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ISSUES AND SOLUTIONS ASSOCIATED WITH REMOTE SENSING APPLICATIONS FOR BRIDGE MONITORING

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As part of the US DOT Research and Innovative Technology Administration (RITA) sponsored National Consortium of Remote Sensing Technologies (NCRST), the Center for Transportation Policy Studies at the University of North Carolina at Charlotte is teaming up with state and regional departments of transportation, consulting engineers and professional aerial photographers in developing advanced remote sensing (RS) technologies for bridge monitoring. Contrast to conventional monitoring technologies such as embedded sensors or ground penetrating techniques, RS technologies respond naturally to the service requirements for bridge inspection needs - considering the size and locations of bridges. However, several critical questions also come up including: What is the required resolutions for monitoring technologies for bridges? And how it can be implemented into existing state DOT work flow? These two questions reflect that remote sensing applications to bridge health monitoring presented critical technology and business challenges to the bridge industry that were previously not encountered by other proposed embedded or contact sensing systems including: the lacking of high resolution/low cost techniques and interpretations of damages identified, the lack of experiences of bridge engineers with remote sensing and geospatial technologies, inadequate vendors and missing coordination with remote data in bridge management software. These challenges are further distended by the shift of bridge management paradigm from bridge maintenance to bridge preservation, which demands even higher level of technology requirements.

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ABSTRACT: As part of the US DOT Research and Innovative Technology Administration (RITA) sponsored National Consortium of Remote Sensing Technologies (NCRST), the Center for Transportation Policy Studies at the University of North Carolina at Charlotte is teaming up with state and regional departments of transportation, consulting engineers and professional aerial photographers in developing commerical remote sensing (CRS) technologies for bridge monitoring. Several critical questions come up regarding the implementation of the technology including: What is the required resolutions for monitoring technologies for bridges? And how it can be implemented into existing state DOT work flow? These two questions reflect that remote sensing applications to bridge health monitoring presented critical technology and business challenges to the bridge industry that were previously not encountered by other proposed embedded or contact sensing systems including: the lacking of high resolution/low cost techniques and interpretations of damages identified, the lack of experiences of bridge engineers with remote sensing and geospatial technologies, inadequate vendors and missing coordination with remote data in bridge management software. These challenges are further distended by the shift of bridge management paradigm from bridge maintenance to bridge preservation, which demands even higher level of technology requirements.

1 INTRODUCTION

Since 2007, the Center for Transportation Policy Studies at the University of North Carolina at Charlotte has teamed up with state and regional departments of transportation (DOT), consulting engineers and professional aerial photographers in developing advanced remote sensing (RS) technologies for bridge monitoring. This research partnership is part of the US Department of Transportation Research and Innovative Technology Administration (RITA) sponsored National Consortium of Remote Sensing Technologies (NCRST). During the Phase I study, several issues associated with Commercial Remote Sensing (CRS) and Spatial Information (SI) technology applications for bridge monitoring have been identified through discussion with individual bridge managers from several states and results from a nationwide survey conducted through collaboration between the American Association of State Highway and Transportation Officials (AASHTO) and the research team:

- **Limitations in bridge inspection.** Bridge maintenance is based on a generalized inspection process established by the federal government, which is visually based. State bridge engineers indicated a need for novel and comprehensive techniques to generate meaningful data to help bridge engineers to better assess bridge conditions.
- **Limitations in bridge management styles.** Despite the popular use of the PONTIS Bridge Management System (BMS) adopted by the AASHTO Subcommittee on Bridges and Structures, bridge managers typically establish their own bridge data management tools to supplement the PONTIS output. Use of bridge inspection data for bridge management decision-making varies from agency to agency. PONTIS undergoes continuous updating by the Subcommittee and contractors to AASHTO.
- **Misunderstanding of CRS-SI capabilities.** In the national survey, it is obvious that applications of remote sensing for bridge monitoring are not available and bridge managers generally have limited experiences with the CRS-SI technologies.
- **Complexity in multivariate data integration.** Because CRS data typically exists in image format and bridge data in PDF or text-file formats, the key Phase 1 challenge was to integrate the data into a visualization system, so that the bridge managers can visually study the combined or "fused" data and other information.

Through the partnership, it is quickly recognized that bridge managers have different ways of conducting their businesses, hence, any technology that will have a nation-wide impact needs to be practical, scalable, cost-effective and be able to integrated into system-wide implementation. Such technology currently does not exist. Summarizing the above bridge management and maintenance issues, the following specific research needs are identified:

- The need for cost effective techniques to enhance bridge inspection and monitoring.
- The need to enhance bridge management software to integrate CRS data.
- The need for more exposure to CRS and SI technology applications in bridge management.
- The need to enhance bridge data integration.

2 REMOTE SENSING TECHNIQUES

To address the first research need, a comprehensive review of different remote sensing techniques was conducted and two technologies were recognized and developed: 1) terrestrial 3D scanning laser (also called LiDAR for Light Detection and Ranging) and 2) small format aerial photography. Several applications of the terrestrial 3D LiDAR system have been identified including 1) bridge surface defect quantification, 2) bridge deflection measurement/joint movement measurement, 3) bridge before and post-blast monitoring and 4) bridge underclearance measurement (Liu et al. 2010). Most of these applications are made easy by manipulating the 3D point cloud data generated by LiDAR. Since these LiDAR applications currently do not exist, different software applications (LiBE, LiBE-C and LiBE-D) have been developed. Figure 1 shows LiDAR measurements of bridge clearance.

Bridge	670511 (meter)	670512 (meter)
Inspection Report	4.750	5.588
Laser Data	5.005	5.611

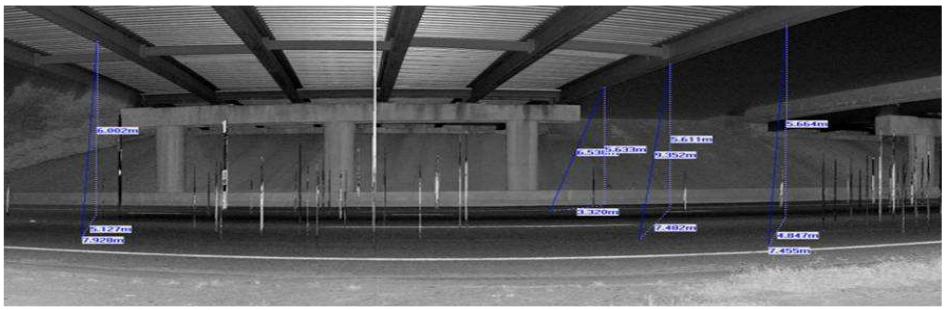


Figure 1. Underclearence measurements using LiDAR reflectivity image

The second technology is a derivative of conventional small format aerial photography (using 35 mm cameras), which differentiate itself from the more popular mapping grade aerial techniques using large to medium format cameras in that it is more cost effective and easier to implement. However, conventional small format aerial photography typically shoots out of the window of an airplane, hence, for bridge monitoring, a unique belly-shooting technique is developed (SI-SFAP for Spatially Integrated Small Format Aerial Photography). The SI-SFAP (Spatial Integrated-Small Format Aerial Photography) uses fixed wing airplanes with bully cameras to capture low-cost, high resolution (sub-inch) images for crack and joint movement analysis of bridge decks. Figure 2 shows images captured using SI-SFAP that showed a six-inch wide joint damage.

GoogleEarth Image (6 inch resolution)

SI-SFAP Image (Sub-inch resolution)

SI-SFAP of a 6-inch wide Joint (Sub-inch resolution)

Figure 2. Comparison of 6-inch resolution and sub-inch resolution aerial scans and detection of joint damages using sub-inch damages.

3 CRS AND BRIDGE MONITORING

For system-wide implementation it is essential to recognize how CRS technologies can be used in bridge monitoring. Since current bridge inspection manuals do not address such issue, a study of the AASHTO Bridge Core Element Code (2011) was performed to identify the most reasonable items that can benefit from CRS technologies. Table 1 shows a condensed table of AASHTO Core Elements and the relevant applications using LiDAR or SI-SFAP techniques. For example, both Flyover (SI-SFAP) and LiDAR are applicable for evaluation of concrete decks or slabs, however, any elements

underneath a bridge will not likely be seen by the Flyover technique with the special case of a Through Truss Bridge.

Table 1 CRS applications to CoRe element: decks/Super Structure (Hauser 2009)

Decks/Slabs	**CRS Applications**	**Super Structure**	**CRS Applications**
Concrete (bare)	Flyover, LiDAR	Closed Box Girder	LiDAR
Concrete with overlay	Flyover, LiDAR	Open Girder/Beam	LiDAR
Steel – open grid	Flyover, LiDAR	Stringer	LiDAR
Steel – concrete filled	Flyover, LiDAR	Through Truss	Flyover, LiDAR
Steel – corrugated	Flyover, LiDAR	Deck Truss	LiDAR
Timber (Bare)	Flyover, LiDAR	Timber Truss/Arch	LiDAR

It is critical to recognize that bridge problem detection demands higher resolutions than conventional remote sensor requirements. For example, bridge damages may involve millimeter cracks. Table 2 summarizes several identifiable resolution requirements for bridge monitoring.

Table 2 Resolution requirements for bridge attribute detection (Hauser 2009)

Attributes	**Resolution requirements**
Bridge environment	0.5-10 m
Bridge geometry information	0.5 m
Traffic effects	1 m
Clearance	0.3 m
Bridge intolerable abutment movement	25 mm
Bridge structure surface defects	13 mm
Bridge structure surface cracks	5 mm
Bridge joint movements	50 mm

4 DATA INTEGRATION TECHNIQUES

Number two and number four needs described before deals with the integration of existing bridge data with remote sensing data. Two approaches may be considered in data integration: 1) use a common platform for all data; or 2) establish unqiue approach to integrate data in their current format. The most relevant existing bridge data to structural evaluation are the bridge ratings and results documented in the inspection reports. To “normalize“ CRS data, several damage indices have been defined including LiDAR Defect Rating and BSCI Aerial Photo Rating. LiDAR Defect Rating is essentially a ratio of damaged area to total area of interest on the bridge (Liu 2010). BSCI Aerial Photo Rating is a quantifier based on pavement crack quantification index (Rice 2010). BSCI Aerial Photo Rating is dependent on the quality of the aerial photos. Hence, when the images have significant obstructions such as tree shadows, the images will not result in true represejtaThese damage indices, albeit limited in their physical relevance to actual damages of a structure, are absolute quantifiers comparing to current inspection ratings, which rely on heuristics.

To assess the possibility of the second approach, a common platform for integration is required. Since current BMSs do not include CRS data, a data visualization platform is developed. The basic idea behind IRSV is to provide a common platform that the CRS

data can be shared and displayed such that the capability of CRS technologies in bridge management and maintenance applications can be demonstrated. Figure 3 demonstrates the complexity of data integration and the existing infrastructure management difficulties; the top-left photo represents actual physical conditions on an existing structure that currently are documented by bridge inspectors; lower-left represents the thermal revelations of possible environmental elements that may result in structural deterioration (low resolution CRS information); lower right graphic indicates the functionality of the bridge as a function of traffic flow (intermodal information); and, finally, the upper right shows an aerial view of the Charlotte City Center (geospatial information). It must be noted that issues such as the management and handling of the mega-size image files and traffic data for urban areas of this size present a significant challenge.

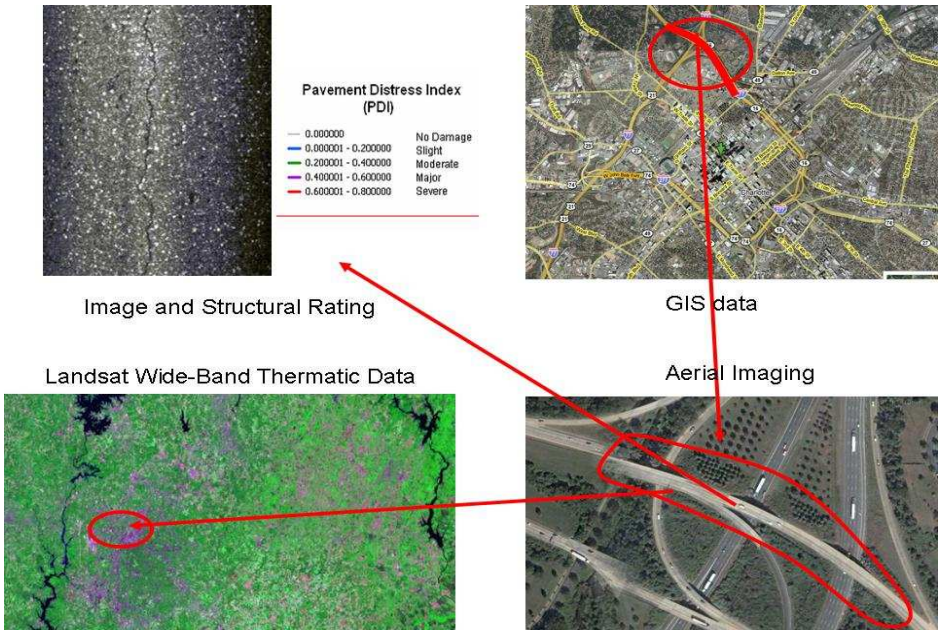


Figure 3. Data integration for IRSV for test case bridges.

There are several methods in establishing multivariate data correlations, in IRSV, a knowledge-based approach is adopted (Lee et al. 2009). Built-in interconnectivity of IRSV allows bridge managers to manipulate domain data (bridge information) into different visualizations, thus enabling a learning/knowledge - sharing/ knowledge creation mechanism. This mechanism is illustrated in Figure 4. The visualization component is built on the platform of an interaction-enabled large display technology. The IRSV

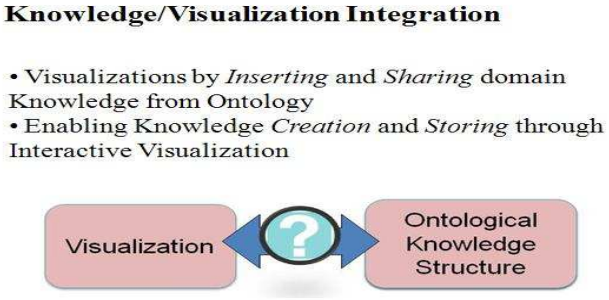
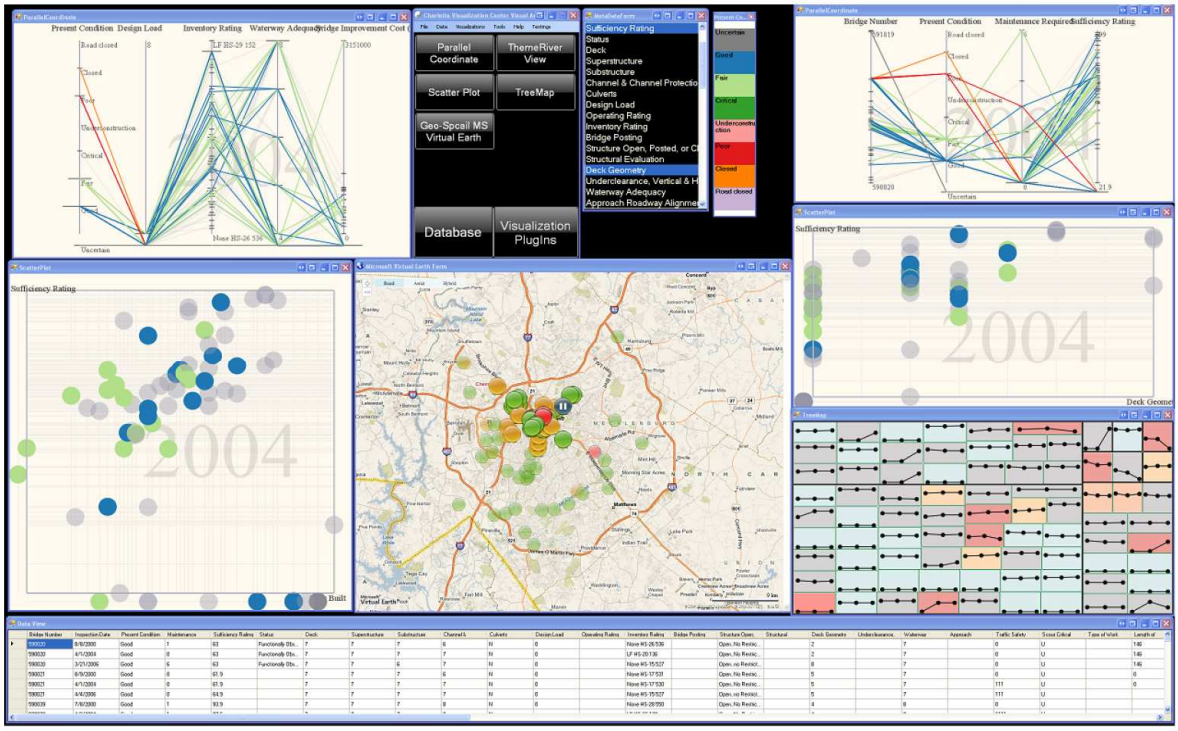


Figure 4. IRSV fucntionality in knowledge/ visualization integration.

(Integrated Remote Sensing and Visualization) program provides several data visualization tools that the bridge managers can use for all the bridge in the inventory (Wang et al. 2009).

Figure 5 shows IRSV designed to assist bridge managers on depicting four analytical aspects: geospatial, temporal, relational and bridge details per-inspection. For each aspect, IRSV utilizes different types of interactive visualizations views to represent the corresponding information. Instead of fixing the dimensions for each view, IRSV allows bridge managers to interactively select demanded data dimensions on the fly and create appropriate views as they proceed – the system will then automatically coordinate these views and provide bridge managers a highly interactive visual data exploration



environment. The critical elements in IRSV or any CRS-based BMS will include: 1) bridge information, 2) data management system, 3) data acquisition/analysis processes, 4) personnel involved and 5) service environment. Hence, system-wide security is an essential implementation consideration. Development of a systemic security plan, the individual clientele must be engaged and dictate the security design including establish the security objectives, defining the control policies and outlining the hierarchy of security measures. The security issue is related at both information and software levels and can be vastly different issues. For software security, several measures can be established during the life cycle of a software development. Measures typically include establishing a clear security objective and design the software around the objective. Proper and efficient feedback systems can be established allowing reporting of security breaks back to the code developers to revise and update the software system.

Information security, on the other hand, refers to the protection of critical information and information systems

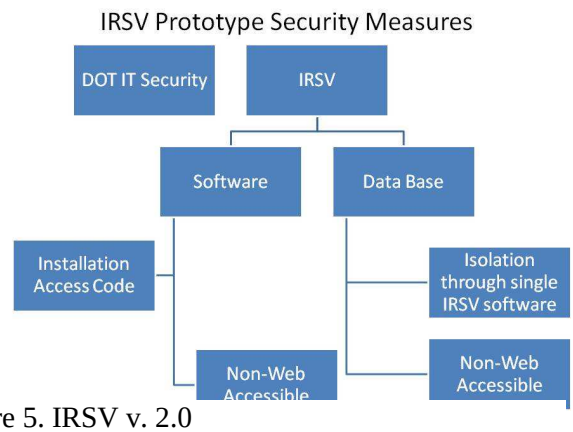


Figure 5. IRSV v. 2.0

from unauthorized access, use, disclosure, disruption, modification or destruction. Effective information security relies on measures such as access protocols and/or cryptographic control, internal/external security assessments, education/awareness building, standalone hardware, and information infusion segregation, etc.

Currently, state and federal publications on bridge inspection and management practices do not have specific recommendations on the security measures of bridge management systems. IRSV system security protocol is established with minimal access rights (rights limited only to bridge managers accessed via a single workstation).

Figure 6. Security measures for IRSV prototype system

Figure 6 shows the IRSV prototype security relationship and measures. Physical access to IRSV installed workstations will be controlled locally at DOT sites. Cyber-access to IRSV installed workstations will be controls by DOT IT system security. Thus, even though the database (including all image files) that are not encrypted, access to these data are controlled at the physical and cyber levels by DOT IT policies and security solutions. This will allow for the diverse security policies and systems that are anticipated across various DOTs.

5 COMMERCIALIZATION

Finally, need number four is regarded as a critical process of disseminating and promoting the use of CRS technology (commercialization). A first question that should be addressed is how implementation of CRS technology would impact existing bridge inspection practices. An obvious advantage of CRS technology is their full-field and measure-from-a-distance nature, which reduces traffic disruption during monitoring, which will be a significant improvement over any existing inspection techniques. However, the most significant contribution of remote sensing should be the provision of physical quantification, which may be lacking based on current visual inspection procedure.

Figure 7 shows conventional bridge inspection process which started with bridge inspectors review previous inspection report (from two years ago) and identify potential existing problems. Since field visual inspection is warranted, bridge inspectors then negotiate access to site and possible traffic control assistance. Systematic close up inspections of the bridge conditions are then conducted to identify problems to the three key bridge components: bridge deck, bridge superstructure and bridge substructures.

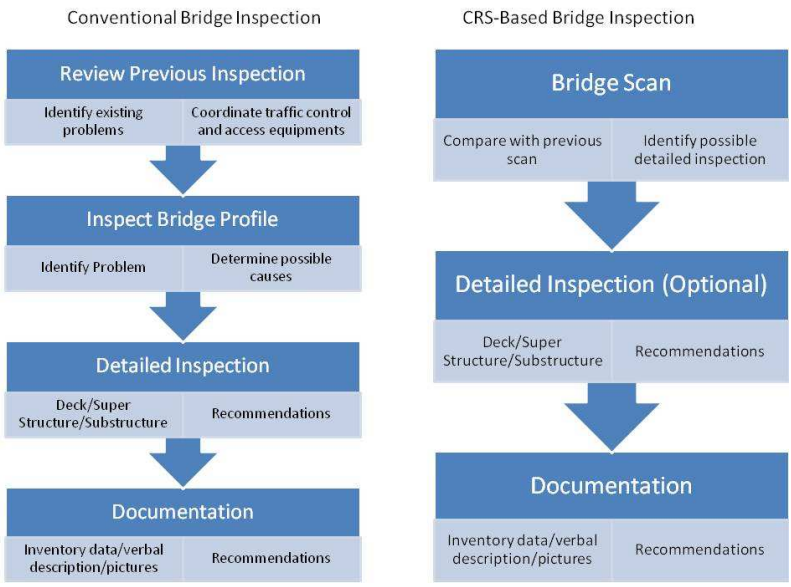


Figure 7. Modified bridge inspection workflow based on CRS technologies vs. conventional bridge inspection

The CRS technologies as outlined in this study can significantly reduce the process by allowing bridge inspectors to first conduct a flyover of the bridge and conduct preliminary walk-through and LiDAR of the bridge defective areas without negotiating site access. Inspectors can then compare the scan results from the CRS scans to provide solid evidence of possible worsening of an existing defect, to establish a possible bridge movement from comparing the aerial photos and to determine level of additional inspections required.

6 OUTREACH

The other consideration in commercialization is active outreach activities. Rehm (2011) indicated that the process of technology adoption within DOTs typically involve a champion at the mid-management level. Hence, outreach efforts should consider wide range information dissemination and demonstration. Three approaches were adopted for this study: 1) dissemination via mail-out information packages to different DOTs; 2) dissemination via project website (www.ncrst.uncc.edu); and 3) dissemination via project partnership. A critical partnership for this study is the AASHTO TSP-2 (Transportation System Preservation Technical Services Program). Key functions of the TSP-2 are information clearinghouse on infrastructure preservation and the forum for idea exchanges. Through TSP-2, useful information was identified regarding the implementation of LiDAR technologies at different state agencies. Finally, active National Advisory Committee (NAC) involving experts in the discipline are critical in ensuring the technology validation and appropriate business approach.

7 CONCLUSION

This paper summarizes the Phase I and II USDOT-RITA NCRST projects, which provided the opportunity to critically evaluate new CRS technologies developments and the implementation of these technologies to bridge monitoring. The investigation of possible integration of remote sensors into bridge inspection helped identify the deficiencies in conventional CRS technologies and the need for commercialization. Several approaches have been taken to ensure the information dissemination can reach a wide audience, which was accomplished via collaboration via inter-agency groups such as the TSP-2.

8 ACKNOWLEDGEMENTS

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