MichiganTech Transportation Institute

Memo

To: T. Ahlborn, D. Harris, L. Sutter, R. Shuchman, and the rest of the Project Team

From: H. de Melo e Silva, C. Brooks, D. Banach, J. Burns, D. Dean, R. Dobson, A. Endsley, R. Hoensheid, R. Oats, K. Vaghefi

CC: C. Singh

Date: April 11, 2012

Number: 26

Subject: Outline of chapters 5 and 7 (final report) and abstracts of final papers developed for each technology and the economic evaluation.

The final report of the *Bridge Condition Using Remote Sensors* project includes sections for each technology (chapter 5) and the economic evaluation (chapter 7). Each section for the technologies will follow the general outline listed below.

- **Introduction;** technology overview, literature review, and state of practice of the technology.
- **Methodology;** laboratory testing, proof of concept, software description, and field deployment.
- **Results and Discussion;** field demonstration results and discussion, pros and cons, and integration into the Decision Support System.
- **Implementation and Next Steps;** challenges for implementation, costing comments, merging (data fusion) with other technologies, and future plans.

These sections are described in the form of abstracts which are being developed into papers to be included in the final report. The abstracts for each technology can be found below. Chapter 7 of the final report will include the economic evaluation, following its own outline described later in the "Economic Evaluation" section of this memorandum.

3D OPTICAL BRIDGE-EVALUATION SYSTEM (3DOBS)

"Designing and Deploying the 3D Optical Bridge-evaluation System to Assess Bridge Deck Surface Condition"

3DOBS (3D Optical Bridge-evaluation System) uses 3D optical photogrammetric methods to produce high-resolution Digital Elevation Models (DEM) of bridge decks and other bridge elements, and includes automatic detection of surface spalls and their characteristics. Currently, the calculation of the National Bridge Inspection (NBI) rating for a bridge deck is done by inspectors visually inspecting the bridge deck. 3D optical photogrammetry is an innovative technology that can help assess bridge deck condition while at the same time enhance the ability to compare data for future reference and decision making. This technology is also less expensive than other modeling technologies, such as LiDAR (Light Detection and Ranging), and it can provide high resolution results (down to 5 mm 'x' and 'y' and 2 mm 'z').

3DOBS was developed by taking a Digital Single Lens Reflex camera (DSLR), mounting it to a truck and driving it across a bridge at appropriate speeds. The resulting photos were then processed in a close range photogrammetry software that produced a DEM of the bridge deck for four bridges in Michigan. The DEMs were then run through an automated spall detection algorithm developed at the Michigan Tech Research Institute (MTRI). The algorithm located spalls, calculated area and volume of individual spalls, and the percent of the total bridge deck that is spalled. For example, one bridge was calculated to have 6.99% surface spalling using 3DOBS. A version for assessing the underside of bridge deck was also developed.

While the current version of the system has been successful in producing surface DEMs and locating spalls, it was limited by the speed of the collection setup to 1-2 mph, which means that lanes would have to be closed for collects. Upgrades are described to enable faster data collection at near-highway speeds of at least 40 mph by upgrading the camera component of the system.

BRIDGE VIEWER REMOTE CAMERA SYSTEM (BVRCS)

"Deployment of the vehicle mounted Bridge Viewer Remote Camera System to Generate a Geospatially Referenced Photo Inventory for Bridge Decks"

The Bridge Viewer Remote Camera System (BVRCS) is an optical assessment technology that was developed and deployed by mounting low-cost cameras on a vehicle to capture a location-tagged photo inventory of a bridge deck. Currently bridges are inspected by field crews visiting bridges and taking photos of only major problems that are found during inspections. There are companies with dedicated equipment that will deploy dedicated vehicles to take a photo inventory, however the cost per deployment can be expensive. BVRCS costs less than $1,000 to deploy and can be mounted to any vehicle for deployment to multiple bridges without additional cost. This technology is composed of two point-and-shoot cameras, a low-cost global positioning system (GPS), and a laptop with software that is used to trigger the cameras. The cameras are mounted to the front of the vehicle and in the current version of BVRCS are driven at a speed of less than 5 mph.

Because the cameras capture regularly spaced photos of the bridge deck, a photo inventory of the entire bridge is generated. After the collection, the photos are processed in a GPS photo tagging software that spatially references the photos as Google Earth KML layers and Esri shapefiles. While this system is very effective at generating a photo inventory of the bridge deck, the current setup is limited by how slow the vehicle has to drive. Despite the speed, it took less than 30 minutes for setup, collect both lanes of a two lane bridge and breakdown of the system. This can be avoided by upgrading the cameras and future versions of this technology could be implemented without disrupting traffic by collecting at near-highway speeds of at least 40 mph.

GIGAPAN SYSTEM (GigaPan)

"GigaPan System: A High-resolution Photo Inventory Tool for Bridge Structures"

GigaPan is an optical assessment tool capable of creating high-resolution photo inventories of bridge structure components such as fascia and deck undersides. The original GigaPan project was a collaboration between Carnegie Mellon University and the National Aeronautics and Space Administration (NASA), with funding provided by Google, with the intent of creating a commercially viable, low-cost photographic robot and software package to catalogue the world (see <http://www.gigapan.com/>). The GigaPan EPIC hardware (costing about $800) with a Canon PowerShot SX110 IS camera ($250) was deployed to capture a very high-resolution composite photo image of the fascia and underside of four bridges in Michigan.

The GigaPan Stitch software compiled the individual images and produced high-resolution panoramic images that can be used for condition evaluation, especially to visually assess changes over time, and are easily accessible via any web browser despite typically being over one gigabyte in size. The resulting location and time-stamped composite photos have been made available to transportation agency end-users through the overall project's web-based bridge condition Decision Support System (DSS).

THERMAL INFRARED (ThIR)

"Implementation of Thermal Infrared Imagery for Concrete Bridge Inspection"

Accurate inspection and assessment of the transportation infrastructure has become a critical issue for bridge inspectors and transportation authorities in recent years. Specifically in concrete bridge components, the accurate assessment of subsurface delaminations and cracks has become a burden due to the difficulties in detecting these types of defects during the biannual visual inspections. Subsurface delaminations mostly occur within reinforced concrete bridges and eventually develop into spalls on the bridge. This evolution of decay highlights the importance of detecting this type of deterioration. Thermal infrared (ThIR) imagery has been recognized as a useful tool for detecting delaminations and subsurface defects that are not visible to the human eye. This technology collects surface radiant temperature and presents the results as a ThIR image. During the day, delaminated areas within the concrete will appear as higher temperature areas within the thermal infrared image compared to the sound concrete area around them.

This remote sensing technology can yield both qualitative and quantitative indicators of condition. A delamination map, created from the outputs of a ThIR bridge inspection, can help to document delaminations in a format useful to transportation agencies. Total area of delamination on the entire bridge deck can be calculated from the ThIR images and can be reported as a percentage of delamination over the entire bridge deck. The purpose of this paper is to summarize the results of the laboratory study and deployment of this technology on three concrete bridge decks in Michigan as well as discuss the challenges that a bridge inspector may face during data collection and processing and how these challenges could be overcome for practical deployment. Applying this technology can provide transportation agencies with useful measures for maintenance and repair decision making.

DIGITAL IMAGE CORRELATION (DIC)

"Using Digital Image Correlation for Condition Assessment of Global Behavior Measurements on Bridge Members"

Digital Image Correlation (DIC) is an optical based remote sensing technology suggested for condition assessment of challenges on the global metric level of a bridge system. DIC has been primarily deployed in controlled laboratory environments, but the technique holds great promise for implementation in field environments for in-service bridge performance evaluation. With DIC, sequential digital images before and after loading are compared optically using computer processing algorithms where pixel movement is tracked. The resulting pixel movement is then correlated to displacement and deformation which can be related to the structure's translation, rotation, and/or deformation.

The computer algorithms used for DIC comprised of (1) a commercially available code and (2) a The MathWorks MATLAB developed routine with features specific to bridge testing such as relative referencing for minimizing effects of camera movement and element scaling to provide reference measurements within tracked images. In this investigation, DIC was employed in a series of laboratory experiments using a variety of specimens, under both static and dynamic conditions. This method encompasses many variables in its analysis that were investigated in detailed laboratory evaluation and experimental setups. In the series of experiments, the variables that were considered included: lighting, surface pattern, camera stability, loading, measurement distance, and angle, in an effort to mimic conditions that would be observed in a field test of an in-service bridge. Results from the laboratory investigation confirmed the performance of the technique while allowing for consideration of factors that would be present in a field environment (wind/vibration, lighting, and measurement distance/angle).

These additional laboratory studies allowed for the creation of an improved in-field deployable system for the DIC. The benefits of the DIC definitely show great potential for bridge health indicators, as well as providing performance measurements of global behavior of bridges.

LIGHT DETECTING AND RANGING (LiDAR)

"The Evaluation of Surface Defect Detection using Light Detection and Ranging for Bridge Structural Health Monitoring"

Routine bridge inspections require labor intensive and subjective visual interpretation to determine bridge deck surface condition. Light Detection and Ranging (LiDAR), a relatively new class of survey instrument, has become a popular and increasingly used technology for providing as-built and inventory data in civil applications. While an increasing number of private and governmental agencies possess terrestrial and mobile LiDAR systems, an understanding of the technology's capabilities and potential applications continues to evolve.

LiDAR is a line-of-sight instrument and as such, care must be taken when establishing scan locations and resolution to allow the capture of data at an adequate resolution for defining features that contribute to the analysis of bridge deck surface condition. Information such as the location, area, and volume of spalling on deck surfaces, undersides, and support columns can be derived from properly collected LiDAR point clouds. The LiDAR point clouds contain information that can provide quantitative surface condition information, resulting in more accurate structural health monitoring. LiDAR scans were collected at four study bridges, each of which displayed a varying degree of degradation. A variety of commercially available analysis tools and an independently developed algorithm written in Esri ArcGIS Python (ArcPy) were used to locate and quantify surface defects such as location, volume, and area of spalls. The results were visual and numerically displayed in a user-friendly web-based decision support tool integrating prior bridge condition metrics for comparison. LiDAR data processing procedures along with strengths and limitations of point clouds for defining features useful for assessing bridge deck condition are discussed. Point cloud density and incidence angle are two attributes that must be managed carefully to ensure data collected are of high quality and useful for bridge condition evaluation. Mobile LiDAR datasets are evaluated and compared to terrestrial LiDAR data as a potential data source for bridge condition evaluation. When collected properly to ensure effective evaluation of bridge surface condition, LiDAR data can be analyzed to provide a useful data set from which to derive bridge deck condition information.

ULTRA WIDE BAND IMAGING RADAR SYSTEM (UWBIRS)

"Applications of Ground Penetrating Radar for Assessment of Subsurface Bridge Condition Indicators"

While optical remote sensing technologies provide information about the surface condition of bridge decks, radar systems, employing low frequency electromagnetic waves that penetrate the deck material, provide information about the deck interior. Previous studies have demonstrated that down-looking, low frequency, ground penetrating radar (GPR) can image delaminations, defects, and rebar within concrete bridge decks. Several commercial companies have developed production systems to produce reflectivity maps that are indicative of deck defects such as subsurface delaminations. These maps, or more specifically metrics derived from these maps, can be used within the Decision Support System (DSS) to provide quantitative measures of deck condition which contribute to the overall bridge condition metric. The current program reviewed available commercial systems for compatibility and utility with the DSS and conducted a limited set of radar measurements to extend the use of radar technology for bridge assessment.

Radar measurements conducted under this program as part of the field testing aimed to extend use of radar technology for bridge assessment in two ways. First, current commercial radar systems used to survey deck condition utilize arrays of truck or cart mounted antennas that are scanned at a vertical oriented close to the deck surface. These systems operate in close proximity to the deck and may require the bridge to be closed for extended periods of time to complete the scan. To mitigate these limitations, an alternate imaging approach where a single radar antenna viewing the deck surface at an oblique angle from the side was investigated as part of a potentially less-expensive Ultra Wide Band Imaging Radar System (UWBIRS). This approach would allow a vehicle mounted radar travelling in one lane to produce a two-dimensional image of an adjacent lane, and thus, potentially reducing data collection time and interference with traffic. The imaging geometry is also similar to the geometry that would be provided by a standoff airborne radar, so the data collection provided information for assessing the potential utility of a standoff airborne sensor.

The second radar application investigated as part of the field demonstration was the use of low frequency radar to image the interior of concrete box beams. Lack of visual access to the interior of box beams makes condition assessment difficult. Low frequency, 3D imaging radar potentially provides a means of interrogating the structure interior. For each application, a prototype low frequency, wideband radar system was developed using a commercially available transmitter/receiver unit. These systems were used to image bridge structures as part of the summer field demonstrations, and resulting data were evaluated for their utility for bridge condition assessment. In this section, currently available commercial radar systems will first be reviewed, and their applicability to the DSS will be discussed. Subsequently, the exploratory radar measurements conducted as part of the field demonstrations will be reviewed. The radar systems and experiments conducted as part of the field demonstrations will be described, and the results of the experimental collections and their utility for structure assessment will be summarized. Advantages and limitations of the approaches will be presented, along with recommendations for potential future work.

SYNTHETIC APERTURE RADAR (SAR)

"Synthetic Aperture Radar Speckle for Bridge Deck Condition Assessment"

In this investigation, the project team attempted to correlate bridge surface roughness as measured using Synthetic Aperature Radar (SAR) airborne imagery with bridge deck condition from established techniques, namely the NBI (National Bridge Inventory) inspection. Coherence speckle, often observed as "graininess" in radar backscatter images, is produced due to phase differences between picture elements (pixels) in the scene. In turn, these phase differences in the image correspond to phase differences between scattering elements in the scene such as height differences on the order of the radar wavelength (or optical wavelength in the case of optical speckle from coherent light sources). If a surface is rough at that scale then the speckle pattern observed may contain a measure of that roughness.

Airborne SAR data were obtained for three demonstration bridges in Michigan. Due to inadequate collection geometry in the available satellite imagery, the imagery from all but one of the bridges could not be analyzed. The project team applied a technique first developed under a previous study, Transportation Applications of Restricted-Use Technologies (TARUT), but, lacking timely ground data for the bridge(s), was not able to assess the performance of the technique. The report lays out the steps needed for validation of the technique, describes the methodology employed, and comments on the commercial viability and practicality of the technique.

INTERFEROMETRIC SYNTHETIC APERTURE RADAR (InSAR)

"Assessing the Use of Commercial Interferometric Aperture Radar Imagery for Detection of Bridge Settlement"

Interferometric Synthetic Aparture Radar (InSAR) displacement mapping (D-InSAR) techniques have demonstrated utility in detecting sub-centimeter resolution elevation changes over time in studies of land subsidence and in studies of smaller-scale targets such as buildings. In this analysis it was sought to assess the potential to detect bridge settlement for two bridges where known elevation changes have occurred by using two-pass D-InSAR with commercially available SAR (Synthetic Aperture Radar) imagery from the ERS-2 satellite.

Imagery for each bridge was acquired before and after known elevation changes and processed using ERDAS IMAGINE's D-InSAR module. The resulting displacement maps did not definitively reflect the known changes in elevation for either bridge. The principal conclusion was that the commercial SAR imagery used in this task was not optimal for detection of bridge settlement due to relatively coarse horizontal resolution (> 4 m) which affected the vertical resolution change detection. Additionally, displacement detection may have been hampered by low radar return of paved roads. Other projects using D-InSAR methods to detect settlement of relatively small target features are reviewed for comparison.

MULTISPECTRAL SATELLITE IMAGERY (MSI)

"Assessing the Overall Condition of Bridge Decks by Using Commercial High-resolution Multispectral Satellite Imagery"

Commercial high-resolution multispectral satellite imagery, such as WorldView-2, IKONOS, and GeoEye-1, has a spatial resolution of up to 0.5 m which is a relatively coarse resolution when compared to other more "onsite" remote sensing techniques. Therefore this technology was used to evaluate the overall condition of the bridge deck rather than individual areas, as was done for the Transportation Applications of Restricted-Use Technologies (TARUT) study. For testing this technology, archived imagery from IKONOS and WorldView-2 was used for the field demonstration sites. The imagery was first pan-sharpened before the analysis was run to increase the resolution of the spectral bands to match the higher-resolution panchromatic band. Based on previous work at the Michigan Tech Research Institute (MTRI), the VIS2-band differencing technique was adapted for evaluating bridge condition.

In this technique an input integer was generated for each bridge by subtracting band 1 from band 4 for IKONOS imagery and band 2 from band 8 in WorldView-2 imagery and then averaging the pixel values of each bridge. This value was used to correlate to the condition of the bridge deck as determined by the inspection reports. With this technology an overall condition indicator for a bridge deck can be calculated without closing lanes or disrupting traffic. However, despite this advantage, satellite imagery is more expensive than some other technologies and it is dependent on whether the satellite is over the target site when clouds are not present, and does not provide detailed condition information.

ECONOMIC EVALUATION

The decision to integrate remote sensing technologies into bridge inspection practices can be viewed as an investment strategy for both the public and private sectors. The economic indices (e.g., capital and operational costs) are critical for quantifying and qualifying the ability of the proposed new technologies to meet the functional and operational needs of the bridge inspection process. This economic assessment is designed to assess the cost effectiveness of remote sensing technologies by comparing marginal costs of employing sensor technologies to the marginal enhancements that they provide, and therefore to ensure a practical, cost-effective product to be integrated into transportation agency operations.

Input data was obtained from field demonstrations, vendor interviews, and two rounds of interviews with the Michigan Department of Transportation (MDOT) stakeholders. The cost benefit analysis was conducted based on several assumptions (e.g., adoption curve of new technologies, time period of analysis, and geographic coverage) and deployment scenarios of remote sensing technologies (e.g., combinations of technologies and service types). This evaluation also examines the benefits of the project's Decision Support System (DSS) integrated with remote sensing indicators of bridge conditions. Finally, this evaluation recommends strategies to achieve cost effectiveness of remote sensing technologies.

Chapter 7 of the final report of the *Bridge Condition Using Remote Sensors* project will include the economic evaluation of commercial remote sensing technologies considered and the DSS for bridge health monitoring. The chapter will follow an outline which is different than the outline of the technologies above. It is listed below.

- **Introduction**
- **Bridge Inspection and Maintenance in the Context of Shrinking Transportation Revenue**

- **Description of Existing Bridge Inspection Practices**
- **Remote Sensing Technologies for Bridge Condition Assessment**
- **Economic Evaluation of Bridge Inspection Using Remote Sensing Technologies**
- **Summary and Discussions**