technologies can contribute to transportation infrastructure assessment. Different radar platforms operate at different wavelengths of the radio spectrum. Table 1 lists some example radar bands that operate at different wavelengths and frequencies. The relationship between wavelength and frequency is define by the equation $c = \lambda v$ where c = the speed of light, λ = wavelength, and v = frequency. More important to bridge assessment is that different wavelengths have different penetrative capabilities, such as is seen in applications of GPR in bridge deck assessment. Longer wavelengths have greater penetration but with the tradeoff of lower spatial resolution (i.e., you can see further in, but smaller features are harder to discern), while shorter wavelengths typically do not penetrate as far, but small features are easier to identify (Aronoff 2005).

Table 1: Examples of radar bands, frequency, and their wavelength

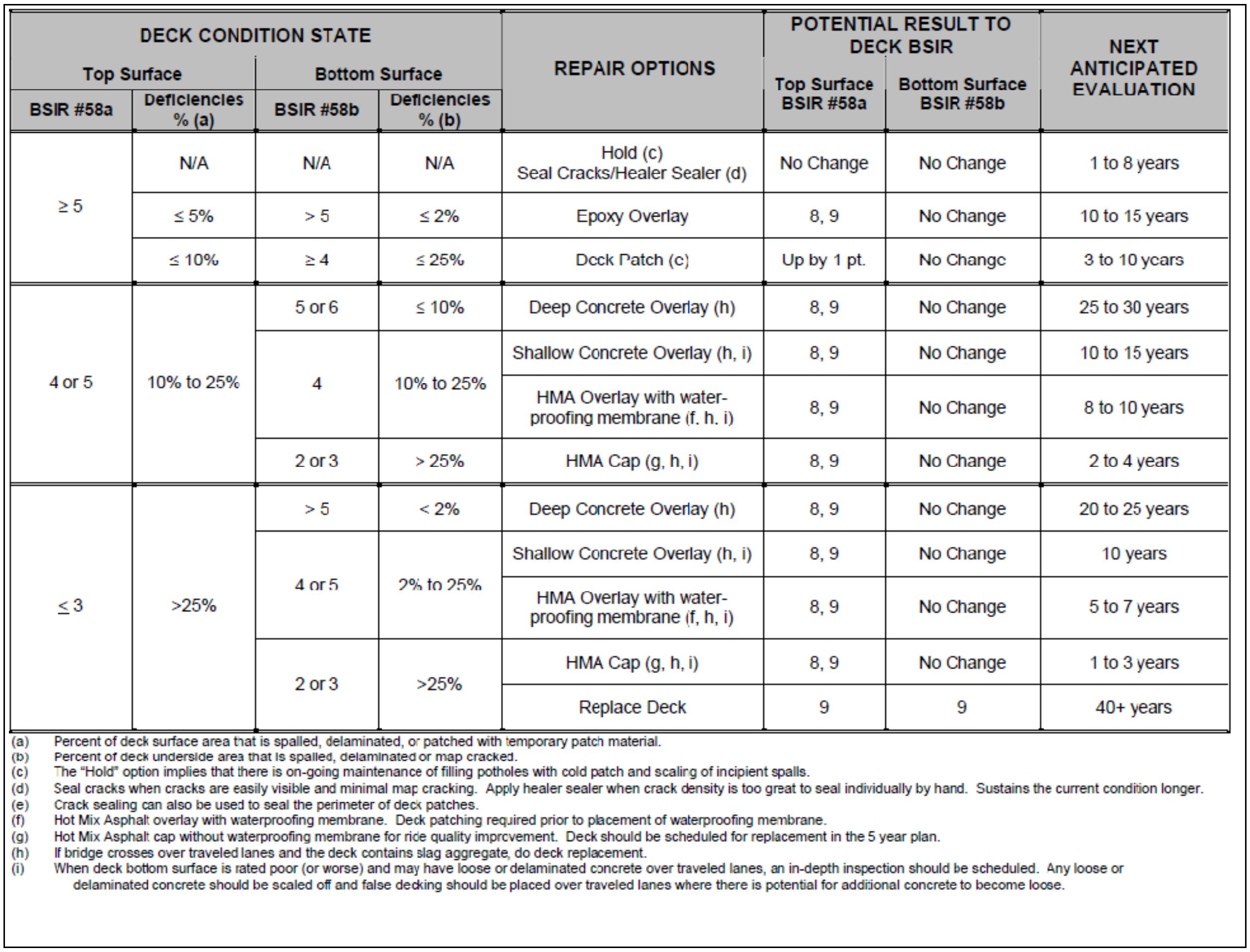
Radar Band	Frequency (GHz)	Wavelength (cm)
Ka	26 - 40	0.8 – 1.1
K	18.5 – 26.5	1.1 – 1.7
Ku	12 - 18	1.67 – 2.5
X	8 - 12.5	2.4 – 3.8
C	4 - 8	3.8 – 7.5
S	2 - 4	7.5 - 15
L	1 - 2	15 – 30
P	0.3 - 1	30 - 100

Additional resources are available to understanding remote sensing. This report further defines particular technologies and their applications to bridge condition assessment in the upcoming sections.

3.0 Challenges for National Bridge Inventory Infrastructure

To maintain updated records on infrastructure within the national bridge inventory, routine bridge inspections must be completed at a minimum of every two years. Bridge inspections processes are crucial to the life cycle preservation of bridge structures as they help to maintain safe operating conditions, prioritize maintenance and repair operations, and dictate funding priorities. With these processes, bridges can be monitored and issues mitigated to help extend the service life of a structure. The primary components of a bridge can be categorized as the bridge deck, superstructure and substructure. While all three components are essential to the performance of a bridge, considerations for the deck and superstructure are presented herein. From a maintenance and condition evaluation perspective, the bridge deck and superstructure are of major interest because they have the primary role of transferring loads to the substructure. In addition, the deck serves as the driving surface while also providing protection from the environment and contaminants (salts and chemicals) to the superstructure and substructure elements below. The expectation is that remote sensing technologies have the greatest potential to address challenges associated with these components.

In the United States, the majority of the bridges constructed and in service utilize reinforced concrete decks, with the remaining population comprised of a variety of alternative materials such as: timber, steel orthotropic, steel grid, and composite or polymeric. Bridge decks can be classified, to certain extent, as a sacrificial element because it can be replaced as it degrades [Figure 4]. However, as the integrity of the deck is compromised during the degradation process, the protection afforded to the superstructure and substructure elements also diminishes, often providing a catalyst for deterioration or accelerating degradation of these elements. The use of remote sensing technologies for condition assessment of concrete bridge decks has the potential to make a significant impact on current practices from an inspection and maintenance point of view as well as from a safety perspective. From a broad perspective, the issues that most often plague concrete bridge decks can be categorized by location as either surface challenges or subsurface challenges, with one often leading to the manifestation of the other.



DECK CONDITION STATE				REPAIR OPTIONS	POTENTIAL RESULT TO DECK BSIR		NEXT ANTICIPATED EVALUATION
Top Surface		Bottom Surface			Top Surface BSIR #58a	Bottom Surface BSIR #58b	
BSIR #58a	Deficiencies % (a)	BSIR #58b	Deficiencies % (b)				
≥ 5	N/A	N/A	N/A	Hold (c) Seal Cracks/Healer Sealer (d)	No Change	No Change	1 to 8 years
	≤ 5%	> 5	≤ 2%	Epoxy Overlay	8, 9	No Change	10 to 15 years
	≤ 10%	≥ 4	≤ 25%	Deck Patch (c)	Up by 1 pt.	No Change	3 to 10 years
4 or 5	10% to 25%	5 or 6	≤ 10%	Deep Concrete Overlay (h)	8, 9	No Change	25 to 30 years
		4	10% to 25%	Shallow Concrete Overlay (h, i)	8, 9	No Change	10 to 15 years
				HMA Overlay with water-proofing membrane (f, h, i)	8, 9	No Change	8 to 10 years
		2 or 3	> 25%	HMA Cap (g, h, i)	8, 9	No Change	2 to 4 years
≤ 3	>25%	> 5	< 2%	Deep Concrete Overlay (h)	8, 9	No Change	20 to 25 years
		4 or 5	2% to 25%	Shallow Concrete Overlay (h, i)	8, 9	No Change	10 years
				HMA Overlay with water-proofing membrane (f, h, i)	8, 9	No Change	5 to 7 years
		2 or 3	>25%	HMA Cap (g, h, i)	8, 9	No Change	1 to 3 years
				Replace Deck	9	9	40+ years

(a) Percent of deck surface area that is spalled, delaminated, or patched with temporary patch material.
(b) Percent of deck underside area that is spalled, delaminated or map cracked.
(c) The "Hold" option implies that there is on-going maintenance of filling potholes with cold patch and scaling of incipient spalls.
(d) Seal cracks when cracks are easily visible and minimal map cracking. Apply healer sealer when crack density is too great to seal individually by hand. Sustains the current condition longer.
(e) Crack sealing can also be used to seal the perimeter of deck patches.
(f) Hot Mix Asphalt overlay with waterproofing membrane. Deck patching required prior to placement of waterproofing membrane.
(g) Hot Mix Asphalt cap without waterproofing membrane for ride quality improvement. Deck should be scheduled for replacement in the 5 year plan.
(h) If bridge crosses over traveled lanes and the deck contains slag aggregate, do deck replacement.
(i) When deck bottom surface is rated poor (or worse) and may have loose or delaminated concrete over traveled lanes, an in-depth inspection should be scheduled. Any loose or delaminated concrete should be scaled off and false decking should be placed over traveled lanes where there is potential for additional concrete to become loose.

Figure 4: Michigan Department of Transportation Bridge Deck Preservation Matrix (Michigan Department of Transportation 2008)

The superstructure elements of most bridges in the United States are typically constructed of either steel or concrete (pre-stressed or reinforced) girders and are frequently paired with a reinforced concrete deck. These members serve as the primary load carrying members and their importance correlates directly to safety and integrity of the structural system. Superstructure elements are not replaced as often as bridge decks in maintenance operations and they are expected to last for the duration of the bridge design life. However, the consequences of failure for superstructure elements are critical considering human life factors. These dramatic consequences are highlighting the importance of quality inspection and maintenance practices for these members. Thus, the issues related to the condition of superstructure members must be observed over time and must also consider challenges on the surface as well as those internal to the member.

Other issues related to bridge performance can only be observed at the bridge system or global level due to the couple multi-directional response and redundancy inherent to most bridges. These challenges are essential to assessing performance of a structure versus the intended design behavior and have the potential to characterize the overall health and performance of a bridge.

In this evaluation, bridge challenges are organized into five categories including:

- Deck surface
- Deck subsurface
- Girder surface
- Girder subsurface
- Global metrics

The division into these five categories allowed for a focused investigation on certain bridge condition challenges more susceptible to that particular bridge location and the pairing of appropriate remote sensing technologies to evaluate the challenge. In the following section, those bridge categories and the identified challenges within those locations are discussed. The challenges selected were based on specific issues that were deemed critical to bridge performance and issues that manifest into poor condition ratings during inspections. Also included within each of the identified challenges are potential remote sensing technologies for each particular challenge with more detail provided in the Performance Evaluation of Remote Sensing Technologies section (section 5). General details on the appropriateness of the remote sensing technology for each challenge are presented within the Technology Rating Methodology section (section 4) with specific details provided in Table 3.

3.1 Deck Surface

The deck surface plays an important role in bridge maintenance because deterioration at this location can lead to further subsurface issues which can affect the entire bridge system. There are several different challenges associated with maintaining a bridge deck including: surface cracking, spalling and scaling along with issues with the expansion joints. When considering bridge deck inspections, some primary difficulties relate to assessing condition in a safe manner without disrupting traffic, and this becomes increasingly difficult on the underside of bridges. Assessment of the deck surface using remote sensing technologies, specifically optical (non-penetrative) approaches, appears promising especially considering that most deck surface issues are assessed visually in a routine inspection.

3.1.1 Map Cracking

Map cracking is a challenge associated with concrete decks in which the surface has a pattern of cracks caused by material failure. The magnitude of the cracks considered in this study ranged from 1/16” to 3/16” in width (FHWA 2006). An example of map cracking is presented in Figure 5. Traditional inspection techniques used for the assessment of map cracking include: visual evaluation, ultrasonic testing and impact-echo testing (FHWA 2006).

Potential remote sensing technologies for measuring map cracking:

- 3D photogrammetry
- StreetView-style photography
- Thermal IR
- LiDAR
- Optical interferometry
- EO airborne/satellite imagery
- Spectra
- Acoustics
- Radar (backscatter/speckle)

Figure 5: Map cracking on bridge deck surface (FHWA 2006)

3.1.2 Delamination

Delaminations revealed through surface cracks are similar to map cracking, but the actual locations of delaminations are beneath the concrete surface. These delaminations will typically turn into spalls over time. The magnitude of delamination cracks considered in this study was 1/16” to 3/16” in width (FHWA 2006). Similar to surface crack evaluation, traditional inspection techniques used for the assessment of surface cracks include: visual evaluation, ultrasonic testing and impact-echo testing (FHWA 2006).

Potential remote sensing technologies for measuring delamination:

- 3D photogrammetry

- StreetView-style photography
- Thermal IR
- LiDAR
- Optical interferometry
- Spectra
- Acoustics

3.1.3 Scaling

Scaling is an issue with the deck surface that covers the loss of material due to material degradation. Within this review, scaling is considered on the order of magnitude of 1/4” to 1” in depth (FHWA 2006). Figure 6 provides a representative example of moderate surface scaling of the deck surface. The current method for identifying the amount of scaling on a bridge structure is visual assessment and quantification.

Potential remote sensing technologies for measuring scaling:

- 3D photogrammetry
- StreetView-style photography
- Thermal IR
- LiDAR
- Optical interferometry
- EO airborne/satellite imagery
- Spectra
- Radar (backscatter/speckle).

Figure 6: Concrete deck surface scaling (FHWA 2006)

3.1.4 Spalling

Spalling is an issue with the deck surface that covers the loss of material due to delaminations in the concrete deck. With this review, spalling is considered on the order of magnitude of 1/4” to 1” in depth (FHWA 2006). An example of spalling in the concrete deck surface is shown in Figure 7. The current method for identifying the amount of spalling on a bridge structure is visual assessment and quantification.

Potential remote sensing technologies for measuring spalling:

- 3D photogrammetry
- StreetView-style photography
- Thermal IR
- LiDAR
- Optical interferometry
- EO airborne/satellite imagery
- Spectra
- Radar (backscatter/speckle)

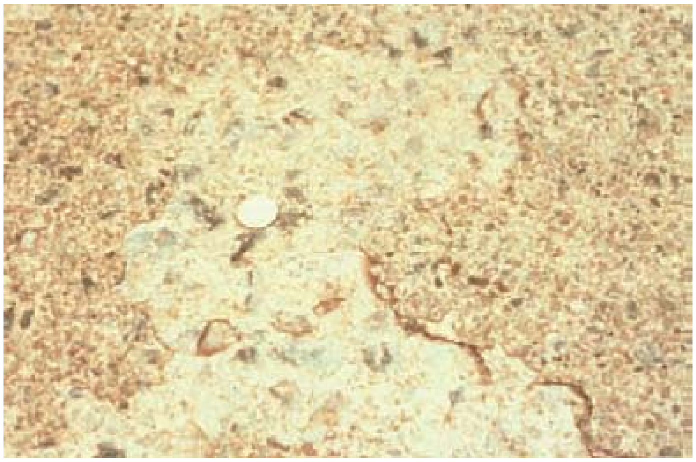


Figure 7: Spalling on concrete deck surface (FHWA 2006)

3.1.5 Expansion Joints

There are several different issues related to the expansion joints of the bridge. These include torn or missing seals, armored plate damage, chemical leaching on the bottom of joint, cracks within two feet of the joint and spalls within two feet of the joint. The indicators for the majority of these issues are represented by the titles of the different issues whereas the magnitude of the sensitivity for cracking and spalling is identical to those for surface cracking (1/16” to 3/16” in width) and spalling (1/4” to 1” in depth) (FHWA 2006). These issues are currently assessed through visual inspection by the bridge inspector. With the cracking and spalling, it is at the discretion of the inspector if they were caused by an expansion joint failure.

Potential remote sensing technologies for measuring expansion joint challenges:

- 3D photogrammetry
- StreetView-style photography
- Thermal IR
- LiDAR
- Optical interferometry
- EO airborne/satellite imagery
- Spectra
- Radar (backscatter/speckle)

3.2 Deck Subsurface

The main challenge with assessing the condition of the deck throughout its depth is that it is not visible to human eye. This can severely limit the identification of issues occurring below the deck surface. While these issues are of significant importance to bridge inspectors, traditional subsurface evaluation techniques are extremely limited and have only had moderate success within the bridge community. Similar to deck surface evaluation, there are still issues with keeping the traffic disruption during inspections to a minimum. The primary challenges associated with a bridge deck subsurface can be categorized as: material in the expansion joint, delamination, scaling and spalling on an unobserved surface (interior or hidden), corrosion and chloride ingress.

3.2.1 Expansion Joint

Excessive material in the expansion joint causes increased stresses in the components of the bridge due to the inability to expand. The quantity of material is inconsequential, but the presence of material fill is typically noted from visual assessment. Figure 8 shows an expansion joint that was filled with material.

Potential remote sensing technologies for measuring expansion joint challenge:

- Optical interferometry

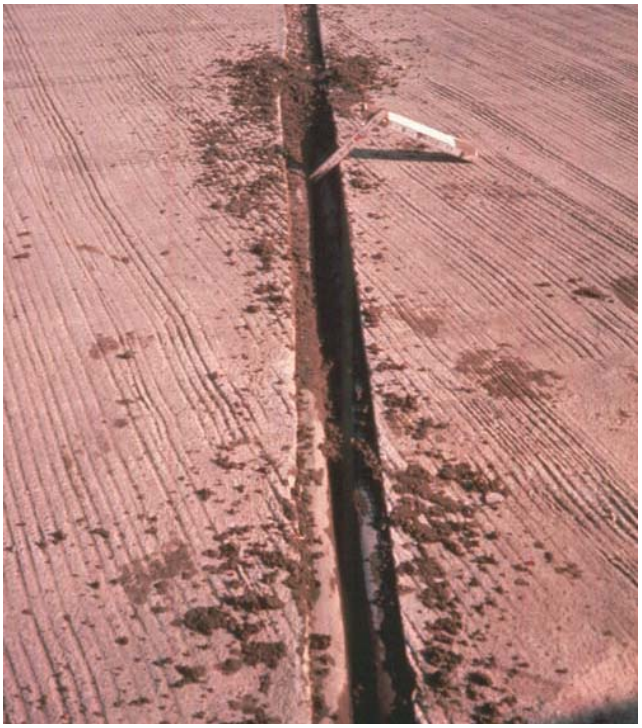


Figure 8: Material in expansion joint (FHWA 2006)

3.2.2 Delamination

Delamination in a concrete deck is the separation of material along a horizontal plane within the concrete interior. There are several indicators that can possibly show where a delamination has occurred including: a hollow sound, internal horizontal crack, moisture in horizontal cracks and fracture planes or open spaces in the concrete. The magnitude for the internal horizontal crack considered in this evaluation was considered to be approximately on the order of 0.004” (0.1 mm) level (FHWA 2006). No quantitative measure of moisture was considered, but the extent of the horizontal crack is determined by comparing the difference of the moisture content in the crack to the moisture content of the surrounding concrete. Similarly, relative changes in the measured radar signal with the use of integrated volume are used to evaluate fracture planes or open spaces within the concrete interior. Current techniques used to location delaminations include: acoustic wave sonic/ultrasonic velocity measurements, ground-penetrating radar, infrared thermography, ultrasonic testing, chain drag and visual evaluation (FHWA 2006).

Potential remote sensing technologies for measuring delamination:

- Ground-penetrating radar
- Thermal IR
- Acoustics
- Radar (backscatter/speckle)

3.2.3 Scaling

Scaling of material in the deck subsurface is defined as any loss of material that cannot be seen from the surface. The concept is to apply the instrument from the deck surface and observe the unseen section of the deck. The magnitude of material loss considered for this review, was ¼” to 1” in depth (FHWA 2006). Current practice for detecting scaling includes visual evaluation when it is observable.

Potential remote sensing technologies for measuring scaling:

- Ground-penetrating radar
- Thermal IR

3.2.4 Spalling

The concept of spalling of the deck subsurface is analogous to the aforementioned definition for subsurface scaling. Similarly, the magnitude of material loss considered for this review was ¼” to 1” in depth (FHWA 2006). Figure 9 shows an example of subsurface spalling representing the bottom surface of a bridge deck. Current practice for detecting spalling would be visual evaluation. The current in practice techniques for detecting spalling would be visual evaluating when it is observable.

Potential remote sensing technologies for measuring spalling:

- Ground-penetrating radar
- Thermal IR

Figure 9: Spalling on bridge deck surface

3.2.5 Corrosion

Reinforcement corrosion in a bridge deck results in a volume expansion of the deck due to the growth of corrosion by-products. The consequences of this volume expansion include: delamination and crack enlargement, as well as reduction in reinforcement cross section, load capacity and stiffness of the bridge deck (Nowak et al. 2000). The presence of corrosion and evolution of corrosion rate has been identified by changes in concrete resistivity. Higher concrete resistivity measurements in the range of 5 to 20 kΩ-cm imply lower corrosion rates (ACI 2001). Other mechanisms for assessing corrosion have centered on identify size and consistency of embedded reinforcing steel. Figure 10: Corroded reinforcement in bridge deck provides a typical example of high level corrosion of reinforcing steel and the associated ramifications. Current approaches for measuring corrosion include: half-cell potential, acoustic emissions, nonlinear vibro-acoustic method, four-probe electrical resistivity test, electrical resistant method, optical fiber sensors, magnetic flux leakage, magnetostrictive sensors, and microwave based thermoreflectometry (Sekulic et al. 2001).

Potential remote sensing technologies for measuring corrosion:

- Ground-penetrating radar

- Acoustics
- Radar (backscatter/speckle)

Figure 10: Corroded reinforcement in bridge deck

3.2.6 Chloride Ingress

Chloride contamination in concrete is a contributing factor to accelerate corrosion of reinforcement embedded in concrete bridge decks. Commonly accepted threshold values of 0.4% to 1% chloride by mass of concrete in the concrete cover, have been classified for medium corrosion risk (Angst et al. 2009). A number of standard AASHTO and ASTM tests (AASHTO T-260, ASTM C 1152, ASTM C 1218, AASHTO T277-93) and the neutron probe test have been used to quantify chloride ingress (ACI 2001; FHWA 2006).

Potential remote sensing technologies for measuring chloride ingress:

- Ground-penetrating radar
- Radar (backscatter/speckle)

3.3 Girder Surface

As the primary load carrying members within a bridge, defects observed in and on a girder have the potential to result in a decrease in section capacity. Several challenges associated with the girder surface include: steel structural cracking, concrete structural cracking, steel section loss, concrete section loss, and deterioration of protective paint. These challenges can be associated with either material distress or unexpected structural behavior issues, but in both cases the ramifications with respect to safety are paramount.

3.3.1 Steel Structural Cracking

One challenge that arises in bridges is structural (or large) cracking on the bridge girder. Structural cracking is categorized as the separation or breakage of materials. This type of structural cracking has various implications pertaining to the type of failure (flexure, shear, torsion, and fatigue). Within this evaluation, the specified resolution for steel structural cracking was selected as hairline size cracks with an approximate size of 0.004" (0.1mm) cracks or smaller (FHWA 2006). Current practices for evaluating structural cracks in steel include visual evaluation, eddy current applications, magnetic particle and imaging devices.

Potential remote sensing technologies for measuring steel structural cracking:

- 3D photogrammetry
- Optical interferometry
- Thermal IR
- Spectra

3.3.2 Concrete Structural Cracking

Concrete structural cracking can be defined as the separation of sections of concrete girder components. Similar to steel structural cracking, concrete structural cracking has various implications pertaining to the type of failure (flexure, shear and torsion). Within this evaluation, the specified resolution for concrete structural cracking was selected as hairline size cracks with an approximate size of 0.004" (0.1mm) cracks or smaller (FHWA 2006). Current techniques for evaluating structural cracking in concrete are similar to those of the steel structural cracking and include: visual evaluation, imaging devices, eddy current and magnetic particle applications (FHWA 2006; AASHTO 2008).

Potential remote sensing technologies for measuring concrete structural cracking:

- 3D photogrammetry
- Optical interferometry
- Acoustics
- Thermal IR
- Spectra

3.3.3 Steel Section Loss

Steel section loss is defined as the change (reduction) in area or volume of a structural component in which the structure's stiffness or strength is decreased. Indicators of this type of steel section loss would be a loss or change in cross sectional area or thickness of elements. Representative examples of steel section loss are shown in Figure 11a and 11b. A quantitative measure of section loss is essential to determine the appropriate reduction, relative to design values, in capacity and stiffness that must be considered for structural load rating and capacity analyses. Techniques commonly used for measuring steel section loss include: visual evaluation, dye penetration, fiber optics and imaging devices (FHWA 2006).

Potential remote sensing technologies for measuring steel section loss:

- Thermal IR
- LiDAR
- EO airborne/satellite imagery
- Radar (backscatter/speckle)
- 3D photogrammetry

(a)

(b)

Figure 11: a) Steel section loss in bridge girder viewed from the side; b) Steel section loss viewed from along the beam

3.3.4 Paint

Paint is typically used as a protective layer on steel beams (often aesthetics on concrete beams) to prevent or minimize corrosion from initiating or continuing to grow. The loss of this protective coating provides a mechanism for corrosion to initiate, but may also be indicative of underlying issues with the member such as member cracking. Figure 12 demonstrates loss of paint from the surface of the girders. Current methods used for evaluating the condition of paint include visual evaluation and imaging techniques (FHWA 2006).

Potential remote sensing technologies for measuring paint condition:

- Thermal IR
- Spectra

Figure 12: Paint loss on girder surface

3.3.5 Concrete Section Loss

Concrete section loss is defined as the loss of area or volume of the concrete along the surface where the stiffness or strength is compromised. Indicators of concrete section loss would be a loss or change in cross sectional area or thickness of elements (spalled sections of concrete are typical). Figure 13 shows the section loss in a concrete girder component in which the reinforcement is showing. Similar to steel section loss, a quantitative measure of section loss is essential to determine the appropriate reduction, relative to design values, in capacity and stiffness that must be considered for structural load rating and capacity analyses. Current techniques used for evaluating section loss include visual evaluation, imaging devices, and fiber optics (FHWA 2006).

Potential remote sensing technologies for measuring concrete section loss:

- 3D photogrammetry
- Thermal IR
- LiDAR
- EO airborne/satellite imagery
- Acoustics
- Radar (backscatter/speckle)

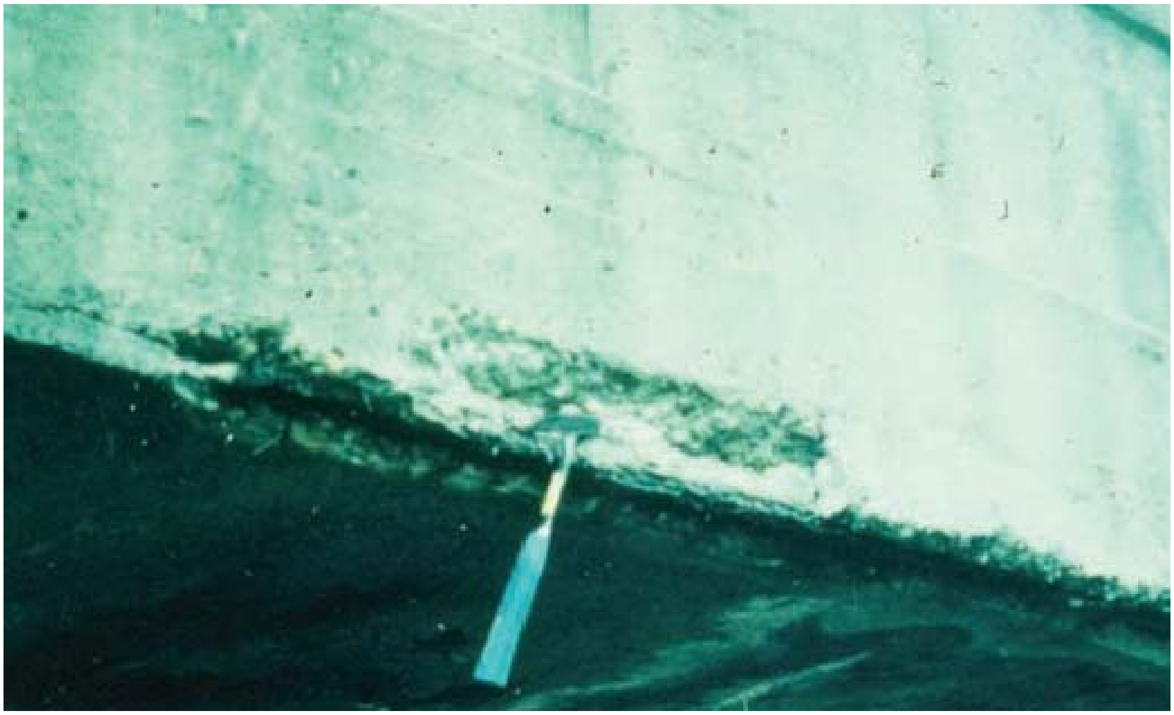


Figure 13: Concrete section loss (FHWA 2006)

3.4 Girder Subsurface

Issues occurring within the cross-section of girders have the same consequences as those on the girder surface. However, the difficulty of observing these issues is significantly more as challenge may be hidden or not easily accessible. Several challenges associated with the girder subsurface include: concrete structural cracking, concrete section loss, prestress strand breakage, reinforcement corrosion, and chloride ingress.

3.4.1 Concrete Structural Cracking

Concrete structural cracking can be defined as the separation of sections of concrete girder components (previously defined). These are distinguished from surface cracks in that they are not visible from the surface as would be the case for interior sections of side-by-side box beams. This type of concrete structural cracking has various implications pertaining to the type of failure (flexure, shear and torsion). Within this evaluation, the specified resolution for concrete structural cracking was selected as approximately 0.03125” (0.8mm). Current techniques for evaluating subsurface concrete structural cracking include: imaging devices, eddy current, and magnetic particle applications (FHWA 2006; AASHTO 2008).

Potential remote sensing technologies for measuring concrete structural cracking:

- Thermal IR
- Acoustics

3.4.2 Concrete Section Loss

Concrete section loss is defined as the loss of area or volume of the concrete along the surface where the stiffness or strength is compromised (previously defined). This section loss is distinguished from surface concrete section loss in that the area or volume would not be visible from the surface as would be the case for interior sections of side-by-side box beams. Indicators of concrete section loss would be a loss or change in cross sectional area or thickness of elements (spalled sections of concrete are typical). A quantitative measure of section loss is essential to determine the appropriate reduction, relative to design values, in capacity and stiffness that must be considered for structural load rating and capacity analyses. Current techniques for evaluating subsurface concrete section loss include: imaging devices, visual inspection (if accessible) and fiber optics (FHWA 2006).

Potential remote sensing technologies for measuring concrete section loss:

- Acoustics
- Radar (backscatter/speckle)

3.4.3 Prestress Strand Breakage

Within a prestressed concrete girder, the prestressing strand provides the tensile resistance to the girder, but also minimizes crack formation under service loads. Breakage of these prestressing strands results in a redistribution of stresses within the member and potential failure of the structure. In this evaluation, the sensitivity of resolution would be to the size of the strand under consideration, 0.08” (2mm) for an individual wire or 0.375” (9.5 mm) for a typical strand (PCI 2004). Current practices used for investigating strand breaks include visual evaluation (sag in structure or exposed broken strand), eddy current, ground penetrating radar (GPR) and ultrasonic wave applications (FHWA 2006).

Potential remote sensing technologies for measuring prestress strand breakage:

- Ground-Penetrating Radar
- Acoustics
- Radar (backscatter/speckle)

3.4.4 Corrosion

Reinforcement corrosion within bridge girders yields by-products, causing a volume change in the surrounding concrete which causes the formation of cracks and delaminations near surfaces, similar to the case for deck subsurface corrosion (previously described). Figure 14 demonstrates the effects of corrosion on reinforcing bars in a concrete bridge girder. As with the deck subsurface scenario, the presence of corrosion and evolution of corrosion rate has been identified by changes in concrete resistivity. Higher concrete resistivity measurements in the range of 5 to 20 kΩ-cm imply lower corrosion rates (ACI 2001). Other mechanisms for assessing corrosion have centered on identify size and consistency of embedded reinforcing steel. Current approaches for measuring corrosion include: half-cell potential, acoustic emissions, nonlinear vibro-acoustic method, four-probe electrical resistivity test, electrical resistant method, optical fiber sensors, magnetic flux leakage, magnetostrictive sensors, and microwave based thermoreflectometry (Sekulic et al. 2001).

Potential remote sensing technologies for measuring corrosion:

- Ground-Penetrating Radar
- Acoustics
- Radar (backscatter/speckle)

Figure 14: Corroded reinforcing bars

3.4.5 Chloride Ingress

Similar to bridge decks (previously described), chloride contamination is a contributing factor to accelerate corrosion of reinforcement embedded in concrete bridge girders decks. Commonly accepted threshold values of 0.4% to 1% chloride by mass of concrete in concrete cover, have been classified for medium corrosion risk (Angst et al. 2009). A number of standard AASHTO and ASTM tests (AASHTO T-260, ASTM C 1152, ASTM C 1218, AASHTO T277-93) and the neutron probe test have been used to quantify chloride ingress (ACI 2001).

Potential remote sensing technologies for measuring chloride ingress:

- Ground-Penetrating Radar
- Radar (backscatter/speckle)

3.5 Global Metrics

The challenges described in the previous sections related specifically to member behavior and material degradation issues. Other challenges which related to the entire bridge system cannot be categorized within these definitions are categorized in this evaluation as global metrics. Global metric challenges include: change in bridge length, bridge settlement, bridge movement, surface roughness and vibration. These challenges may not be observable during a routine inspection of the bridge or individual elements, but their influence on the system behavior has the potential to influence the member categories.

3.5.1 Bridge Length

Change in bridge length (often a reduction) resulting from pavement shove has the potential to change the state of stress within a bridge. This change in length can also influence support restraint by altering design boundary conditions (e.g. squeezing expansion joints and rotating support rockers). This change in length is taken along the span of the bridge. According to Manual for Bridge Inspection, bridge length measurements will take place when bridge plans are not available; 0.1ft is the limit of accuracy for measuring this feature (AASHTO 2008). Current methods for measuring bridge length include: measuring wheel and electronic distance meter (EDM) (AASHTO 2008).

Potential remote sensing technologies for measuring bridge length:

- 3D photogrammetry
- EO airborne/satellite imagery
- Digital image correlation
- InSAR

3.5.2 Bridge Settlement

Bridge settlement, defined as vertical movement of the bridge (z-axis), can cause cracks to form within the bridge deck, superstructure and/or substructure. Bridge settlement can be uniform or differential, with differential settlement resulting in more severe damage within the structure due to unforeseen constraint. Soil bearing failure, consolidation of soil, scour, undermining and subsidence from mining or solution cavities are the main causes of the bridge settlement vertical movement (FHWA 2006). In this evaluation, an approximate sensitivity of ¼" to ½" was defined. Current methods for evaluating settlement have included GPS and tiltmeters (FHWA 2006).

Potential remote sensing technologies for measuring bridge settlement:

- 3D photogrammetry
- Digital image correlation
- LiDAR
- InSAR

3.5.3 Bridge Movement

Bridge movement is defined as horizontal movement of the bridge either in the longitudinal or transverse directions (X or Y axis). Horizontal movement of bridge can cause cracks on the bridge deck and substructure. In this evaluation, an approximate sensitivity of ¼” to ½” was defined. Current methods for measuring bridge movement included strain sensors and tiltmeters (FHWA 2006).

Potential remote sensing technologies for measuring bridge movement:

- 3D photogrammetry
- Digital image correlation
- LiDAR
- InSAR

3.5.4 Surface Roughness

Surface roughness correlates primarily to user comfort and ride quality, but has broader implications with respect to dynamic amplification on a bridge, with a rougher surface correlating to lager dynamic response within the structure. Current methods for assessing road surface roughness primarily rely on visual evaluation methods with subjective ratings.

Potential remote sensing technologies for measuring surface roughness:

- 3D photogrammetry
- StreetView-style photography
- LiDAR
- Optical interferometry
- EO airborne/satellite imagery
- InSAR
- Radar (Backscatter/Speckle)
- Spectra

3.5.5 Vibration

Vibration is defined as the oscillation or periodic motion of a rigid body. In bridges, vibration is considered as the oscillation of its structural members. Typically, vibrations documented out of the bridge’s natural vibration range can indicate problems such as unseen cracks or fractures within the structure. Typical methods used for vibration measurements include accelerometers and GPS receivers. In this evaluation, the range of fundamental frequencies considered ranged from 0.5-20 Hz range with relatively small amplitudes, representing a range common to routine bridges.

Potential remote sensing technologies for measuring vibration:

- Optical interferometry
- Digital image correlation
- InSAR
- Radar (backscatter/speckle)

4.0 Technology Rating Methodology

The demonstration rating given in this commercial remote sensing evaluation is an unweighted, cumulative score of points awarded to a particular technology's capability in detecting a specific indicator of bridge structural health. The criteria for each technology-indicator appraisal was developed based on the experience, and each is intended to be an objective dimension of remote sensing technology as it would be used in bridge condition assessment. The rating system is similar to the work of Gucunski, et al. (2010), where non-destructive evaluation/testing (NDE/NDT) techniques were assigned grades to assess their performance for various NDE/NDT applications. Our assessment encountered some of the same difficulties as theirs, particularly the lack of information in the literature regarding specific performance measures. The performance criteria that Gucunski, et al. (2010) used were: i) accuracy, ii) repeatability, iii) ease of data collection, analysis, and interpretation, iv) speed of data collection and analysis, and v) cost of data collection and analysis. The list of criteria used in this evaluation is listed in the left column of Table 2.

A major component in the rating of technologies for bridge condition evaluation was a growing library of references that we initially generated for the State of the Practice Synthesis Report (Ahlborn et al. 2010 b). The highest level of detail and scope applicable to bridge-related remote sensing were used wherever possible for this commercial remote sensors rating methodology. Ideal inputs for the commercial sensor evaluation were papers that demonstrated a remote sensing technology in the field, attempted to characterize a potential defect or other relevant aspect of bridge condition, reported on the resolution or sensitivity they achieved, and estimated the error. In addition, the domain expertise of the project team, particularly in the areas of radar (including GPR and InSAR), interferometry, digital image correlation, electro-optical (EO) imagery from both airborne and satellite instruments, as well as high-resolution "StreetView-style" digital panoramas were critical to the evaluation.

All performance criteria receive a score from 0 to 2 (low to high). This narrow range was chosen so as to avoid artificially inflating scores. For all performance criteria, a higher score is more satisfactory; a score of zero indicates the technology does not satisfy that criterion.

Criteria A and B: The most important criteria in the appraisal are criterion A and B, respectively: whether the technology has the capability to satisfy the spatial, spectral, or temporal resolution required and whether or not the technology is commercially available, only research-grade, or has never been used for that application before. Their importance is reflected in the total rating, for if either one of these criteria received a zero score, the total rating is zero. This reflects the fact that if the technology does not meet the requirements (i.e. it cannot sense the bridge condition indicator of interest) or is not actually available for use (i.e. only theoretical) for a given indicator, then the technology is not considered applicable for observing that specific bridge condition indicator and it is not recommended for further research and development or commercial implementation as part of this study. At this point in the assessment of remote sensing technologies' performance, the even weighting of each rating is a demonstration methodology and will be reviewed as part of supplementary report in the future. Additional knowledge of the capabilities of the remote sensing technologies may allow for more refined rating scales and weighting.

Table 2: Definition for the criteria used in rating remote sensing technologies for their efficacy in detecting bridge condition indicators

Criteria		Score (0-2)	
A:	**Is the requirement met?**	**2**	Resolution is specifically within the current capabilities of the technology Full range of measurements are met or better Other requirements directly measured
		1	Lower limit of resolution/requirements is not within capabilities, but upper limit is Technology can measure somewhere between the range or within 25 % of upper limit Some requirements are only indirectly measured
		0	Upper limit of resolution not met within 25 % current capabilities do not allow direct measurement at any necessary resolution
B:	**Availability of instrument**	**2**	Technology is currently commercially available and used for similar application(s) Technologies components are immediately available for use as manufacturer intends (e.g. there is no commercial DIC or 3D Photogrammetry platform, but digital cameras are widely available for the same purpose)
		1	Technology is available only for research purposes Components are available commercially but they may have not been applied to this purpose and are not specifically designed for the application
		0	A complete system has not been demonstrated in research The technology is only theoretically available and would have to be built from very fundamental components
C:	**Cost of measurement**	**2**	Low capital cost Moderate capital cost with reuse (low operational cost)
		1	Moderate capital cost Low capital cost with high operational cost (e.g. dedicated equipment that cannot quickly or easily be reused)
		0	High capital cost Moderate capital cost with high operational cost
D:	**Pre-collection preparation**	**2**	Absolutely no preparation of the structure No/minimal calibration of the instrument are required
		1	The structure requires moderate preparation The instrument requires moderate calibration
		0	Both the structure and/or instrument require extensive preparation

E: Complexity of analysis	**2**	Analysis consists of either pattern recognition by user (bridge inspector can easily understand the output) Automated "turn-key" processing by a computer (software commercially available)
	1	Analysis consists of detailed measurements made by a human user from raw data Processing by an algorithm that must be tuned or trained for each dataset More than one algorithm is needed
	0	Analysis consists of very complex calculations and measurements made by a human user from raw data Processing by an algorithm that either i) requires extensive human supervision ii) a large amount of time per bridge (more than a day) iii) requires multiple algorithms chained together WITH human-in-the-loop I/O
F: Ease of data collection	**2**	Instrument is used in a straightforward manner as intended by manufacturer AND requires little more from the operator than supervision (i.e. "push the start button and start collecting") Easily accessible structure components
	1	Instrument is used in a custom fashion (may have been modified for this purpose) Requires input from operator Requires real-time verification (QA/QC) of results Environmentally dependent Considerable time window for data collection Physical challenges
	0	Instrument is used in a custom fashion AND requires EITHER input from the operator OR real-time verification (QA/QC) of results Hidden components Team needed
G: Stand-off distance rating	**2**	No part of the platform is touching the earth
	1	Part of the platform is on the earth or bridge (i.e. on a ground-based vehicle or some other grounded mount) AND the instrument is NOT in contact with the structure
	0	Instrument is in direct contact with structure; technique is not technically remote sensing
H: Traffic Disruption	**2**	Absolutely no lane closure or traffic disruption
	1	Minor/ short term traffic disruption or minor lane closure
	0	Major/ long term traffic disruption or major lane closure

Criterion C: the cost of measurement is an important consideration as the most likely customer of remote sensing technologies for bridge condition evaluation will be state and local transportation agencies (DOTs) whose budgets are modest. The cost of measurement has been defined on a “per bridge” basis where possible. Such an estimate is extremely difficult to produce when evaluating hypothetical use cases; best judgments based on our domain expertise and experience were used.

Criterion D: the pre-collection preparation is intended to be a measure of the amount of time and work required to prepare a bridge structure, element, or remote sensing instrument (i.e. calibration) before usable data can be collected. Depending on the technology and the application, this has been deemed to include such preparation as installing corner reflectors for radar on a structure, calibrating a camera with specific shots, loading a structure or element, or artificially illuminating a target.

Criterion E: the complexity of the analysis is similar to criterion D, and is intended to represent the amount of time and work required to process the remote sensing data collected into useful information for bridge condition assessment. If the data can be interpreted immediately after acquired by the device—not including any post-processing that may be done automatically by the receiver—the highest score is given for criterion E. If the remote sensing data do require post-processing, in order to receive the highest score for criterion E that processing must be what is termed “turn-key”—it must generally consist only of “plugging in” data and having it automatically processed by an algorithm, much like inserting a key into a lock and turning it. This criterion reflects yet another condition of industry: state and local DOTs typically have neither the time nor the expertise for sophisticated post-processing of bridge condition data.

Criterion F: the ease of data collection reflects how easy it is to make measurements that characterize the condition of a bridge. The highest score is given to technologies that require little more of an operator than pushing the “start” button. Another way of measuring this ease for commercial instruments is to specify whether the instrumentation is used as the manufacturer intended or has been modified for use in an unconventional way. If the latter is true, it is assumed that the instrument’s operation is not straightforward. An additional consideration in this criterion is that the structural element intended to be scanned is easily accessible. This also reflects the industry condition that end-users may likely have no formal remote sensing instrument training or, at the very least, no special expertise in the technique as it is applied.

Criterion G: the stand-off distance rating is like a “remote sensing quotient” in that it is a measure of how far the instrument is from the target or target enclosure’s surface (for subsurface features) when making a measurement. Technologies that receive a score of zero for a particular application are those which require direct contact and are therefore not technically remote sensing technologies at all. “Near bridge,” non-contact technologies receive a one, while stand-off technologies more traditionally defined as remote sensing receive a two.

Criterion H: traffic disruption is intended to measure how much the technique interferes with traffic when collecting data. This may not be independent from criterion G because technologies with high stand-off distances present no opportunity for traffic disruption. However, it was important to capture a representational score for technologies at low stand-off that do not interfere with traffic, such as GPR or StreetView-style imagery which may both be operated from a vehicle moving with traffic. This is an important measure of a commercial technology’s practicality for bridge condition evaluation as, according to a personal estimate from Michigan DOT bridge inspectors, lane closures can cost from $2,000 to $3,000 a day. Scored results of the rating methodology are listed in Table 3.

Table 3: Performance Rating of Commercial Remote Sensing Technologies

Location	Challenges	Indicator	Desired Measurement Sensitivity	Rating Based, in Part, on Theoretical Sensitivity for Measurement Technologies											
				GPR	Spectra	3D Photo-grammetry	EO Airborne/ Satellite Imagery	Optical Inter-ferometry	LiDAR	Thermal IR	Acoustics	DIC	Radar (Backscatter/ Speckle)	InSAR	Streetview-Style Photography
Deck Surface	Expansion Joint	Torn/Missing Seal		0	8	14	12	11	13	11	0	0	9	0	13
		Armored Plated Damage		0	0	14	12	11	13	11	0	0	0	0	13
		Cracks within 2 Feet	0.8 mm to 4.8 mm (1/32" to 3/16") width	0	8	14	0	12	12	11	0	0	9	0	13
		Spalls within 2 Feet	6.0 mm to 25.0 mm (1/4" to 1") depth	0	8	14	12	12	12	11	0	0	9	0	13
		Chemical Leaching on Bottom		0	11	0	0	0	0	0	0	0	0	0	0
	Map Cracking	Surface Cracks	0.8 mm to 4.8 mm (1/32" to 3/16") width	0	8	14	12	12	12	11	8	0	9	0	13
	Scaling	Depression in Surface	6.0 mm to 25.0 mm (1/4" to 1") depth	0	8	14	12	12	12	11	0	0	9	0	13
	Spalling	Depression with Parallel Fracture	6.0 mm to 25.0 mm (1/4" to 1") depth	0	8	14	12	12	12	11	0	0	9	0	13
	Delamination	Surface Cracks	0.8 mm to 4.8 mm (1/32" to 3/16") width	0	8	14	0	12	12	11	8	0	0	0	13
Deck Subsurface	Expansion Joint	Material in Joint		0	0	0	0	11	0	0	0	0	0	0	0
	Delamination	Moisture in Cracks	Change in moisture content	11	0	0	0	0	0	11	0	0	0	0	0
		Internal Horizontal Crack	Approximately 0.1 mm (0.004") level	0	0	0	0	0	0	11	8	0	0	0	0
		Hollow Sound		0	0	0	0	0	0	0	8	0	0	0	0
		Fracture Planes / Open Spaces	Change in signal from integrated volume	12	0	0	0	0	0	0	8	0	12	0	0
	Scaling	Depression in Surface	6.0 mm to 25.0 mm (1/4" to 1") depth	12	0	0	0	0	0	11	0	0	0	0	0
	Spalling	Depression with Parallel Fracture	6.0 mm to 25.0 mm (1/4" to 1") depth	12	0	0	0	0	0	11	0	0	0	0	0
	Corrosion	Corrosion Rate (Resistivity)	5 to 20 kΩ-cm	0	0	0	0	0	0	0	0	0	0	0	0
		Change in Cross-Sectional Area	Amplitude of signal from rebar	13	0	0	0	0	0	0	8	0	13	0	0
	Choride Ingress	Choride Content through the Depth	0.4 to 1.0 % chloride by mass of cement	12	0	0	0	0	0	0	0	0	12	0	0
Girder Surface	Steel Structural Cracking	Surface Cracks	< 0.1 mm (.004"), hairline	0	8	11	0	12	0	11	0	0	0	0	0
	Concr. Structural Cracking	Surface Cracks	.1 mm (.004")	0	8	11	0	12	0	11	8	0	0	0	0
	Steel Section Loss	Change in Cross-Sectional Area	Percent thickness of web or flange	0	0	11	12	0	13	11	0	0	11	0	0
	Paint	Paint Condition	Amount of missing paint (X %)	0	9	0	0	0	0	11	0	0	0	0	0
	Concrete Section Loss	Change in Cross-Sectional Area	Percent volume per foot	0	0	11	12	0	13	11	7	0	11	0	0
Girder Subsurface	Concr. Structural Cracking	Internal Cracks (e.g. Box Beam)	Approx 0.8 mm (1/32")	0	0	0	0	0	0	11	8	0	0	0	0
	Concrete Section Loss	Change in Cross-Sectional Area	Percent volume per foot	0	0	0	0	0	0	0	7	0	11	0	0
	Prestress Strand Breakage	Change in Cross-Sectional Area	Wire 2 mm or strand 9.5 mm diameter	9	0	0	0	0	0	0	8	0	9	0	0
	Corrosion	Corrosion Rate (Resistivity)	5 to 20 kΩ-cm	0	0	0	0	0	0	0	0	0	0	0	0
		Change in Cross-Sectional Area	Amplitude of signal from rebar	8	0	0	0	0	0	0	8	0	13	0	0
	Choride Ingress	Choride Content through the Depth	0.4 to 1.0 % Chloride by mass of cement	10	0	0	0	0	0	0	0	0	11	0	0
Global Metrics	Bridge Length	Change in Bridge Length	Accuracy to 30 mm (0.1ft) (smaller)	0	0	15	13	0	0	0	0	9	0	12	0
	Bridge Settlement	Vertical Movement of Bridge	Approximately 6 mm to 12 mm	0	0	12	0	0	12	0	0	9	0	12	0
	Bridge Movement	Transverse Directions	Approximately 6 mm to 12 mm	0	0	12	0	0	12	0	0	9	0	12	0
	Surface Roughness	Surface Roughness	Change over time	0	9	14	13	12	12	0	0	0	11	13	13
	Vibration	Vibration	.5 -20 Hz, amplitude?	0	0	0	0	12	0	0	0	10	12	12	0

5.0 Performance Evaluation of Remote Sensing Technologies

Several remote sensing technologies were explored in broad, but appropriate, categories for their effectiveness and practicality in evaluating bridge condition. An emphasis on commercial availability and well-established practices was used in the literature search wherever possible to keep a focus on the potential for implementation. The commercial availability of these technologies has been represented, as detailed in the “Technology Rating Methodology” section. Included in this section is a short definition of each of the remote sensing modalities considered for review. They are defined here to better constrain the techniques that have been rated for their sufficiency in conveying information about bridges’ structural health. Additionally, detailed information on these techniques is available in the State of the Practice Synthesis Report (Ahlborn et al. 2010 b).

5.1 Ground Penetrating Radar (GPR)

GPR is a type of radar acquisition characterized by relatively low electromagnetic frequencies (center frequencies as low as 100 MHz but usually no lower than 500 MHz) and a wide bandwidth, intended to maximize depth penetration and the radar’s sensitivity to embedded features. In this review, both air- and ground-coupled GPRs that are either pulsed or continuous wave (CW/FM-CW) operation were considered.

The functional difference between GPR and other ground-based radar measurements, as mentioned, is based merely on collection frequencies and bandwidth. As such, in the rating of this technology and the suite of commercial GPR systems available the scope was limited to subsurface applications, specifically the bridge deck subsurface and girder subsurface. Furthermore, most commercial GPR systems intentionally “gate-out” or ignore returns from the air-ground interface. Although it would be easy to modify a commercial GPR to include surface information or modify a more generalized radar system (or network analyzer) to work as a GPR, it was decided that limiting the scope of this technology category to typical subsurface applications was appropriate. For completeness, both subsurface and surface applications are included for review in the “Radar Images, Backscatter, and Speckle” category, however, the subsurface ratings for that category are identical to those found in GPR—a consequence of the fact that GPR is just a special type of radar collection.

GPR is already commercially available and many companies offer GPR instrumentation for purchase for a wide variety of applications. A representative list of commercial GPR systems is included in Table 4. Some companies perform GPR surveys as a service and do not sell instrumentation; some of these are listed in Table 5. GPR can be performed from a moving vehicle platform (Shuchman et al. 2005), enabling rapid bridge condition characterization on an inventory scale. Analysis of GPR data can be complex, however, as signals must be “migrated” to identify subsurface features and for some applications the dielectric properties of the medium need to be estimated. While used for moisture or chloride evaluations, GPR is sensitive to environmental factors such as rain and snow, though some users of commercial GPR systems indicate the effect is not significant (Kim et al. 2003). There is commercial software available for post-processing radar data, most notably the RADAN software suite developed by Geophysical Survey Systems Incorporated (GSSI), which automatically integrates GPS location data.

Table 4: Representative list of some common commercial GPR systems available for purchase

Instrument	Company	Bandwidth
Profiler EMP-400	GSSI*	1-16 kHz
TerraVision	GSSI	400 MHz
BallastScan	GSSI	2.0 GHz
BridgeScan	GSSI	1.6 GHz
RoadScan	GSSI	500 MHz
StructureScan Mini	GSSI	1.6 GHz
StructureScan Standard	GSSI	1.6 GHz or 2.6 GHz
StructureScan Professional	GSSI	1.6 GHz
StructureScan Optical	GSSI	1.6 GHz or 2.6 GHz
SIR-20 or SIR-3000	GSSI	Depends on choice of antenna
OKO-2	Geotech	Depends on choice of antenna
Detector DUO	IDS Australasia	250 MHz, 700 MHz
RIS-MF	IDS Australasia	200-600 MHz
Aladdin	IDS Australasia	2.0 GHz
GPR for Road	IDS Australasia	600 MHz and 1.6 or 2.0 GHz
Mira Series	Mala Geoscience	
CX Concrete Imaging System	Mala Geoscience	
ProEx System	Mala Geoscience	

***Geophysical Survey Systems Incorporated**

In general, GPR scored very high for concrete deck applications in this evaluation. With the exception of detecting moisture in cracks, however, the technology only partially or indirectly met the requirements for detecting subsurface conditions. The reason is that, as with all radar techniques, features that may be smaller than a range bin (smaller than the limit of resolution) are usually still able to be detected by their contribution to the overall signal from that range bin. In this way, the question of whether or not GPR can detect a subsurface feature should instead be framed as whether or not GPR is *sufficiently sensitive* to an embedded feature, as GPR makes no direct measurement of a target's dimensions. GPR does provide, however, a measurement of the target's position within a subsurface cross-section, and this is how the technique has been successfully employed in locating rebar as well as providing qualitative estimates of the rebar's condition. Rebar, made of metal and therefore highly conductive, causes diffractions in the GPR reflection data (Cardimona et al. 2000), which, when migrated, collapse to the point of origin. Currently, the technique is limited to deformation mapping—the gridding of GPR reflection amplitudes. Harris, et al. (2010) demonstrated that this technique performs just as well or better than standard methods (half-cell potential and sounding) at locating areas of rebar corrosion in most cases. Barrile and Pucinotti (2005) used this technique to characterize the number and position of longitudinal rebar, detect voids, and derive stirrup spacing in structural members. Both studies used commercial radar systems; Harris et al. (2010) utilized a GSSI instrument while Barrile and Pucinotti (2005) used an RIS-series instrument built by IDS Australia.

Table 5: Representative list of companies that perform GPR surveys as a service

Company	Website
NGPRS	http://www.ngprs.com/
GPA Data LLC	http://www.gprdata.com/
Sensors & Software Inc.	http://www.sensoft.ca/index.html
Penetradar Corporation	http://www.penetradar.com/index.htm
GPR Professional Services Inc.	http://www.gprps.com/
Global GPR	http://www.global-gpr.com/
Virtual Underground	http://www.virtualug.com/Services.html
GeoView Inc.	http://www.geoviewinc.com/services/civil.htm

Radar has been shown to be sensitive to moisture content. Maierhofer and Leipold (2001), using a GSSI SIR 10 radar system operated at 500, 900, 1000, and 1500 MHz, determined that by measuring the travel time of the backside reflection, determining the permittivity, and generating calibration curves, the moisture of a mortar structure could be determined to within between 1 and 5 percent by volume. In place of calibration curves, an inversion model of moisture in concrete might be used in order to estimate the moisture content. Some bridge managers or inspectors may be interested in quantifying the amount of moisture content and, where that is the case, GPR is also an appropriate choice: it can be used in detecting relative changes in moisture content where strict environmental controls are employed (the technique is sensitive, of course, to moisture held by a bridge after a rainstorm and would be affected by snow or standing water on the bridge deck).

GPR has been frequently used to locate delaminations in concrete bridge decks. These experiments have constrained the penetration depth of GPR to between 7 and 12 cm at typical stand-off and emission frequencies (Warhus et al. 1994). Voids and areas of potential delamination are mapped with GPR, but the dimensions of these areas are not usually known due to the limitations of the technology. By combining synthetic aperture radar (SAR) with GPR, Scott et al. (2001) have demonstrated the potential to measure the dimensions of subsurface features. In the FHWA-funded project "HERMES", the HERMES mobile road assessment system was used to locate and characterize the condition of embedded steel reinforcement, detect corrosion-related delamination, as well as locate voids and debonds. HERMES, used ultra-wideband sources emitting in the 0.5 to 5 GHz range, was developed by the Lawrence Livermore

National Laboratory. They were able to penetrate only to 12 cm below the concrete surface, and acknowledged the need for improved range resolution and signal-to-noise ratio as well, but found that synthetic aperture radar (SAR) processing enabled them to display 2D projections of 3D bridge deck features.

It is expected that GPR measurements made from the top of the deck will also be useful for characterizing conditions on the deck's bottom surface, specifically scaling and spalling [Figure 15]. However, in considering GPR for use in characterizing the condition of girders, beams, and piers, it is anticipated that the need to scan or "sweep" the surfaces of these elements with the GPR (from below the bridge) will significantly increase the time and cost of a bridge inspection with this tool. Other areas of concern which may be evaluated with GPR include: corrosion, prestress strand breakage, and internal structural cracks of the girder subsurface. It was determined that GPR does not meet the requirements for detecting corrosion, as the technique does not measure resistivity directly and it seems unlikely to be back-calculated from the dielectrics. GPR also rated insufficiently for detecting internal concrete structural cracks, as domain experience highlighted that the technology is not sensitive enough. It is believed that commercial GPR systems should however have the potential to provide information about prestress strand breakage although it may not be cost-effective or practical from a concept-of-operations perspective.

Figure 15: Significant spalling of a bridge bay that merits full replacement

Commercial GPR seems promising for characterizing chloride ingress in girders and the deck subsurface, however. The potential use of GPR for this application was first reported by Maser (1986) when it was observed that radar signal was attenuated in areas of high chloride concentration. The available literature shows that the presence of chloride in a concrete deck increases the material's conductivity and decreases its permittivity. This increase in conductivity results in signal attenuation as less electromagnetic energy is reflected back throughout the volume (Lim 2001). Kim et al. (2003) noted that areas with a high dielectric constant (low electromagnetic velocity) and high attenuation are typically zones of delamination, which are likely marked by high moisture and chloride content.

When assessing GPR as a technology for use in non-destructive evaluation, it should be noted that the technology cannot be used to resolve some embedded features directly. Delaminations are one such example; however, they are also the most common bridge condition issue GPR is used to detect. The previously noted delamination indicators—high dielectric constant and signal attenuation—are mapped for the entire bridge deck, but the results are limited to delamination. For this approach, the processing required is not complex, and may include only noise elimination and frequency tilt removal, but more advanced processing has the potential to produce greater accuracy.

5.2 Spectral Analysis

Spectral analysis is the measurement of a target surface's spectral reflectance or absorption of light (both visible and infrared). This includes spectroscopy—any measurements based on identifying characteristic peaks or spectra corresponding to structural defects as well as infrared (IR) spectroscopy, which is distinct from IR deformation mapping or thermal mapping–techniques that are instead magnitude-based. Reflectance and/or absorption are measured using a camera with a range of color bands (termed multispectral or hyperspectral electro-optical imaging) so the response within fine wavelength bins is known. The device used to measure reflectance and/or absorption is referred to as a *spectroradiometer*. Spectral analysis is typically described as the identification of characteristic peaks—wavelengths at which a large amount of radiation is absorbed or reflected.

Though spectroscopy can convey information about a target's composition, it is really limited to surface features since that is what absorbs or reflects the light captured by a spectroradiometer. A representative list of commercial spectroradiometers currently available is provided in Table 6. For cost comparative purposes, ASD FieldSpec 3 cost approximately $60,000 (as of 2007). In the performance evaluation of this technology, it was found that spectroscopy is impractical for most deck surface applications with the exception of chemical leaching. The problem inherent in using spectral analysis for crack detection, spotting expansion joint damage, or delamination cracks is that the only indicator of these features which can be detected is the shadow of the feature or a tone difference between the damaged and undamaged concrete. It is anticipated that it would be challenging to obtain consistent detection results for that application with this technique. Other deck features such as scaling and spalling could potentially be detected by the difference in tone between intact concrete and the feature of interest, but this precludes direct measurement and there is no way to measure the dimensions of these features using this technology. Spectral analysis is then restricted to a defect detector rather than a robust technology for measuring bridge condition. It is not clear how deck features could be deconvolved from the total signal—how a defect that makes up a certain proportion of the spectroradiometer's area of integration could be quantified. According to the available literature, no attempt has been made to produce calibration curves or a model of spectral reflectance based on bridge deck defects.

In addition to these difficulties, this imaging technology requires the surfaces be clean and visible. Unfortunately, their appearance is likely to be highly variable due to dirt, water, debris, snow, or ice. To remove these obstructions, some surface preparation before data collection would be required. In general, spectroradiometers also need to be white-balanced before collection. Field collection is typically done with a backpack unit and hand-held spectroradiometer, however, a vehicle-mounted device is conceivable. A preliminary field test performed by the project team using an ASD FieldSpec3 highlighted the difficulty in obtaining consistent spectral signatures of bridge condition—a significant obstacle for practical implementation. According to the available literature, spectroradiometers have not been demonstrated for use in evaluating bridge condition.

Table 6: Representative list of some commercially available spectroradiometers

Instrument Name	Company	Bandwidth	Spectral Resolution
PS-100	Apogee Instruments Inc.	350-1000 nm	0.5 nm
PS-200	Apogee Instruments Inc.	300-850 nm	0.5 nm
FieldSpec 3	ASD Inc.	350-2500 nm	3 nm (700 nm), 10 nm (1400/2100 nm)
FieldSpec 3 Hi-Res	ASD Inc.	350-2500 nm	8.5 nm (1000-2500 nm), 6.5 nm (1800-2500 nm)
Visible Compact	Edmund Optics	380-750 nm	4 nm
Visible Compact Near IR	Edmund Optics	350-1050 nm	6 nm
LS-100	EKO Instruments	350 - 1050 nm	
MS-701	EKO Instruments	300-400 nm	0.8 nm
GS-1290-0	Gamma Scientific	200-780 nm	0.6 nm
GS-1290-1	Gamma Scientific	260-900 nm	0.6 nm
GS-1290-2	Gamma Scientific	300-1100 nm	0.9 nm
GS-1290-3	Gamma Scientific	380-810 nm	0.4 nm
GS-1290-DMS-1	Gamma Scientific	380-930 nm	0.6 nm
GS-1290-DMS-2	Gamma Scientific	380-1100 nm	0.9 nm
GS-1290-DMS-3	Gamma Scientific	380-800 nm	0.4 nm
SPR-4001	Luzchem Research Inc.	235-850 nm	1 nm
SPR-03	Luzchem Research Inc.	235-1050 nm	1 nm
CS-2000	Konica Minolta	380-780 nm	1 nm

Though it requires some pre-collection preparation and the collection geometry might not allow for rapid assessment, spectral analysis does appear promising for objectively characterizing chemical leaching. Kanada, Ishikawa et al. (2005) investigated the use of spectral analysis as compared to traditional techniques of detecting carbonation and chloride intrusion. They found characteristic peaks in absorbance curves where an increase at 2266 nm was associated with chloride intrusion, an increase at 1750 nm with sulfate attack, and a decrease at 1410 nm associated with carbonation. Difference spectra enabled even easier distinction between unaffected concrete and damaged concrete. Paint loss has been detected through a different technique called laser-induced breakdown spectroscopy that uses highly energetic laser pulses to ablate surface material before analyzing the spectra of the emission. Stand-off distances are low where this technique has been employed, however, ranging from 0.5 to 2.4 meters (Cremers 1987). The same can likely be expected for passive spectral analysis techniques in this area.

5.3 3D Photogrammetry

3D photogrammetry is the generation of 3D models from stereo pairs of electro-optical (EO) imagery in the visual spectrum. These models provide depth and height information that cannot otherwise be obtained from individual EO images. The instrumentation, consisting merely of high-quality digital cameras, is already commercially available. The cameras are conventionally flown aboard an aerial platform, either manned or unmanned. However, in order to achieve the resolution required for some applications, a lower stand-off distance is often necessary. In the performance rating of 3D photogrammetry it was found that the technology scored very high for deck surface applications and global metrics; less so for girder surface features. Deck surface features such as spalling, scaling, and expansion joint damage are 3D features that are likely to be measurable with 3D photogrammetry in most cases. Map cracking, cracks near expansion joints, and delaminations expressed as surface cracks are features which do not have an important depth component but are also likely to be measurable with 3D photogrammetry. The scale of features in the image plane can be known from the collection geometry; by knowing the distance from the camera to the target and camera specifications. There are no theoretical resolution limits specified in the literature as the resolution is a product of the collection geometry. Deck and girder surface features that require higher feature resolution imagery is likely best suited for a vehicle-mounted system, where as global metrics may be evaluated using an aerial platform, such as an unmanned aerial vehicle (UAV). Knowing the collection geometry for deck surface features is straightforward for a vehicle-mounted camera imaging the deck from a fixed height. Underneath the bridge, however, this is a much more difficult proposition and so 3D photogrammetry is less practical for girder surface features. Stereo photographs for use in typical commercial 3D photogrammetry cannot be oblique—girders, beams, and bays that are not directly above the instrument, fascia beams that are too high at close stand-off, and pier surfaces that are not facing the instrument will not allow for viable measurement with this technique. In order to image these surfaces with 3D photogrammetry, the operational costs will increase with the time spent and lane closure(s) required.

5.4 EO Airborne and Satellite Imagery

EO sensors collect imagery in the visual, near-IR, or thermal IR bands. In this category, imagery collected either by earth-observing satellites or aerial vehicles was considered. The aerial vehicles may be manned or unmanned, and this category excludes imagery that is used in 3D models (excluding imagery collected as stereo pairs) as such imagery as technology for review has already been captured under “3D Photogrammetry.”

EO imagery may be useful for identifying deck condition indicators. Hauser and Chen (2009) reported a lower limit of 13 mm resolution using small-format aerial photography (SFAP), which may be sufficient for spotting some features or defects of bridge decks including spalling, scaling, and map cracking. A partial list of companies providing aerial photography services is included in Table 7. It is less likely that this imagery will be capable of resolving expansion joints and damage to them, but sub-pixel estimates of expansion joint conditions can likely be made with advanced post-processing. Sub-pixel (or "mixed pixel") detection techniques have been demonstrated in other applications where the problem domain is essentially the same. Kant and Badarinath (2002) showed that oil fires less than 2% the spatial extent of a pixel could still be identified. Mikhail, Akey et al. (1984) achieved accuracies to within 0.03-0.05 pixel in measuring the position of sub-pixel targets. This indicates that the potential exists for detecting the presence of cracks that are otherwise too small to resolve and damage to expansion joints. Of course, quantifying and rigorously characterizing these features or defects may not be possible unless the resolution is improved.

Table 7: A list of some companies offering aerial photography by commission

Company	Services	Instrument	Spectral Range
Aero-Metric, Inc.	Aerial photography		
Air Flight Services	Aerial photography, airborne video surveillance, aerial mapping and surveys		
Airborne Corporation	Aerial photography	UltraCamX (Vexcel Imaging)	
Airborne Scientific, Inc.	Aerial photography, wide area oblique imagery, orthophotography, remote sensing, videography photo aircraft rent/support		
ASL Borstad Remote Sensing Inc.	Airborne image data acquisition	CASI SFSI-2 AISA	403-914 nm 1230-2380 nm 400-2400 nm
ATLIS Geomatics	Air photo acquisition	DiMAC Digital Frame Sensor	
Cooper Aerial Surveys Co.	Aerial survey, photo, and mapping	Leica RC-30	
Digital Aerial Solutions, LLC	Digital aerial imagery	ADS 40	4 bands, 610-885 nm
HyVista Corporation Pty Ltd	Airborne hyperspectral remote sensing data		
I. F. Rooks and Associates, Inc.	Aerial photography, helicopter mapping, topographic and planimetric mapping		
Richard B. Davis Co., Inc.	Aerial photography, aerial mapping and photogrammetry		
Terresense	Airborne remote sensing services		

Much of concrete deck cracking sensitivities are below the lower limit of aerial EO resolution specified by Hauser and Chen (2009) in their report to the U.S. Department of Transportation (Report #01221). This includes cracks near expansion joints and delamination cracks. Spaceborne EO resolution is even coarser: the commercial platforms offering the highest resolution today are GeoEye-1 at 0.41 m and WorldView-2 at 0.46 m. A partial list of companies that sell and acquire on-demand satellite imagery is provided in Table 8. Structural cracks below the deck are also too fine to be resolved with current commercial capabilities [Figure 16]. In addition to the resolution requirements of defect detection on girder surfaces, in order to view these surfaces at all, highly oblique imagery is required. Such an extreme viewing angle cannot be achieved by commercial space-based platforms, and even many aerial platforms are unlikely to be able to provide a sufficient viewing angle. Pictometry International, however, is one company that specializes in oblique aerial photography. Though structural cracks are too fine to be resolved, steel and concrete section loss might be identified through aerial photography, particularly when acquired from low-altitude flights by unmanned aerial vehicles (UAVs).

It is anticipated that EO imagery will be very useful for investigating a bridge's global metrics of structural health as the medium offers a synoptic view. Identifying bridge settlement, however, cannot be done without taking stereo pairs of EO images, and this technique is categorically excluded from this discussion: instead, see "3D Photogrammetry." Transverse bridge movement also cannot be detected from this kind of imagery because it is below the limit of resolution. A change in bridge length, however, could be detected using SFAP. A pixel-to-pixel match of two images separated in time is not necessary in order to assess a change in bridge length. Rather, a comparison of the total length of the bridge, measured to a high degree of precision in both photographs, would suffice. Deck surface roughness is another area where EO imagery can provide useful information, as demonstrated in the TARUT study, which used commercial EO satellite imagery (Digital Globe's Quickbird at 2.4 m spatial resolution) as an input to generating a road sufficiency rating (Brooks et al. 2007) for a Michigan freeway. Sub-pixel techniques and the comparison of tone changes over time can also indirectly relate how surface roughness is changing.

Barriers to entry with this technology start with the costs; commercial satellite imagery on-demand costs anywhere from \$800 to \$3200. Archived imagery—imagery that a third party requested in the past—is significantly cheaper (with minimum orders of around \$300), but may not suit the real or perceived immediacy of the application. Aerial imagery costs are generally limited to the costs of commissioning a flight, but are not insubstantial. In all cases, these costs can be offset or mitigated by encompassing a large volume of the bridge inventory with a purchase that captures multiple bridges within a single satellite scene or sequence of aerial photographs. With on-demand satellite imagery, an additional consideration must be the time it takes to acquire the imagery which could be up to 2 months if the satellite is already tasked for government work or if cloud cover obscures the scene.

Table 8: A list of some companies offering satellite imagery for sale or by commission

Satellite	Spectral Resolution	Spatial Resolution	Revisit Time	Owner
SPOT 4	4 bands, 500-890 nm, 1580-1750 nm	10 m pan, 20 m multi-spec	2-3 days	CNES (distributed by Spot Image)
SPOT 5	4 bands	2.5 m pan, 10 m multi-spec	2-3 days	CNES (distributed by Spot Image)
Quick Bird	4 bands, 450-900 nm	0.61 m pan, 2.4 m multi-spec	2-3 days	DigitalGlobe
Worldview-1	NA	0.50 m pan	2-5 days	DigitalGlobe
Worldview-2	8 bands	0.46 m pan, 1.8 m multi-spec	1-4 days	DigitalGlobe
GeoEye-1	4 bands, 450-920 nm	0.41 m pan, 1.65 m multi-spec	< 3 days	GeoEye
IKONOS	4 bands, 445-853 nm	0.82 m pan, 4 m multi-spec	3 days	GeoEye
OrbView-2	8 bands, 402-885 nm	1.1 km multi-spec	1 day	GeoEye
EROS-A		1.9 m pan		ImageSat International
EROS-B		0.7 m pan		ImageSat International
Kompsat-2	4 bands, 450-900 nm	1 m pan, 4 m multi-spec	3 days	Korean Aerospace Research Institute (distributed by Spot Image)
Formosat-2	4 bands	2 m pan, 8 m multi-spec	1 day	NSPO (distributed by Spot Image)
RapidEye				RapidEye AG
WNISAT-1				Weathernews Inc.

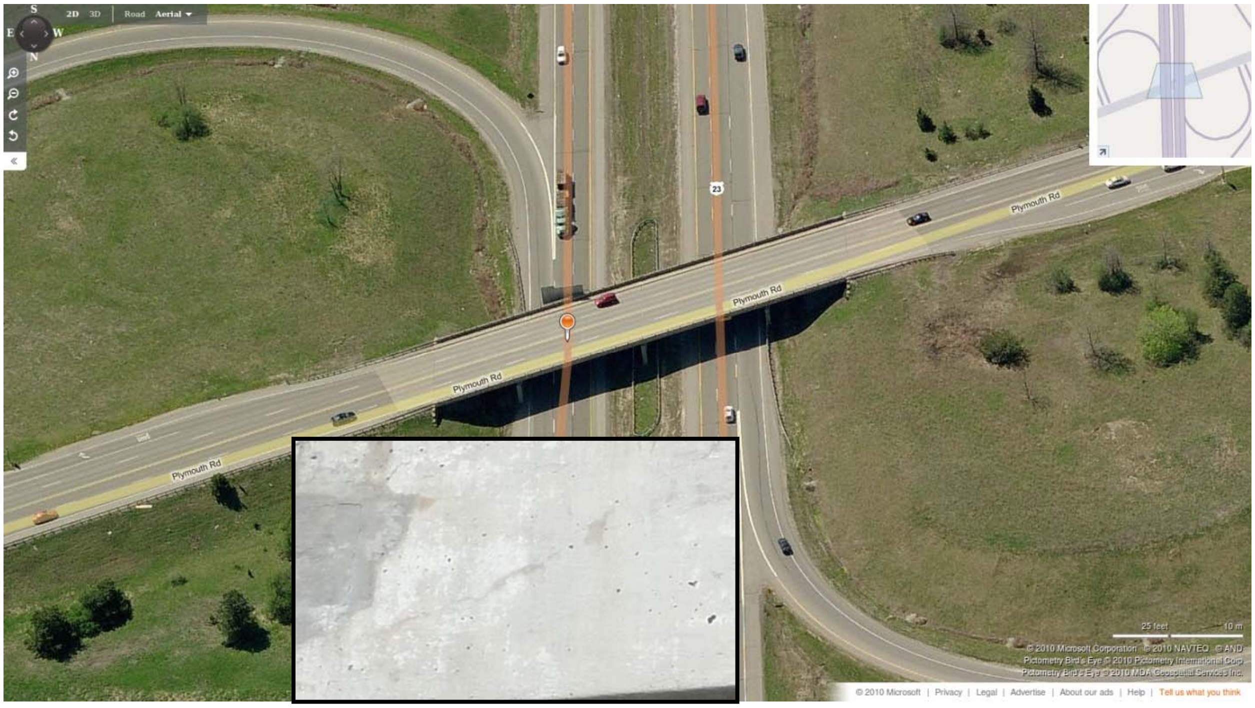


Figure 16: Example image from Bing Maps' "Bird's eye" imagery exhibiting Pictometry International's oblique aerial photography.

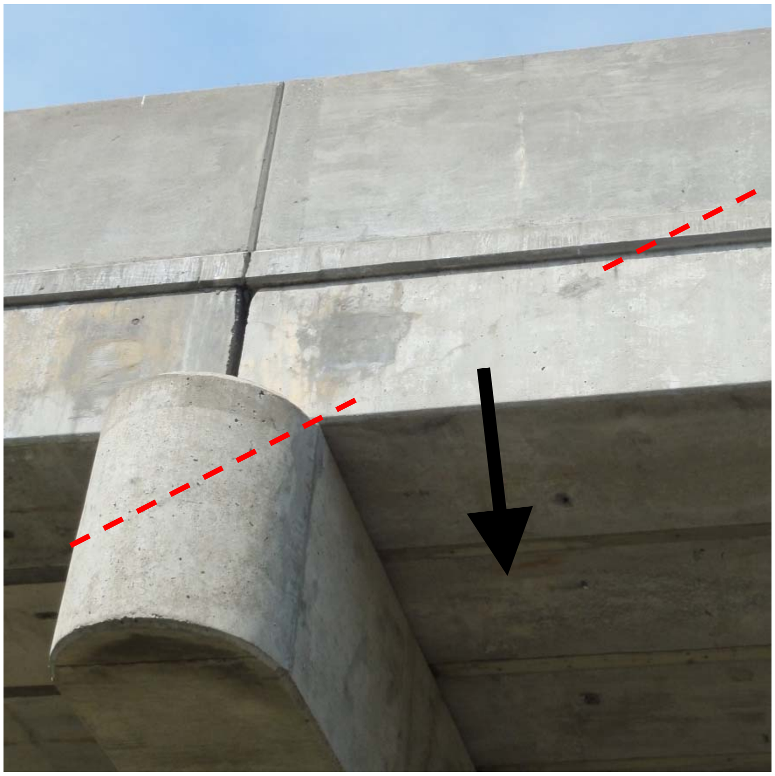


Figure 17: Photograph of fascia beam on box-beam bridge with thin, 45-degree crack near top of pier and post-tension box

5.5 Optical Interferometry

Interferometry is a broad term, but here it is limited to the use of images with visual, near-IR, or thermal IR wavelengths from which interferograms are made and interference fringes derived. Most notably, this consists of techniques to generate Young's fringes/isothetic fringes and (optical) speckle pattern interferometry (SPI). This category excludes interferometric radar techniques, which are considered under “Radar Images, Backscatter, and Speckle.”

Interferometry can potentially yield information about subsurface features and internal stresses, but the depth to which it is sensitive is extremely shallow—delaminations deeper than 0.7 mm (in composite laminates) were beyond detection by holography in one study (Ambu et al. 2006). In the performance assessment, it was found that the technology, like most digital camera-based (CCD-based) techniques, was most useful for yielding information about deck surface conditions. The technology’s semblance to other optical imaging techniques means that its resolution capabilities are also a product of the collection geometry; for interferometry the spatial resolution is especially high. It was determined that the resolution offered by this technology may be too fine for some applications, such as expansion joint damage including a torn or missing seal and armor plate damage on strip-seal joints. Surface cracks at millimeter and sub-millimeter scales have successfully been detected using optical interferometric techniques, namely electronic SPI or ESPI (Hatta et al. 2005). The measurement of spalls and scaling on the concrete deck should be possible as sub-millimeter depth resolution has already been achieved for other materials (Krajewski 2006).

Optical interferometric techniques are likely to also provide an indication of whether expansion joints are filled with gravel and other debris based on their resolution capabilities. The high resolution this technique promises makes it one of the few technologies reviewed that may help in measuring fine structural cracks in concrete or steel girders and beams (Figure 17). The global metrics of bridge structural health that this technology is likely to assist in characterizing include vibration and surface roughness. These are classic problem domains that optical interferometry is applied to. ESPI, SPI, and speckle photography are all virtually direct measures of surface roughness. Even though the wavelengths of light are far smaller than the grain size of a concrete deck’s potential roughness, optical interferometric techniques possess the spatial resolution from which surface roughness can be derived as well. As for vibration, the frequency response of video cameras—the common collection platform for optical interferometry—is likely to be more than adequate for bridge structure and structural element vibrations.

Commercial interferometry systems are already available, most notably those of Dantec Dynamics (formerly Dantec Ettemeyer), which manufactures the Q-300 3D ESPI system, and Trilion Optical Test Systems. Commercial software such as ISTRA (from Dantec Dynamics) exists that can be used for data processing as well as control acquisition (Hatta et al. 2005). The underlying algorithms of this processing are well-understood and require no user intervention—processing is fully automated. This technology presents a moderate to high capital cost for state and local transportation agencies, but the equipment can be re-used over the entire bridge inventory for a long time

5.6 LiDAR

Light Detection and Ranging is the use of timed light pulses to measure the distance to a target. In this review, both terrestrial laser scanning (TLS) and aerial/airborne laser scanning (ALS) were considered. Simply put, this category includes any sensor that collects point elevations/positions by timed laser pulses. LiDAR was initially considered in this performance assessment for a wide variety of bridge structural health concerns. After review, it was found that the technology was most applicable for deck surface and global structural health applications.

LiDAR scanning is most often used to generate high-density 3D models of target surfaces and structures, and it is anticipated that this derivative product will retain its value for bridge structural health monitoring. A high-resolution 3D model of the bridge deck surface, with up to 1 mm^2 grid spacing (Laefer et al. 2009), can enable the extraction of information on expansion joint conditions such as seal and armor plate integrity, cracks and spalls near expansion joints, map cracking, scaling and spalling of the riding surface, and delaminations expressed as surface cracks. There are limitations to LiDAR's effectiveness for these applications, particularly in its tendency to overestimate crack widths.

In measuring the dimensions of concrete volume loss (such as spalling and loss of section), Teza, Galgaro et al. (2009) found that, at 50 m standoff with TLS, LiDAR's depth resolution is limited to 1.09 cm with an accuracy of 0.5 cm. Hauser and Chen (2009) found that resolution of LiDAR for section loss was 0.5 mm. By any estimate, commercial LiDAR capabilities only partially meet the requirements for sensing the bridge deck condition indicators highlighted in the challenges section; they do not meet the lower limit of resolution. The lower resolution limit of LiDAR does not meet the upper limit required for resolving structural cracking of steel and concrete girders (see Figure 17 for an example). The sensing requirements for steel and concrete section loss in the girder subsurface, as laid out for performance evaluation, state that a volume percent needs to be known. Based on Hauser and Chen's estimate (2009), however it is clear that LiDAR can contribute useful information for identifying and mapping steel and concrete section loss. LiDAR in combination with high-resolution digital photography of a bridge, in a "StreetView" style system (similar to Google StreetView) holds promise as a means of assisting bridge inspectors with reviewing and understanding bridge condition features, as will be discussed below.

LiDAR can also make a contribution to the understanding of a bridge's global metrics. It is anticipated that through scanning a bridge profile with TLS, bridge settlement on the order of 6 to 12 mm should be measurable. However, there is no reported margin of error in the available literature. With the appropriate scan geometry, likely from either bridge approach or an aerial platform, the long-term, transverse movement of the bridge can also be detected. No consideration was given to the application of LiDAR for measurement of bridge vibration, although such a scenario is clearly similar to laser vibrometry (laser Doppler vibrometry or LDV and continuous scan LDV), commercial LiDAR systems optimized for point cloud generation are not designed for this use.

Difficulties in implementing commercial LiDAR as part of any bridge structural health evaluation include the high capital cost of equipment with potentially high operational costs. Some acquisitions, for example, have been documented to take up to a full day to complete for a single bridge (Lubowiecka et al. 2009). These operational costs might be high with less streamlined systems, but with fully-automated, modern, commercial instrumentation the use of LiDAR for these applications should have low operational costs. More modern, sophisticated instrumentation also allows for more rapid collection, as well, potentially imaging the entire bridge deck or substructure while driving by.

LiDAR processing consists mostly of transforming the coordinates for use in the real-world coordinate system. Commercial software is available that does this automatically, but additional tasks such as the subdivision of point clouds (into structural elements) and curvature computation (for volume calculations) are additional steps that may be necessary for damage identification and 3D modeling.

5.7 Thermal/Infrared (IR) Imaging

Thermal/infrared (IR) imaging, in this case, refers to magnitude-only-based deformation mapping; the production of deformation maps by mapping thermal anomalies/contrasts. The collection of these data can be passive (solar illumination or night collection) or active (artificial illumination or cooling [e.g. liquid nitrogen]). This category excludes IR spectroscopy, which is considered under "Spectral Analysis."

For obvious reasons, infrared imaging promises to be useful in characterizing several deck and girder surface features, but the performance rating of the technology indicates it may have the potential to convey information about some subsurface conditions as well. These include features indicative of delaminations, scaling and spalling of the deck underside, as well as structural cracking. Delaminations are the most common feature IR imaging is used to detect. DelGrande and Durbin (1999), in a paper that distinguishes itself by the adoption of "thermal inertia" mapping, describe both laboratory and field validation of a custom IR imaging system. They report being able to distinguish true delaminations in the field from surface clutter or shadow based on the size, shape, relative volume and location, as well as thermal contrast of thermal anomalies. IR imaging has been used frequently to find areas of debonding and air-filled voids in composite concrete decks, but by most accounts the data analysis has been limited to defect mapping and few, if any constraints, have been discovered and reported. Stimolo (2003), however, reported on the detection of delaminations, cavities, and air blisters at 10^{-2} to 10^{-3} m spatial resolution and 2.0 - 3.5 m standoff using passive, solar radiation and the Agema LW900 IR camera, but also reported some limitations to the technique including the lack of depth information and the technology's sensitivity to environmental interference.

A literature review found no studies where surface defects such as expansion joint damage, cracks and spalls near expansion joints or otherwise, and map cracking were imaged using IR thermography, but it is believed that these defects will exhibit thermal anomalies. In these applications, though IR thermography may not provide sufficient resolution of the extent or dimensions of bridge condition indicators, the technology should enable the detection of these features where they occur and provide an estimate of the surface area or volume. Hu et al. (2002) demonstrated the use of IR thermography to predict crack propagation, however, the technique was not applied to locating existing cracks. Concrete and steel structural members will store and transfer heat differently when damaged so concrete and steel section loss and structural cracking, as well, can likely be detected using IR thermography. It is also anticipated that paint condition can also be assessed with IR thermography.

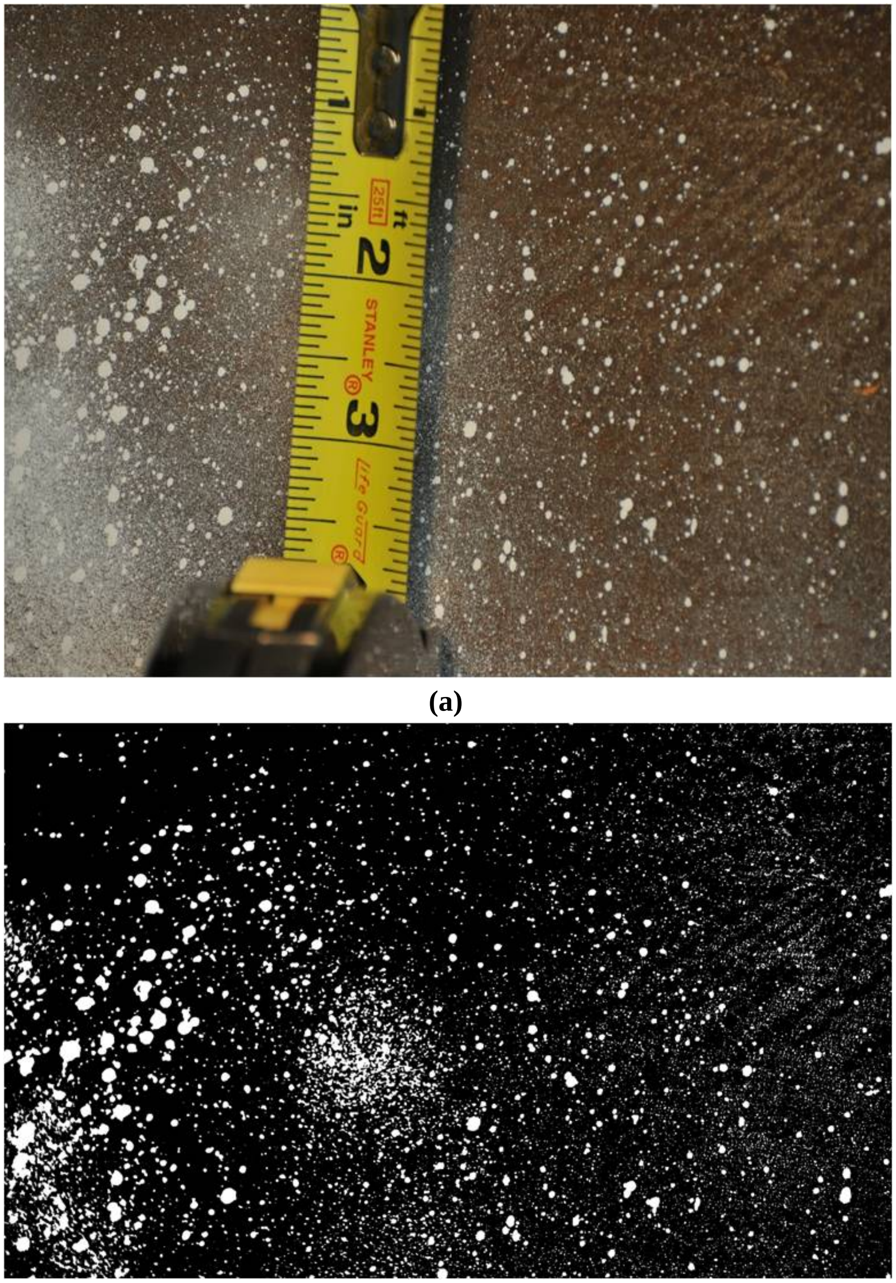
5.8 Digital Image Correlation (DIC)

The term "digital image correlation" (DIC) refers to a technique consisting of the correlation, typically on a pixel-by-pixel basis, of two electro-optical images separated in space or time. This is done by automated computer algorithms which measure changes between the two photographs and calculate the displacement of features in the image plane (structural elements) or, most commonly, markers such as paint spots (Figure 18) or a pattern of dots projected on a surface. These displacements may be rigid, global displacements or local deformation.

The rating of this technique for application to bridge condition issues is based on the strict definition above. As such, four applications were identified for which DIC might be useful: detecting a change in bridge length, measuring bridge settlement, measuring transverse bridge movement, and measuring the vibration of a bridge or a structural element. These are all global metrics of a bridge and this is a consequence of the fact the technique is limited to the correlation of surface observations separated in time. It would not be appropriate to use this technique to detect bridge conditions that do manifest themselves in displacement, deflection, or deformation over time. For these applications, DIC did not score high in the performance evaluation. This is due in part to systematic qualities such as the need for a projected or painted pattern on the target surface, the required post-processing, and the short stand-off distance. This technique boasts high spatial resolution; with project experiments confirming that 1/10th of an inch resolution (2.5 mm) can be achieved at close stand-off. There is, however, a compromise between spatial resolution and extent; in order to achieve higher spatial resolution, only a small coverage area can be imaged and thus, for larger targets, multiple images must be stitched together. The frequency response is dependent on the camera used, and may not be sufficiently high enough for measuring the vibration of some bridges. To its advantage, the camera-target geometry ensures that data collection will not interfere with bridge traffic, but the target surface preparation is a part of the measurement that demands contact with the bridge structure. Hutt and Cawley (2008) describe their collection using a two-camera system developed by Dantec Dynamics and processing using ARAMIS (software by Gesellschaft für Optische Messtechnik or GOM), which consisted of simple-windowed block matching where correlations took from a few seconds up to several minutes. Kuntz et al. (2006) used CORRELI 3D and a fast Fourier transform (FFT) algorithm to measure displacements of 1.4 microns as well as cracks.

DIC is really only practical for measuring vibration and in that application still suffers from an unknown frequency response, necessary target preparation, and small coverage area.

Where DIC might be used for measuring bridge settlement, transverse movement, or detecting a change in bridge length the required temporal resolution makes the technique impractical. To enable the correlation of images separated by 6 months, a year, or several years, the camera would have to remain in the exact same place, sheltered from environmental interference and anything else that would induce artificial displacements. These displacements are likely inevitable, and though their effect can probably be removed with sophisticated post-processing, only non-rigid displacements and deformations would be preserved. Even when the technique is applied to images separated seconds or less in time, the post-processing is not trivial. The analysis can be performed automatically using an analysis package such as MATLAB software, but requires additional post-processing and tuning for meaningful results. Image processing is often required before analysis to increase the contrast of the fiducial markers or features of interest (Figure 18b). Inversion in MATLAB 7.0+ is the most common processing technique in the available literature.



(a)

(b)

Figure 18: Two images of paint spots on a structural I-beam for digital image correlation. (a): the paint spots should have a wide distribution of sizes; (b): post-processing of images is used to bring the spots to a contrast threshold

5.9 Radar Images, Backscatter, and Speckle

Radio detection and ranging (radar) is a well-established technique for calculating the distance to, as well as the speed and direction of a target. In this case, the term "speckle" refers only to coherent, radar speckle which is a feature of any radar image (and is usually considered noise). Also considered in this category are the amplitude-only radar images or "backscatter" images. The use of Synthetic Aperture Radar (SAR) processing was considered, but did not exclude measurements performed without SAR. Interferometric SAR (InSAR) is excluded from this category and considered in the "Interferometric Synthetic Aperture Radar (InSAR)" category.

These generalized radar collection techniques, based on backscatter or coherent speckle without interferometric processing, have a wide variety of applications for monitoring bridge structural health. Of these applications, those which deal with subsurface features or defects have been scored the same as for GPR. This is because GPR is just a type of radar collection—one characterized by a wide bandwidth and low emission frequencies. This distinction is still useful, however, because GPR has become such a specialized, commercialized technique for the transportation industry. In other words, the GPR category refers specifically to the off-the-shelf GPR instruments that state and local transportation agencies are already familiar with, while this category deals with a much broader set of instruments designed for a much broader set of applications. Importantly, this more general category not only includes GPR, but also coherent speckle, synthetic aperture radar (SAR) processing, and commercial radar systems, not designed strictly for ground penetration.

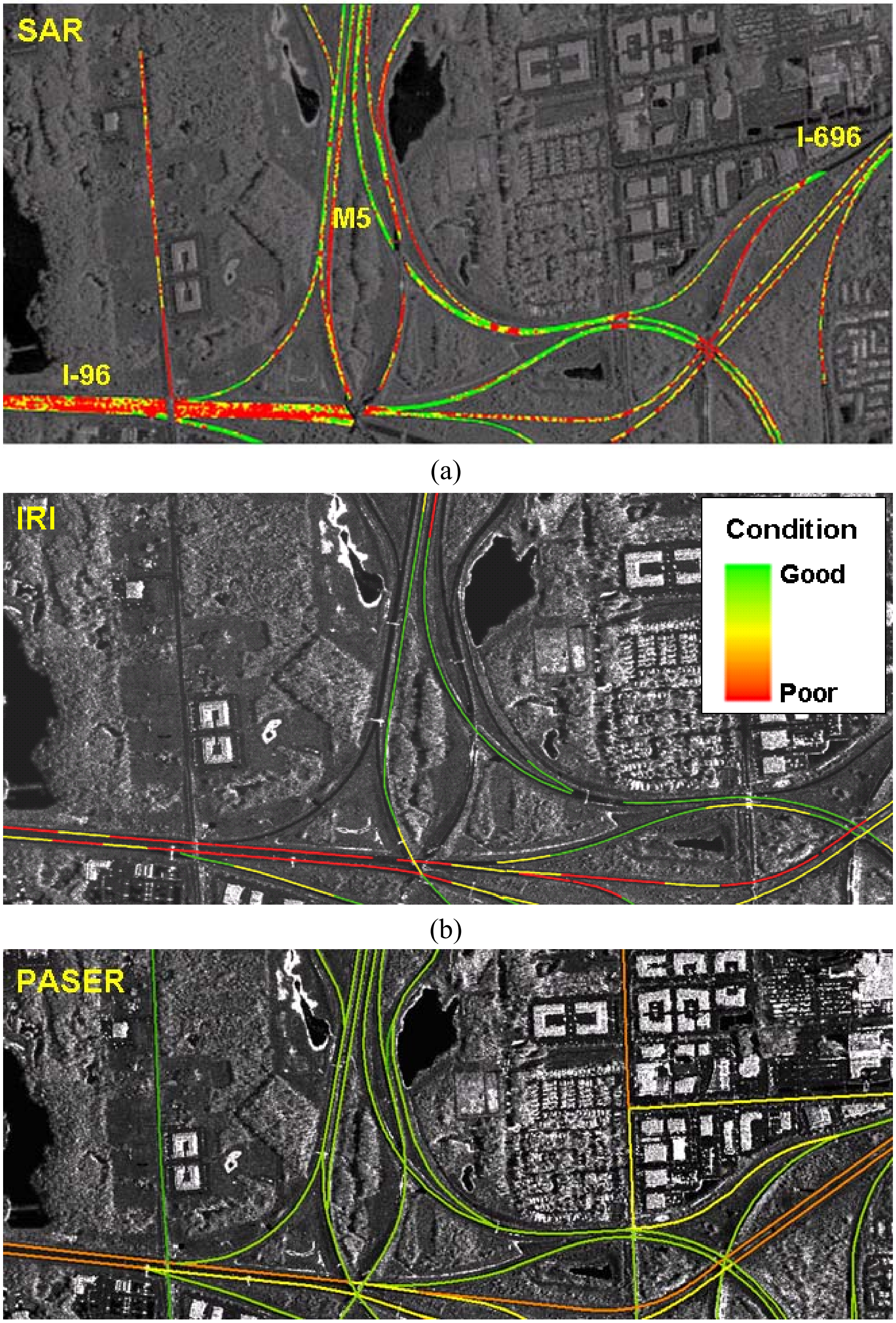
The performance evaluation of radar indicates that the technology is not well-suited for resolving deck and girder surface features. This is primarily because—as previously noted in the section on GPR—radar is not capable of directly resolving features at the required scale. It is possible that a vehicle-mounted radar platform moving along a bridge deck to create a synthetic aperture can achieve sufficient cross-range resolution so as to be sensitive to cracks and spalls. These features have not been the focus of research in radar for structural health monitoring; instead, displacement, vibration, surface roughness, and subsurface features are the subjects of exploration, according to the current literature.

Fine structural cracks in steel or concrete are thought to be too small for the sensitivity of practical radar deployment. Steel and concrete section loss, however, might be measurable as a bulk effect if it is above a certain threshold and may be quantified through modeling or calibration. For the girder subsurface, radar and GPR can both make valuable contributions to the assessment of reinforcing bar condition. Barrile and Pucinotti (2005) bounded the error of rebar diameter estimation to within 3 mm at the 86% significance level for 13, 25 and 38 mm bars. These rebar diameters are still larger than the diameter of some reinforcement in concrete girders and the error may be too great for any meaningful interpretations to be made. Chloride ingress detection and moisture content characterization are also promising applications of both GPR and other radar techniques.

While commercial GPR cannot characterize global metrics of a bridge because of its collection geometry, most other radar platforms and techniques are also insufficient for these applications because they lack the required resolution or sensitivity. For global metrics such as change in bridge length, bridge settlement, and transverse bridge movement, interferometric radar techniques, such as InSAR, promise to be helpful and provide great efficiency. Several Italian reports on ground-based interferometric radar address these condition indicators with measurements down to 0.1 mm displacement resolution at up to 2 km stand-off distance (Pieraccini et al. 2008). Both interferometric radar and non-interferometric radar may shed light on surface roughness. Without resorting to interferometric processing, coherent radar speckle can provide an indirect measurement of surface roughness. As reported by Shuchman,et al. (2005), speckle contrast from SAR imagery can be correlated with road surface roughness measured in situ in order to derive a calibration curve from which surface roughness can then be remotely sensed (Figure 19a) This was done for the TARUT study and the results compared to the International Roughness Index or IRI (Figure 19b) and the PASER standard (Figure 19c). Radar can also provide a measure of vibration in bridges and other structures, using Doppler techniques or interferometric techniques (see section on InSAR). Using interferometric radar, displacements on the order of 0.1 mm (Pieraccini et al. 2009) have been measured with a frequency resolution of about 0.02 Hz (Gentile 2009).

Radar data collection might require significant preparation depending on the application. A visit to the bridge ahead of collection may be necessary to plan the collection geometry. Such a visit might reveal that reflector targets need to be installed on the structure. When collection begins, it is likely that a skilled operator will be needed. In addition, the collection geometry and required resolution indicate that the instrumentation will likely be deployed on the bridge deck close to the surface. As with GPR, more versatile radar instrumentation can likely be operated for a vehicle-mounted platform; however, it is possible that lane closure(s) will be necessary.

There are several commercial radars already available. The Olson Instruments IBIS-S system is one frequently described as part of civil engineering research in literature (Olson 2010). From experience with the commercial system built by Akela Inc., data processing can be done in a dedicated environment such as the commercial RADAN software program by GSSI or using custom algorithms developed in MATLAB. The processing likely consists of migration or coordinate transformations and will not be simple. Advanced post-processing is required to achieve the highest resolution and the best results.



(a)

(b)

(c)

Figure 19: Three images of road surface (pavement) condition from TARUT study (Brooks, Schaub et al. 2007). (a): road roughness as determined from SAR speckle contrast; (b): road roughness according to the International Roughness Index (IRI); (c): rough sufficiency according to the PASER standard

5.10 Interferometric Synthetic Aperture Radar (InSAR)

Interferometric synthetic aperture radar (InSAR) is a type of radar collection with two antennas in which the resultant two images are made to interfere; and pixel-by-pixel differences in amplitude and phase are compared. This category includes microwave differential interferometry. SAR images are coherent radar images in three dimensions, where the first two coordinates specify the spatial location of a signal and the third coordinate contains the phase. It is the phase information from which height or depth measurements are made (Shinozuka et al. 2000). There are many commercial vendors of synthetic aperture radar (SAR) data whose products can be used to create InSAR images. Most notable among them are MDA Geospatial Services Inc., which markets data from the Canadian platforms RADARSAT-1 and RADARSAT-2. A longer list, including both commercial and non-commercial instruments is provided in Table 9.

The cost of InSAR for most bridge remote sensing applications is encapsulated by the price of commercial SAR imagery, which is not insignificant. In addition, for change detection in global metrics, multiple images of the same scene at different times would need to be purchased. Ground-based acquisitions have capital costs associated with the equipment purchase and possible operational costs depending on deployment and the expertise of the available staff. Complex processing is also required for InSAR data, as artifacts commonly need to be removed, including problematic multiple reflections from bridges over water. It is not clear that commercial vendors remove these artifacts before distributing the imagery. In addition to artifact removal, significant pre-processing is required to transform InSAR data into a world coordinate system (Soergel et al. 2008). However, aerial or space-borne InSAR offers the potential of rapid assessment of bridges from high stand-off without requiring calibration or preparation of the structure and without interfering with traffic.

In the performance evaluation, InSAR was determined to be useful in only a few applications, all of which were global metrics and in these applications, the technique scored well. Bridge settlement is one metric that may be measurable using InSAR, which is capable of detecting changes in height by the calculation of phase differences in the two signals. The changes must at least be on the order of a wavelength in size to be detected and even at X-band, 10 GHz, the wavelength is 30 mm. This means that only changes of at least 30 mm can be detected at that frequency. However, at higher frequencies and smaller wavelengths, smaller changes might be detected. Shinozuka et al. (2000) report detecting a 10 cm change in building height using this technique on simulated data.

InSAR might also be useful for detecting changes in bridge length and position (transverse bridge movement). For this application, the difference in backscatter between two images would be used rather than the phase difference. Using backscatter from range bins rather than phase information limits the resolution to that of the SAR image, which is typically on the order of 10^{-1} to 10^{0} m. Changes in surface roughness of the concrete deck can also be fully recovered from the ratios of InSAR coherence from image to image (Hajnsek and Cloude 2005).

Change in surface roughness can also be measured from coherent speckle contrast in SAR imagery, as described in the previous section "Radar Images, Backscatter, and Speckle" (see Figure 19). Whether or not InSAR can sufficiently measure bridge vibration is less clear, as there is no indication from the available literature as to how sensitive InSAR is to frequency. However, the amplitudes of vibration that need to be detected are likely within the capabilities of ground-based InSAR (Pieraccini et al. 2000). It is unlikely that vibration can be measured sufficiently from aerial or space-borne platforms.

Table 9: Partial list of commercial and non-commercial SAR

Sensor	Owner	Platform	Country	Ownership
RADARSAT-1	MacDonald, Dettwiler and Associates Ltd.	Satellite	Canada	Commercial
RADARSAT-2	MacDonald, Dettwiler and Associates Ltd.	Satellite	Canada	Commercial
AirSAR	Jet Propulsion Laboratory (JPL)	Airborne	U.S.	Government
UAVSAR	Jet Propulsion Laboratory (JPL)	Airborne	U.S.	Government
ERS	European Space Agency (ESA)	Satellite	E.U.	Government
ENVISAT	European Space Agency (ESA)	Satellite	E.U.	Government
JERS	National Space Development Agency of Japan	Satellite	Japan	Government
TerraSAR-X	InfoTerra	Satellite	Germany	Commercial

5.11 Acoustics

Acoustics is not strictly a remote sensing technique. Although the subsurface bridge condition indicators that are measured with acoustic techniques are not in contact with the equipment when a measurement is made, the bridge or structural element itself is in contact with the instrument. The technique utilizes reflected or transmitted acoustic waves (sound waves) in a medium to measure certain parameters of that medium and infer its condition or composition. Sophisticated instrumentation is used to monitor these acoustic waves and objectively measure their flight time (travel time through a medium), frequency content, and amplitude. There are different ways of measuring acoustic waves and these have given rise to different acoustic techniques. All modern, instrumented acoustic techniques are considered here, including i) acoustic emission monitoring, the measurement of ultrasonic wave velocity, ii) the impact-echo method, where the frequency content of a reflected wave is measured, iii) acoustic tomography, and iv) Lamb wave monitoring. Though these techniques are similar in spirit to the tap test and chain dragging, those traditional methods of bridge inspection are not considered in this category nor in any part of this technology performance evaluation.

As acoustics require significant traffic disruption, preparation of the structures, are in direct contact with the bridge or structural element, and are sensitive to environmental noise, they did rate well in this performance evaluation for any application. This literature review indicated the technologies are only applicable to subsurface features or cracks and section loss of deck and girder surfaces.

5.12 StreetView-style Photography

The term “StreetView-style Photography” refers to any serial collection of photographs from the ground (from the bridge deck) with a 3D geospatial projection, especially where the photographs have been projected into a continuous 360-degree viewing environment (see Google StreetView). This instrumentation has the potential to be mounted on a vehicle platform for rapid collection and with little to no interference with traffic. As many bridges may not allow for driving underneath or along side, this category must be limited to collection from a vehicle driving along the deck surface.

The value of this technology is realized when the bridge inspector or manager uses a StreetView-style application to assess a bridge from the office. The technology enables anyone to review a bridge’s structural condition, in which indicators can be detected visually, without actually traveling to the bridge (see Figure 20). Bridge inspectors might find such an application useful for reviewing a bridge they have already performed an inspection on or for looking at updated imagery of a bridge ahead of its next scheduled inspection. Such a scenario might occur where an inspector suspects that he or she should increase the inspection frequency of a bridge, but does not have the funds or time to do so. In the performance evaluation of high-resolution, panoramic photography such as StreetView, it was determined the technology would be most useful for bridge deck surface features including torn or missing expansion joint seals, damage to armored expansion joint plating, cracks and spalls near expansion joints, map cracking, scaling and spalling of the bridge deck, and delaminations expressed as surface cracks. For all of these features, StreetView-style imagery offers immediate commercial viability, automated image processing for visual inspection of results, a vehicle-based collection platform and, consequently, no traffic disruption whatsoever. The resolution requirements for these challenges can very likely be met, but there appears to be no available literature on using high-resolution panoramas to assess these or any other bridge condition indicators. It is likely that hairline cracks in steel or concrete are too fine to be resolved from this imagery, buthigh-resolution panoramas may be useful in assessing surface roughness in addition to the deck challenges previously described.

The capital cost of StreetView-style photography instrumentation could be high if a dedicated, commercial platform is used (such as the Trimble MX-8, which also offers 3D laser scanning). However, high-resolution digital cameras mounted on a vehicle could potentially provide the same results at a lower cost. Data collection consists merely of driving along or underneath a bridge and so operational costs should be very low.

Figure 20: Example image from Google's StreetView showing the underside of a box-beam bridge in Michigan. With higher-resolution panoramas, such an interface could be extremely valuable to bridge inspectors and managers.

6.0 Conclusions and Recommendations

While remote sensing technologies have been successfully implemented in a number of industries, their use within the transportation industry has been somewhat limited to date. This report presents a performance evaluation and rating of commercially available remote sensing technologies for infrastructure condition assessment, specifically bridges. In this study, a number of remote sensing technologies were reviewed to evaluate their potential to detect a series of indicators related to common challenges faced by the typical U.S. bridge. The technologies evaluated include:

1. Ground Penetrating Radar (GPR)
2. Spectral Analysis (Spectra)
3. 3D Photogrammetry
4. EO Airborne and Satellite Imagery
5. Optical Interferometry
6. LiDAR
7. Thermal/Infrared Imaging
8. Digital Image Correlation
9. Radar Imaging, Backscatter, and Speckle
10. Interferometric Synthetic Aperture Radar (InSAR)
11. Acoustics
12. StreetView-style Photography

Each remote sensing technique was rated using criteria that assessed the following:

A) Accuracy
B) Commercial availability
C) Cost of measurement
D) Pre-collection preparation
E) Complexity of analysis and interpretation
F) Ease of data collection
G) Stand-off distance
H) Traffic disruption

The challenges considered were grouped into broad fields related to their location of occurrence including the deck surface, deck subsurface, girder surface, and girder subsurface, in addition to a global metrics category describing the challenges that pertain to the bridge system level performance. Within these broad categories, specific challenges (e.g. spalling on bridge deck surface, delamination within the bridge deck, prestress strand breakage internal to a concrete girder, etc.) and pertinent indicators of these challenges were established as the threshold for assessing remote sensor viability. Using the rating criteria, sensor technologies were scored for their applicability to the challenges within the broad categories. As a whole, the results of this evaluation demonstrated that remote sensing technologies could have a potentially significant impact in the assessment of bridge condition and that successful implementation will likely require using the sensors in a complementary manner such as: integrating the sensors in a vehicle-mounted system to minimize traffic impacts, coupling sensors with traditional assessment methodologies, and utilizing temporal sensor outputs to enhance the bridge inspection and decision making process. Some of the key findings from the evaluation include (see Table 3 - Performance Rating of Commercial Remote Sensing Technologies):

a) 3-D Photogrammetry and StreetView-Style Photography appear to have the greatest potential for evaluating deck surface conditions. These conditions primarily relate to challenges observable with the human eye, but have the added benefit of providing qualification of the challenge of interest. Other relevant challenges that may be addressed by these technologies include surface issues on the superstructure elements such as cracking and section loss and stand-off observables such as long-term structure movement.
b) EO Airborne/Satellite Imagery, Optical Interferometry, and LiDAR demonstrated applicability to deck surface challenges as well, but were not always able to satisfy the resolution requirements. These technologies demonstrated promise to global metrics related to system performance such as long-term structure movement as well as real-time measurement of vibration.
c) Radar technologies including GPR and higher frequency radar (backscatter/speckle) as well as thermal/infrared imaging provided the most promise for subsurface challenges, but can be limited in resolution (radar and thermal/infrared) or have challenges associated with collection (thermal/infrared).

While the rating results highlighted sensor technologies that have the potential to impact current practices, it also highlighted technologies that have low potential and those requiring additional research, sensor development and commercialization. Ongoing and future activities of this study will investigate the performance of some of these technologies for specific challenges related to bridge performance. The technologies to be evaluated include: digital image correlation, radar (including GPR), optical interferometry, spectral reflectance, StreetView-style photography, and 3D digital photogrammetry. These technologies were selected based on the preliminary rating with consideration of the domain expertise of the project team and other ongoing projects in these areas.

7.0 References

Ahlborn, T. M., D. K. Harris, C. N. Brooks, K. A. Endsley, D. C. Evans and R. C. Oats (2010 a). Remote Sensing Technologies for Detecting Bridge Deterioration and Condition Assessment. NDE/NDT for Highways and Bridges: Structural Materials Technology (SMT) 2010. New York, American Society for Nondestructive Testing (ASNT).

Ahlborn, T. M., R. Shuchman, L. L. Sutter, C. N. Brooks, D. K. Harris, J. W. Burns, K. A. Endsley, D. C. Evans, K. Vaghefi and R. C. Oats (2010 b). The State-of-the-Practice of Modern Structural Health Monitoring for Bridges: A Comprehensive Review.

Ambu, R., F. Aymerich, F. Ginesu and P. Priolo (2006). "Assessment of NDT interferometric techniques for impact damage detection in composite laminates." Composites Science and Technology 66(2): 199-205.

American Association of State and Highway Transportation Officials (AASHTO) (2008). "Bridging the Gap: Restoring and Rebuilding the Nation's Bridges."

American Association of State Highway and Transportation Officials (AASHTO) (2008). The Manual for Bridge Evaluation.

American Concrete Institute (ACI) Committee 222 (2001). Protection of Metals in Concrete Against Corrosion , Farmington Hills, MI.

Angst, U., B. Elsener, C. K. Larsen and O. Vennesland (2009). "Critical chloride content in reinforced concrete – a review." Cement and Concrete Research 39: 1122-1138.

Aronoff, S. (2005). Remote Sensing for GIS Managers. Redlands, CA, ESRI Press.

Barrile, V. and R. Pucinotti (2005). "Application of radar technology to reinforced concrete structures: a case study." NDT & E International 38: 596-604.

Brooks, C., D. Schaub, B. Thelen, R. Shuchman, R. Powell and E. Keefauver (2007). TARUT pilot studies technical details report. Deliverable 5.3-B. M. D. o. Transportation, Michigan Tech Research Institute.

Cardimona, S., B. Willeford, J. Wenzlick and J. Anderson (2000). Investigation of bridge decks utilizing ground penetrating radar. International Conference on the Application of Geophysical Technologies to Planning, Design, Construction, and Maintenance of Transportation Facilities. St. Louis, Missouri, U.S.A.

Cremers, D. A. (1987). The analysis of metals at a distance using laser-induced breakdown spectroscopy.

DelGrande, N. and P. F. Durbin (1999). Delamination detection in reinforced concrete using thermal inertia. Nondestructive Evaluation of Bridges and Highways III, Newport Beach, CA, USA, SPIE.

Falkner, E. (1995). Aerial Mapping: Methods and Applications. Boca Raton, FL, Lewis Publishers – CRC Press

Federal Highway Administration (FHWA). (2009). "National Bridge Inventory (NBI)." from http://www.fhwa.dot.gov/bridge/deficient.cfm.

Federal Highway Administration (FHWA). (2004). "National Bridge Inspection Standards (NBIS)." from www.fhwa.dot.gov/bridge/nbis.htm.

Federal Highway Adminstration (FHWA) (2006). Bridge Inspector’s Reference Manual (BIRM). Washington, D.C.

Gentile, C. (2009). Radar-based measurement of deflections on bridges and large structures: advantages, limitations and possible applications. IV ECCOMAS Thematic Conference on Smart Structures and Materials.

Gucunski, N., S. Nazarian, P. Shokouhi and D. Kutrubes (2010). SHRP 2 validation study of performance of NDT technologies in identification and characterization of concrete bridge deck deterioration. NDE/NDT for Highways and Bridges. New York City, NY, U.S.A., American Society for Nondestructive Testing**:** 121-128.

Hajnsek, I. and S. Cloude (2005). "The potential of InSAR for quantitative surface parameter estimation." Canadian Journal of Remote Sensing 31(1): 85-102.

Harris, D., S. Hong and S. A. Newbolds (2010). Practical evaluation of bridge deck reinforcement corrosion using ground penetrating radar, half-cell, and sounding. TRB Annual Meeting, Transportation Research Board.

Hatta, H., M. S. Aly-Hassan, Y. Hatsukade, S. Wakayama, H. Suemasu and N. Kasai (2005). "Damage detection of C/C composites using ESPI and SQUID techniques." Composites Science and Technology 65(7-8): 1098-1106.

Hauser, E. W. and S.-E. Chen (2009). Integrated remote sensing and visualization (IRSV) system for transportation infrastructure operations and management. Charlotte, NC, U.S.A., Center for Transportation Policy Studies, University of North Carolina at Charlotte.

Hu, C. W., J. K. C. Shih, R. Delpak and D. B. Tann (2002). Detection of air blisters and crack propagation in FRP-strengthened concrete elements using infrared thermography. Inframation - The Thermographer's Conference.

Hutt, T. and P. Cawley (2008). "Feasibility of digital image correlation for detection of cracks at fastener holes." NDT & E International 42: 141-149.

Kanada, H., Y. Ishikawa and T. Uomoto (2005). Utilization of near-infrared spectral imaging system for inspection of concrete structures. New Technologies for Urban Safety of Mega Cities in Asia. Singapore.

Kant, Y. and K. V. S. Badarinath (2002). "Sub-pixel fire detection using Landsat-TM thermal data." Infrared Physics & Technology 43(6): 383-387.

Kim, W., A. Ismail, N. L. Anderson, E. A. Atekwana and A. Buccellato (2003). Non-destructive testing (NDT) for corrosion in bridge decks using GPR. The 3rd International Conference on Applied Geophysics. Orlando, Florida, U.S.A.

Krajewski, J. E. (2006). Bridge inspection and interferometry. Worcester, Massachusetts, Worcester Polytechnic Institute. Master of Science in Civil Engineering**:** 120.

Kuntz, M., M. Jolin, J. Bastien, F. Perez and F. Hild (2006). "Digital image correlation analysis of crack behavior in a reinforced concrete beam during a load test." Canadian Journal of Civil Engineering 33: 1418-1425.

Laefer, D. F., M. Fitzgerald, E. M. Maloney, D. Coyne, D. Lennon and S. W. Morrish (2009). "Lateral image degradation in terrestrial laser scanning." Structural Engineering International 19: 184-189.

Lim, M. K. (2001). NDE Using Impulse Radar to Evaluate Material Properties in Concrete Structures. Structural Faults and Repair 2001. P. M. Forde. London, UK, Published by Engineering Technics Press, Edinburgh.

Lubowiecka, I., J. Armesto, P. Arias and H. Lorenzo (2009). "Historic bridge modelling using laser scanning, ground penetrating radar and finite element methods in the context of structural dynamics." Engineering Structures 31(11): 2667-2676.

Luhmann, T., S. Robson, S. Kyle and I. Harley (2006). Close-range photogrammetry: principles, methods, and applications. Hoboken, NJ Caithness : Whittles.

Maierhofer, C. and S. Leipold (2001). "Radar investigation of masonry structures." NDT & E International 34(2): 139-147.

Maser, K. R. (1986). Detection of progressive deterioration in bridge decks using ground penetrating radar. ASCE/EM Division Specialty Conference. Boston, MA, U.S.A., American Society of Civil Engineers.

Michigan Department of Transportation. (2008). "Bridge Deck Preservation Matrix." from http://www.michigan.gov/documents/mdot/MDOT_BridgeDeckMatrix_182438_7.pdf.

Mikhail, E. M., M. L. Akey and O. R. Mitchell (1984). "Detection and sub-pixel location of photogrammetric targets in digital images." Photogrammetria 39(3): 63-83.

National Cooperative Highway Research Program (NCHRP) (2007). Bridge Inspection Practices - NCHRP Synthesis 375. Washington DC, Transportation Research Board.

Nowak, A. S., M. M. Szerszen and D. A. Juntunen (2000). Michigan deck evaluation guide. C. a. T. Division. Lansing, MI.

Olson, L. D. (2010). Innovations in bridge superstructure condition assessment with sonic and radar methods. NDE/NDT for Highways and Bridges. New York City, NY, U.S.A., American Society for Nondestructive Testing.

Pieraccini, M., M. Fratini, D. Dei and C. Atzeni (2009). "Structural testing of Historical Heritage Site Towers by microwave remote sensing." Journal of Cultural Heritage 10(2): 174-182.

Pieraccini, M., M. Fratini, F. Parrini, C. Atzeni and G. Bartoli (2008). "Interferometric radar vs. accelerometer for dynamic monitoring of large structures: An experimental comparison." NDT & E International 41(4): 258-264.

Pieraccini, M., D. Tarchi, H. Rudolf, D. Leva, G. Luzi, G. Bartoli and C. Atzeni (2000). "Structural static testing by interferometric synthetic radar." NDT & E International 33(8): 565-570.

Precast / Prestressed Concrete Institute (PCI) (2004). PCI Design Handbook. Chicago, IL., PCI.

Scott, M., A. Rezaizadeh and M. Moore (2001). Phenomenology study of HERMES ground-penetrating radar technology for detection and identification of common bridge deck features.

Sekulic, D., D. Bjegovic and D. Mikulic (2001). "Non-destructive methods for monitoring of reinforcing steel in concrete." Structural Faults and Repair.

Shinozuka, M., R. Ghanem, B. Houshmand and B. Mansouri (2000). "Damage detection in urban areas by SAR imagery." Journal of Engineering Mechanics 126(7): 769-777.

Shuchman, R., N. Subotic, C. Roussi, J. Ruiter, W. Buller and D. Schaub (2005). Simulated RADAR data sets for transportation applications of the restricted use technology study, Altarum.

Soergel, U., E. Cadario, A. Thiele and U. Thoennessen (2008). "Feature extraction and visualization of bridges over water from high-resolution InSAR data and one orthophoto." IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 1(2).

Stimolo, M. (2003). Passive infrared thermography as inspection and observation tool in bridge and road construction. Non-Destructive Testing in Civil Engineering 2003.

Teza, G., A. Galgaro and F. Moro (2009). "Contactless recognition of concrete surface damage from laser scanning and curvature computation." NDT & E International 42: 240-249.

Warhus, J. P., J. E. Mast, E. M. Johansson and S. D. Nelson (1994). Improved ground-penetrating radar, bridge decks. Structural Materials Technology Non-Destructive Technology Conference. Atlantic City, NJ, U.S.A.