# Evaluation of Commercially Available Remote Sensors for Highway Bridge Condition Assessment

Khatereh Vaghefi[1]; Renee C. Oats[2]; Devin K. Harris, A.M.ASCE[3]; Theresa (Tess) M. Ahlborn, M.ASCE[4]; Colin N. Brooks[5]; K. Arthur Endsley[6]; Christopher Roussi[7]; Robert Shuchman[8]; Joseph W. Burns[9]; and Richard Dobson[10]

**Abstract:** Improving transportation infrastructure inspection methods and the ability to assess conditions of bridges has become a priority in recent years as the 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 nondestructive 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 because remote sensors do not come in direct contact with the structure. The purpose of this paper is to evaluate 12 potential remote sensing technologies for assessing the bridge deck and superstructure condition. Each technology was rated for accuracy, commercial availability, cost of measurement, precollection preparation, complexity of analysis and interpretation, ease of data collection, stand-off distance, and traffic disruption. Results from this study demonstrate the capabilities of each technology and their ability to address bridge challenges. **DOI:** 10.1061/(ASCE)BE.1943-5592.0000303. *© 2012 American Society of Civil Engineers.*

**CE Database subject headings:** Nondestructive tests; Structural response; Monitoring; Radar; Digital techniques; Imaging techniques; Highway bridges; Inspection; Remote sensing.

**Author keywords:** Nondestructive testing/evaluation; Structural health monitoring; Noncontact; Radar; Thermal IR; Photogrammetry; Digital image correlation; Bridge inspection.



[1]Graduate Research Assistant, Dept. of Civil and Environmental Engineering, Michigan Tech Transportation Institute, Michigan Technological Univ., Houghton, MI 49931 (corresponding author). E-mail: kvaghefi@mtu.edu

[2]Graduate Research Assistant, Dept. of Civil and Environmental Engineering, Michigan Tech Transportation Institute, Michigan Technological Univ., Houghton, MI 49931.

[3]Assistant Professor, Dept. of Civil and Environmental Engineering, Michigan Tech Transportation Institute, Michigan Technological Univ., Houghton, MI 49931.

[4]Associate Professor, Dept. of Civil and Environmental Engineering, Michigan Tech Transportation Institute, Michigan Technological Univ., Houghton, MI 49931.

[5]Research Scientist, Michigan Tech Research Institute, Michigan Technological Univ., Ann Arbor, MI 48105.

[6]Assistant Research Scientist, Michigan Tech Research Institute, Michigan Technological Univ., Ann Arbor, MI 48105.

[7]Senior Research Scientist, Michigan Tech Research Institute, Michigan Technological Univ., Ann Arbor, MI 48105.

[8]Codirector, Michigan Tech Research Institute, Michigan Technological Univ., Ann Arbor, MI 48105.

[9]Senior Research Scientist, Michigan Tech Research Institute, Michigan Technological Univ., Ann Arbor, MI 48105.

[10]Research Associate, Michigan Tech Research Institute, Michigan Technological Univ., Ann Arbor, MI 48105.

Note. This manuscript was submitted on April 28, 2011; approved on August 30, 2011; published online on August 30, 2011. Discussion period open until April 1, 2013; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Bridge Engineering***, Vol. 17, No. 6, November 1, 2012. ©ASCE, ISSN 1084-0702/2012/6-886–895/$25.00.

## 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 United States 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). As of 2010, the number of bridges listed as structurally deficient was 69,223 (11.5% 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 [Federal Highway Administration (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 verify its structural integrity and safety. 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. The use of remote sensing technologies presents a potential complement to this challenge and has the potential to augment current practices by providing both qualitative and quantitative measures of a bridge's condition in a noncontact manner. This paper details the evaluation of remote sensing technologies to assess and monitor the condition of bridge infrastructure while improving the efficiency of inspection, repair, and rehabilitation efforts.



J. Bridge Eng. 2012.17:886-895.

## Bridge 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). Routine or hands-on type inspections serve 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). All inspectors must be certified through a National Highway Institute (NHI) comprehensive training program and are required to keep this certification current through refresher courses.

According to NBIS, publicly owned bridges in the United States must be inspected at least every 2 years, whereas bridges with problem areas need to be inspected more frequently than the minimum 2-year requirement. 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, visual evaluation serves as the primary tool used by inspectors. Other techniques for assessment can be employed, such as specialized sensor technologies to evaluate specific challenges or measurement of the bridge response to known loading; however, these techniques are rarely used in routine and hands-on inspections. As a result, routine inspections are highly subjective and rely on experience-based knowledge that must be developed over time. At first glance this may appear ineffective, but when considering the volume of in-service bridges, available resources, and most importantly, the lack of an all-encompassing solution for evaluating structural condition, few alternative approaches exist.

### *Nondestructive Evaluation Remote Sensing Approaches for Bridge Condition Assessment*

Bridge inspection procedures commonly use nondestructive evaluation (NDE) methods for assessment of the condition of bridges with visual inspection being the predominant method. Visual inspection consists of two components: routine inspections and in-depth inspections. Technical reviews of visual inspection reliability have found that routine inspections are completed with significant variability (Washer 2001). The use of remote sensing technologies presents a potential alternative method to assessing bridge condition challenges and has the potential to augment current practices by providing both qualitative and quantitative measurements. 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). From an infrastructure perspective, remote sensing can be defined as a form of stand-off SHM, and a form of NDE and nondestructive testing (NDT), where the device-gathering data are not in contact with the object or feature being measured. Remote sensing is distinct from what is called remote monitoring, in that it does not include emplaced sensors, such as strain gauges or temperature sensors. These sensors are in direct contact with the bridge component whose characteristics are being measured. Classic examples of remote sensing that may be familiar to the bridge engineer or inspector include satellite imagery, aerial photography, laser scanning [such as light detection and ranging (LIDAR)], and ground penetrating radar (GPR). 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.

### *Challenges on Bridge Structures*

With routine bridge inspection processes, bridges can be monitored and issues or challenges are mitigated to help extend the service life of a structure. This integration of remote sensing has to be evaluated for each primary bridge structure component to attend to the relevant challenges in those locations. The primary components of a bridge can be categorized as the bridge deck, superstructure, and substructure. Although all three components are essential to the performance of a bridge, only considerations for the deck and superstructure are presented herein.

Bridge decks serve as the driving surface while also protecting the superstructure and substructure from the environment and contaminants (salts and chemicals). Bridge decks can be classified, to a certain extent, as a sacrificial element because they can be replaced as they degrade over time. However, as the integrity of the deck is compromised through the degradation process, the protection afforded to the superstructure and substructure also diminishes, often providing a catalyst for deterioration or accelerating degradation of these elements. 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.

Elements of bridge superstructure in the United States are typically constructed of either steel or concrete (prestressed or reinforced) girders and are frequently paired with a reinforced concrete deck. These members serve as 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. Defects observed in and on a girder have the potential to result in a decrease in cross-section capacity. Issues occurring within the girder's cross section have the same consequences as those on the girder surface. However, detecting these issues is significantly more challenging because they may be hidden or not easily accessible.

Other bridge health challenges, related to the bridge system as a whole, cannot be categorized within the individual elements or components. These challenges, referred to as global metrics, may not be observable during a routine inspection of the bridge or individual elements, but their change has the potential to indicate overall condition change.

In this study, the challenges associated with bridges have been organized into (1) deck surface, (2) deck subsurface, (3) girder



J. Bridge Eng. 2012.17:886-895.

| | | | Rating Based, in Part, on Theoretical Sensitivity for Measurement Technologies | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Location | Challenges | Indicator | 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 | 14 | 0 | 12 | 12 | 11 | 0 | 0 | 9 | 0 | 13 |
| | | Spalls within 2 Feet | 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 | 14 | 12 | 12 | 12 | 11 | 8 | 0 | 9 | 0 | 13 |
| | Scaling | Depression in Surface | 0 | 8 | 14 | 12 | 12 | 12 | 11 | 0 | 0 | 9 | 0 | 13 |
| | Spalling | Depression with Parallel Fracture | 0 | 8 | 14 | 12 | 12 | 12 | 11 | 0 | 0 | 9 | 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 | 11 | 0 | 0 | 0 | 0 | 0 | 11 | 0 | 0 | 0 | 0 | 0 |
| | | Internal Horizontal Crack | 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 | 12 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 0 | 12 | 0 | 0 |
| | Scaling | Depression in Surface | 12 | 0 | 0 | 0 | 0 | 0 | 11 | 0 | 0 | 0 | 0 | 0 |
| | Spalling | Depression with Parallel Fracture | 12 | 0 | 0 | 0 | 0 | 0 | 11 | 0 | 0 | 0 | 0 | 0 |
| | Corrosion | Corrosion Rate (Resistivity) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Change in Cross-Sectional Area | 13 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 0 | 13 | 0 | 0 |
| | Choride Ingress | Choride Content through the Depth | 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12 | 0 | 0 |
| Girder Surface | Steel Structural Cracking | Surface Cracks | 0 | 8 | 11 | 0 | 12 | 0 | 11 | 0 | 0 | 0 | 0 | 0 |
| | Concr. Structural Cracking | Surface Cracks | 0 | 8 | 11 | 0 | 12 | 0 | 11 | 8 | 0 | 0 | 0 | 0 |
| | Steel Section Loss | Change in Cross-Sectional Area | 0 | 0 | 11 | 12 | 0 | 13 | 11 | 0 | 0 | 11 | 0 | 0 |
| | Paint | Paint Condition | 0 | 9 | 0 | 0 | 0 | 0 | 11 | 0 | 0 | 0 | 0 | 0 |
| | Concrete Section Loss | Change in Cross-Sectional Area | 0 | 0 | 11 | 12 | 0 | 13 | 11 | 7 | 0 | 11 | 0 | 0 |
| Girder Subsurface | Concr. Structural Cracking | Internal Cracks (e.g. Box Beam) | 0 | 0 | 0 | 0 | 0 | 0 | 11 | 8 | 0 | 0 | 0 | 0 |
| | Concrete Section Loss | Change in Cross-Sectional Area | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 0 | 11 | 0 | 0 |
| | Prestress Strand Breakage | Change in Cross-Sectional Area | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 0 | 9 | 0 | 0 |
| | Corrosion | Corrosion Rate (Resistivity) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Change in Cross-Sectional Area | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 0 | 13 | 0 | 0 |
| | Choride Ingress | Choride Content through the Depth | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11 | 0 | 0 |
| Global Metrics | Bridge Length | Change in Bridge Length | 0 | 0 | 15 | 13 | 0 | 0 | 0 | 0 | 9 | 0 | 12 | 0 |
| | Bridge Settlement | Vertical Movement of Bridge | 0 | 0 | 12 | 0 | 0 | 12 | 0 | 0 | 9 | 0 | 12 | 0 |
| | Bridge Movement | Transverse Directions | 0 | 0 | 12 | 0 | 0 | 12 | 0 | 0 | 9 | 0 | 12 | 0 |
| | Surface Roughness | Surface Roughness | 0 | 9 | 14 | 13 | 12 | 12 | 0 | 0 | 0 | 11 | 13 | 13 |
| | Vibration | Vibration | 0 | 0 | 0 | 0 | 12 | 0 | 0 | 0 | 10 | 12 | 12 | 0 |

**Fig. 1.** Performance rating of commercial remote sensing technologies for each bridge challenge

surface, (4) girder subsurface, and (5) global metrics. Fig. 1 provides a table summary of the broad challenges, their associated indicators, and scored results of the potential remote sensing technologies for identifying indicators. The following sections define remote sensing technologies and rating methodology for assessing the capability of each remote sensor to address these challenges in designated bridge locations.

## Remote Sensing Technologies

The ability to apply remote sensing techniques to the bridge inspection and monitoring practice has great potential value, especially considering the sheer number of bridges in the U.S. transportation system and limited funding for inspection, maintenance, and rehabilitation (Ahlborn et al. 2010b). This paper focuses on 12 forms of remote sensing technologies that are potentially valuable to assess bridge conditions. The technologies, described in following sections, include three-dimensional (3D) optics (including photogrammetry), high-resolution StreetView-style digital photography, optical interferometry, spectral analysis, digital image correlation (DIC), electro-optical (EO) satellite and airborne imagery, LIDAR, thermal infrared (IR) imaging, radar (including backscatter and speckle), GPR, interferometric synthetic aperture radar (InSAR), and remote acoustics. The discussions also include the locations of bridge health challenges that are more applicable for deployment of each remote sensing technology.

### *Three-Dimensional Optics*

#### Deck Surface, Girder Surface, and Global Metrics Challenges

Three-dimensional optics (specifically photogrammetry) is a technology that can provide depth and height information that cannot otherwise be obtained from an individual image. This can be done by overlapping two images, taken from two different angles of an object, with at least 60% overlap when combined. The instrumentation consists of commercially available, high-resolution digital cameras. The cameras can be mounted on an aerial or satellite platform, either manned or unmanned; however, to achieve the resolution required for bridge assessment applications, a much lower stand-off distance is often necessary. A vehicle-mounted system may be best suited for imaging deck and girder surface features that require high-feature resolution. Global metrics may be evaluated using an aerial platform, such as an unmanned aerial vehicle (UAV) or airplane (Ahlborn et al. 2010a). Fig. 2 demonstrates the application of 3D optics for calculating the volume of spalls on inaccessible locations using close-range photogrammetry tools.

### *Streetview-Style Photography*

#### Deck Surface and Global Metrics Challenges

The term StreetView-style photography refers to any serial collection of photographs with a 3D geospatial projection, especially where the photographs have been projected into a continuous 360° viewing environment (Fig. 3). The description that follows is based





J. Bridge Eng. 2012.17:886-895.

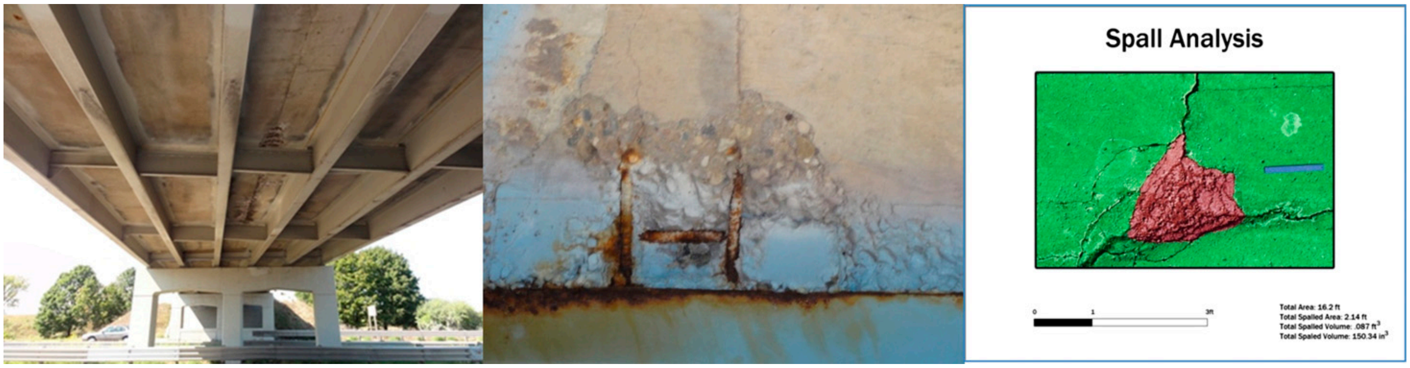


**Fig. 2.** Application of 3D optics for calculating the volume of spalls for inaccessible locations on the bridge deck


**Fig. 3.** Example image of part of a bridge deck taken with a bridge viewer remote camera system

on the original concept presented by Google's StreetView. This type of instrumentation is typically mounted on a vehicle platform for rapid collection with little or no interference with traffic. Because many bridges may not allow for driving underneath or alongside, 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.

Bridge inspectors might find such an application useful for reviewing a bridge in which they have already performed an inspection on by looking at updated imagery ahead of its next scheduled inspection. This 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. 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 (Ahlborn et al. 2010a).

### *Optical Interferometry*

#### Deck Surface, Girder Surface, and Global Metrics Challenges

Interferometry refers to a nondestructive technique that involves combining two or more light waves to obtain finer information in the image. Interferometry consists of techniques that generate Young's fringes and/or isothetic fringes as well as (optical) speckle pattern interferometry (SPI). Speckle patterns in this technique can be used to determine surface features and surface roughness on the bridge deck. In the performance assessment, it was determined that the technology, like most digital camera-based [charge-coupled device (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, including the capabilities of the digital camera used for sensing; for interferometry, the spatial resolution is especially high (Ahlborn et al. 2010a).

Surface cracks at millimeter and submillimeter scales have successfully been detected using optical interferometric techniques, namely, electronic SPI (ESPI) (Hatta et al. 2005). The measurement of spalls and scaling on the concrete deck should be possible because submillimeter 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.

### *Spectral Analysis*

#### Deck Surface and Girder Surface Challenges

Spectral analysis is the measurement of a target surface's spectral reflectance or absorption of light (both visible and IR). Spectral analysis is typically described as the identification of characteristic peaks—wavelengths at which a large amount of radiation is absorbed or reflected. This includes spectroscopy—any measurements based on identifying characteristic peaks or spectra corresponding to structural defects, as well as 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 as multispectral or hyperspectral EO imaging), so response at fine wavelength bins is known.

A spectroradiometer is used to measure reflectance and/or absorption. In general, these devices need to be white balanced before collection. Field collection is typically done with a backpack unit



J. Bridge Eng. 2012.17:886-895.

and hand-held spectroradiometer; however, a vehicle-mounted device is conceivable. In the performance evaluation of this technology, it was determined that spectroscopy is impractical for most deck surface applications, except for chemical leaching. 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. 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 (Ahlborn et al. 2010a).

### *Digital Image Correlation*

#### Global Metrics Challenges

DIC refers to a technique consisting of the correlation, typically on a pixel-by-pixel basis, of two EO images separated in space or time. This is done by automated computer algorithms that measure changes between the two photographs and calculate the displacement and/or rotation of unique features in the image plane (structural elements), or most commonly, markers such as paint spots (Fig. 4) or a pattern of dots projected on a surface. These displacements may be defined as rigid, global displacements, or local deformation. This technique was found to be sufficient for applications such as measuring bridge settlement, transverse bridge movement, vibration of a bridge or a structural element, and detecting a change in bridge length. All of these applications are concerned with the 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, which are representative of comprehensive bridge structural health.

DIC is practical for measuring vibration, and in that application, still has to address an unknown frequency response, necessary target preparation, and small coverage area. The frequency response is dependent on the camera used, and may not be 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) described their collection using a two-camera system developed by Dantec Dynamics and processing using *ARAMIS* [software by Gesellschaft für Optische Messtechnik (GOM)], which consisted of simple-windowed block matching where correlations took from a few seconds up to several minutes.

### *Electro-Optical Airborne and Satellite Imagery*

#### Deck Surface, Girder Surface, and Global Metrics Challenges

EO imagery is a technique to obtain information from airborne or satellite images in the visual, near IR, or thermal IR bands. Manned or unmanned aerial vehicles may be considered, and this category excludes imagery that is used in 3D models (excluding imagery collected as stereo pairs) because the collection of such imagery has already been discussed in the "Three-Dimensional Optics" section. 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. Brooks et al. (2007) were able to calculate the sufficiency rating for Michigan road segments with 88.1% accuracy on asphalt roads and 80.5% for concrete roads using commercially available satellite imagery. These methods have the potential to be applied to bridge deck surfaces.

It is less likely that this imagery will also be capable of resolving expansion joints and damage to them, but subpixel estimates of expansion joint conditions can likely be made with advanced postprocessing. Subpixel (or mixed pixel) detection techniques have been demonstrated in other applications where the technological approach is essentially similar. Kant and Badarinath (2002) showed that oil fires less than 2% the spatial extent of a pixel could still be identified. Mikhail et al. (1984) achieved accuracies to within 0.03−0.05 pixel in measuring the position of subpixel targets. This indicates that the potential exists for detecting the presence of cracks that are otherwise too small to resolve as well as damage to expansion joints.

### *Light Detection and Ranging*

#### Deck Surface, Girder Surface, and Global Metrics Challenges

LIDAR is a technique used to measure the range (distance) to the object according to the laser pulse travel time and speed between sensor and target. This technology includes terrestrial laser scanning (TLS) and aerial/airborne laser scanning (ALS). A typical LIDAR instrument includes a receiver, a transmitter, and a system controller unit. A review of the literature suggests that this technology is most applicable for deck surface and global structural health challenges (Ahlborn et al. 2010a). Hauser and Chen (2009) demonstrated that LIDAR can contribute useful information to identify and map steel and concrete section loss. LIDAR, in combination with high-resolution digital photography of a bridge,

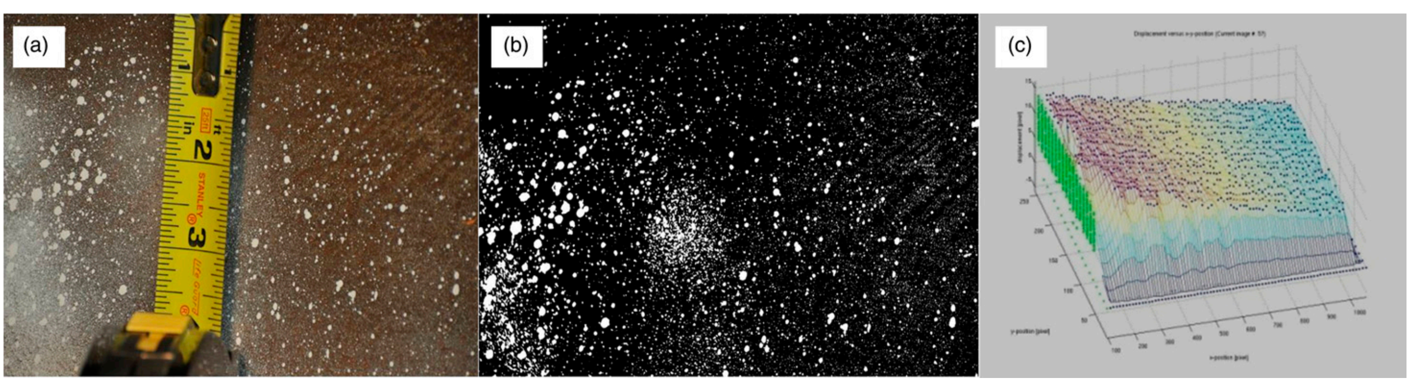


**Fig. 4.** Images of paint spots on a structural I-beam for digital image correlation: (a) paint spots should have a wide distribution of sizes; (b) postprocessing of images is used to bring the spots to a contrast threshold; (c) postprocessing displacement response



J. Bridge Eng. 2012.17:886-895.

in a StreetView-style system, holds promise as a means to assist bridge inspectors with reviewing and understanding bridge condition features (Ahlborn et al. 2010a), as well as creating readily available 3D models of bridges and their surrounding environment.

### Thermal Infrared

#### Deck Surface, Deck Subsurface, Girder Surface, and Girder Subsurface Challenges

Thermal IR imaging is a technology based on measuring the radiant temperature of the material. This has been used in bridge condition assessment to evaluate subsurface issues in concrete. The concept behind this technique is that the anomalies and subsurface delaminations interrupt the heat transfer through the concrete. Thus, surface delaminations will appear as hot spots during the day and cold spots during the night (Washer et al. 2009). Emissivity of the materials is one of the factors that can affect the thermal IR measurement. Emissivity depends on the amount of radiant flux (the amount of electromagnetic energy exiting an object) emitted from the material. Surface roughness, color, and moisture content are some of the factors that can influence the emissivity of the materials.

ASTM D4788 (ASTM 2007) describes the test method, equipment, and environmental condition for detecting delamination in concrete bridge decks with this technique. Although this technique has been used mostly for detecting subsurface anomalies, surface defects will likely manifest as thermal anomalies in the thermal IR image. 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 as well. Laboratory setup and thermal IR image of the test specimen with simulated defects are demonstrated in Fig. 5.

### Radar

#### Deck Surface, Deck Subsurface, Girder Surface, and Girder Subsurface Challenges

Radio detection and ranging (Radar) is a technique to record range (distance) to an object based on the round trip travel time and velocity of the wave propagation. For bridges, this technique provides penetrative capabilities that can be used to detect subsurface features. Although moisture can attenuate the signals and efficiency of the method, this technique can be deployed in all weather conditions. The use of SAR is considered in this evaluation. SAR is a technique developed to create a large antenna aperture synthetically to obtain a narrower beam width and demonstrate finer details. This advanced radar processing helps to increase cross-range resolution and operating frequency, allowing for clearer subsurface imaging (Morey 1998). Moreover, SAR has the capability to be mounted on a vehicle, the forward motion of which provides the necessary translation of the antennas, and take measurements while moving along the bridge.

### Ground Penetrating Radar

#### Deck Surface, Deck Subsurface, Girder Surface, and Girder Subsurface Challenges

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 of penetration and the radar's sensitivity to embedded features. This category includes both air- and ground-coupled antennas. Ground-coupled surveys require the antenna to rest on the ground and can collect data at walking speeds (8 km/h), whereas the air-coupled antenna can be mounted on a moving vehicle (80 km/h). Commercial GPR systems are mostly used for subsurface assessment (deck and girder subsurface).

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 because of the limitations of the technology. By combining SAR with GPR, Scott et al. (2001) demonstrated the potential to measure the dimensions of subsurface features. In a FHwA funded project, the High Speed Electromagnetic Roadway Mapping and Evaluation System (HERMES) was used to locate and characterize the condition of embedded steel reinforcement, detect corrosion-related delamination, as well as locate voids and debonded areas. Depth of penetration achieved with this system was 12 cm below the concrete surface (Scott et al. 2001).

### Interferometric Synthetic Aperture Radar

#### Global Metrics Challenges

Interferometric SAR (InSAR) uses SAR data collection and processing to acquire data from two different viewing angles to form detailed images. Phase and amplitude differences of these images are compared with make measurements. Aerial- or space-borne InSAR offers the potential for rapid assessment of bridges from high stand-off distances without requiring calibration or preparation of the

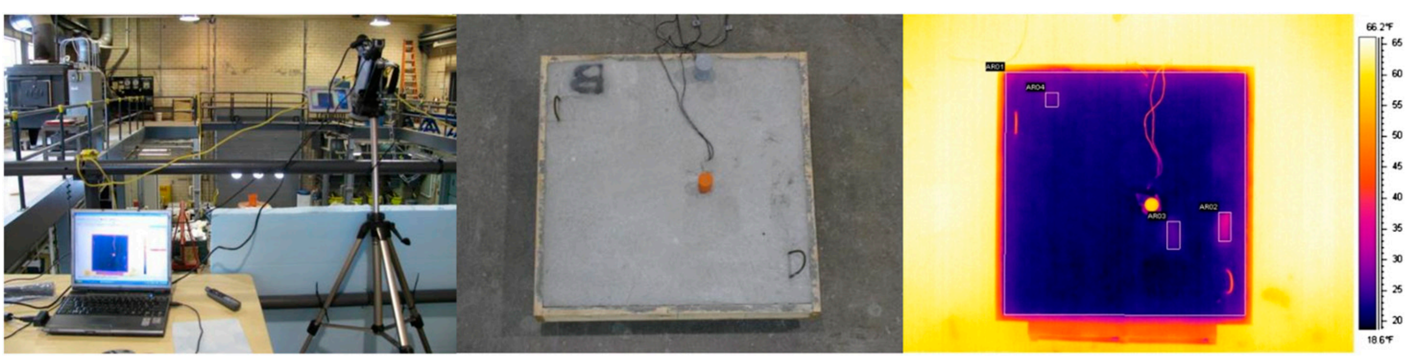

**Fig. 5.** Thermal IR laboratory setup and thermal IR image of the slab with simulated defects; defects can be seen as thermal anomalies



J. Bridge Eng. 2012.17:886-895.

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 the technique scored well in these applications. Interferometric radar techniques have the potential to monitor change in bridge length, bridge settlement, and transverse bridge movement by calculating phase differences between the two radar images of the same scene (Ahlborn et al. 2010a). InSAR data can also be applied to calculate road surface condition indicators, such as the international roughness index (IRI) (Brooks et al. 2007).

Measurement of these phase differences allows for the detection of small changes in surface elevation; bridge settlement is therefore one metric that may be obtained using InSAR. 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. Several Italian reports on ground-based interferometric radar addressed these condition indicators with measurements down to 0.1-mm displacement resolution at up to 2-km stand-off distance (Pieraccini et al. 2008).

Excluding operational costs, which in this case would be limited to personnel and processing time, the cost of InSAR for most bridge remote sensing applications is encapsulated by the price of commercial SAR imagery. However, ground-based acquisitions have capital costs associated with the equipment purchase and possible additional operational costs depending on deployment and the expertise of the available staff.

### *Remote Acoustics*

#### Deck Surface, Deck Subsurface, Girder Surface, and Girder Subsurface Challenges

Acoustics is a well-established method to detect bridge subsurface deteriorations. 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 measure their amplitude, frequency content, and travel time through a medium. Acoustic emission impact-echo method, acoustic tomography, and Lamb-wave monitoring were considered in this evaluation. Although these techniques are similar 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. In this evaluation, it is indicated the technologies are only applicable to subsurface features or cracks and section loss of deck and girder surfaces (Ahlborn et al. 2010a).

## Technology Rating Methodology

The 12 remote sensing technologies discussed in the previous section were evaluated and assigned grades under eight criteria. These criteria were established based on application requirements of the remote sensing technique for bridge condition assessment. The assessment was mostly based on existing literature and professional experience; however, the lack of sufficient information in the literature regarding specific performance was one of the difficulties in the rating. The technologies were rated based on eight criteria significant for condition assessment. The list of criteria (A−H) and rating system associated with each one is described in Table 1.

All performance criteria receive a score from 0 to 2, where a higher score is more satisfactory and zero indicates that the technology does not satisfy that criterion. An overall perfect score for each technology would be 16. The most important criteria in this assessment were Criteria A and B, whether the technology has the capability to satisfy each indicator at the required resolution and whether the technology is commercially available, only research grade, or has never been used for that application before, respectively. Their importance is reflected in the total rating; 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 (and receives a score of 0). The cost of measurement, considered in Criterion C, is an important factor in this evaluation because of the modest budget of the user base, which consists mostly of state and local transportation agencies. This criterion was judged for each technology based on professional experience and was defined on a per bridge basis.

Criterion D considered the amount of time and work required to prepare a bridge structure, element, or remote sensing instrument (i.e., calibration) before usable data could be collected. The complexity of the analysis is considered in Criterion E 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 and whether data can be interpreted immediately after acquired by the device or if it requires further post-processing. Ease of data collection is reflected in Criterion F. This criterion considered whether the training needed for the operator or the instrumentation is used as the manufacturer intended or has been modified for use in an unconventional way. The stand-off distance of the instruments is assessed in Criterion G; it indicates a measure of how far the instrument is from the target or target enclosure's surface (for subsurface features) during the data collection procedure. Traffic disruption is an important factor that be considered in any commercial technology's practicality for bridge condition evaluation. This factor was considered in Criterion H and intended to measure how much the technique interferes with traffic when collecting data. More detailed description of the rating system associated with each criterion is presented in the project report (Ahlborn et al. 2010a). Scored results of this study are demonstrated in Fig. 1.

## Conclusions

Although remote sensing technologies have been successfully implemented in a number of industries, their application to monitoring and maintenance of transportation infrastructure has been somewhat limited to date. 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 importantly, monitoring the condition of a bridge using remote sensors can eliminate the need for traffic disruption or total lane closure because remote sensors do not come in direct contact with the structure.

Monitoring how damage or deterioration changes over time will provide state and local engineers with additional information needed 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 conditions. Improved assessments allow for limited resources to be better allocated in repair



J. Bridge Eng. 2012.17:886-895.

**Table 1.** Definition for the Criteria Used in Rating Remote Sensing Technologies for Their Efficiency in Detecting Bridge Condition Indicators (Ahlborn et al. 2010a, reproduced with permission)

| | Criteria | Score (0–2) | |
|---|---|---|---|
| A | Is the requirement met? | 2 | • Resolution is specifically within the current capabilities of the technology<br>• Full range of measurements are met or better<br>• Other requirements directly measured |
| | | 1 | • Lower limit of resolution/requirements is not within capabilities, but upper limit is<br>• Technology can measure somewhere between the range or within 25% of upper limit<br>• Some requirements are only indirectly measured |
| | | 0 | • Upper limit of resolution not met within 25%<br>• 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)<br>• 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<br>• 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<br>• 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 | Precollection preparation | 2 | • Absolutely no preparation of the structure/no or 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)<br>• Automated turn-key processing by a computer (software commercially available) |
| | | 1 | • Analysis consists of detailed measurements made by a human user from raw data<br>• 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<br>• Processing by an algorithm that (1) requires extensive human supervision, (2) a large amount of time per bridge (more than a day), or (3) requires multiple algorithms chained together with human-in-the-loop input/output |
| 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)<br>• Easily accessible structure components |
| | | 1 | • Instrument is used in a custom fashion (may have been modified for this purpose)<br>• Requires input from operator/requires real-time verification (quality assurance/quality control) of results<br>• 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 (quality assurance/quality control) 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 |





J. Bridge Eng. 2012.17:886-895.

and maintenance efforts, thereby extending the service life and safety of bridge assets, and minimizing costs of service-life extension.

This report presented a performance evaluation and rating of commercially available remote sensing technologies for infrastructure condition assessment, specifically bridges. In this study, 12 remote sensing technologies were reviewed to evaluate their potential to detect a series of indicators related to common challenges faced by typical U.S. bridges. Using a rating methodology developed specifically for assessing the applicability of these remote sensing technologies, a collective evaluation of these technologies for bridge challenges located throughout the bridge was performed.

The key findings within this rating methodology assessment are as follows.

- Technologies such as 3D optics (including photogrammetry), StreetView-style photography, LIDAR, optical interferometry, thermal IR, spectral analysis, and radar demonstrate the potential to detect surface-related challenges. These challenges primarily include those that are observable to the human eye and can provide additional quantified measurements of the features of interest. Three-dimensional optics and StreetView-style photography have the greatest potential and resolution in this case. EO airborne and/or satellite imagery and LIDAR demonstrated applicability to deck surface challenges as well, but were not always able to satisfy the resolution requirements.
- Radar technologies, including GPR and SAR collection, as well as thermal IR imaging, have the greatest potential to measure subsurface bridge condition challenges but are limited in spatial resolution (radar and thermal IR) or present difficulties associated with data collection (e.g., impacts of the environment on thermal IR data). Acoustics also demonstrated promise in detecting subsurface-related challenges; however, this technique requires contact with the bridge in most cases, which precludes it from consideration as remote sensing.
- EO airborne and/or satellite imagery, 3D optics, InSAR, DIC, and LIDAR are technologies with the potential to detect global metric challenges. Among these, InSAR and DIC are the most promising and have the greatest potential to meet the requirements for these applications.

## Future Work

Although this evaluation highlights sensor technologies that have the potential to enhance current practices, it also highlights some technologies that have low potential and require 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. These technologies were selected based on the preliminary rating with consideration for other ongoing projects in these areas and include 3D optics, StreetView-style photography, DIC, EO satellite imagery, thermal IR, radar (including GPR), and InSAR. In addition, the output from these studies will form a framework for a decision support system demonstration for bridges that will complement bridge inspectors' maintenance and rehabilitation decisions in a safe and timely manner.

## Acknowledgments

This work was supported by the Commercial Remote Sensing and Spatial Information Technologies program of the Research and Innovative Technology Administration (RITA), U.S. Department of Transportation (USDOT), Cooperative Agreement No. 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.

## References


AASHTO. (2008). "Bridging the gap: Restoring and rebuilding the nation's bridges." ⟨http://www.transportation1.org/BridgeReport/front-page.html⟩ (Nov. 22, 2010).

Ahlborn, T. M., et al. (2010a). "An evaluation of commercially available remote sensors for assessing highway bridge condition." ⟨http://www.mtri.org/bridgecondition/doc/RITA_BCRS_Commercial_Sensor_Evaluation.pdf⟩ (Nov. 22, 2010).

Ahlborn, T. M., Harris, D. K., Brooks, C. N., Endsley, K. A., Evans, D. C., and Oats, R. C. (2010b). *Remote sensing technologies for detecting bridge deterioration and condition assessment. NDE/NDT for highways and bridges: Structural materials technology (SMT) 2010*. American Society for Nondestructive Testing (ASNT), New York.

Aronoff, S. (2005). *Remote sensing for GIS managers*, ESRI Press, Redlands, CA.

ASTM. (2007).: "Standard test method for detecting delaminations in bridge decks using infrared thermography." *D4788-03*, West Conshohocken, PA.

Brooks, C., Schaub, D., Thelen, B., Shuchman, R., Powell, R., and Keefauver, E. (2007). "TARUT pilot studies technical details report." ⟨http://tarut.org⟩ (Oct. 7, 2010).

Falkner, E. (1995). *Aerial mapping: Methods and applications*, Lewis Publishers−CRC Press, Boca Raton, FL.

Federal Highway Administration (FHwA). (2004). "National bridge inspection standards (NBIS)." ⟨www.fhwa.dot.gov/bridge/nbis.htm⟩ (Oct. 7, 2010).

Federal Highway Adminstration (FHwA). (2006). *Bridge inspector's reference manual*, BIRM, Washington, D.C.

Federal Highway Administration (FHwA). (2009). "National bridge inventory (NBI)." ⟨http://www.fhwa.dot.gov/bridge/deficient.cfm⟩ (Oct. 7, 2010).

Hatta, H., Aly-Hassan, M. S., Hatsukade, Y., Wakayama, S., Suemasu, H., and Kasai, N. (2005). "Damage detection of C/C composites using ESPI and SQUID techniques." *Compos. Sci. Technol.*, 65(7-8), 1098−1106.

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

Hutt, T., and Cawley, P. (2008). "Feasibility of digital image correlation for detection of cracks at fastener holes." *NDT Int.*, 42(2), 141−149.

Kant, Y., and Badarinath, K. V. S. (2002). "Sub-pixel fire detection using Landsat-TM thermal data." *Infrared Phys. Technol.*, 43(6), 383−387.

Krajewski, J. E. (2006). "Bridge inspection and interferometry." M.Sc. thesis, Worcester Polytechnic Institute, Worcester, MA.

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

Morey, R. M. (1998). "Ground penetrating radar for evaluating subsurface conditions for transportation facilities." *Synthesis of Highway Practice 255,* Transportation Research Board, Washington, DC.

National Cooperative Highway Research Program (NCHRP). (2007). "Bridge inspection practices." *NCHRP Synthesis 375*, Transportation Research Board, Washington, DC.

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

Scott, M., Rezaizadeh, A., and Moore, M. (2001). "Phenomenology study of HERMES ground-penetrating radar technology for detection and identification of common bridge deck features." *Rep. FHWA-RD-01-090*, Federal Highway Administration, Research, Development, and Technology Turner−Fairbank Highway Research Center, Springfield, VA.

Warhus, J. P., Mast, J. E., Johansson, E. M., and Nelson, S. D. (1994). "Improved ground-penetrating radar, bridge decks." *Structural Materials Technology Non-Destructive Technology Conf.*, U.S. Dept. of Energy/ Lawrence Livermore National Laboratory, Livermore, CA.

Washer, G. (2001). "Reliability of visual inspection for highway bridges." 〈http://www.fhwa.dot.gov/publications/research/nde/01020.cfm〉 (Nov. 22, 2010).

Washer, G., Fenwick, R., Bolleni, N. and Harper, J. (2009). "Effects of environmental variableon infrared imaging subsurface features of concrete bridges." *Transportation Research Record 2108*, Transportation Research Board, Washington, DC, 107−114.