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INTEGRATED REMOTE SENSING AND VISUALIZATION (IRSV) SYSTEM FOR TRANSPORTATION INFRASTRUCTURE OPERATIONS AND MANAGEMENT

-PHASE ONE-

VOLUME 1

SUMMARY REPORT

By

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15. Supplementary Notes

This is the first of seven volumes that provide a comprehensive description of the IRSV Phase One project. The Proof of Concept version of the IRSV System will have further testing in additional state and local DOTs or highway agencies in upcoming Phase Two effort, to be concluded in 2012.

16. Abstract

The Integrated Remote Sensing and Visualization System (IRSV) is being designed to accommodate the needs of today's Bridge Engineers at the state and local level from the following aspects:

- Better understanding and enforcement of a complex inspection process that can bridge the gap between evidence gathering and decision making through the implementation of ontological knowledge engineering system;
- Aggregation, representation and fusion of complex multi-layered heterogeneous data (i.e. infrared imaging, aerial photos and ground-mounted LiDAR etc.) with domain application knowledge to support an understandable process for decision-making;
- Robust visualization techniques with large-scale analytical and interactive visualizations that support users' decision making; and
- Integration of these needs through the flexible Service-oriented Architecture (SOA) framework to compose and provide services on-demand.

The specific objectives of the project are to:

- Enhance the National Bridge Inspection System (NBIS);
- Provide opportunities for state and local DOTs to develop remote sensing and visualization applications for BMS;
- Provide temporal bridge condition tracking;
- Enable agencies to make more precise damage assessments; and
- Provide better and more systematic data interpretation through parallel data displays.

This first Volume, based on a more complete, seven-volume set of reports, describes the development of the IRSV to date as a summary for management review and understanding. Our intent is to ultimately establish a component of an on-going nationwide dialogue and upgrade of bridge management systems in state and local transportation agencies.

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Executive Summary

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We also acknowledge and appreciate the excellent review and input of our National Advisory Committee: Sreenivas Alampalli, New York State DOT; Mrinmay (Moy) Biswas, North Carolina DOT; Hamad abu-Harash, Iowa DOT; Kelley Rehm, American Association of State Highway and Transportation Officials (AASHTO); K. T. Thirumalai, STI International; Dan Turner, University of Alabama; and Phillip Yen, FHWA Turner-Fairbank Research Center.

1.1. Introduction

The intent of this multi-year research project is to develop and validate Commercial Remote Sensing (CRS) and Spatial Information (SI) applications that can enhance current bridge management systems (BMS). Federal mandates the national bridges be inspected every other year. Current bridge inspection practices do not involve remote sensing techniques (FHWA 2006a). Hence, a bridge data management system, Integrated Remote Sensing and Visualization (IRSV), is developed to accommodate geospatial information and remote sensing data. The IRSV can serve as a remote sensing data management and decision-making tool. A longer-range objective is to enable the IRSV components to be integrated into PONTIS and other state and local BMS applications. IRSV contains a high resolution visual database using, in part, on-site bridge inspection data. Current National Bridge Inventory System (NBIS) does not include remote sensing data or similar image-based data (FHWA 1995). IRSV addresses this deficiency by including remote sensing data developed within this project which include LiDAR imaging, sub-inch aerial photography, and Infrared images.

Our goal for IRSV is to alleviate limitations in current bridge management systems by uncovering potential Commercial Remote Sensing applications that address complex issues in data fusion of multiple formats, particularly in time series data that are not always available. IRSV can provide temporal data transformation and detailed bridge damage information to enhance our understanding and quantification of various types of bridge damage, both on bridge decks and in structural members. Further development efforts are being coordinated through AASHTO and the FHWA. To ensure a practical, cost-effective product that is able to be integrated into system-wide implementation, the IRSV development will be enhanced by working with highway agencies nationwide that will serve as future test sites. Other highway agencies that will serve as the next test sites include New York, Iowa, Alabama, Texas, and Los Angeles County. The specific objectives of the project are: 1) to enhance the National Bridge Inspection System (NBIS), 2) to provide opportunities for state and local DOTs to develop the visualization and system requirements for their own BMS; 3) to provide temporal bridge condition tracking; 4) to enable agencies to make more precise damage assessments; and 5) to provide better and more systematic data interpretation through parallel data displays.

Partners in this first phase research project have included the City of Charlotte DOT and the North Carolina DOT. The multi-disciplinary research team includes the UNC Charlotte Center for Transportation Policy Studies (lead), the Charlotte Visualization Center, ImageCat, Inc., Boyle Consulting Inc., and Dr. C. Michael Walton, P.E.

1.2 Literature Review

1.2.1 Commercial Remote Sensing Applications

For the past fifty years, several commercial remote sensing-spatial information (CRS-SI) technologies for wide-bandwidth spectral information sensing and imaging have been developed integrally with satellite/airborne/ground based surveillance platforms such as IKONOS, Quickbird and OrbView-3. Additional airborne sensors including ADAR 5500, Intermap STARS-3i, and TerraPoint. LiDAR remote sensing systems including LandSat, SPOT and the AVHRR, are technically-proven and available commercially. Several of these CRS-SI technologies have been implemented for traffic management and environmental studies (NCRST 2000).

Remote sensing is defined as the sensing technique that collects information of an object, area, or phenomenon from some distance without actually contacting it. Our definition does not include any specific distance. Typically, remote sensing refers to imagery and image information taken by airborne and satellite systems (US Army Corps of Engineers 2003). As remote sensing platforms, satellites provide a significant amount of remote sensing imagery today. Based on spatial resolution, satellite data is classified as coarse resolution data or high resolution data. Ranging from dozens of meters to several hundred kilometers, coarse resolution satellite data are mainly used for large scale problem monitoring, such as weather prediction or marine observation (Glantz et al. 2009 and Ahn et al. 2006). High resolution wide-bandwidth sensing and imaging also make infrastructure monitoring and management possible (Pieraccini et al. 2004 and 2008).

To address resolution issues for bridge monitoring, we first explore the tolerance of bridge displacements. Moulton et al. (1985) collected data from 314 bridges in 39 U.S. states, the District of Columbia, and four Canadian provinces, and generated bridge tolerance movement criteria based on the data. Table 1.1 lists the attributes associated with bridge performance monitoring. The bold items are the ones that can be collected by remote sensing devices.

Currently, many commercial satellite sensors can provide earth images with a resolution near or better than 0.5 m. GeoEye launched the world’s first one-meter commercial remote sensing satellite IKONOS in 1999. The latest launched GeoEye-1 (September of 2008) has a ground resolution of 0.41 m (2009). DigitalGlobe now offers commercial panchromatic satellite data reaching the resolution of 0.46 meter from Worldview-2 satellite (2009).

Compared to satellite imagery, airborne sensors have the potential of providing images with higher resolutions. In particular, the Small Format Aerial Photography (SFAP) technique that equips low flying small airplanes with professional grade video/ photogrammetry equipment can provide extremely high-resolution photos or videos. InSiteful imagery (2007) provides aerial photography with a resolution of 0.013 m, which can be made faster than most ortho-photography. Figure 1 is an airborne image (0.013 m resolution) of a bridge in Charlotte, North Carolina taken using the Small Format Aerial Photography (SFAP) technique. It was taken by a Canon 5D camera on a C210L aircraft at 300m above ground level. The rutting of the bridge deck can be detected (in white circle) in Figure 1.1. Table 1.2 compares the resolution between different airborne/satellite acquisition approaches.

Table 1.1 Sensing and measurement attributes for bridges

Damage	*Deterioration*	*Operation*	*Service*
Impact	**Corrosion**	**Traffic Counts**	**Congestion**
Overload	Fatigue	Maximum Stress	Highway Crashes
Fire	Loss of Prestress Force	Stress Cycles	Reduced Traffic Capacity
Scour	Unintended Structural behavior	**Deflection**	Reduced Load Capacity
Seismic	Chemical Changes	**Displacement**	Increasing Traffic
Cracking	**Transportation Property Loss**	**Clearance**	Delay
Settlement	Water absorption	**Bridge Geometrics**	Unreliable travel time

Figure 1.1 Aerial photo of NCDOT bridge 590179 (Source: InSiteful Imagery, Inc., 2009)

It is important to understand that values in Table 1.2 are taken from highest resolution sensors in a corresponding satellite. Ground based sensors provide detailed object information with better resolution than satellite and airborne-based sensors. Most ground-based remote sensing devices can measure damage to a structure with accuracy in millimeters. A number of research projects have related using ground-based remote sensing techniques for infrastructure monitoring (Fuchs et al. 2004a and 2004 b, Sakagami et al. 2002, Tarchi et al. 2000 and Jiang et al. 2002). The techniques include, among others, ground based interferometric SAR, digital and video camera, infrared camera, and ground penetrating radar. Table 1.3 lists several popular ground base remote sensing techniques and corresponding resolutions. In particular, infrared imaging and LiDAR techniques are reviewed and recommended for bridge health monitoring.

Table 1.2 Summary of resolution comparison for different data acquisition approaches

Provider	Technology	Resolution
DMSP satellites	Operational Linescan System (OLS) sensor	2.7 km
Meteosat satellites	Imaging radiometer sensitive to visible band	2.5 km
GMS satellites	Visible and infrared spin scan radiometer	1.25 km
GOES satellites	Multispectral channels imaging radiometer	1 km
HCMM satellite	Visible and thermal infrared radiometer	500 m
Skylab space station	Multispectral camera (S-190A)	60 m
MOS-1 satellites	Multispectral electronic self-scanning radiometer	50 m
Landsat satellites	Thematic mapper (TM) sensor	30 m
SPOT satellite	Scanning HRV sensor	10 m
IRS satellites	Panchromatic (PAN) high resolution camera	5.8 m
Worldview-2 satellite	star trackers	0.46 m
GeoEye-1	GeoEye-1	0.41 m
STAR	Spaceborne Radar Systems	5 m
Digital image systems	Digital camera	0.3 m
InSiteful Imagery	Small-format aerial photography	0.013 m

Table 1.3 Ground based remote sensing techniques: resolution comparison

Remote Sensing Techniques	Functional Description	Resolution or Limitation
Digital and video camera	Surface images for defect detection and displacement measurement	Depending on equipment character and distance to object
Interferometric radar	Static and dynamic displacement measurement	0.5mm
3D laser scanner	Static and dynamic displacement measurement and defect detection	0.5mm with the distance of 30 meters
Infrared camera	Structure interior defect detection	0.25mm and maximum measure depth is 12.7mm for composite reinforcement
Ground penetrating radar	Structure defect detection and material thickness measurement	2.6% material thickness measurement error; for concrete and polystyrene maximum measure depth is 700mm

Due to the natural geospatial representation and unique data acquisition features of remote sensing techniques, many researchers (Welch, 1982, Benson, 2000 and Park et al. 1999) have shown their interest in the potential applications of remote sensing for infrastructure analysis. Current application areas of remote sensing for infrastructure can be roughly classified into three categories: construction planning and management, transportation, and structural health monitoring. Research for infrastructure planning and management is typically based on the visual interpretation of satellite imagery combining with digital elevation model of the objective area (Tralli et al. 2005, Stramondo et al. 2006, Eguchi et al. 2005, Simonetto and Oriot 1999, Forzieri et al. 2008, Eihoz 2006 and Ghose et al. 2006). Satellite imagery has been widely used for roadway identification and mapping (Saxena 2001, Amekudzi and Baffour 2002, Morain 2002, Uddin 2002, Caceras 2007, Keskinen 2007 and Hinz et al. 2000, 2003).

Due to the resolution requirements for structural health monitoring, the literature review at this point is devoid of citations that relate using satellite data for Structural Health Monitoring (SHM). However, with the advances in high resolution remote sensing technologies, it is anticipated that health monitoring and related applications will be much more widespread in the near future. The obvious advantage of using remote sensing for health monitoring is the ease of data collection. However, with innovative testing technique design and use of the off-the-shelf *Geographical Information System (GIS) application software, very low cost technologies can be developed. To date, most research in SHM using satellite data is concentrated on using Global Positioning Satellite (GPS) for structural static and dynamic displacement data collection (Ko and Ni 2005, Achenbach 2009, Shrive 2005, Karbhari et al. 2009, Zhang et al. 2005, Roberts et al. 2003 and Yao et al. 2008, Brown 2008, Wong 2001, Jiang et al. 2002 and Roberts 2007). GPS provides absolute 3D position of receivers fixed on structures with accuracy in millimeters. The number of monitoring points is determined by the number of receivers that are installed on the target structure. Since GPS satellites collect earth surface point position and elevation information periodically, with the proper data processing system developed, GPS can provide real time monitoring of structures.

Ground base remote sensing as a type of SHM tool can obtain more detailed structure information than satellite and airborne sensors. Structural displacement, strain, distress, surface crack, corrosion and collision damage, and critical structural factors, such as bridge clearance, degree of curve and skew distance (Herold et al. 2005 and 2006), etc. can all be extracted directly from surface data provided by remote sensing devices in the forms of multi-spectral photography, radar images or 3D geometry data. With proper signal processing and analysis methods, and a computer model of the structure, surface information acquired can be used for subsurface defect identification. Laser radar systems, also called LiDAR (Light Detection and Ranging), constitute an optical remote sensing technology developed for range detection. These 3D laser scanners have the advantage of high speed data collection and large coverage area.

Fuchs (2004a and 2004b) and others established the Nondestructive Evaluation Validation Center (NDEVC) at FHWAs Turner-Fairbank Highway Research Station, which has extensively tested laser-based systems for bridge evaluation. These systems can measure point displacement with the installation of light reflective targets. The system has been shown to be useful tool in measuring unprepared surface movements for load testing without targets. The scanner can reach accuracy in sub millimeters over a 30 m range. Pieraccini (2006) used laser scanning to quantify infrastructure displacement induced by a landslide. A kinematic terrestrial based laser scanning system that can be deployed on moving vehicles or watercraft was introduced by Glennie (2007). The system covers 360 degrees and a 3D point cloud is geo-referenced using a high accuracy GPS/INS system. Mobile 3D laser scan systems are less accurate than fixed location scanners and can reach accuracy in centimeters. Drawback of the kinematic terrestrial based laser scanning system is that their 3D scan accuracy is directly affected by the accuracy of recorded GPS data.

1.2.2 Commercial Remote Sensing Limitations

During the Phase 1 study, several issues associated with the application of Commercial Remote Sensing (CRS) and Spatial Information (SI) technology to bridge monitoring have been identified which signified the importance of this research. The following issues were identified through discussion with individual bridge managers from several states and results from a nationwide survey (2008) conducted through collaboration between the American Association of State Highway and Transportation Officials (AASHTO) and the research team that asked questions associated with remote sensing technologies. The responses from 38 states led to the following conclusions:

- **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 databases to help bridge engineers 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, many bridge managers 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. The current version being developed is version 5.2.

- **Misunderstanding of CRS-SI capabilities.** In responses to 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 exist 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.

During Phase 1, we interacted with bridge managers to understand how bridges are managed by the different partners. We recognized that, in order to develop a system that can have a wide national impact, the system needs to be practical, scalable, cost-effective and able to be integrated into system-wide implementation. Such a system would require a more comprehensive review of bridge types and damage histories, as well as different bridge management techniques and styles. To address this need, we formed a national advisory board consisting of bridge and transportation experts. We also collaborated with AASHTO for assistance, with very positive support and collaboration to date. One of the recent steps in learning more about AASHTOs PONTIS software system is participation in the PONTIS User Group meeting in Newport Beach in September 2009.

1.3 IRSV System Concept

1.3.1 Rationale for IRSV System

In order to be able to demonstrate the capability of commercial remote sensing in bridge management and maintenance applications, there is a need to provide a common platform that the CRS data can be shared and displayed. Current Hence, the goal of the phase I study was to develop a common platform that allows the display and integration of commercial CRS-SI data. The system will provide real-time structural information, structural loss estimation, and post-event damage assessment. However, the integration of collected data of different frequencies and nature and the identification of critical and useful information for infrastructure management are essential and require advanced digital information and data visualization techniques. Hence, the IRSV system is designed to address the complexities in developing a multi-layered continuous data fusion system including bandwidth and time-scale ranging; data fusion for multiple partnerships; data presentation and visualization; GIS compatibility; data indexing and management; "meaningful" data synthesis; and transportation operation hierarchy integration.

Figure 1.2 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; lower right graphic indicates the functionality of the bridge as a function of traffic flow; and, finally, the upper right shows an aerial view of the Charlotte City Center. 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. This project will address this issue by using advanced data management algorithms (visual analytics) and data modeling (domain modeling) to explore methods to optimize "useful" information and reduce data redundancy.

1.3.2 Domain Modeling

Critical aspects in the integration of multi-variate data analysis, including different data formats, different data sampling processes, periods and durations, and data interpretation methods, require a domain-customized data analyzer that can be comfortably adapt to the specific needs of the target users. It is with this goal in mind that the IRSV system is being established. Domain modeling is the process of familiarization and characterization of the domain subjects and domain experts (managers). Domain modeling is used in this study to customize the IRSV system with the proper data structure and the construction of knowledge inference machine using domain expert knowledge.

The domain area for the IRSV development is geopolitical based and is focused around Charlotte region. The domain in this case is the management and inspection of the bridge inventory within the target population, which in current study is the city of Charlotte. Figure 1.3 shows the bridge management domain model structure for Charlotte area bridges, which consists of three key elements: bridge management tool, bridge data (in association with bridge physical health states) and bridge operators. The operators are people who have to deal with the ownership/ management/collection of the bridge data.

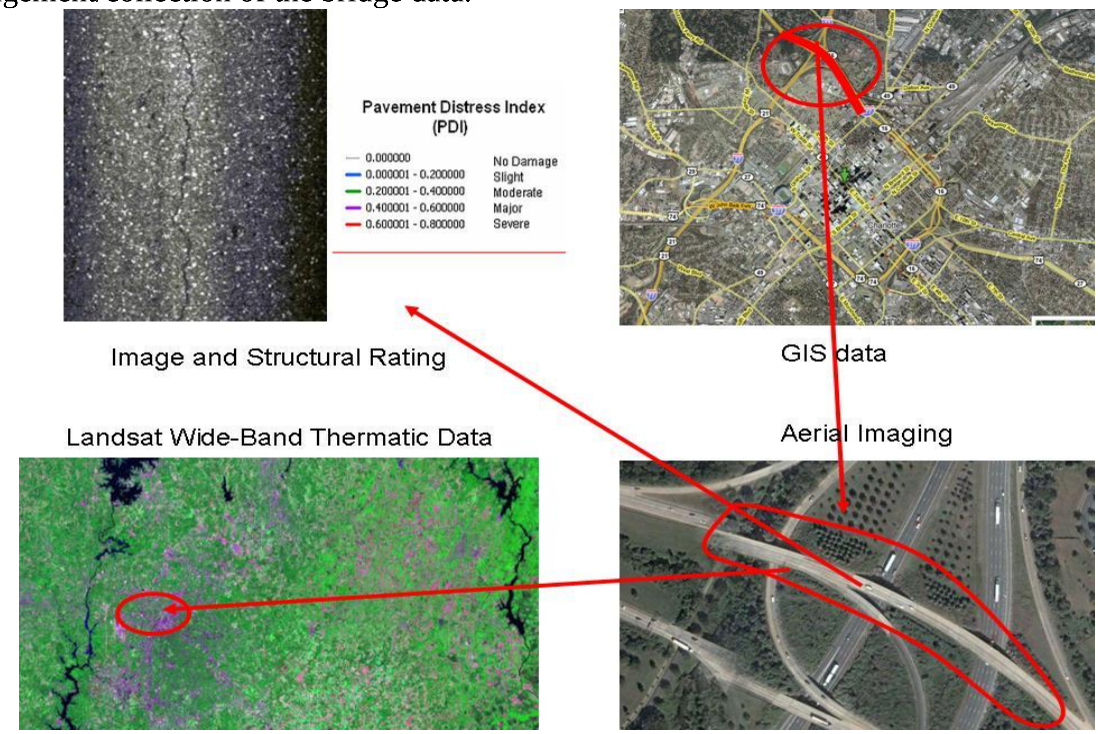


Figure 1.2 Data integration for IRSV for test case bridges

The owners of the bridges in this study area include the Charlotte DOT and NC DOT Division 10. Domain experts identified in this study are Mr. Garland Haywood of NCDOT Division 10 and Mr. Jimmy Rhyne of Charlotte DOT. Hence the elements in the domain model in this study include the physical bridges in Charlotte area identified both by the national bridge inventory database number, physical latitude and longitude coordinates (global Geographic Coordinate System, GCS) and the bridge types; bridge management tools; data associated with bridge management; and last, the operators including bridge managers and inspectors.

Current management tools used for bridge management in the area include NCDOT in-house BMS (Bridge Management System), Mr. Haywood's personal spreadsheet in MS Access, Mr. Jimmy Rhyne's data in MS Excel format, and Charlotte city asset management software (by Hanson Llyod Asset Management Ltd). The inference tool is basically the domain expert knowledge of Mr. Garland Haywood and Mr. Jimmy Rhyne. Bridge database include all existing data organized by NCDOT according to NBIS requirements, but also include customized data by the individual bridge owners. For example, other than bridge sufficiency and inventory ratings, Charlotte DOT has their own bridge rating number to determine their bridge conditions.

Domain operators are the persons physically involved in the management and the generation of bridge data, especially associated with physical inspection data, which include both bridge managers and the bridge inspectors. For North Carolina, all bridge ratings are performed by the

State Bridge Maintenance Division, which also served as the state bridge data depository. Hence, bridge operators also include the State BMS managers.

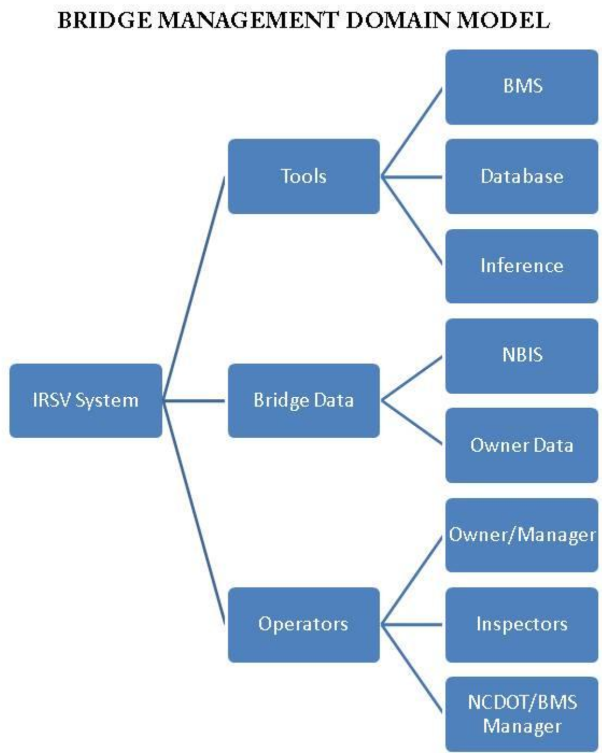


Figure 1.3 Charlotte area bridge management domain model

1.3.3 IRSV System Overview

Figure 1.4 shows the schematic of the foundation of IRSV with integrated data from CRS, SI and structural evaluation, which are displayed under a large-scale visualization system with built in database and genomic knowledge simulation.

IRSV system design can be best described as a bridge data management and visualization software that consists of a bridge database, a knowledge modeling module, high-resolution visualization module, a multi-variate bridge element visualization module and an high-resolution Image analysis module called Automated Management of Bridge Information Systems (AMBIS).

The 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 1.5. The different system components are described below.

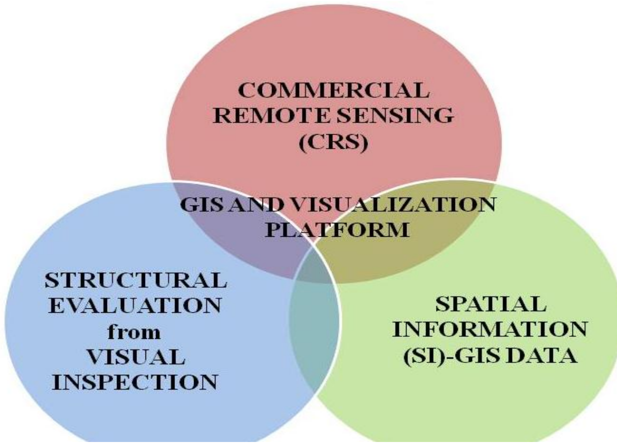


Figure 1.4 Schematics of data integration

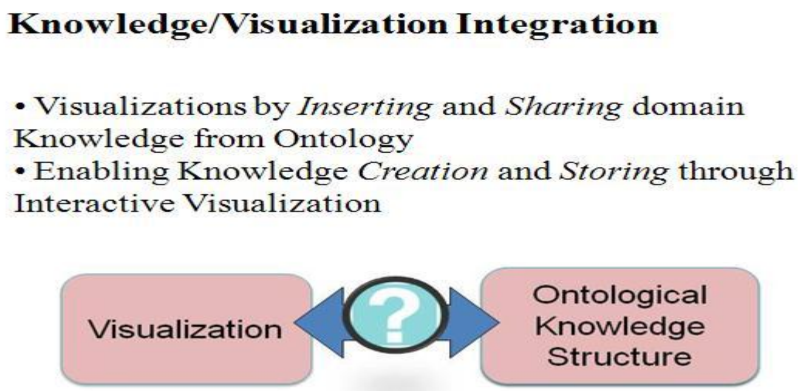


Figure 1.5 Schematic of IRSV functionality in knowledge/visualization integration

1.4 IRSV Components

1.4.1 Knowledge Modeling

Goals and Objectives

Knowledge modeling and database development is necessary to support bridge inspection processes by developing a system based on a knowledge-based approach that provides a scalable and adaptable platform support solution. This approach will help build common understanding through application of a service-oriented architecture (SOA) concept. This SOA paradigm led to an approach of building a knowledge base from detailed process and decision-making descriptions by bridge engineers from the City of Charlotte and the North Carolina DOT. When implemented, the IRSV system will provide a common platform to integrate heterogeneous system components to share bridge data and domain knowledge that will be flexible, scalable and adaptable. Another objective was the reorganizing and developing of the database in a SQL (Standard Query Language) Server. Based on the capability of the SOA concept, a decision-making approach was studied by creating a prototype/ proof of concept user interface.

One of the challenging research issues in the IRSV project is to gather various types of "evidence" that supports decision-making in the bridge inspection process. The IRSV system is also an integration of multiple software solutions. Each of these solutions is designed to solve a very specific set of problems. These systems are perceived to have heterogeneous data and operational requirements. The design and development process of these systems are independent of each other, which presents considerable challenge to fully integrate the various components of the system. The IRSV system requires an architecture that provides a flexible and scalable solution that enables integration among these software solutions.

Yet another objective was to develop a computing framework that can support human input and experience by providing "tools" with the knowledge-base that captures explicit definition of languages as reflected in the process, their relationships among attributes, and their understanding at different levels of abstraction. Various analytical or visualization tools can be used by an engineer for decision making. These tools must integrate with the knowledge base in a seamless and transparent way, so that the tool need not understand the underlying intricacies of the complex data structures and the way these data are stored. Examples of the way that bridge maintenance, repair and replacement decisions in a general way are shown in Figure 1.6. In more specific detail, bridge decisions made by CDOT and NCDOT bridge management engineers that may be representative of other local governments and state highway agencies is shown in Figure 1.7.

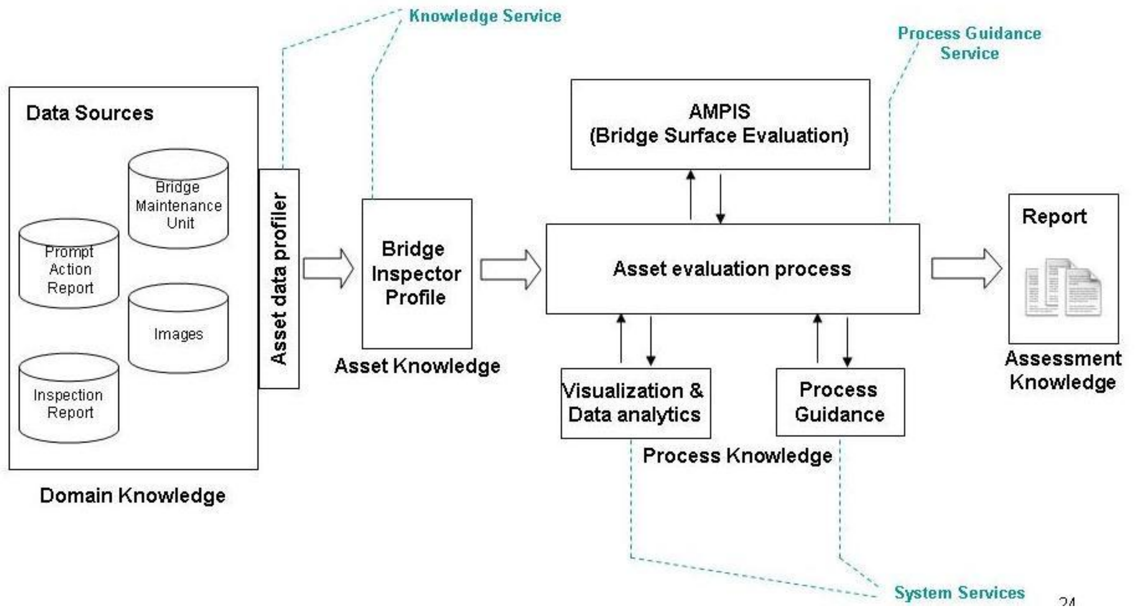


Figure 1.6 Generic decision process illustrating application of knowledge modeling

Approach to the Research

The IRSV is a system that uses an integration of multiple types of collected bridge data, such as textual data, satellite images, sensor images, aerial images, and geospatial notations. Generating results from the conventional database query process can be time-consuming or even ineffective, especially when the database contains a large number of heterogeneous data sets. The use of the IRSV model will enable users to retrieve bridge data directly from the database using Semantic Matching Operation (SMO) provided by the Problem Domain Ontology (PDO). However, there are some scalability issues:

- Generating results from the conventional database query process can be a time consuming effort, especially if the database has a large number of variables.
- The query process does not guarantee a solution to a given problem and may require multiple queries and manual intervention in order to produce a "sensible" output.

This approach will enable the creation of meaningful and useful database queries through interactive knowledge acquisition with the subject matter expert. The formulated conceptual space bridges the gap between evidence gathering that can be understood by the combination of the complex data with domain knowledge in a decision making process. The complex data-space must be mapped automatically to easily comprehend the conceptual space.

By introducing an enhanced domain knowledge modeling technique, IRSV will enable bridge inspectors to raise the level of their analyses from a data level to a conceptual level by leveraging their domain knowledge understanding and its associated representation.

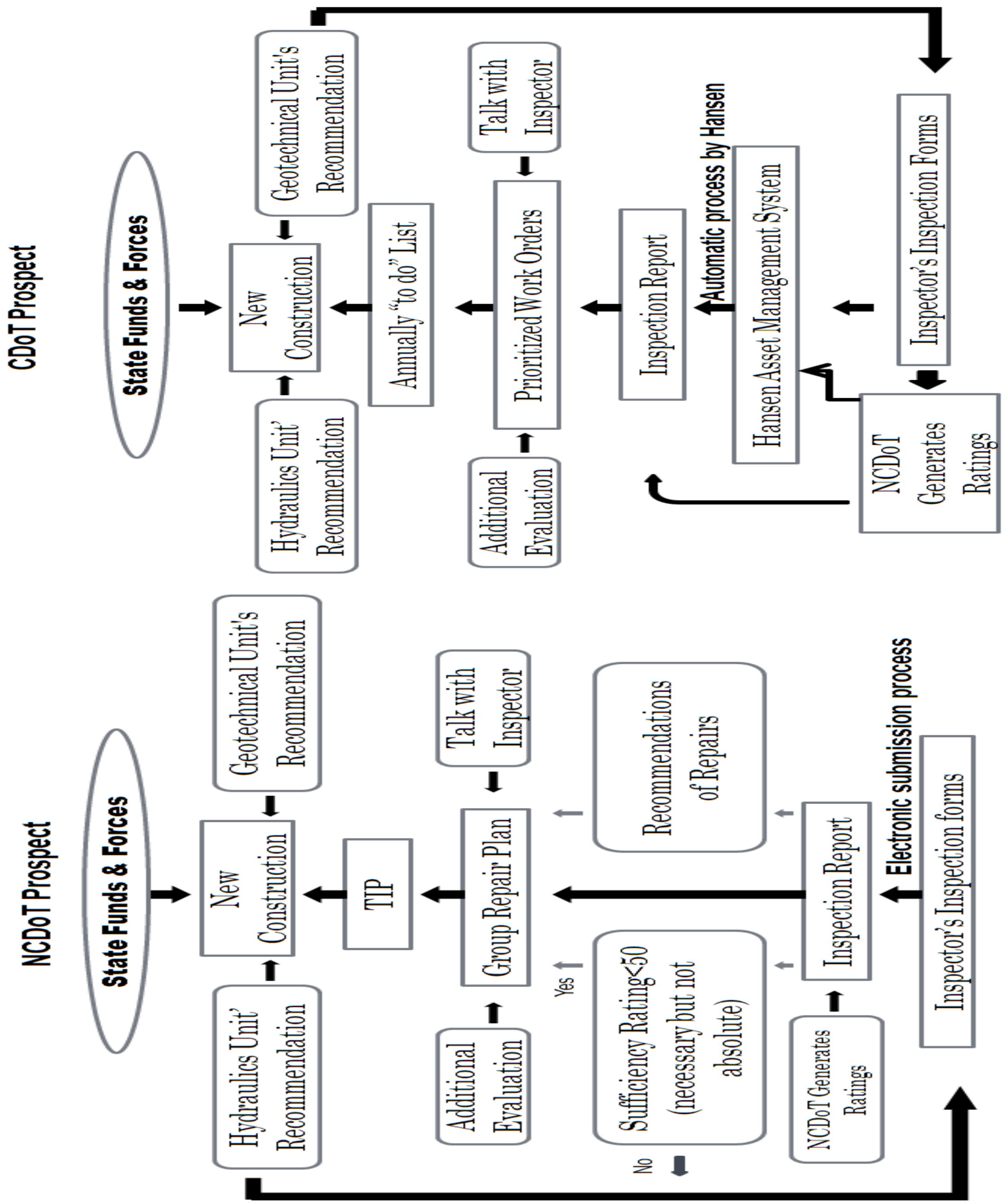


Figure 1.7 NCDOT and CDOT bridge engineer's decision making processes

Figure 1.8 describes the proposed framework for the integration of conceptual and actual space (labeled "data space" in figure 1.8). It demonstrates a scenario where the bridge inspector wants to know about material types that require mitigation strategies based on damage classification. A key component of this framework is the knowledge representation that supports the Bridge Problem Domain. Thus, users of the IRSV System will retrieve all related data from the database by composing a query that uses the ontology (or knowledge-based) concepts, properties and features through the knowledge mediator. Such queries are different from those constructed on a database schema. The difference is that database schemas are about the efficient organization of data for storage and retrieval. The problem domain ontology, however, will enable users to construct queries based on a better understanding of the conceptual space. Also, the concepts defined in the knowledge structure are not present in the database.

The approach of enhanced domain knowledge modeling will make the IRSV system more scalable and flexible to map and process the large repository of complex data with multiple formats. This will also enable the plug-and-play of other types of knowledge-based approaches into the IRSV system.

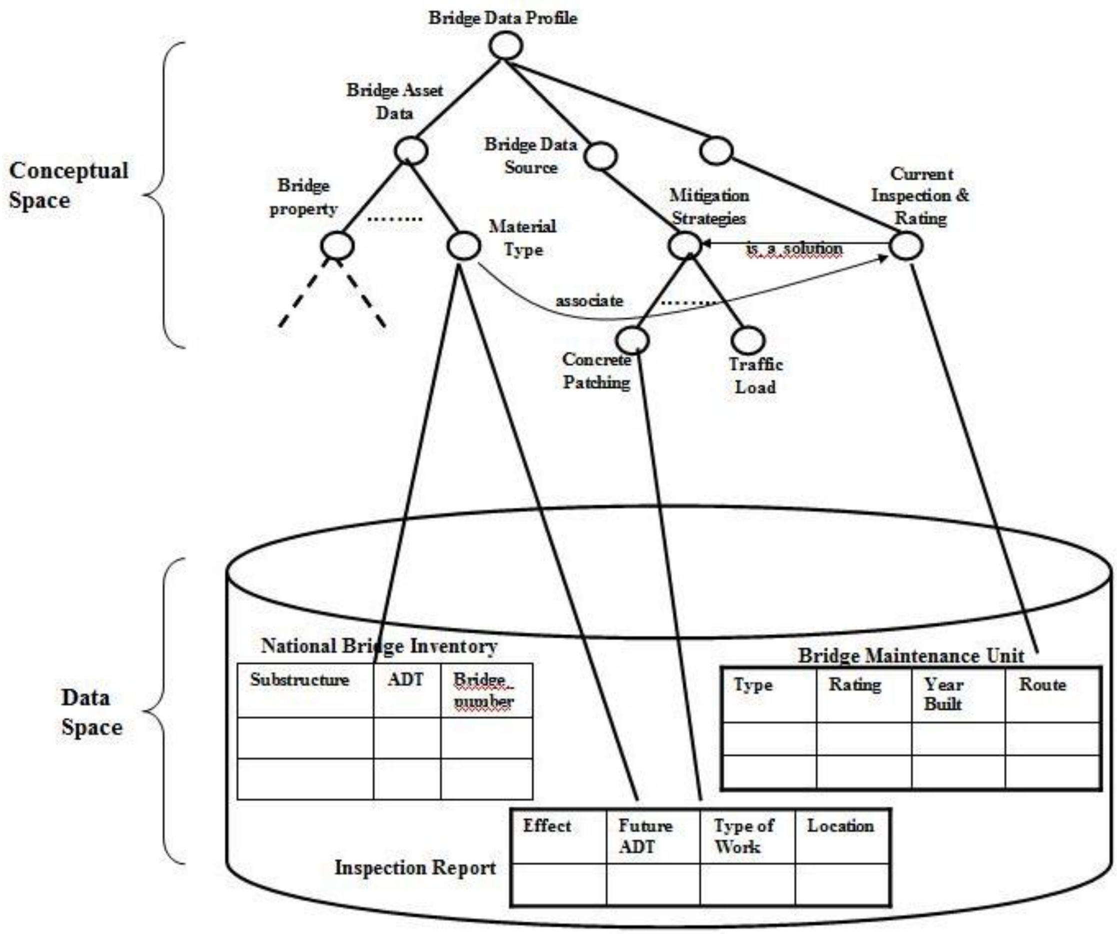


Figure 1.8 Example for integration of conceptual space and instance space

<u>Deployment</u>
The Integrated Remote Sensing and Visualization model at this stage of its development contains four modules on the client system. The <u>first module</u> is the Generic Object Model (GenOM) which is used to design the knowledge structure or ontology for bridge inspectors. With the

support of this knowledge structure the bridge inspector can infer the rules with the help of an inference engine that is provided in the GenOM tool. The second module deployed is the IRSV prototype user interface, which is modeled primarily based on the inputs provided from NC DOT and Charlotte DOT bridge engineers (Figure 1.7).

The IRSV prototype user interface depicts the workflow of these DOT processes. The prototype tries to associate the system's look and feel to the flow of activities followed by the DOT personnel in inspecting and evaluating the bridges. The primary focus of the IRSV user interface is to combine bridge inspection data and domain knowledge based on the knowledge representation and a goal-driven modeling technique.

The key feature of the IRSV prototype user interface is to create a data profile for bridges and correlate profiles to existing data sources. Logical reasoning is based on "what – if" conditions through the conceptual space. The user interface will also generate a report that includes the summary of analysis, mitigation strategies with the help of metrics and measures defined in the conceptual space, and store this process as a customized process that can be repeated.
The IRSV prototype will also employ a primitive user interface which helps in exploring and using the functionalities of the services created. This is the third module. The fourth and final module is a Web Service, based on the concept of Service Oriented Architecture in which the services will be passed on to other modules.

The structure of database schema was developed using SQL Server 2005. Bridge data for three years (2000, 2004 and 2006) on two-year cycles were provided by NCDOT and CDOT. Around 300 bridges maintained by the NCDOT and 200 maintained by the City of Charlotte are imported in the SQL Server at UNCC. After importing the data, the model was successfully deployed on desktop computers at both the Charlotte DOT and Division 10 of the NCDOT.

1.4.2 Laser based Scanning

Laser based scanning systems is an optical remote sensing technique that measures scattered light to identify the shape of a distant object. Several terminologies have been applied to similar technologies including LiDAR and Ladar (Laser Radar, Stone et al. 2004). The key difference between LiDAR and Radar is that shorter wavelengths (such as ultraviolet and near-infrared) are used. Recent advances in Light Detection And Ranging (LiDAR) scanning techniques have made it more attractive and cost-effective for bridge damage assessment and overall bridge management. LiDAR scans provide high resolution, 3D optical images that can be used to quantify bridge component conditions including collision damage, large permanent deformations, overload cracking and different kinds of surface erosion. Different practical applications of the remote sensing technique for bridge heath monitoring are presented to demonstrate the potential in enhancing the bridge management decision-making process at the state, local or regional level. "Remote sensing" in the context of this research project applied to any method that does not come in contact with, or be imbedded in a bridge member. Although these methods will never substitute for traditional bridge inspection methods, the combination of these remote sensing techniques could yield a better understanding of bridge health condition in a simple yet comprehensive way.

LiDAR is the optical remote sensing technology developed for range detection. The images produced by LiDAR result in millimeter resolution. A typical LiDAR system is formed by a transmitter, a receiver and a signal processing unit. The transmitter emits a series of light to the object. The receiver receives the reflected energy and the time cost of the reflected energy traveled back from the object is measured in the signal processing unit (Carrara 1995). Then the two way distance between the scanner and the object can be calculated by multiplying the speed of light with its travel time. One cycle of a measuring process can only collect the range information of an object in its direction of view. To obtain the surrounding information instead of a single point, a reflection mirror with an oblique surface is placed opposite to the scanner transmitter, rotating 360 degree vertically. The laser head itself also rotates 360 degrees horizontally (Figure 1.9). After the scanner head rotates 360 degree horizontally, a full scan can be finished. The scanner head and mirror direction as well as the collected range information forms the 3D position of each point relative to the scanner. A point “cloud” of the target surface is formed by the combination of these 3D points.

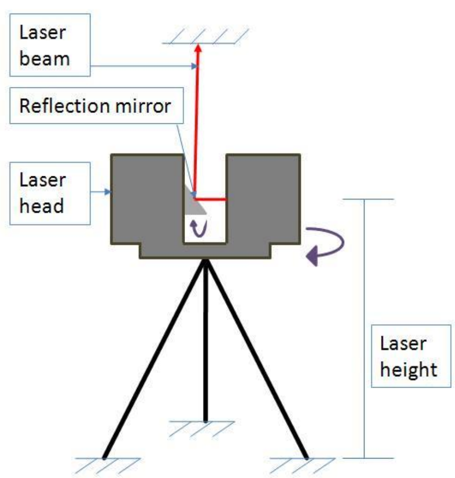


Figure 1.9 Schematic of laser scanner operation

A LiDAR-based automated bridge structure evaluation system, called LiBE (LiDAR Bridge Evaluation), was developed over the course of this project with the functions of a) defect detection and quantification, b) clearance measurement, and c) displacement measurement for bridge static load testing. The following descriptions will introduce the potentials of LiBE for bridge health monitoring.

Bridge defect detection and quantification

The LiBE protocol developed for this project for damage detection and quantification uses a second-order analysis technique to detect structural problems and to quantify surface defects. By recording the surface topology of any component of the bridge deck and superstructure, the laser radar can detect different levels of damage on the structure and differentiate damage types by contrasting surface flatness and smoothness. LiBE detected bridge defects based on its surface roughness and bias to the surface plane. The target area is first divided into small grids. In this case, using a 10 X 10 point grid results in a 0.01m X 0.01m resolution.

The gradient of each point and the distance between the point and the surface plane are calculated in each grid. A grid is determined to be defective depending on the number of irregular points within the grid. An omni-directional search reveals defective grid connectivity. The area and volume of each defective area can be calculated based on the area of each defective grid. The rate of irregularity in each grid determines the severity of the problem. The benefit of using the LiDAR scans becomes more clear when data are collected for the defective area over a period of time, yielding the rate of mass loss in the bridge element.

Clearance measurement

Bridges with low clearance are vulnerable to being struck by over height trucks and other high loads. North Carolina DOT (NCDOT 2000) sets the design requirement for bridges over interstates and freeways at 5.0m; over other roads bridge clearance must be 4.6m. Several older roadway bridges that were built prior to 2000 in Mecklenburg County have a minimum vertical clearance lower than 4.6m. Most of these bridges have experienced collision damage, which can increase deterioration and reduce their service life. Collision accidents also cause injuries and there have been fatalities. Figure 1.10 and Figure 1.11 show that during inspection intervals of eight months and three months respectively, both of Bridge 590700 and Bridge 590704 have encountered new collision damage to the structures (circled).

In the ideal case, with accurate calibration before a scan, the z value of each scan point equals to the vertical distance between the point and the scanner head. By matching the point on the deck with each point on the ground, the clearance above each ground point is measured by calculating the z value difference between the ground point and the matching point.

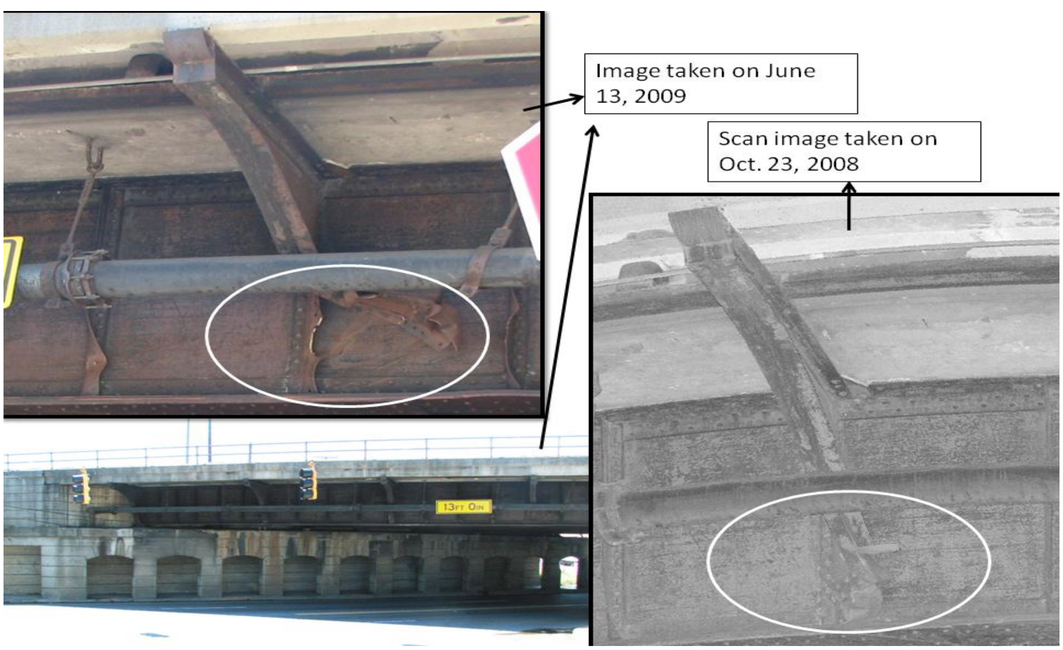


Figure 1.10 Collision damage comparison of Bridge 590700

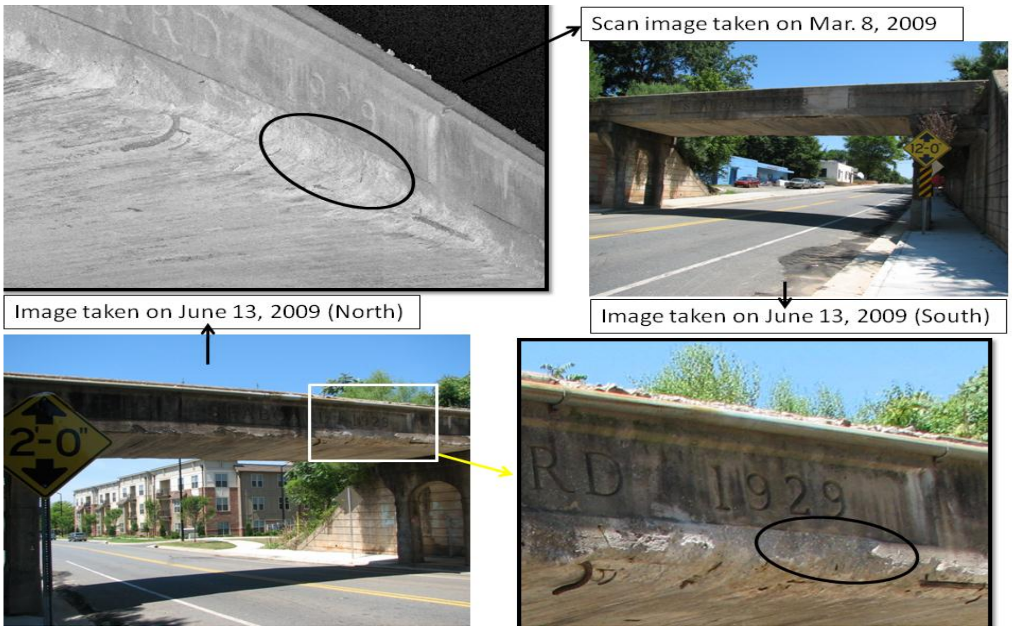


Figure 1.11 Collision damage comparison of Bridge 590704

<u>Displacement measurement in load testing</u>

By comparing the deck surface position before and after loading, LiDAR scan can be used for displacement measurement during bridge load testing. The accuracy of the measurement is in millimeters. Strain gauge and displacement transducer have been widely used in bridge load testing to measure strain and displacement. Both of these two methods need to contact the surface of the bridge components and the measuring is restricted only to the sensor installation locations. LiDAR scan is a noncontact method and can provide the displacement of the entire scanned surface simultaneously. This information is useful for bridge structure computer model updating and structure performance monitoring.

The scanned records of the bridge can provide bridge managers direct information on current conditions of the bridge. The LiDAR-based bridge measurements and evaluations are repeatable. With the utilization of LiDAR technology and an automated data processing system, bridge inspection accuracies can be improved significantly. More accurate bridge inspections and damage evaluations can lead to better maintenance decisions.

1.4.3 High Resolution Aerial Photography

Aerial photography is the original form of remote sensing and remains the most widely used method. Typical applications include: geographical mapping, military reconnaissance, environmental studies, and geological explorations (*5*). These photos are generally taken at high altitudes, i.e. 5,000 ft and higher, providing general spatial information such as coordinates, orientations and colors. For a tool to aid in bridge inspections, higher resolution images are needed. As a result, the aerial photographs used in this study are taken from a much lower altitude (approx. 1000 ft) such that higher resolution digital images can be captured. This technique is called Small-Format Aerial Photography (SFAP). Since these photos are from a lower altitude, the orthogonal rectification of the imagery was not performed. The photographic scale of the photo can be determined using Equation 1.

$$Scale = \frac{L}{H} \tag{1}$$

where, L is the lens focal length, and H is the camera or flight height (Figure 1.12).

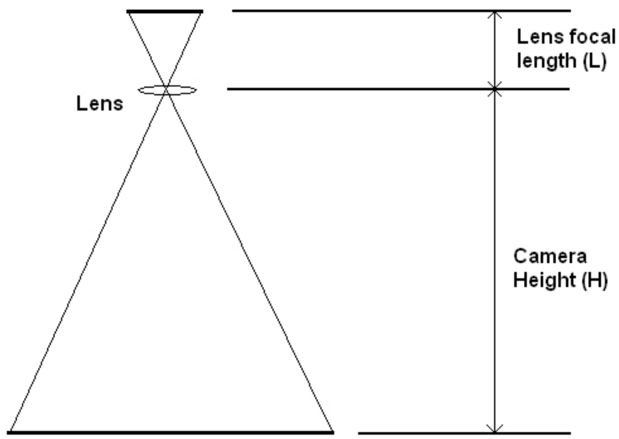


Figure 1.12 Representation of image scale capture

The resolution of the digital images is defined as the ratio of the actual physical dimension to the physical length of the object in photo. The main intent of the aerial photo as a remote sensor is to detect structural defects and other related structural problems, such as bridge movements, integrity from cracking, or other major damages to the bridge super structure. Figure 1.12 shows the aerial crack detection process where cracks are seen as features with darker color pixels than the surrounding color and then marked as possible cracking. It should be noted that surface roughness, discoloring and other surface conditions could cause the pixels to appear like cracks. Similar problems appear when using the color identification technique on both concrete and asphalt bridge surfaces. Once cracking and expansion joints were identified, assumptions can then be made about structural integrity. Using this approach, the digital photos are used to measure the cracks including, length, width, crack type, and severity. The depth of the crack would be the only identity that cannot be determined even with higher resolution images. Other defects such as patching, scaling, spalling, exposed reinforcement, and potholes can also be identified using aerial photography.

The high-resolution, SFAP technology is dependent on actual flight height and photo quality. Figure 1.13 shows a typical bridge (NCDOT Bridge # 590379) image obtained in our project. Photo quality implications and problems include, but are not limited to: shadows from surrounding objects (marked on side B), material surface roughness, traffic, lighting situations, and possible lens smudging/major vibrations (which would leave images blurred and the resolution would be altered). Side A on Figure 1.13 shows the crack analysis using aerial photography method, effectively identifying cracks larger than 0.5 inch (shown as white markings). Also shown on Image A are the joint openings between bridge spans at the expansion joints.

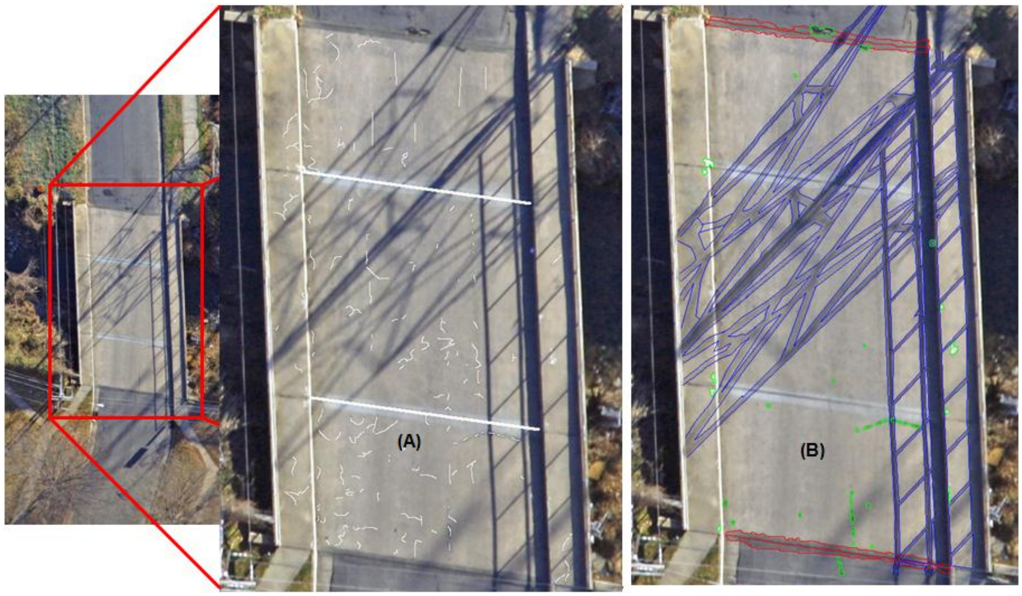


Figure 1.13 Aerial photo processing: (A) crack analysis (B) noise analysis

1.4.4 Automated Management Bridge Information System (AMBIS)

The goal of this component of the project shifted from its original intent which was originally to 1) demonstrate that commercially-available remote sensing data and digitized transportation system information can be combined to effectively produce inventory information about transportation infrastructure, and 2) show that these data can also be used to monitor and evaluate the current state of repair of critical infrastructure components, e.g., bridges and roads.

While these objectives remain key in achieving the overall goals of this study, ImageCat's role was modified in 2008 to focus exclusively on modifying an existing pavement management tool (AMPIS – see Chung and Shinozuka, 2004) so that it could be more directly applied to bridge structures. Specifically, two major modifications were proposed: 1) to modify AMPIS so that it could serve as a "ground-truth" data collection tool – collected data/images would be used to compare interpreted images from high-resolution aerial imagery to actual ground conditions, e.g., distressed bridge surfaces, and 2) adjust image processing algorithms within AMPIS to automatically distinguish bridge distress conditions from other artifacts (e.g., shadows) using high-resolution imagery in order to monitor the current state of bridge decks. With these modifications, AMPIS (Automated Management Pavement Inspection System) was used as the base to develop AMBIS which stands for *Automated Management Bridge Information System*.

Conceptual Framework for AMBIS

The conceptual framework for AMBIS is illustrated in Figure 1.14. Like its predecessor (AMPIS), the system architecture is comprised of three distinct levels: data acquisition, core analysis, and data management. The three levels allow a user to collect raw data from the field, to process and analyze this information so that distressed bridge states can be effectively identified, and to easily present the results of the analysis through a data management interface.

The *Data Acquisition* level is comprised of three specific data collection components: video camera, GPS technology, and remotely-sensed imagery (e.g., high-resolution aerial imagery). The video camera allows high-resolution field data be collected on bridge deck surfaces, as well as on approach structures (e.g., ramps, abutments, etc.) leading to the bridge. This field data – in the form of continuous video or extracted photos – is geo-referenced using a GPS hand-held unit. The remotely-sensed data can be accessed from either satellite imagery (with a spatial resolution of less than 1 meter) or aerial photographs (with a spatial resolution on the order of centimeters). Note that in the case of monitoring changes to bridge decks over time, multiple, time-sequenced images are required.

The *Core Analysis* level consists of four major components: a geo-referencing tool, an image processing algorithm, a bridge management module, and a reporting structure. The geo-referencing tool links raw images and GPS coordinates stored during data collection deployments to create a trail of locations from where each image sequence is produced. This trail is displayed within an AMBIS mapping-interface, allowing easy identification of problematic sections of the bridge. The image processing algorithm is designed to translate geo-referenced images into a set of vectors which characterize the surface features of a bridge deck in order to determine distress conditions and provide an overall rating (e.g., U.S. Army, 1982). For example, Figure 1.15 illustrates how surface distress is identified. The first image illustrates the raw road surface image, the second image displays an intermediate image showing potential cracks identified by using edge detection algorithms, and the last image illustrates the process of identifying and classifying road cracks. The length and pattern of these tracks are used to determine the stress conditions of the road surface.

The final distress determination is integrated into an AMBIS report that contains both estimated distress states and distress types which can range from simple cracks to more extensive distress, such as potholes and other compression failures. The AMBIS report feeds into the bridge management component, which allows the processed images to be linked to other key bridge information, such as year built, physical dimensions of the bridge, bridge deck skew angles, number of columns, etc. In a larger context, this information will be housed in module that is part of the IRSV system.

The last level is the *Data Management* layer. In this layer, we produce information that can be directly imported into the IRSV system. Currently, the data formats include database elements (in the form of Microsoft Access Database), images (both video and still) and GIS data (locations of bridges and GPS trails identifying where images were taken).

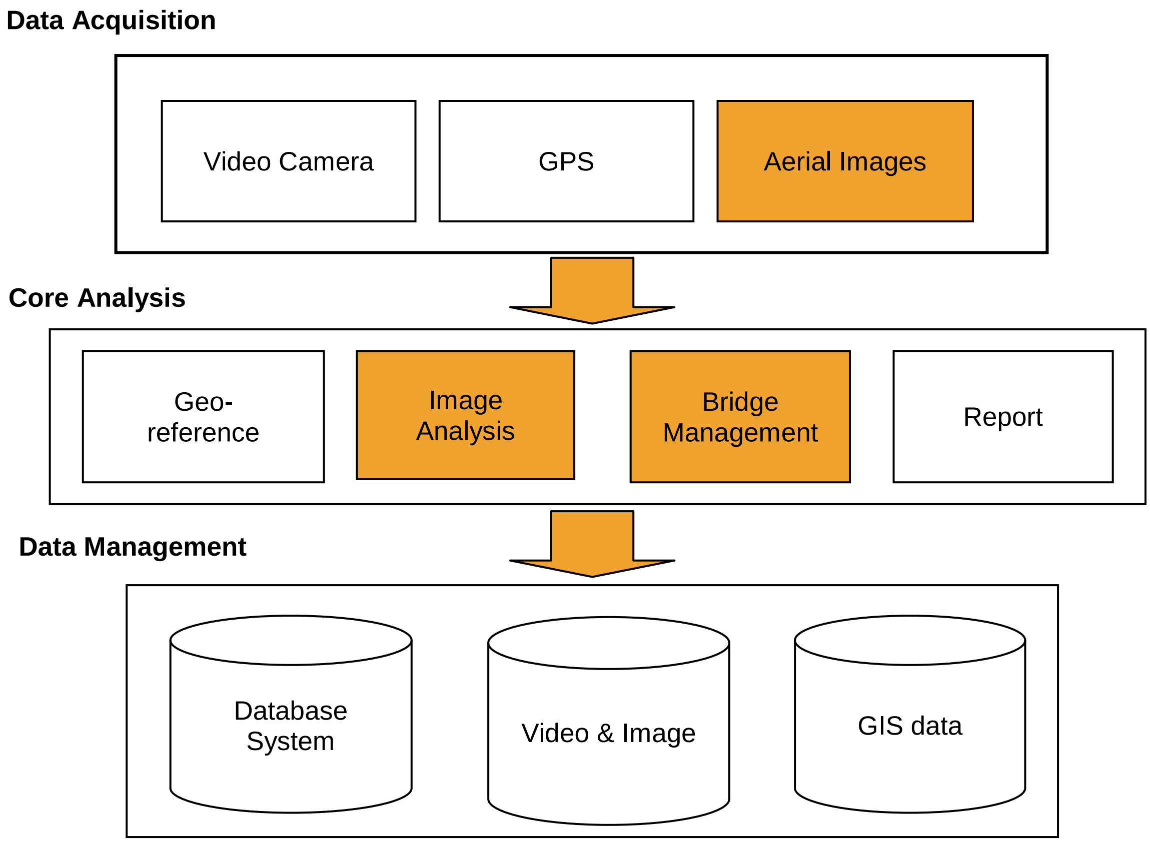


Figure 1.14 System architecture for AMBIS

a) Raw Image b) Edge Detection c) Feature Extraction

Figure 1.15 Image processing steps within AMBIS

<u>Integration with IRSV</u>

In this project, ImageCat has worked closely with UNCC's Software and Information Systems (SIS) group to create a database link between the IRSV data model and the AMBIS internal database. Common elements of the bridge database are now shared between IRSV and AMBIS. The AMBIS workflow was revised so that when a user defines a project to collect and import data, all the data is linked by the unique bridge identifier. This effectively allows a very tight integration between the two systems without sacrificing the flexibility and modularity of AMBIS. While running the program, IRSV requests analysis results for a specific bridge from AMBIS, the results are returned, and IRSV posts the results to users.

These results are imported into the IRSV system and are accessed through the IRSV inference engine, in a similar manner that data from the bi-annual on-site visual inspection is imported into the IRSV visual images. The relationship among the remote sensing databases (such as high resolution aerial photography), the analysis components (AMBIS and Ground Truth Analysis), NBIS Database, and the IRSV Rating for each bridge is shown in Figure 1.16. As the result from the AMBIS analysis program, and the on-site "ground truth" inspections and resultant proof of concept index, a comparison can be made with the calculated IRSV Bridge Rating. This rating is assumed to be on a scale of 1 to 9, in order to give it the same range of ratings that is commonly (but not universally) provided by bridge management engineers based on NBIS (National Bridge Inspection System) inspection data.

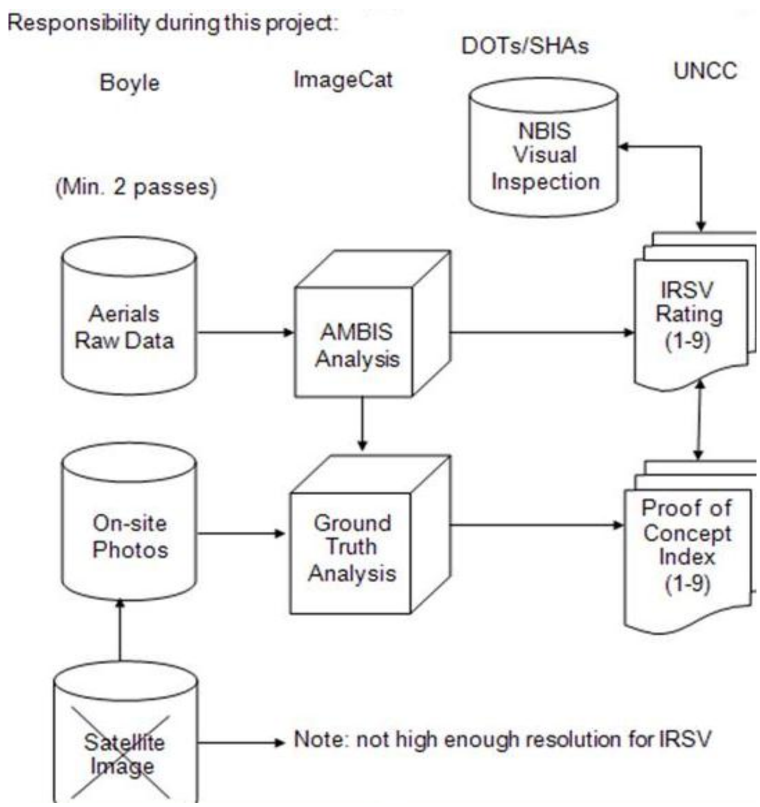
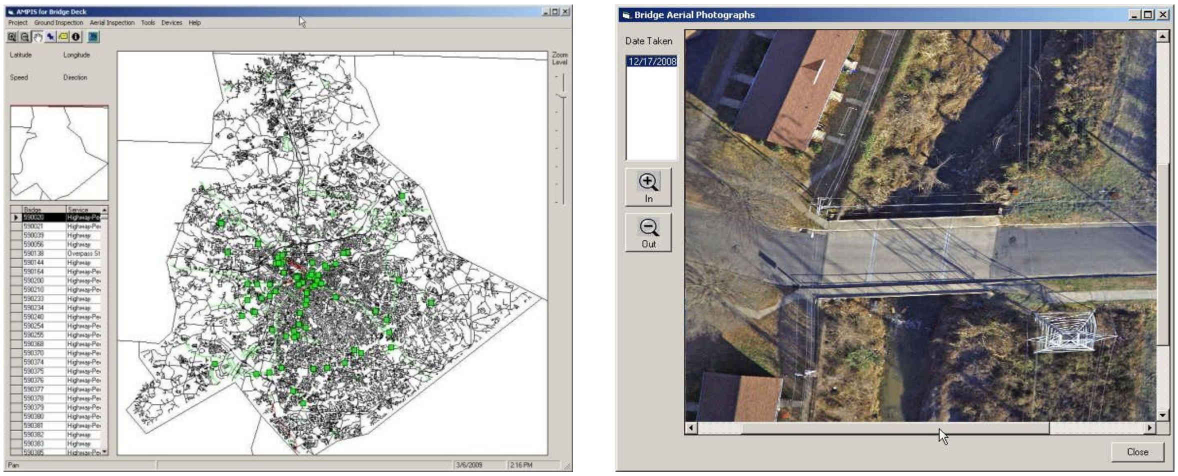


Figure 1.16 Image processing for IRSV bridge ratings

Several changes were made to the AMBIS user interface to accommodate system integration and the modified work flow. The overall user interface was adjusted to provide a more map-centric look and feel (Figure 1.17(a)), additional GIS data was included to support displaying bridge data, and lastly, changes were made to dialog boxes for creating projects, managing projects and collecting inspection data. In addition, we also added a visualization module for showing the sub-inch aerial photographs within the AMBIS user-interface (Figure 1.17(b)).



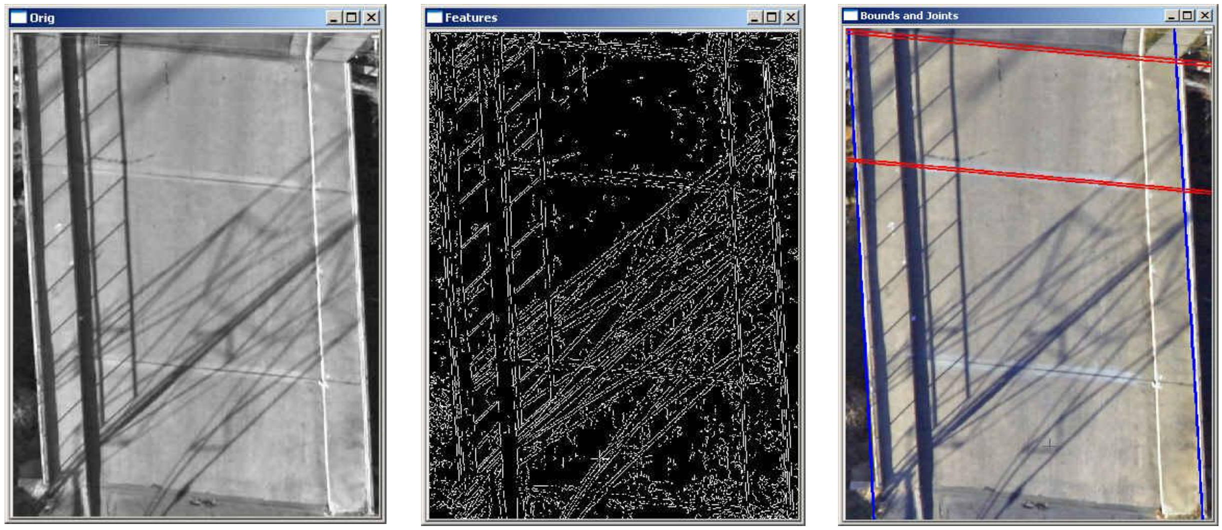
a) A new map-centric interface

b) Integration of very-high resolution aerial photography

Figure 1.17 Modified AMBIS user dialogs

The high-resolution images presented some unique challenges, and ImageCat worked closely with the *Structures Group* to determine the best technique for processing these images. The ultimate objective is to provide meaningful metrics to bridge inspectors and/or managers through image processing techniques. These processes should be automated, and provide robust statistics back to users regardless of lighting conditions, road conditions, traffic, or weather conditions. The Structures Group identified changes in joint conditions as being one of the most important indicators of damage observable from a bridge deck surface, so emphasis was placed on extracting the joints with the image processing algorithms.

ImageCat explored different alternatives for processing aerial photographs. The challenge was to recognize joints, but ignore shadows, which often had a very similar pattern to the joints or may interrupt the pattern of the joints. The preliminary results shown in Figure 1.18 provide an example. From the original image in Figure 1.18(a), we extracted many different features visible in Figure 1.18(b). From Figure 1.18(c), we are able to identify and quantify the joints between bridge deck slabs in two-thirds of the cases.



a) Raw image | b) Results of edge detection and filtering | c) Results of joint detection algorithm

Figure 1.18 Preliminary results of the joint detection algorithm in AMBIS

<u>Future Challenges</u>

Remote sensing data analysis of very high-resolution aerial photographs presents some unique challenges because of the amount of data that needs to be analyzed. Although the large amount of data makes it possible to detect smaller features such as joints between bridge slabs, the high-resolution imagery also presents greater filtering challenges, as every shadow and obstacle is perfectly captured. A future research objective is to determine the optimum approach for extracting features and filter noise from these high-resolution images.

In addition to optimizing the image analysis algorithm, we must understand the significance of the metrics produced by the analysis. For example, we must addresses questions such as - if the joint has a separation of 5 inches, what type of sub-structure problems might this indicate? The IRSV Research Team is continuing to work toward better interpretation of the results of the analysis in a manner that presents meaningful results to the bridge inspectors.

1.4.5 Visualization

The visualization component is built on the platform of an interaction-enabled large display technology. Based on discussions with NCDOT, we designed our interactive visual analytics system (Figure 1.19) to assist bridge managers on depicting four analytical aspects: Geospatial, Temporal, Relational and bridge Details per-inspection. For each aspect, our system utilizes different types of interactive visualizations views to represent the corresponding information. Instead of fixing the dimensions for each view, our system allows bridge managers to interactively select demanded data dimensions on the fly and create appropriate views as they proceed. Our system will then automatically coordinate these views and provide bridge managers a highly interactive visual data exploration environment.

The Visualization Components include Microsoft Virtual Earth (Center), Parallel Coordinate and Scattered Plot views (at four corners), Temporal Analysis view (Third from Top Right) and original data grid (at bottom). (Please refer to Appendix B for larger scale images of the individual components shown in Figure 1.18.)

According to bridge managers in NCDOT, understanding the relationships among different bridge attributes is useful to make accurate maintenance decisions; those interdependencies and correlations among the attributes could provide great help when trying to comprehensively understand the bridges physical patterns. Since there are nearly sixty attributes collected in the inspection reports, it is often difficult for them to learn those relationships.

To facilitate bridge managers to depict the relational information, our system adopts two types of data-driven visualizations: the Parallel Coordinate (PCView) and the Scatter Plot(SPView). With both these views, our system not only supports bridge managers to depict correlations among different attributes (PCView), but also allows them to review and compare different bridges on two fixed dimensions(SPView). Therefore our system provides them comprehensive understanding about the correlations and differences among their bridge assets.

These temporal-enabled Parallel Coordinate and Scatter Plot views are dedicated to assist bridge mangers on depicting the relational information among bridges and their attributes.
Lastly, a detail view displays the other three analytical aspects on a per-bridge level, which allows the bridge managers to “drill down” to the bridge details and access the original reports at any time during their decision making process.

Considering the map is arguably the most intuitive entrance for bridge managers to locate their bridges, our system provides them a highly interactive geospatial view, using the Microsoft Virtual Earth (MSVE), which has been proved for its capability and flexibility in showing geo-information. Utilizing the rich geo-information provided by Microsoft Virtual Earth, IRSV supports the interaction with geospatial databases. By placing each bridge on the map, detailed geographic relationships and patterns immediately become apparent.

With this extensive information pool, bridge managers have the capability to develop more precise local environmental and traffic conditions, and therefore make corresponding decisions. Therefore, with this interactive geospatial view, the bridge managers would easily navigate around their bridge assets and select different regions of interests. In addition to conventional bridge data, we collected extensive bridge information from various sources, including high resolution fly-over imageries, remote sensing data, and 3D LiDAR data.

The IRSV system uses the bridge as the object to coordinate among views. Since the underlying object is the same, passing message and sharing context becomes trivial. The bridge managers can now interact with data such as time, geo-locations, bridge attributes, etc. and understand what the correlations are among these dimensions. By presenting a more comprehensive understanding of the bridge assets, the system provides the power to help bridge managers make more objective decisions.

Figure 1.19 shows where bridges in the south of Charlotte, NC, are mostly in good condition (green icon), while the ones in north are in fair condition (yellow icon). The bridge icons can be selected based on categorical dimensions of the data such as ”Present Conditions” or ”Structural Types” that can easily reveal patterns based on locations. Moreover, an important benefit of using MSVE is used to provide bridge managers additional geo-information, such as aerial images and traffic amounts.

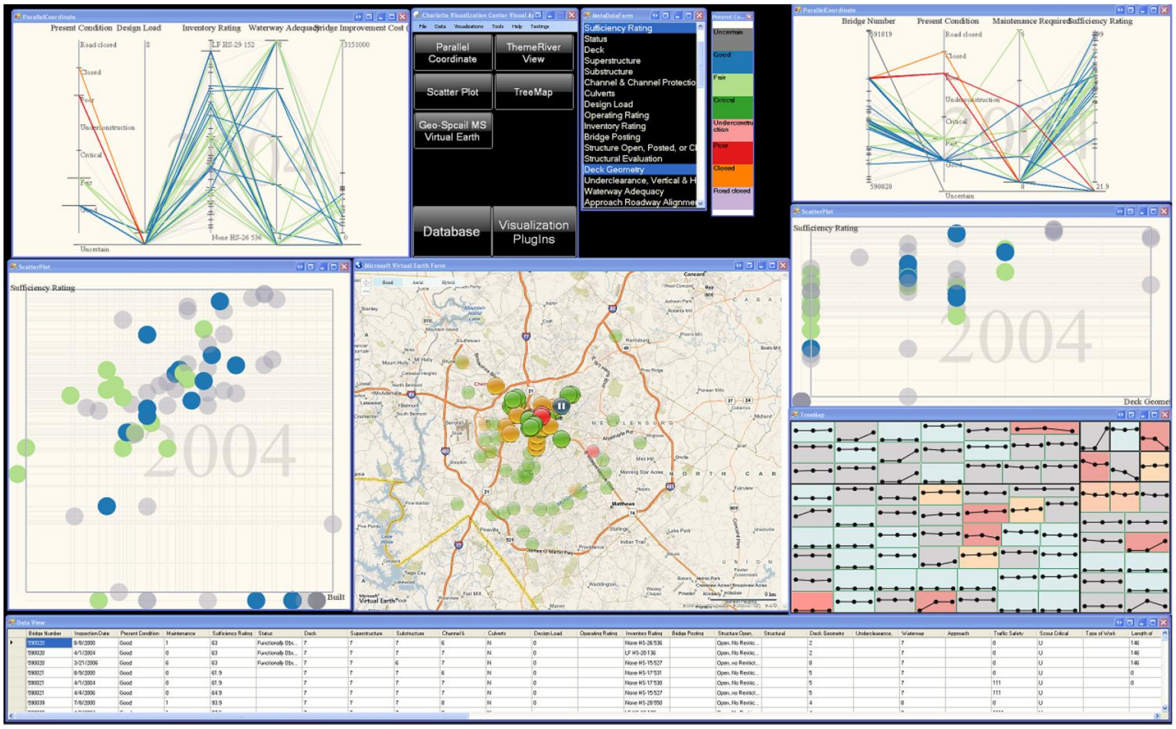


Figure 1.19 Overview of IRSV visualization

1.5 Demonstrations of IRSV System to date

Several case studies have been conducted throughout the course of the past two years, as the "proof of concept" IRSV model was in its developmental stage. Four examples are shown here to illustrate the capabilities of two CRS technologies: Laser Scanning and High Resolution Aerial Photography.

1.5.1 Test Results: Los Angeles County DPW Bridge

Figure 1.20 is an example of LiBE application, with data obtained at a bridge on the Imperial Highway crossing the Long Beach Freeway, Route 710 in Los Angeles, California. The lower right image in Figure 1.20 illustrates the detection and quantity of the damage on the front girder that is typical of losses caused by vehicle collisions with a bridge girder. LiDAR scan provides precise quantities of material loss. The bridge managers recognized the benefits derived and the potential applications of remote sensing technologies in helping quantify bridge damage that cannot be accomplished using visual inspection only.

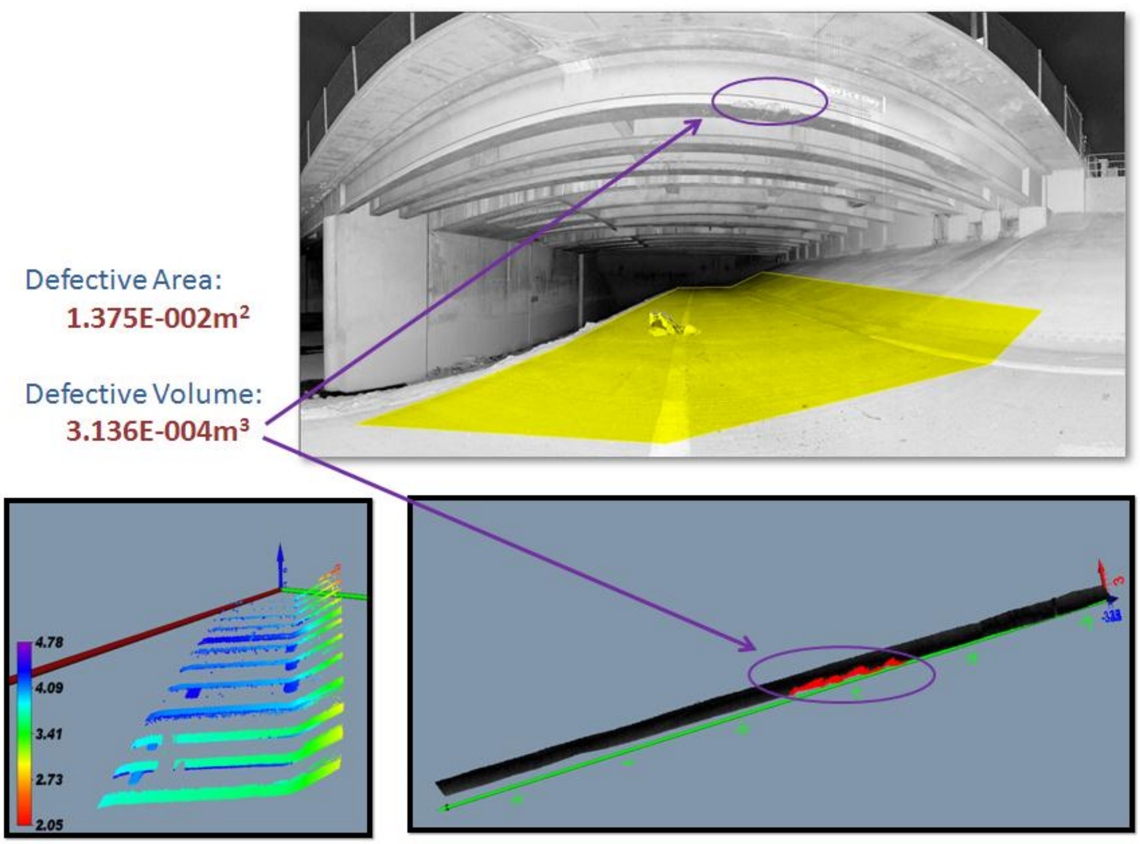


Figure 1.20 LiBE results from Imperial Highway bridge study

Another application of LiDAR bridge data to the bridge is clearance measurement. Bridges with low clearance are vulnerable to vehicle collision damage. Clearance height changing over time can reflect vertical structural movement, ground settlement, or pavement overlays. Clearance measurement by LiBE (lower left in Figure 1.21**)** indicated that the bridge clearance is increasing from the front side to the back side. At the damage location, the clearance was measured as 3.6m, which is 0.6m longer than the posted limit of 3.0m.

1.5.2 Test Results: NCDOT Bridge # 590704

The minimum vertical clearance area is located in around the center of the deck on the north side. The clearance of the bridge is increasing from that location to all around. Therefore the south side of the bridge has higher clearance than the north side and corners of the south side have the highest clearance among all the locations. By comparing bridge condition on the south side (top right image in Figure 1.21) and on the north side (bottom left image in Figure 1.21), less collision damage can be found on the south side of the bridge than on the north side. Also less damage has been detected on the right corner of the south side than on the right corner of the north side, although both of the corners are near the traffic directions. It can be concluded that clearance here is the main factor that determines the damage level of the bridge. Proper pavement treatment can be proposed to increase the minimum vertical clearance of the bridge and this clearance measurement method can be used to guide the treatment. Figure 1.22 is a plot of the vertical clearance of Bridge 590704.

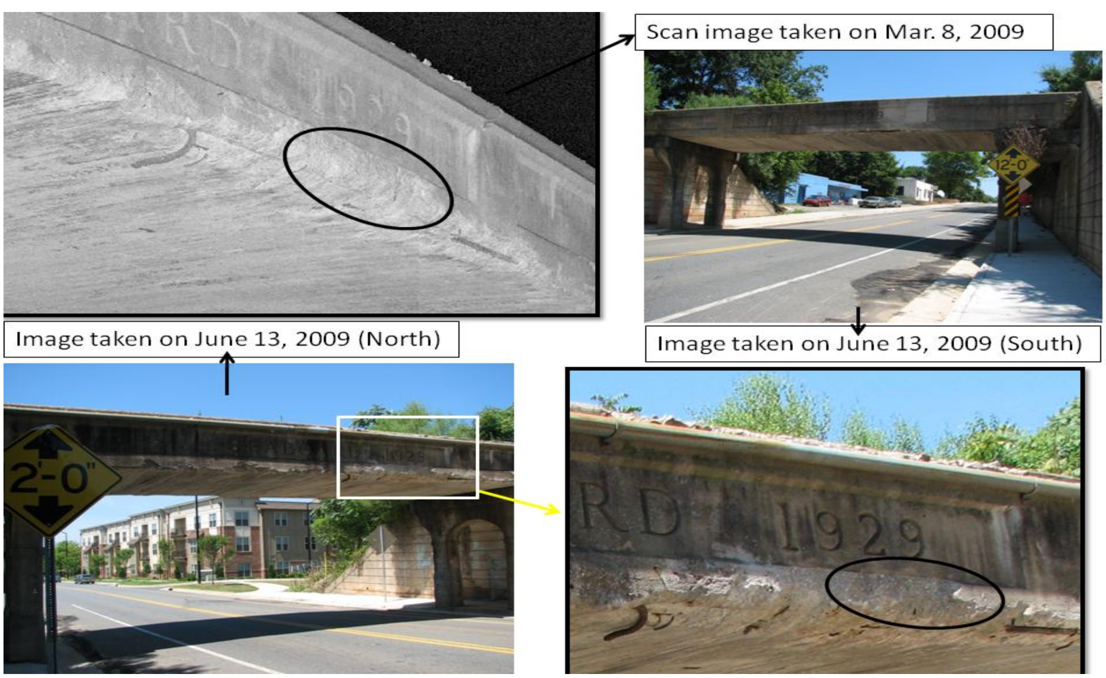


Figure 1.21 Collision damage comparison of Bridge 590704

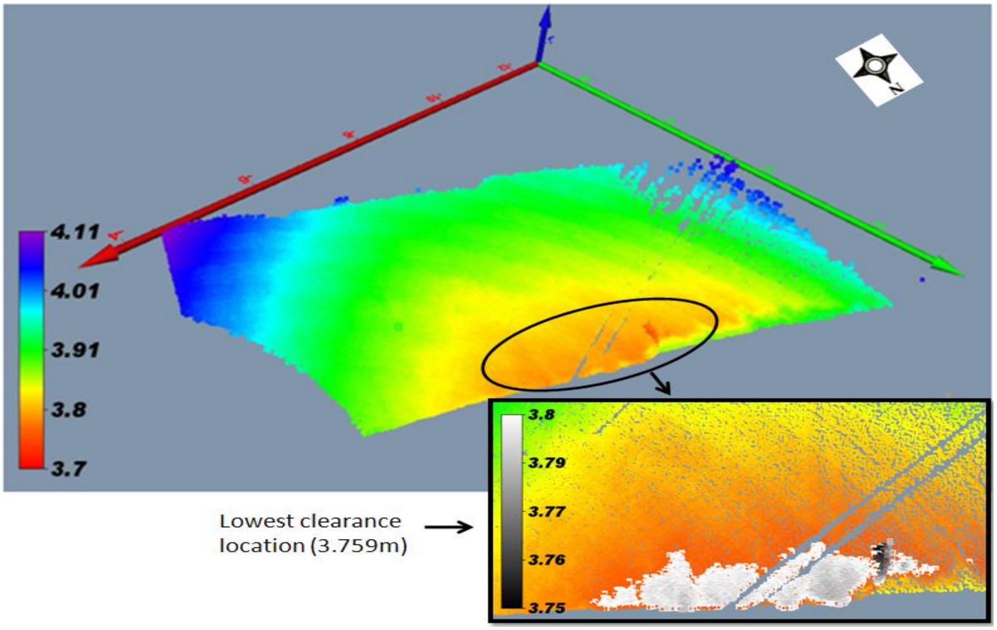


Figure 1.22 Vertical clearance plot of Bridge 590704 (looking south).

1.5.3 Test Results: Load Testing, NCDOT New Bridge Construction

The 3-D laser scan technique has also been used for load testing of a bridge on Langtree Road over Interstate I-77 near Charlotte, NC (Figure 1.23**).** This recently-constructed bridge has three spans, with nine steel girders under the reinforced concrete deck. For load testing, two heavy-duty dump trucks were used to provide the static loading at fixed locations on the bridge. Truck A weighed 55,640 pounds, and Truck B weighed 54,820 pounds.

Figure 1.23 High performance steel bridge

The top right image of Figure 1.24 was taken under the tested bridge. Truck A and Truck B were parking side by side with girder seven (counting from right to left) passing through their center during loading. The bottom image of Figure 1.24 renders the displacements of sample points on the bridge girders, which were generated by LiBE based on the LiDAR data. From the displacements display it can be seen that parts of the three girders which were near the truck location have relative larger displacements than other locations.

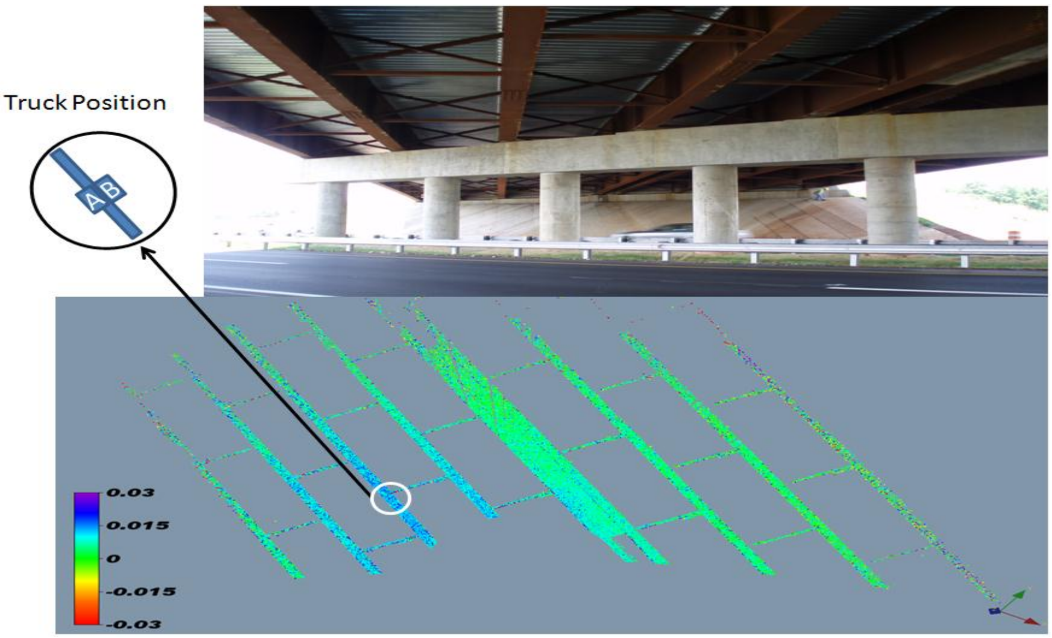
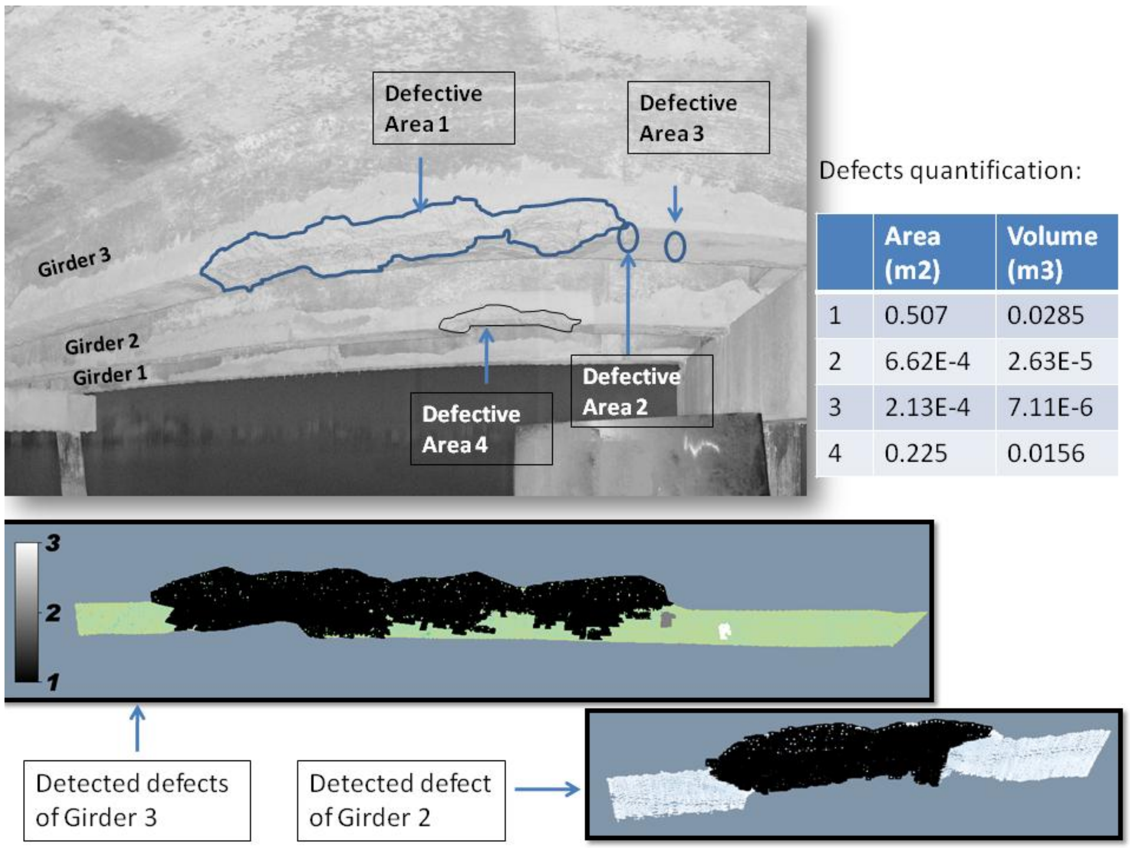


Figure 1.24 Load testing using LiDAR scan

1.5.4. Test Results: NCDOT Bridge in New Hanover County, NC

One of the most difficult challenges in conducting a LiDAR scan of bridge superstructure is where bridges traverse a waterway. The research team worked with the Division Bridge Engineer in the Wilmington area (New Hanover County) to test out the capability of providing a steady platform and keep it level in order to run a LiDAR scan. In this particular case, a boat that is used by NCDOT personnel for inspection and light maintenance work was provided to provide a platform on a bridge span on US 74 connects Wilmington with Wrightsville Beach (NCDOT Bridge # 640024). The experiment worked better than anticipated, with very little unsteadiness in the 22 ft. "Boston Whaler," which was secured to bridge piers on both ends of the boat to provide a steady platform for the LiDAR. However, one of the factors that made this test successful was a relatively moderate current on the inland waterway on the day the test was run. Figure 1.25 presents the damage detection and quantification results of two girders for that bridge. Defective areas 2 and 3 are two minor irregularities resulting from the exposed ends of stirrups.



Defects quantification:

	Area (m2)	Volume (m3)
1	0.507	0.0285
2	6.62E-4	2.63E-5
3	2.13E-4	7.11E-6
4	0.225	0.0156

Figure 1.25 Damage detection and quantification of NCDOT Bridge # 640024

1.6 Calculation of IRSV-Generated Condition Ratings

1.6.1 CRS technologies and bridge condition ratings

To establish a CRS-based rating system that is consistent with current state bridge appraisals, there is a need to first clarify how AASHTO (1994) specifies bridge condition ratings: Current bridge identifiers "structural deficiency" and "functional obsolete" and the associated Sufficiency Rating values have been used as basis for bridge rehabilitation or replacement criteria. Structural Deficiency means the bridge is not able to carry the truck loads it is designed for, but it also means inadequate waterway for the bridges over water. Functional obsolete is designated to bridges with inadequate capacity or underclearance, but it also represent bridges with roadway inadequate alignments (Kerr, 2006).

AASHTO condition rating (1994) is an objective scaled rating system from 0 to 9. It is a component-based inspection method. The summary rating (Structural Evaluation Appraisal Rating) usually reflects the poorest value of a component with Average Daily Traffic (ADT) correlations. As indicated in Federal Highway Administration (FHWA) to the US Congress that:

> *"Condition ratings are assigned for these primary components during periodic safety inspections. ……………………………The ratings do not translate directly into an overall rating of a bridge's condition, but are good indicators of the quality of specific components." (FHWA, 2006b)*

A critical analysis of the relevancy of the CRS techniques to current bridge monitoring has been performed using the AASHTO CoRe Element Guide (1997), which is summarized in Tables 1.4 to 1.8. Each of the tables addressed one of the four key components of a bridge differentiated in the AASHTO CoRe Element Guide (1997): bridge deck (Table 1.4), superstructure (Table 1.5), substructure (Table 1.6) and joints, bearings and bridge approaches (Table 1.7). Each table indicated the potential applicable CRS technology and if the CoRe element is covered in current phase study. Finally, Table 1.8 addresses critical damage scenarios entitled "smart flags" in the AASHTO Guide (1997). Table 1.8 shows how CRS techniques have been demonstrated four smart flag problems: deck cracking, undersurface damage of deck or slab, settlement and section loss.

Table 1.4 CRS applications to CoRe element: decks/slabs

Core Element Decks/Slabs	Potential CRS Applications	Covered in Current Study
Concrete (bare)	Flyover, LiDAR	Yes
Concrete with overlay	Flyover, LiDAR	Yes
Steel – open grid	Flyover, LiDAR	No
Steel – concrete filled	Flyover, LiDAR	No
Steel – corrugated	Flyover, LiDAR	No
Timber (Bare)	Flyover, LiDAR	No

Table 1.5 CRS applications to CoRe element: superstructures

Core Element Super Structure	Potential CRS Applications	Covered in Current Study
Closed Web/Box Girder	LiDAR	No
Open Girder/Beam	LiDAR	Yes
Stringer	LiDAR	Yes
Through Truss	Flyover, LiDAR	No
Deck Truss	LiDAR	No
Timber Truss/Arch	LiDAR	No
Arch	Flyover, LiDAR	No
Cable (exposed)	Flyover, LiDAR	No
Floor Beam	LiDAR	No
Pin and Hanger Assembly	LiDAR	No

Table 1.6 CRS applications to CoRe element: substructures

Core Element Substructure	Potential CRS Applications	Covered in Current Study
Column or Pile Extension	LiDAR	Yes
Pier Wall	LiDAR	Yes
Abutment	LiDAR	Yes
Submerged Pile Cap/Footing	LiDAR	Yes
Submerged Pile	Not Applicable	No
Pier Cap	LiDAR	No
Culvert	LiDAR	No

Table 1.7 CRS applications to CoRe element: other superstructures/substructures

Core Element Other Sup/Sub	Potential CRS Applications	Covered in Current Study
Strip Seal Expansion Joint	Flyover	yes
Pourable Joint Seal	Flyover	no
Compression Joint Seal	Flyover	No
Assembly Joint/Seal	Flyover	No
Open Expansion Joint	Flyover	yes
Elastomeric Bearing	LiDAR	No
Movable Bearing	LiDAR	No
Enclosed/Concealed Bearing	Not applicable	No
Fixed Bearing	LiDAR	No
Pot Bearing	LiDAR	No
Disk Bearing	LiDAR	No
Approach Slab	Flyover	yes
Bridge Railing	Flyover	yes

Table 1.8 CRS applications to smart flags

Smart Flags	Potential CRS Applications	Covered in Current Study
Steel fatigue	Not Applicable	No
Pack rust	LiDAR	No
Deck cracking	Flyover	Yes
Soffit (undersurface) of Concrete Deck or Slab	LiDAR	Yes
Settlement	LiDAR	Yes
Traffic Impact	Flyover	No
Section Loss	LiDAR	Yes

1.6.2 CRS-based condition rating calculations

As we conclude Phase I, we have tested and validated this approach on 21 different bridges in the Charlotte area in collaboration with NCDOT and Charlotte DOT (16 and five bridges, respectively). The tests present a glimpse to the potentials of the two proposed CRS technologies for bridge monitoring. Several data are not readily available to include in the database at this point in time because of limited bridge types. A complete set of three parameters that are part of the IRSV are included for Bridges # 590179, 590255, and 590140 - BSCI, AMBIS, and LiDAR.

The summary results of bridges studied in this project are shown in Tables 1.9 and 1.10. In Table 1.9, the data in all columns are taken from the most recent NBIS database for each bridge (times over a two-year period that are identified as either 2004 or 2006 in the NCDOT and CDOT databases). Note that the "status" of the bridge (the metrics that receive much attention in the press - functionally obsolete or structurally deficient) is not available for all bridges in our sample. Tables 1.9 and 1.10 are arranged in an order that reflects grouping of bridges that are in the same category, or have very similar structural characteristics. All bridges with the exception of bridge 640024 are located in Mecklenburg County; bridge 640024 is located over the Inter-coastal Waterway between Wilmington and Wrightsville Beach in New Hanover County.

Table 1.10 shows several bridge condition ratings computed from CRS data. The different condition ratings are also identified with the specific problem types that are associated with the AASHTO CoRe element types (Section 1.6.1). Hence, the CRS-based condition ratings are not a bridge-level rating, hence, no attempt is made to compare the condition ratings with the NBIS rating (more detailed discussion is presented in Section 1.6.3). The condition ratings that were calculated from the three technologies used in the IRSV system – Aerial Photos, AMBIS bridge deck analysis, and LiDAR results. These results are presented as a demonstration of the potential condition indicators that can be adopted for bridge monitoring. Although only three bridges (all three are bridges over roadways or water) are completed at this time. In Table 1.10, the existing NBIS Sufficiency Rating is presented along with all three CRS-based condition ratings: BSCI Aerial Photo Rating, AMBIS-DDI Rating and LiDAR Damage Rating. Each of the measurements taken has been "normalized" into a numerical scale.

Table 1.9 Basic Data on Test case bridges, Mecklenburg County, NC

Bridge Number	Owner	Status (DOTs)	NBIS Sufficiency Rating	Condition (DOTS)	Bridge Type
590179	NCDOT	Fair	72.3	*	Concrete
590255	CDOT	Fair	77.7	Obsolete	Steel
590140	NCDOT	Fair	77.5	Obsolete	RC Girder
590147	NCDOT	Fair	30.3	Deficient	RC Girder
590084	NCDOT	Poor	82.1	Obsolete	PCC Cored Slab
590239	NCDOT	Fair	78.2	*	Steel
590059	NCDOT	Poor	35.6	Deficient	Steel Plank
590161	NCDOT	Fair	63.7	Obsolete	Steel
590165	NCDOT	Poor	48.2	Deficient	Steel
590177	NCDOT	Fair	29.1	Deficient	Steel
590296	NCDOT	Fair	94.7	*	Prestressed Concrete
590379	CDOT	Fair	29.3	Deficient	Prestressed Concrete
590511	NCDOT	Good	80.4	*	RC Deck
590512	NCDOT	Good	80.4	*	RC Deck
590038	NCDOT	Fair	45.5	Deficient	RC Deck
590049	NCDOT	Fair	45.3	Deficient	RC Deck
590108	NCDOT	Fair	48.2	Deficient	RC Deck
590176	NCDOT	Fair	70.3	Obsolete	RC Deck
590700	CDOT	Poor		RR Bridge	Steel
590702	CDOT	Good		RR Bridge	Steel
590704	CDOT	Fair		RR Bridge	Concrete
640024	NCDOT	Poor	30.1	Deficient (Div. 3)	Concrete

***** Note: Bridges not showing condition are described as neither deficient nor obsolete

Table 1.10 Comparison of Condition Ratings for Test Case Bridges

Bridge Number	NBIS Sufficiency Rating	BSCI Aerial Photo Rating (Deck Rating)	AMBIS - DDI Rating (Deck Rating)	LiDAR Damage Rating (Super Structure/Substructure Rating)
590179	72.3	99.0	45.7	69.0
590255	77.7	47.5	96.9	59.1
590140	77.6	91.0	99.1	90.0
590147	30.3	99.0	99.1	46.3
590084	60.7	99.0	98.16	-
590239	78.2	78.9	86.65	-
590059	35.6	-	-	-
590161	63.7	26.2	56.88	-
590165	48.2	48.7	88.11	-
590177	29.1	38.9	65.62	-
590296	94.7	-	-	-
590379	29.3	62.0	82.85	-
590511	80.4	93.4	82.85	-
590512	80.4	97.9	-	-
590038	45.5	76.0	56.33	-
590049	45.3	49.2	77.62	-
590108	48.2	77.5	85.07	-
590176	70.3	-	98.69	-
590700	Poor	-	RR bridge	-
590702	Good	-	RR bridge	78.5
590704	Fair	-	RR bridge	70.7
590376	Fair	45.0	84.8	
640024	Poor	30.1	Wilmington	38.8

These ratings are calculated based on the following:

LiDAR Defect Ratings

LiDAR based rating calculations consist of damage indexing (defect rating) and clearance rating (not included in the table below). The LiDAR-measured Vertical Clearance Ratings are useful to the bridge manager to determine the functionality of the bridge (functionally obsolete). Defect calculations consider both super structure (girders and deck underside) and substructures (pile cap and exposed parts of bridge piers). Table 1.11 shows the detailed calculations that have been used in developing the LiDAR-based Damage Ratings.

Table 1.11 Calculations leading to Derivation of LiDAR Defect Ratings

Bridge Number	NBIS Sufficiency Rating	Defect No.	Area (m2)	Volume (m3)	Damage Ratio	Maximum Depth (M) (meters)	Average Depth (A) (meters)	LiDAR Defect Rating (R)
590179	72.3	1	2.53E-2	2.85E-4	0.0481	0.031	1.01E-02	69.0
		2	1.57E-2	1.30E-4				
		3	1.44E-4	1.14E-6				
		4	9.44E-4	7.25E-6				
590255	77.7	1	2.01E-1	5.98E-3	0.0497	0.162	2.98E-02	59.1
590147	30.3	1	8.07E-2	9.19E-3	0.0333	0.259	9.00E-02	46.3
		2	4.56E-2	2.97E-3				
		3	3.60E-2	2.44E-3				
590702	73.4	1	2.06E-2	3.39E-4	0.0049	0.042	1.64E-02	78.5
590704	87.4	1	4.94E-3	9.85E-5	0.0091	0.080	3.54E-02	70.7
		2	4.85E-3	1.04E-4				
		3	2.98E-1	1.07E-2				
640024	30.1	1	5.07E-1	2.85E-2	0.2169	0.332	5.61E-02	38.8

$$R = 100 \times \left[1.0 - 0.7 \times \sqrt{R} - 0.3 \times \left(\frac{A}{0.075}\right)^{\frac{A}{M}}\right] \qquad \text{IF A} \leq 0.075 \qquad (1)$$

$$R = 100 \times (1.0 - 0.7 \times \sqrt{R} - 0.3 \times (\frac{A}{0.075})^{\sqrt{\frac{M}{A}}}) \qquad \text{IF} \quad \text{A} > 0.075 \qquad (2)$$

Where: R-damage ratio
A-average depth of the defects
M-maximum depth of the defects
0.075m – in practice, this is a typical maximum depth of concrete cover over rebars

Bridge Surface Condition Index (BSCI) Ratings based on Aerial Photos

The bridge surface condition index (BSCI) rating scale for assigning a numerical value to the condition of bridge decks has been taken directly from roadway pavement condition ratings. The BSCI rating process includes: 1) Identify cracks and quantify crack numbers, *N*, from the aerial photos; 2) Determine the area of each span, *A*, of the bridge structure (based on inspection report or original design); 3) Calculate percentage crack density, *D*, using Equation 3; 4) Determine deduction value, *DV*, using Figure 1.26 (or use Equation 4); and finally, 5) Subtract deduction value to get final rating, *BSCI* (Equation 5). The BSCI rating, for the aerial photography method, equations are as follow:

$$D = {}^{N}/_{A} \quad (3)$$
$$DV = 50 \times \log(D) \quad (4)$$
$$BSCI - AP = 100 - \max(\mathrm{DV}) \quad (5)$$

Where: D = Density (number of cracks per bridge deck) X 100
V = Deduct Value (log)

50 X log D is used to normalize the ratings on a linear scale rather than curvilinear. In current rating scheme, distress or damage measurements for bridge deck is similar in the evaluation of cracks in a roadway surface. The scale for the deck distress measurements is shown in Figure 1.27. Table 1.12 shows the BSCI rating of bridges in current study. Included in Volume 6, the importance of temporal measurements of expansion joints are noted in that movements in the bridge superstructure and possibly substructure can be identified.

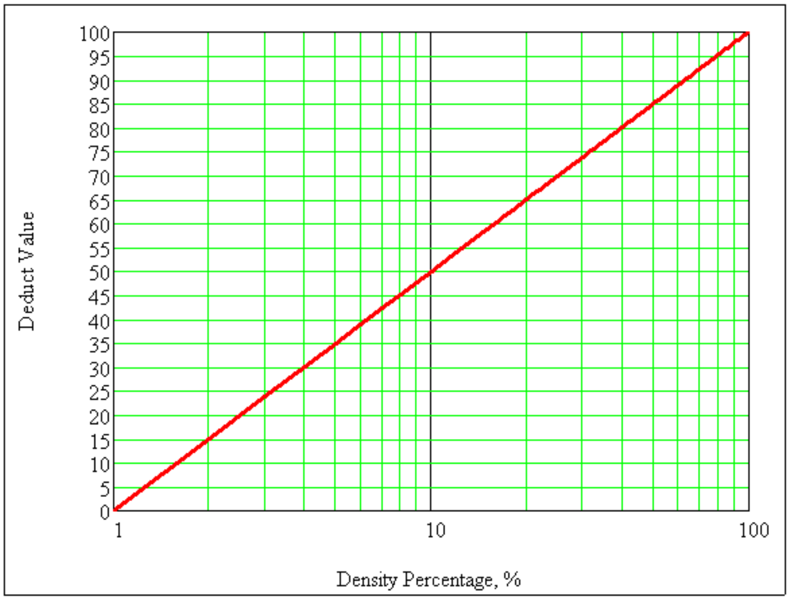


Figure 1.26 Initial logarithmic curve for deduction values versus density

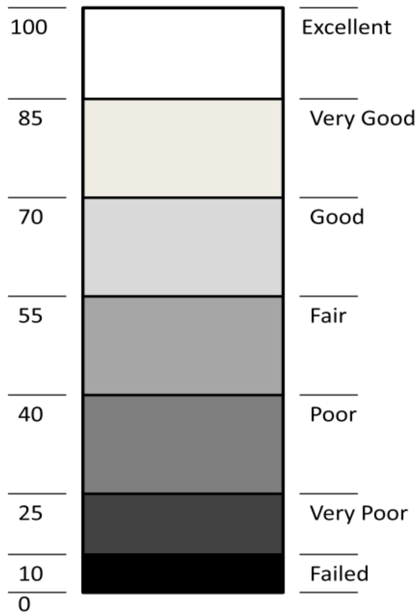


Figure 1.27 Standard rating scale used in Pavement Management System

Table 1.12 BSCI bridge deck rating for pilot test in Mecklenburg County, NC

Bridge Number	BSCI	Notes
590179	99.0	Cars on image are an obstruction
590255	47.5	Average 58.975
590140	91.0	Average 95.05
590147	99.0	
590084	99.0	Deteriorating Expansion joints
590239	78.9	Tree are an obstruction
590059	--	
590161	26.2	Concrete Surface
590165	48.7	
590177	38.9	Shadows
590296	--	
590379	62.0	
590511	93.4	
590512	97.9	
590038	76.0	Shadows
590049	49.2	Shadows
590108	77.5	
590176	--	(Note: 3 RR bridges not rated – no deck!)
640024	30.1	Bridge over saltwater inlet

AMBIS Image Processing and Rating Components

Current rating of the Automated Management Bridge Information System (AMBIS) is also based on a deck distress indexing (DDI) method used in the Automated Management of Pavement Inspection System (AMPIS), a software package developed by ImageCat and originally developed as a collaborative project that included Dr. Howard (Hung Chi) Chung. Dr. Chung was a member of the ImageCat team that provided guidance and technical assistance to the UNCC/ImageCat team in the early stages of the IRSV project. A complete description of the AMPIS model is available at Modena (2002). The initial data base developed for the IRSV project was taken from on-site photographs made by ImageCat research staff, with collaboration with UNC Charlotte research staff. These photos were taken with VGA-resolution cameras and assembled as a collection of bridge deck surface images for each of the 20 bridges.

There are two separate ratings that deal with the distress of bridge deck surfaces: the amount and type of deck cracking or distress; and the separation of joints between bridge spans. Both of these measures reflect distress states that may impact the long-term performance of a bridge. Together with other distress indices (e.g., insufficient vertical clearances beneath bridges), these measures are used to rate the overall performance state of a bridge.

In order to measure deck cracking and joint separation, the project team employed various remote sensing technologies. For deck cracking, the team employed a suite of image processing algorithms initially built for AMPIS for determining the type and extent of deck distress. These algorithms were modified for inclusion in the IRSV system by expanding the types of surfaces considered in the image analysis, e.g., concrete surfaces. For measuring joint separations from very-high resolution aerial imagery, the project team developed a separate set of models that extracted lateral joints from other bridge deck artifacts (e.g., shadows, cars, debris) and measured the amount of separation between spans.

After the bridge surface image is collected, it is processed using GIS warping techniques, image brightness adjustment software, developing a binary image, and using thinning techniques that result in poly-line raster data. Cracks are then computed by connecting vectors with the poly-lines, which based on line geometries, are used to compute crack lengths and orientations. The distress condition is then determined by deck distress indices (DDI) which depend on the geographical features of the cracks. These indices are defined as shown below, where crack length density is denoted by I_l, and crack area density by I_w. These DDI's are expressed in terms of l_i (length of each crack) and w_i (width of each crack). Other parameters α_i (orientation of each crack) and X_c (location of each crack) are also computed and recorded to describe crack patterns.

Table 1.13 shows the ground-truth DDI rating on decks studied. Figure 1.28 takes as an example a bridge deck with eight measured cracks and the formula used in calculating the deck distress index. In the AMPIS model, the metric for measuring cracks was the pavement distress index (PDI), which has morphed into the "DDI" to indicate deck distress index. Finally, the output of a calculated DDI is transitioned through middleware software to integrate with the embedded IRSV database. The software component will include four sub-functions:

1) surface imaging analysis for joint and cracks;

2) quantitative joint displacement analysis (temporal calculations);
3) automated bridge rating based on surface photos;
4) normalizing the DDI value to a 1 to 100 point scale, to be consistent with the other components of the IRSV sufficiency rating; and
5) final data formatting consistent with IRSV requirements.

Table 1.13 DDI Ratings on Deck Distress

Bridge No.	GPS Longitude	GPS Latitude	Structure Type	Yr. Built	DDI Rating
590038	-80.86553	35.22442	Steel	1945	56
590049	-80.88522	35.07933	Concrete	1926	78
590059	-80.68953	35.25128	Steel	1976	-
590084	-80.73167	35.32222	Pre-stressed Concrete	2004	98
590108	-80.83742	35.23742	Steel	2005	85
590140	-80.55408	35.00297	Concrete	1951	99
590147	-80.55408	35.00297	Concrete	1938	99
590161	-80.00214	35.14586	Steel	1961	57
590165	-80.93056	35.16314	Steel	1975	88
590176	-80.85128	35.41492	Steel	1955	99
590177	-80.66333	35.25914	Steel	1970	66
590179	-80.78736	35.24686	Concrete	1937	46
590239	-80.78806	35.24694	Steel	1966	87
590255	-80.81336	35.24621	Steel	1969	97
590298	-80.75361	35.32194	Pre-stressed Concrete	1967	-
590376	-80.88300	35.20783	Steel	1960	66
590379	-80.86883	35.24733	Pre-stressed Concrete	1965	85
590511	-80.74336	35.29578	Steel	1987	83
590512	-80.74336	35.29578	Steel	1987	83

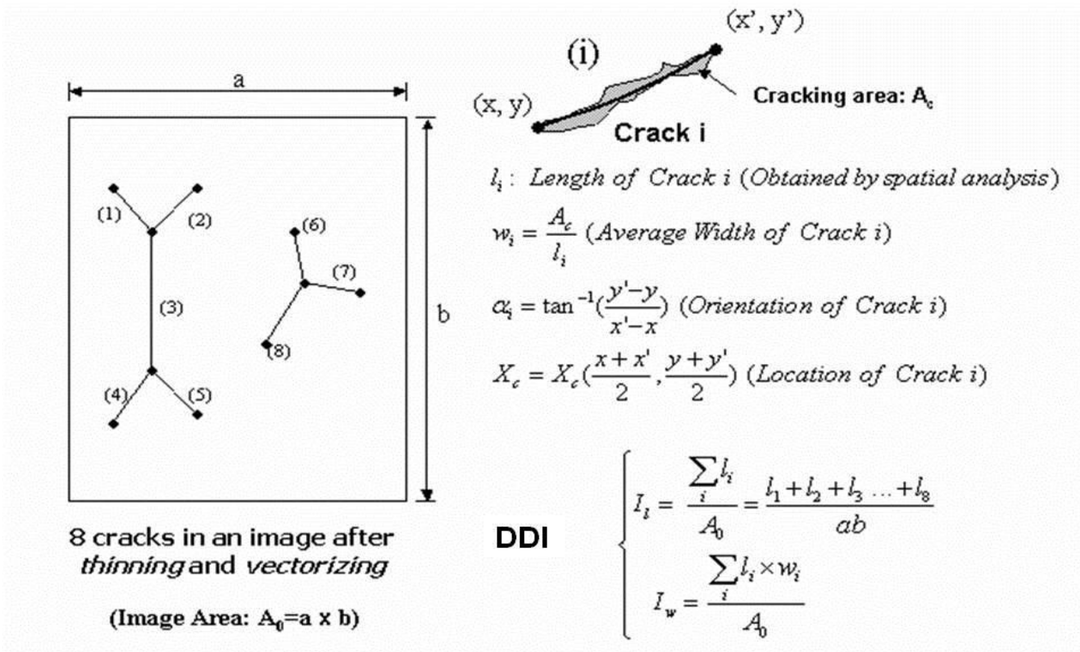


Figure 1.28 Generalized model for DDI rating factor based only on bridge surface cracks

1.7 IRSV System Control Policy and Approach

1.7.1. System Security

IRSV is designed as a customized, client-based bridge data visualization/management system. The critical elements in IRSV include: 1) bridge information, 2) data management system, 3) data acquisition/analysis processes, 4) personnel involved and 5) service environment. 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. US departments of transportation (DOTs) have different security practices/policies; hence, the IRSV system security should be consistent with the sovereignty of the DOTs' security objectives.

It must be recognized that with the integration of the proposed specific CRS data (aerial imaging and LiDAR scan) and SI technology integration, IRSV may have significant implications to national security that are not encountered in current bridge inspection practices. The security issue is related at both information and software levels.

Information security and software security can be vastly different issues. Software security is "the idea of engineering software so that it continues to function correctly under malicious attack" (McGraw, 2004). For software security, several measures can be established during the life cycle of a software development as shown in Figure 1.29. Measures typically include establishing a clear security objective and design the software around the objective. Risk-based security tests can be performed during software development to ensure the end-product measures up to the security 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.

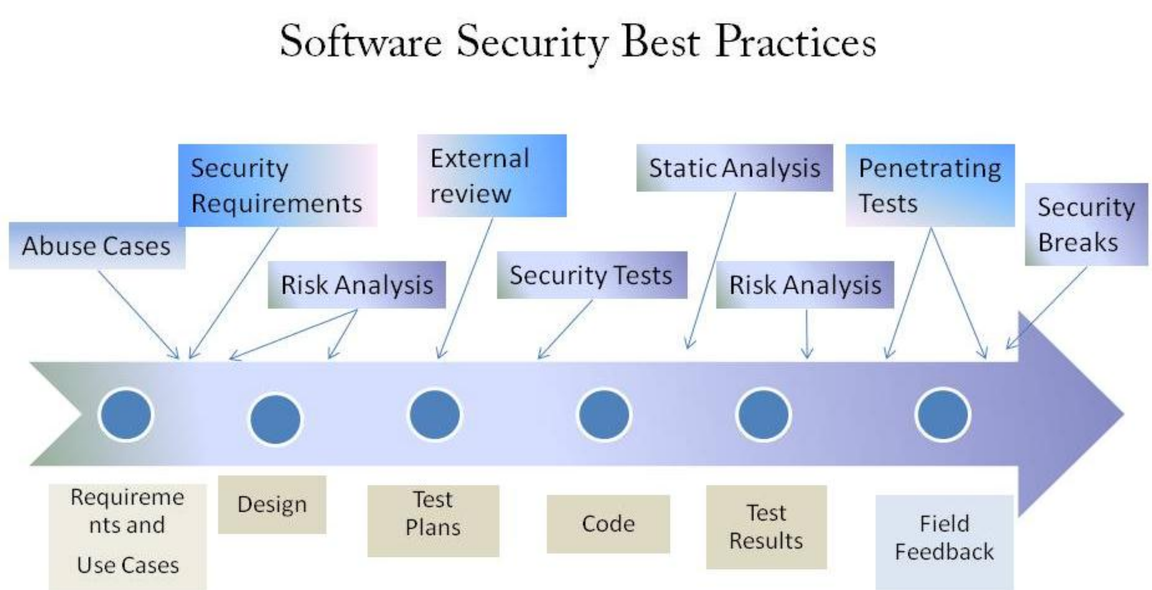


Figure 1.29 Software security measures during development cycle (McGraw 2004)

Information security, on the other hand, refers to the protection of critical information and information systems from unauthorized access, use, disclosure, disruption, modification or destruction (U.S. Code 2009). Similar to software security, 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. It is important to recognize that information security breaches can happen and that risk must be identified.

Our approach to establishing security measures begins with first identifying the human elements that are most likely to result in a security breach. Figure 1.30 shows the human elements identified that may engage in the use of IRSV. The operators are bridge engineers, software developers and DOT bridge database managers. Invited users can be bridge inspectors, subcontracts and researchers. Uninvited users are intruders who may or may not have an ulterior motive to sabotage the system. IT security personnel may vary from DoT to DoT.

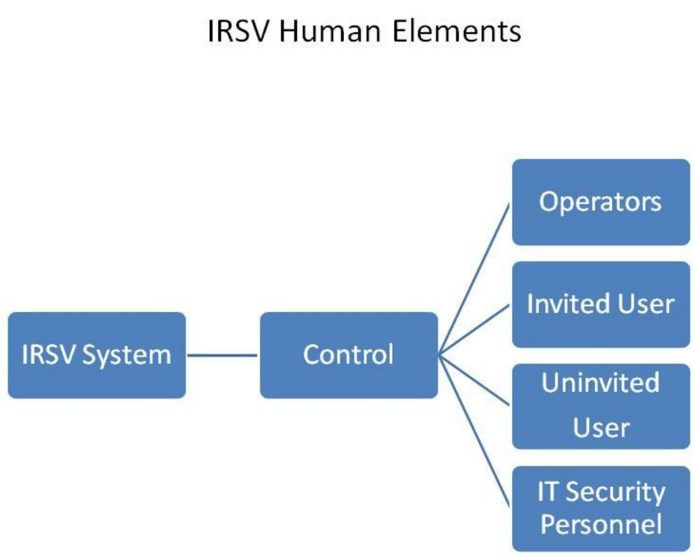


Figure 1.30 Human elements involved in IRSV security

1.7.2. IRSV Security Recommendations

To ensure the security of IRSV, several best practices recommendations have been reviewed and an ICE (Identify, Communicate and Establish) strategy, which encompasses the following suggestions and is mostly condensed from ISO-27002-2005 (ISO 2007), is recommended:

1) Identification
   a) Identify key players: who will be involved in the security measures (i.e., security officers, bridge managers, IT personnel, bridge inspectors, software vendors, bridge maintenance engineers, subcontractors, and the general public), who may have an interest in the bridge information, etc.

b) Identify critical information: bridge data, such as high-resolution aerial photos, that are pertinent to possible structural details that may be used for sabotage planning or other abuses.
c) Identify possible information exchange processes: what are the processes that may allow computer viruses or hacker attacks?
d) Identify security technologies: passwords, access card to hardware, limited wireless access, cryptographic controls, are few potential technologies.
e) Identify business operation continuity processes: if failure occurs, the critical business continuity management process that would minimize loss and resume operation (restoration) quickly needs to be identified.
f) Identify risk potentials and management approaches: if failure occurs, determine anticipated loss to information, DOT and public.
g) Identify potential threats.

2) Communication (education/awareness)
   a) Communicate importance of security objectives to all key players.
   b) Communicate the need of security to all players.
   c) Communicate responsibilities and agreements to all key players.
   d) Communicate importance of incident reports, potential attacks.
   e) Communicate good access practices to all players.

3) Establishment
   a) Establish comprehensive security objectives;
   b) Establish internal security organization;
   c) Establish external audits;
   d) Establish access control processes;
   e) Establish asset management objectives;
   f) Establish key player responsibilities;
   g) Establish education/awareness program.
   h) Establish service delivery compliances;
   i) Establish network security;
   j) Establish incident management processes.
   k) Establish protocol to security bleach/incident reporting.

1.7.3. IRSV Prototype Security Provisions

All state and federal publications on bridge inspection and management practices (AASHTO 1994-2003, Hearn 2007) do not have specific recommendations on the security measures of bridge management systems. It appears that most DOT IT (Information Technology) specialists are responsible for establishing the information security measures. In the case of North Carolina

DOT, information and software security are warranted predominantly through access control and hardware integration control.

The current IRSV prototype system security protocol is established with minimal access rights (rights limited only to bridge managers accessed via a single workstation). The installation process of the IRSV is password protected to prevent unauthorized installs. The security of the IRSV system is provided by the overarching sovereignty of DOT IT security policies where IRSV authentication support, access control, audit logs, etc. will depend on DOT IT security solutions rather than IRSV-specific practices and procedures. Figure 1.31 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. In fact, it is anticipated that enhanced security measures will be custom designed for each clientele during system implementation.

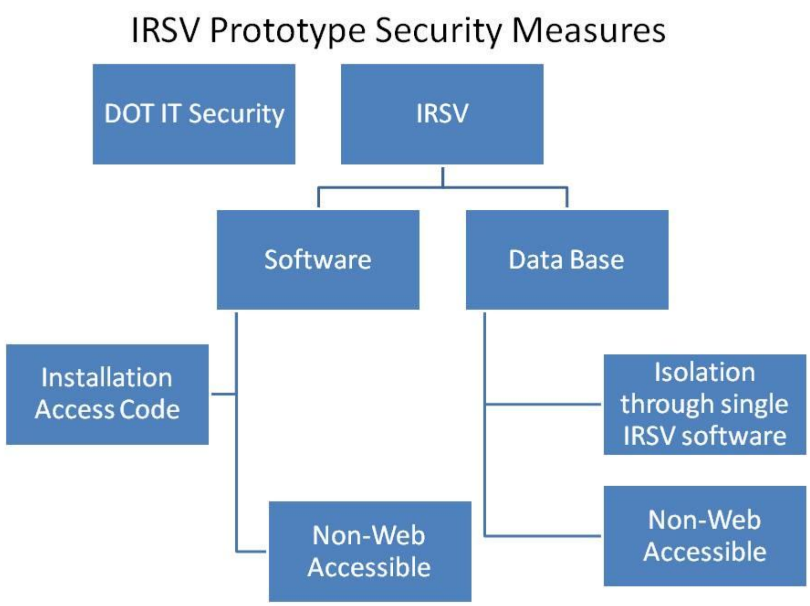


Figure 1.31 Security measures for IRSV prototype system

1.8 Implication to Current Bridge Inspection Process

1.8.1. CRS and SI Technology Transforming Bridge Inspection

Current bridge inspection and evaluation procedures are outlined in standard manuals and guides such as the AASHTO Manual for Condition Evaluation of Bridges (1994). No CRS and SI technologies are outlined either under special or nondestructive testing (NDT) evaluation techniques. As such, it is hard to evaluate the impact due to implementation of CRS and SI technologies to current bridge inspection practices. However, it is recognized that the high resolution technologies proposed in this report may be critical to the shifting of policies from current bridge maintenance to bridge preservation and maintenance (FHWA, 2007). As a result of this shift in policy, The American Association of State Highway and Transportation Officials (AASHTO) formed the TSP-2 (Transportation System Preservation Technical Services Program, 2002). Bridge preservation approach to bridge maintenance and management intends to move from traditional worst first philosophy to a "systematic process of bridge preservation and bridge maintenance" with the goal to prolong the service life expectancy of bridges (FHWA, 2007).

It is anticipated that this shift in bridge maintenance paradigm will motivate research groups to develop much more advanced techniques to enhance bridge monitoring, in particular, CRS technologies. Contrast to traditional (embedded) sensing techniques, several unique features of CRS sensors need to be recognized (Table 1.14):

Table 1.14 Embedded vs. commercial remote sensors

Technical Issues	Embedded Sensing systems	Commercial Remote Sensors
1) Spatial sensing	1) Need multiple sensors networked together with either wire or wireless technologies. 2) Limited by sensor numbers. 3) Many sensors are needed for full spatial coverage.	1) From a distance away with full-view, hence, no network issue. 2) Potentially no sensor limits. 3) Most techniques provide full spatial views, with possible multiple views for complete coverage.
2) Installation	Can be permanently installed.	More difficult as resident sensors.
3) Spatial locationing	Geo-referencing not necessary.	Geo-referencing is critical.
4) Physic-basis	Several technologies can be identified.	Predominantly optical methods.
5) Durability	Severe durability issues.	No durability issues.
6) Monitoring duration	Can provide continuous monitoring.	Most ideal for periodic measurements.
7) Noise and resolution	Noise and resolutions can be issues.	Noise and resolutions can be issues.

Using the FP^2 (Foundation for Pavement Preservation) program as an example, pavement preservation is defined as the "strategy including all activities to provide and maintain serviceable roadway." (FHWA, 2005) Several preventative technologies resulted from pavement preservation, however, ultimately it resulted in better pavement management practices. The contributions from the preventative technologies are to provide the physical data to help establish actual field conditions of the road system and components. The roadway manager can then establish and implement a viable maintenance planning and strategy (NCPP 2001). Monitoring technologies that have been developed under pavement preservation include several automated pavement surveying technologies, many include CRS technologies such as profilemeter and truck-mount LiDAR systems (Kim 2009).

A strong inspection program focusing on preservation maintenance would satisfy the demand from the three maintenance approaches: preventive maintenance, routine maintenance and reactive maintenance (Figure 1.32). Without preservation, the inspection program would only focus on reactive and routine maintenances. It is anticipated that under bridge preservation banner CRS and SI technologies can significantly transform current bridge inspection, in particular, in the structural damage mapping and quantifications. Due to their full-field and measure-from-a-distance nature, CRS technologies can significantly reduce traffic disruption during monitoring, which will be a significant improvement over any existing inspection techniques.

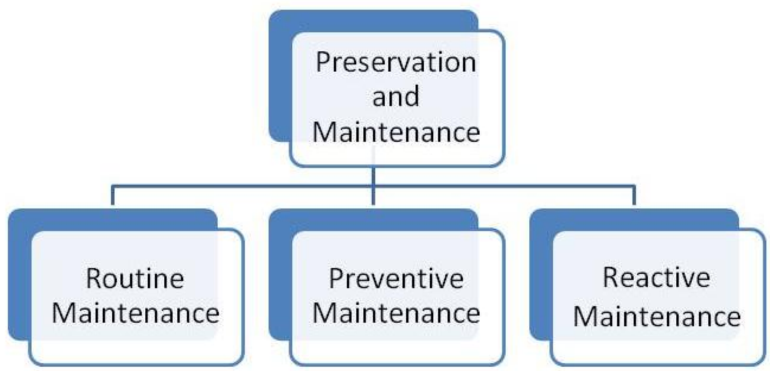


Figure 1.32 Different maintenance approaches for bridge preservation and maintenance

1.8.2. Modified (Simplified) Bridge Inspection Process

Using the two proposed CRS technologies (SI-SFAP and 3D Terrestrial LiDAR scan) as example, conventional bridge inspection process can be modified into a simpler approach (Figure 1.33). Figure 1.33 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. Inspectors arrived at the bridge site and first conduct a visual observation from a distance away to identify any possible change in bridge profile, such as settlements or significant change in bridge profiles. 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. Inspectors are trained to identify bridge component defects such as steel member bending/paint peeling/corrosion/cracking using the AASHTO Guide for CoRe Elements (AASHTO 1997). For fatigue critical members, such as steel girders, bridge inspectors may require detailed inspections to identify possible existence of fatigue cracks. Inspection cycle typically ended with inspector submitting inspection report to DOT and make specific recommendations for possible repair/rehabilitation to bridge components.

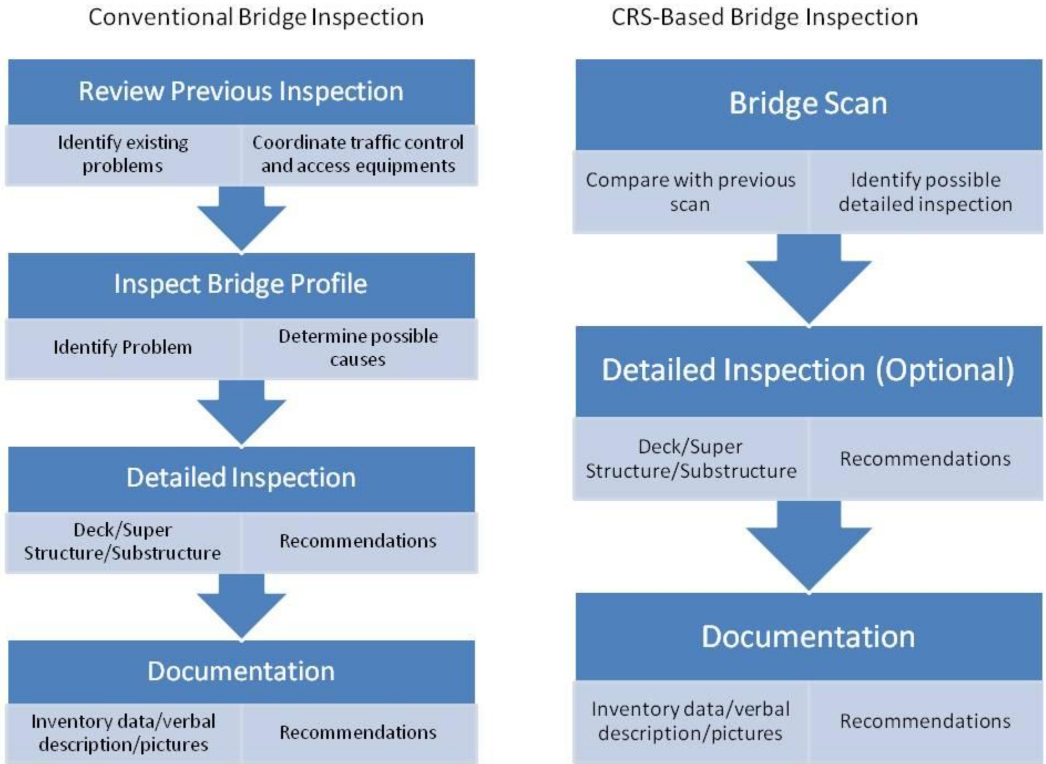


Figure 1.33 Modified (simplified) bridge inspection based on CRS technologies

Even though only limited bridges have been studied, however, 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. The proposed technologies can be applied from a distance away; traffic control is not required, which can avoid disruption of traffic flow. 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. The inspectors can then either request actual access to the bridge for detailed study or can provide direct inspection reports to DOT.

Current proposed CRS technologies are consistent with the AASHTO CoRe (Commonly Recognized Structural Elements) Element by delineating bridge into deck element evaluation (flyover crack and deck surface evaluation), superstructure element evaluation (flyover crack detection and LiDAR) and substructure element evaluation (flyover joint movements and LiDAR scan). Hence, in relation to bridge preservation, CRS technology enables bridge managers to institute a more robust and flexible inspection strategy. The CRS technology-based bridge inspection also provides precision records of time-stamped evidence of state-of-deterioration of the bridge that can be used for next cycle of inspection to establish deterioration rates.

1.9 Summary and Conclusions

Figure 1.34 represents the overall IRSV System Architecture, with a more detailed presentation than Figure 1.2 – representing the evolution of system design throughout the project. IRSV system design can be best described as a bridge data management and visualization software that consists of a bridge database, a knowledge modeling module, high-resolution visualization module, a multi-variate bridge element visualization module and a separate, high-resolution image analysis module called Automated Management of Bridge Information Systems (AMBIS).

There are a number of data sources that have been investigated over the course of the past two years. They are represented along the bottom of Figure 1.34. The data sources of most interest and utility that have emerged are LiDAR scanning, High Definition “Sub-inch” Aerial Photography, and AMBIS (Automated Management Bridge Information System). These three sources provide much useful information that if properly used could enhance the task of transportation infrastructure (e.g., bridge) inspection and health monitoring.

For long-term structural monitoring, the environmental influence cannot be ignored. A 3-D LiDAR scanner collects surface topology data in its line-of-sight with high accuracy up to 70 meters. Due to the ease of operation and large amount of spatial information produced, the 3-D LiDAR scanner has many applications in structural health monitoring. This summary report has introduced three computer based LiDAR applications: (a) automated bridge defect detection and quantification; (b) clearance measurement, and (c) load testing. The defect data that are available from a completely utilized assessment includes bridge deck cracks and joint separations (resulting from aerial photos and AMBIS analysis routine), and substructure defects, damage from collisions, etc. (resulting from LiDAR scans of the complete substructure.)

Results from the small sample of approximately 20 bridges to date in North Carolina and California have provided some evidence that the Aerial sub-inch photography, AMBIS analysis, and LiDAR techniques have some promise of successful applications in bridge health monitoring. Compared to onsite visual bridge inspection and close range photography, remote sensing-based bridge inspection is sensitive to the “noise level” resulting from vehicle traffic, shadows, moisture, and lighting conditions. Bridge monitoring also requires that remote sensing imagery reach a certain degree of resolution in order to detect possible problems. Since different bridges have different properties, not all of the problems associated with a bridge can be identified from the top view.

This report concludes with a section (1.8) discussing the impact of CRS and SI technologies to current bridge inspection practices that include possible transforming existing bridge inspection process to include regular CRS scans, which can significantly reduce the cost of inspection and at the same time, provide reliable data for evidence of deterioration/anomalies as well as for temporal studies.

As emerging inspection assistance tools, remote sensing data should be further explored with a collaborative effort by RITA, FHWA and AASHTO in order to consider standards that may be promulgated for general bridge monitoring and related applications. This is especially critical, considering the potential of the proposed CRS technologies to generate high-resolution imageries that have national security implications. A separate section (1.7) is devoted to the discussion of the system control and security approaches that can be adopted for the IRSV system.

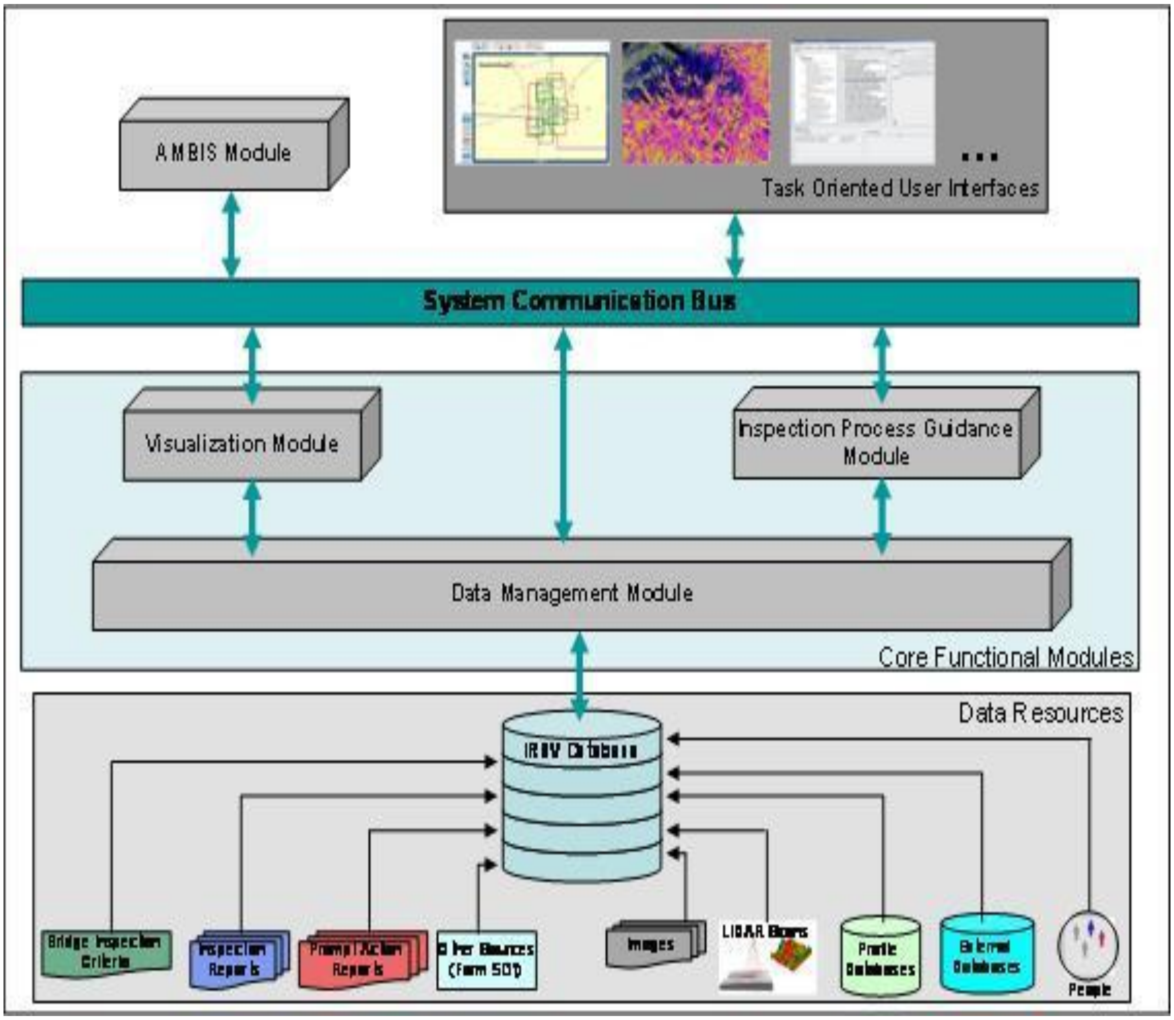


Figure 1.34 IRSV high-level system architecture

Even though cost-effectiveness study is not included in current study, the different CRS technologies proposed present different market potentials. One major difference in potential "marketability" between the use of aerial flyover/ AMBIS process and LiDAR scans is that aerial flyover equipment including aircraft and advanced photographic equipment are readily available throughout the country. LiDAR equipment, on the other hand, are not as readily available and not as readily understood and accepted among the bridge engineering community. Demonstrations of this technology will be necessary on a wide scale basis in order to be understood and accepted. Asset Management programs in DOTs and SHAs are available partners in promoting the concept of LiDAR use in Bridge Management as well as Pavement Management. Given the capabilities of LiDAR scanning, there is considerable room for acceptance. However, as an economical method of obtaining data on the detailed damage and condition of bridge decks, the aerial photography used in this project presents a cost-effective tool.

Output from four different data sources populates the interim IRSV system and together, formulates an overall bridge performance index, or sufficiency rating. Again, these sources include: NBIS Bridge Inspection Data, LiDAR, AMBIS, and high-resolution aerial imagery. For the latter three data sources, the following "distress" metrics have been analyzed for 21 bridges in North Carolina:

1. Decking cracking (Aerial photos and AMBIS output measure type and amount of distress, e.g., block cracking, longitudinal cracking, etc.);
2. Joint displacements (Aerial photos and AMBIS output measure percent displacement relative to allowable separation by bridge type);
3. Distress on substructure (LiDAR output described as mass loss and severity);
4. Load rating (LiDAR output); and possibly
5. Bridge clearance from pavement or surface below the deck (LiDAR output)

At present, the individual metrics for aerial photo/AMBIS and LiDAR have been defined for each bridge with an equal weight. In the future a set of relative weights that effectively assigns importance levels to each distress metric will be added. When combined with the actual measurements for each metric, these weights will help to produce a single index that can serve as an overall rating of the bridge. As we move forward with Phase Two, we will need to accommodate subtle and not so subtle differences among our various state and local partners. Overall, there will likely result from this analysis process a scale comparable to the 1 to 100 scale that many if not most states use to rate the overall condition of their bridges. This one metric is also a combination of metrics that are collected in the bi-annual Bridge Inspection process, for comparison with IRSV output.

Again, in summary, as we conclude Phase I of the overall IRSV project development, we have tested and validated this approach on bridges maintained by the NCDOT in Mecklenburg County, plus five bridges maintained by the City of Charlotte DOT. The research team has had communications and agreement with other states and local governments to continue with the testing and upgrading of the "proof of concept" IRSV System that has thus far been developed.

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Appendix A: List of Acronyms and Definitions

AASHTO - American Association of State Highway Transportation Officials
ACI - American Concrete Institute
AMBIS – Assisted Management Bridge Information System
BHI – Bridge Health Index
BHM – Bridge Health Monitoring
BMS - Bridge Management System (more accurately called a process)
CDOT – City of Charlotte Department of Transportation
CR – Condition Rating
CRS – Commercial Remote Sensing
CRS-SI – Commercial Remote Sensing and Spatial Information
DDI – Deck Distress Index
DLF - Dynamic Load Factor
FEM - Finite Element Method
FHWA – Federal Highway Administration
GenOM – Generic Object Model
GPS - Geographical Positioning Satellite
IDE – Integrated Development Environment
ImageCat – a private sector partner in the IRSV Project
IRSV – Integrated Remote Sensing and Visualization
LADAR – Laser Radar
LiBE – LiDAR Bridge Evaluation
LiDAR – Light Distancing And Ranging
LOS – Level of Service
MR&R – Maintenance, Repair and Rehabilitation
MSVE – Microsoft Virtual Earth
NBIS – National Bridge Inspection System
NCDOT – North Carolina Department of Transportation
NCRS-T - National Consortium for Remote Sensing in Transportation
NCSBEDC – North Carolina Small Business and Economic Development Center
NDE - Non-Destructive Evaluation
NDT – Non-Destructive Testing
NEVC – Nondestructive Evaluation Validation Center
NHS – National Highway System
NIST – National Institute for Standards and Technology
OAM – Office of Asset Management, FHWA
Ontology - another word meaning Database
PCView – Parallel Coordinate View
PDO – Problem Domain Ontology
PMS – Pavement Management System
Point Cloud – A display of 3-D surface points in a laser scanned image
PONTIS – A “Bridgeware” software suite of programs developed through AASHTO that is used by many states as part of their Bridge Management System
RITA – Research and Innovative Transportation Administration

REVISION

SD/FO – Structurally Deficient and/or Functionally Obsolete
SDOF - Single-Degree-Of-Freedom
SFAP - Small Format Aerial Photography
SHM - Structural Health Monitoring
SIS – Software and Information Systems Department at UNC Charlotte
SMO – Semantic Matching Operation
SOA – Service Oriented Architecture
SPView – Scatter Plot View
SQL - Standard Query Language
UNCC – University of North Carolina at Charlotte
USDOT – United States Department of Transportation
VIS – Visualization
VisCenter – Charlotte Visualization center

Appendix B. IRSV Visualization Images

Figure B.1. Geographical reference map

Note: Images have been reconfigured to include the 21 bridges in our Text Case database Regional Geospatial View. Legend for bridges identified below are coded as follows:

Red – significant damage; Blue – Moderate damage; Green – minor to no dam

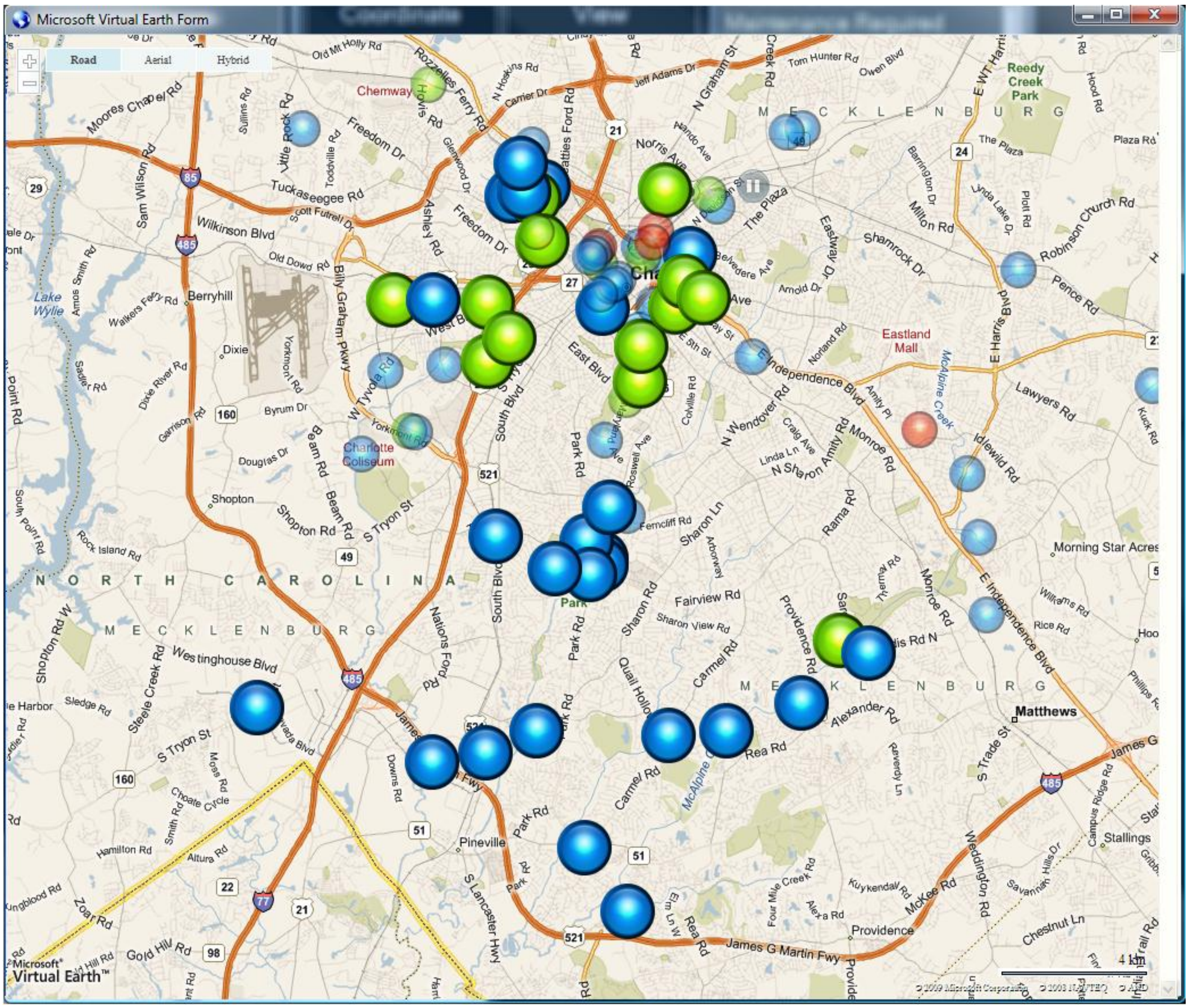

Figure B.2. Relational Visualization --- Scatter Plot

(Sufficiency rating by year bridge was built)

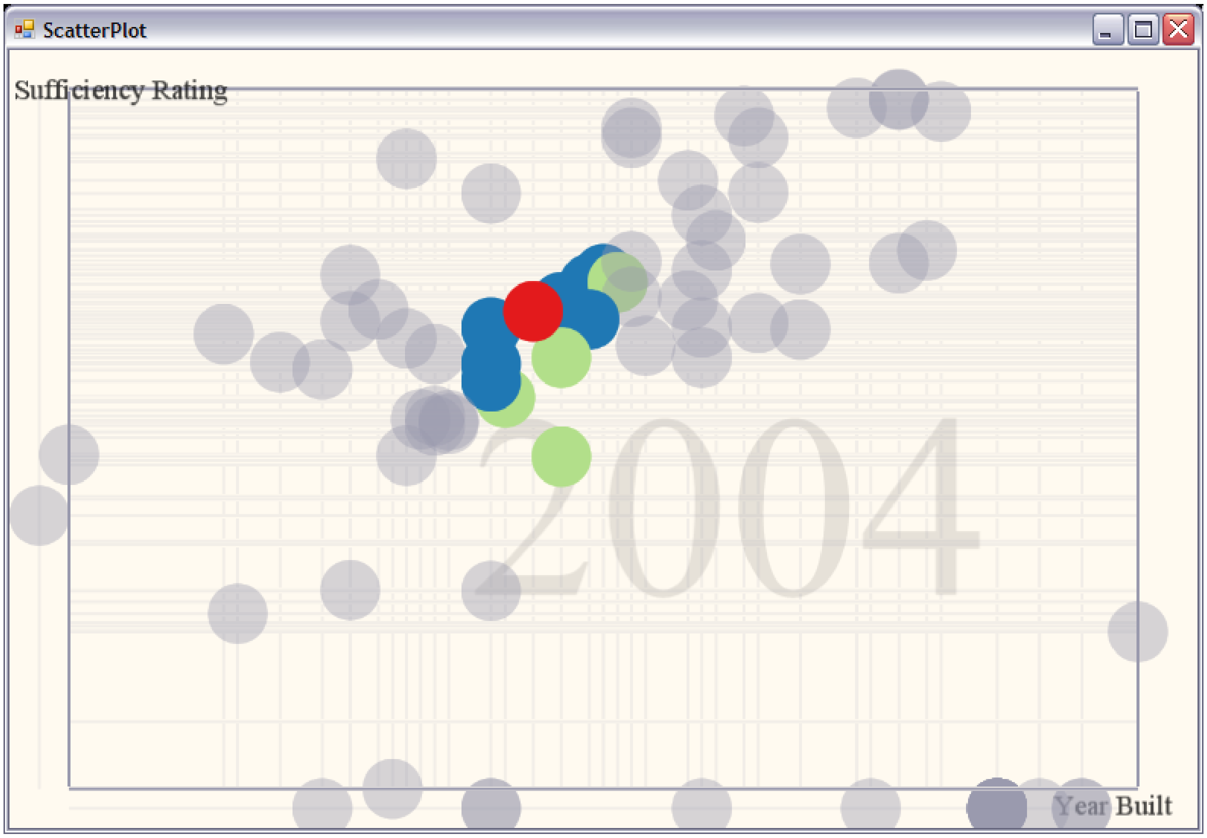

Figure B.3. Temporal Visualization

Three years sufficiency rating, covering one or two visual inspections, over two to four calendar years. More detailed section of this database is shown on the following page.

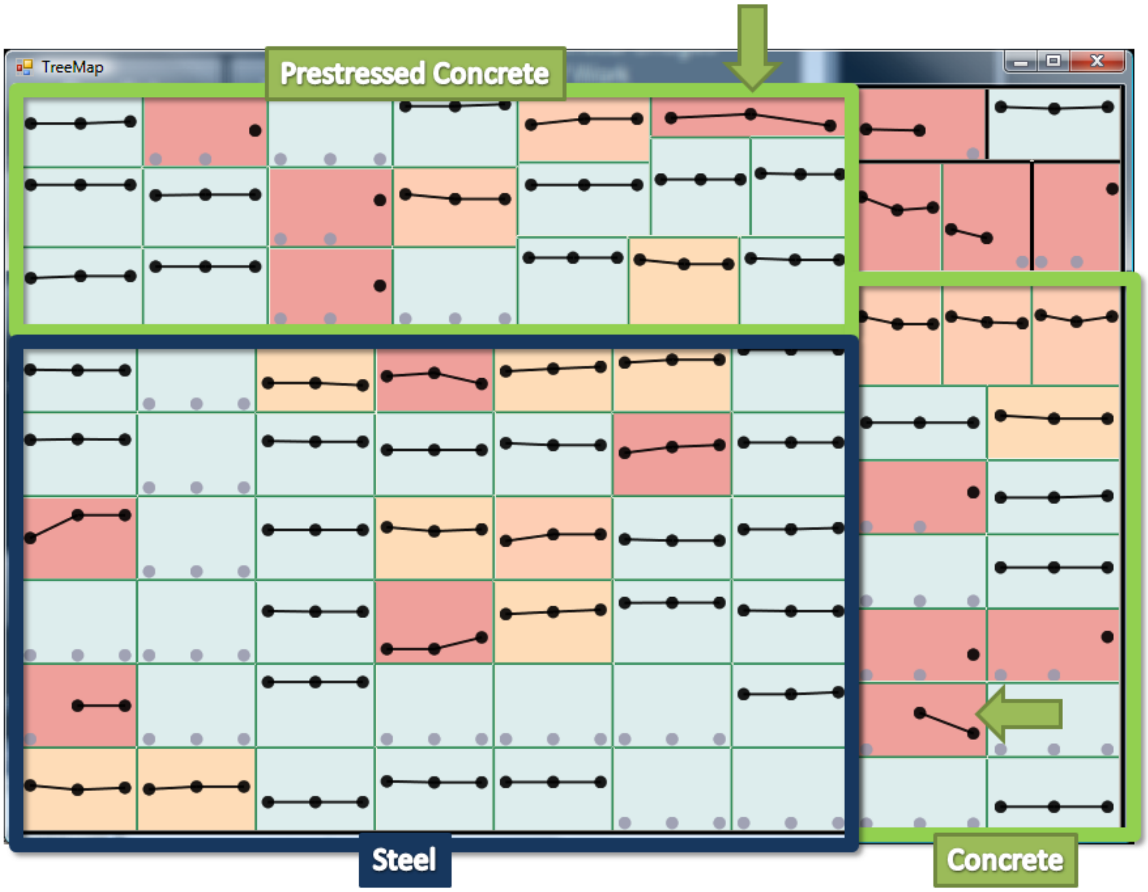

Figure B.4. Sample of temporal data

Detail view of small sample, temporal data, showing various type of construction, with highlight of bridge # 590147 (classified as all concrete bridge)

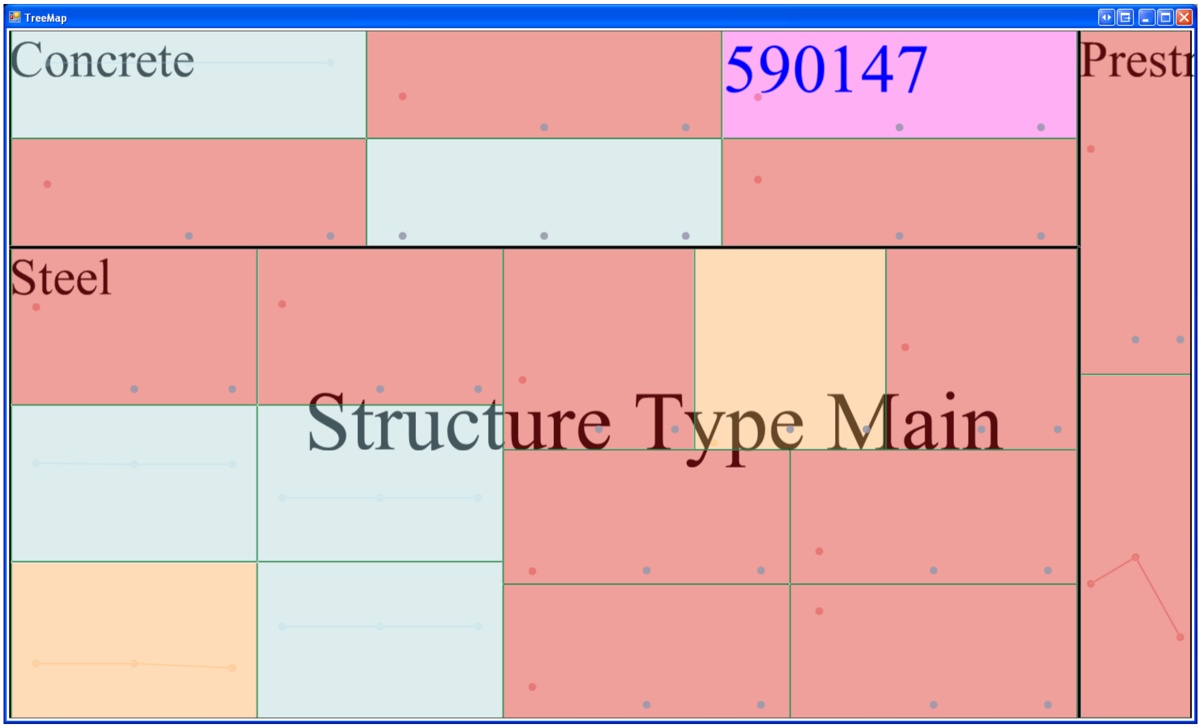

Figure B.5. Relational View: Parallel Coordinates

NOTE: Database shown below is a small sample of the NCDOT and CDOT bridges available and included in the IRSV Project. 52 data points are available in the database, but the following are shown for example only: 1) Present condition, 2) Design load, 3) NBIS Inventory Rating, 4) Waterway adequacy, 5) Bridge improvement costs.

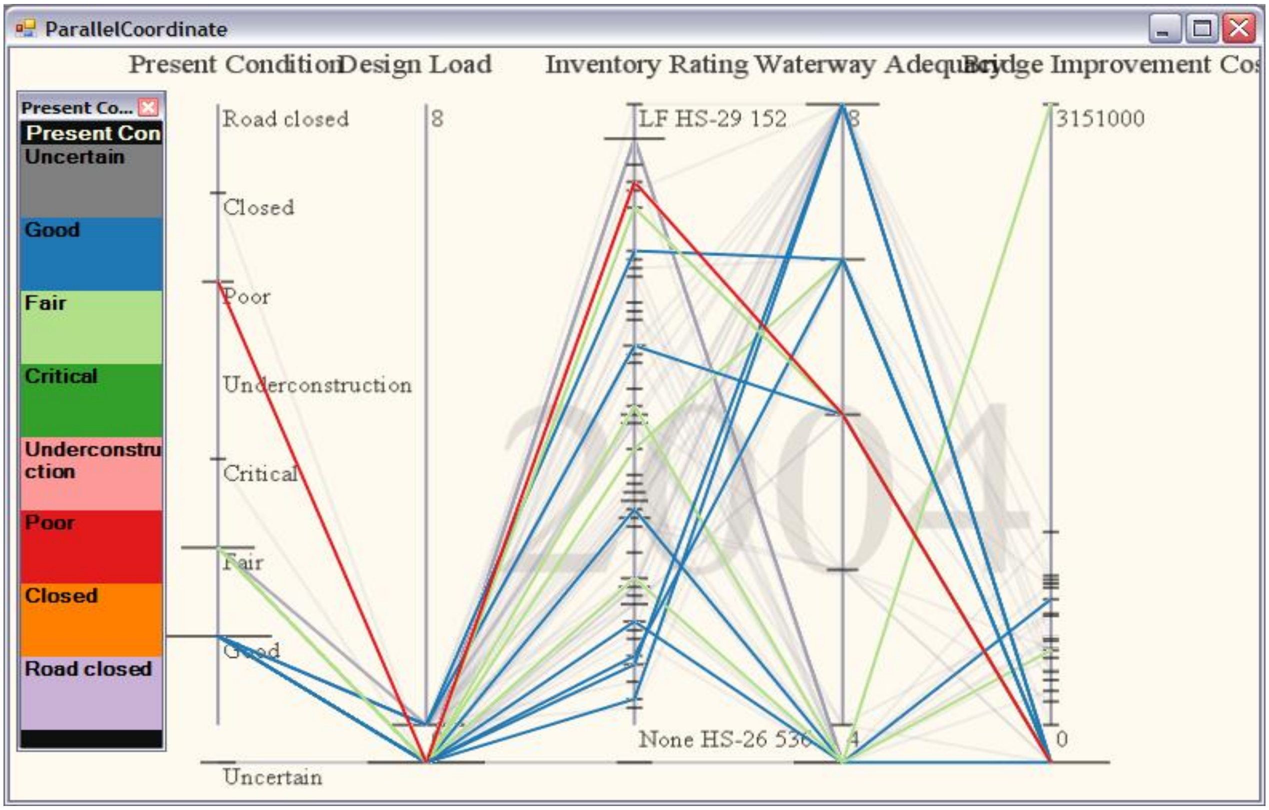

Figure B.6. Detailed Views – schematic, photos, aerial scans, LiDAR images

Figure B.7. Example of High Resolution Aerial Photographs, NCDOT Bridge 590704

Note: Aerial images of each of 21 sample bridges with accompanying data are included in Volume Three.