Integrating structural health monitoring and information technology for efficient bridge management

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ABSTRACT: While the importance of bridge health monitoring applications becomes more and more appreciated, current bridge management practice includes mostly visual inspection methods. Visual inspections include a great deal of uncertainty, since they are mostly limited by the indications at the surface and damage occurring inside the structure which can easily be overlooked. Accuracy of visual inspections depends largely on the experience and expertise of the inspector. Recent studies show that these inspections are also prone to high subjectivity. Instrumentation of bridges can reduce these uncertainties considerably and lead to development of more realistic and accurate prediction models, enhancing the efficiency of bridge management practices. However, there are some issues to be resolved such as evaluation, storage and management of data as well as development of specifications for recommended health monitoring procedures. This paper first presents the structural inspection, evaluation and maintenance procedures employed in practice today. Finally, the paper overviews the use of health monitoring methods together with information technology, condition prediction and decision making to improve bridge management procedures for an ongoing project with Florida Department of Transportation.

1 INRODUCTION

1.1 *Objective of the Paper*

Importance of efficient management is more emphasized than ever in the present day, urging transportation officials seek innovative approaches to handle the aging highway bridge stock. Structural Health Monitoring (SHM) offers new techniques for improving assessment methods significantly. Investigation of this paper is on integrating SHM to transportation management practices, with the use of emerging Information Technologies (IT).

Health monitoring and IT integration is studied within a current project with Florida Department of Transportation (FDOT) to develop an efficient management system framework utilizing these concepts, which will be outlined together with the current status in the project.

1.2 *Asset Management Concept*

Asset management is defined by American Association of State Highway and Transportation Officials (AASHTO) as a "systematic process of maintaining, upgrading, and operating physical assets cost effectively. It includes preservation, upgrading and timely replacement of assets, through cost effective management, programming, and resource allocation decisions". Efficient asset management by providing precise data by health monitoring has promises. An ideal SHM has all management components connected as a single integrated system. The preferred case is that structural monitoring and traffic operation systems are linked and controlled by the same station. This way, all necessary data of the bridge (external forces, stress and strain levels, traffic congestion data, GIS information) are collected through wired or wireless networks of smart sensors, recorded and monitored in the operating station from where responses can be sent to automated systems (automated traffic signals, messages) and surveillance units when necessary. Consequently, bridges can be operated with optimum performance, providing the best utilization of their capacity. In addition, recording and analyzing the information from health monitoring data will lead to improvements in maintenance and structural design methods.

1.3 *Bridge Condition Inspection and Identification*

Advancing technology is changing the perspective in which transportation systems are managed. Communication, sensing and information technologies supply effective tools for maximizing maintenance and operation efficiency. It is becoming a common practice to install traffic monitoring systems either as mounted cameras or automated probes providing

real-time traffic data to be used for congestion monitoring, performance evaluation and emergency routing. Similarly, structural properties of bridges can also be retrieved with the availability of a variety of sensors and data collection systems which are available today with relatively low prices. These systems can be used to obtain information about the structural condition and operation of bridges. Bridges, as transportation assets, require regular maintenance expenditure and corresponding life-cycle operation cost with respect to a given life span. These costs can be reduced by condition-based inspections and maintenance with structural health monitoring.

Nevertheless, instrumentation is yet not a part of inspection of ordinary highway bridges, for which visual inspections are the common practice. Most of the current bridge inventory data consist of component condition ratings based on visual inspections. Ratings are usually assigned on a scale of 0–9 to individual components using the guidelines of National Bridge Inventory (NBI) system, established by the 1968 Federal Aid Highway Act. Inspections are often conducted once every two years. If condition ratings are available for a relatively long period of time, the data can be used to establish bridge (or bridge component) deterioration models. Such models are then used to estimate the future condition of a bridge for the purpose of planning future bridge maintenance and/or repair activities (Bolukbasi, et al., 2004).

Code	Description
N	NOT APPLICABLE
9	EXCELLENT CONDITION
8	VERY GOOD CONDITION - no problems noted.
7	GOOD CONDITION - some minor problems.
6	SATISFACTORY CONDITION - structural elements show some minor deterioration.
5	FAIR CONDITION - all primary structural elements are sound but may have minor section loss, cracking, spalling or scour.
4	POOR CONDITION - advanced section loss, deterioration, spalling or scour.
3	SERIOUS CONDITION - loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2	CRITICAL CONDITION - advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.
1	"IMMINENT" FAILURE CONDITION - major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.
0	FAILED CONDITION - out of service - beyond corrective action.

Figure 1. NBI Condition State Ratings (Federal Highway Administration (FHWA), 1995)

Routine inspection is the most common form of highway bridge inspection to satisfy the requirements of the National Bridge Inspection Standards. The accuracy and reliability of documentation generated during these inspections are critical to the allocation of Department of Transportation construction, maintenance, and rehabilitation resources. Routine inspections are typically completed using only the visual inspection technique and rely heavily on subjective assessments made by bridge inspectors. In light of this, and given the fact that visual inspection may have other limitations that influence its reliability, the Federal Highway Administration initiated an investigation to examine the reliability of visual inspection as it is currently applied to bridges in the United States. Generally, it was found that all structural condition documentation is collected with significant variability. Specifically, 95% of primary element condition ratings for individual bridge components will vary within two rating points of the average and only 68% will vary within one point. Documentation collected to support condition ratings also has significant variability as exemplified by the number and types of field notes and photographs taken by inspectors. With respect to the use of element-level inspections, it was found that element usage was generally consistent with the Commonly Recognized Element Guide. However, there is significant variability in the condition state assignments of those elements and in some cases the condition states are not applied correctly to particular elements (Phares, et al., 2004). In addition to the subjectivity and uncertainty constraints, visual inspection practice is a time consuming task and requires a skilled and experienced personnel. Significant time is also spent for analyzing and interpreting the collected data with this practice.

Many state DOTs are currently implementing PONTIS bridge management software, for efficiently recording, storing and managing bridge inspection data. This software provides a database helping to keep track of the condition ratings assigned to each bridge component. Collection of bridge inspection data is specified by PONTIS for the states utilizing it. This software allows generating deterioration models and running optimization analyses for maintenance and repair scheduling through the lifetime of the bridge, based on the visual inspection data (Thompson, et al., 2003). However, reliable condition assessment and deterioration models require robust analysis techniques, and current optimization practices are limited by the subjectivity and uncertainty of visual inspection procedures and data.

Numerous non-destructive evaluation (NDE) methods are now available with development of advanced sensor devices and data collection techniques. Structural properties can be obtained accurately with health monitoring applications, which are becoming more common and economical. These technologies will eventually become a much more integrated part of bridge management systems; however, current operational frameworks of organizations do not allow efficient use of health monitoring tools. There are also numerous difficulties from the absence of standard practices and guidelines for application, evaluation and efficient use of these methods.

2 INFORMATION USAGE

Although technological state-of-the-art allows implementing intelligent bridge management systems, examples of bridge management systems with highly integrated data collection and analysis are rare. However, the vision of Federal Highway Administration (FHWA) and other transportation agencies is implementation of Intelligent Transportation Systems as standard practice of bridge management in the near future (Pagano and Ogard, 2005).

Information management is the key for efficient transportation asset management. Information related to condition and operation of highway bridges are required by numerous branches of state departments of transportation. The need for data sharing is considered in two dimensions. First dimension is the lateral dimension involving groups in the same level with different scopes; for example, Structures, Maintenance and Operations divisions. Bridge performance information is to be used by the maintenance office for monitoring the performance and planning repair and rehabilitation operations. Necessary for structural design office is the same information to derive and validate data for modeling and analysis. The division associated with traffic operations needs certain data related with bridge usage, which is also of concern for structures and maintenance groups. Lack of communication and information exchange between these offices is a major problem causing collection of duplicate data or delays and for acquiring it. Another kind of lateral information exchange is between districts, where compatibility of information is of concern.

Second dimension is vertical, suggesting the information exchange between higher-level decision-making organizations and operations within the executive branches. A two-way communication link between these agencies is necessary for efficient functioning of the department. The agency headquarters needs the supply of accurate information to be able to conduct network-level trade-off analyses and resource allocation decisions, while vertical information flow is essential for implementing standards and creating harmony among district offices. Information exchange routes are illustrated in Table 1 and Figure 2.

Table 1. Features for Bridge Information Management

Dimension	Feature	Scope
Lateral	Intra-Departmental	Structures (Design), Maintenance (Inspection, Repair & Rehabilitation) and Operations (Traffic Management)
Vertical	Geographical Network Level Project Level	District offices, State DOTs Headquarters Decisions District Office Operations

Common organization schemes of state transportation departments do not allow for efficient management of the information acquired from bridges. Lack or insufficiency of mentioned information exchange mechanisms is causing divisions within state departments of transportation (DOT) to establish their own practices and act as individual DOTs. When conditions in critical bridges or bridge components indicate distress or unexpected behavior, instrumentation for further assessment is the common and desirable approach followed by bridge owners. However, instrumentation and data collection is a portion of the total process of bridge assessment, where evaluation and interpretation of the collected data is the ultimate and most important part. Guidance should be provided to groups undertaking instrumentation tasks, with certain standards and suggested procedures. It is obvious that deploying a sensor network without careful planning regarding the critical sections and analysis methods can lead to accumulation of huge amount of meaningless data, or worse, unsafe results (Aktan, et al., 2003, Masri, et al., 2004, Rens, et al., 2005).

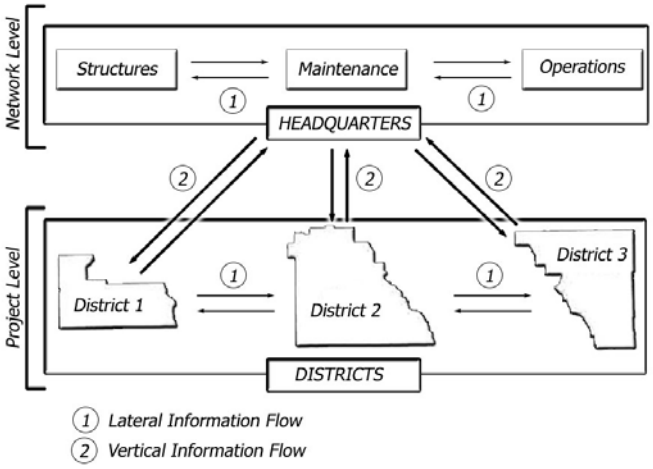

Figure 2. Exchange of Information between DOT Entities

For the cases where instrumentation is appropriately performed, the personnel in charge should have a clear command of what is to be done with the collected data. Many situations call for quick evaluation and decision-making, where public safety may be of concern. Timely appraisal is frequently an issue for many health-monitoring applications, where huge amount of data is collected, sometimes unnecessarily. Absence of a general specification makes the district offices search their own way of analysis each, inevitably causing delayed evaluation. Storage of the collected data reliably is a common problem especially for long-term recording. Data is not made available to other groups, or even within the same group, due to inefficient information management for retrieval of the data.

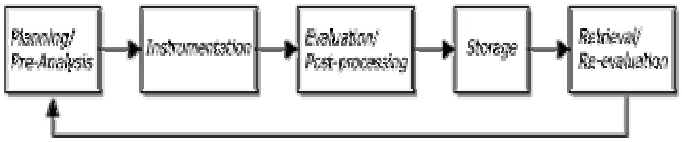

Figure 3. General Steps in Health Monitoring and Data Management

Different procedures in health monitoring instrumentation, data collection, analysis and storage are causing problems in evaluation of bridge performance at higher levels of management, where data from different sources are not compatible to be able to make a comparison.

Commonly, ownership and responsibility of data collection and collected data is not clearly specified. That possibly results in each requirement of data leading to an individual bridge evaluation task even if the required data already exists within the records of a different branch.

3 INTEGRATIVE INFORMATION MANAGEMENT SYSTEM

Problems caused by physical scatter and discrepancy of current data collection and storage system can be overcome by establishing a fundamentally innovative mechanism of information management where all the data is collected in standard formats and transferred to the state-wide bridge management database (BMD), where they are logged and stored. This database is to serve all clients of different layers within the organization up to the level of their involvement with the information and authorization by the system. In addition to serving as a data terminal, the system will provide means of efficient communication among all branches in lateral and vertical dimensions. Conceptual mechanism of database operation is illustrated in Figure 4(a) considering three districts. Left part of the figure indicates the current schema, in which district offices collect and store the data, and report to the headquarter offices, from where they later receive instructions. However, even with a small number of districts, the complexity of these transactions are apparent from the figure, as well as evaluating incompatible data formats from different sources. Also, currently there is no mechanism for information sharing among districts.

Function of the Bridge Management Database is illustrated in Figure 4(b). The database is ideally to replace all interaction practices between DOT entities, and store all transportation data, providing access to data by all entities, providing an information highway and acting as the spine of the organization.

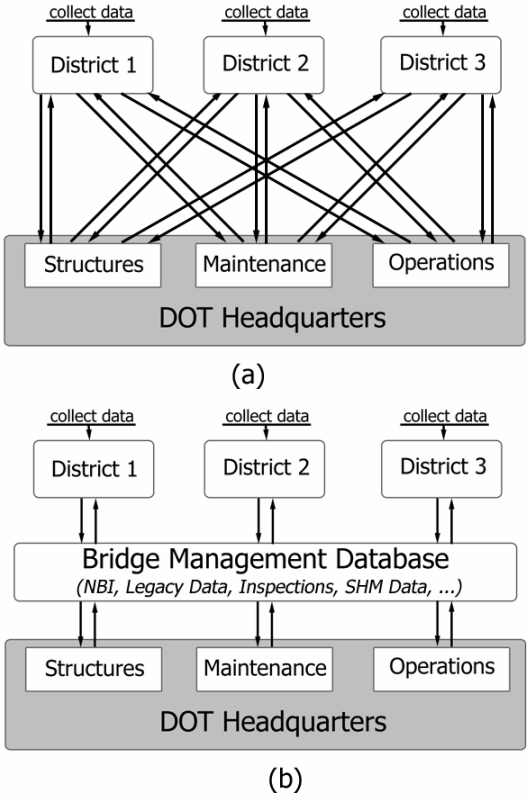

Figure 4. Information and Communication Mechanism with Bridge Management Database

The database should integrate SHM data by directly acquiring bridge monitoring data and transforming them to meaningful indicators with certain subroutines. Issues regarding ownership of data will be resolved by specifying the task of the department sub-divisions as limited to collecting the data and transmitting them to the common database, which should include everything related with the bridge like NBI data, structural condition evaluation, bridge maintenance and rehabilitation operations, deterioration models and reliability analyses.

4 DECISION MAKING TOOLS

Currently, bridge maintenance operations are conducted according to the customary practice and as damage and/or deterioration is detected. However, a more advanced approach to bridge management will be one incorporating life-cycle cost management with probabilistic perspective. Due to uncertainties in evaluating condition and safety indices, they should be defined as probabilistic random variables. By using the data obtained from bridge inspections, probability distribution functions of these indices can be derived. Deterioration of condition and safety indices can be modeled also from the inspection data as bilinear curves. These models are also probabilistic, and the curve indicates the mean value. Figure 5 below shows a very simplified model for bridge condition degradation over time.

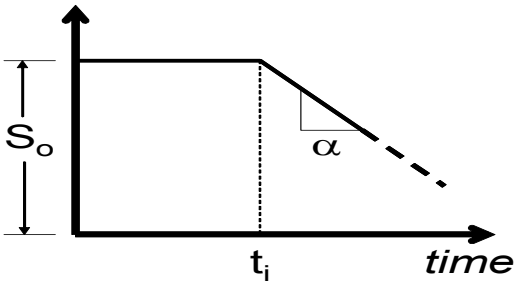

Figure 5. Example Deterioration Model (bilinear)

Influence of different maintenance alternatives on condition and safety indices and the deterioration rate can be modeled as simplified effects on safety and condition indices. Complete bridge performance models allow running maintenance scenarios, keeping the safety and condition indices above certain thresholds, and aiming at minimizing the bridge lifetime maintenance cost for a selected service period.

Figure 6. Example of Rehabilitation Effect on Assumed Deterioration Model

Life-Cycle Maintenance Cost assessment requires reliable historical condition and maintenance data. It is possible to provide the necessary data very reliably with instrumentation, making the uncertainties much smaller and the model more efficient. By using SHM, databases of necessary size, detail and accuracy can be generated for constructing much more precise performance models, leading to more efficient maintenance plans. The models can also be based on analysis results that can be supplied instantly from raw data collected by the system.

Bridge monitoring instruments will also detect any abrupt changes in the bridge condition due to an extreme event or an unexpected distress, updating the management plans for quick decision making, which would be crucial in case of an excessive event. SHM methods eliminate the bias and limitations of critical structural components. Safety indices can be evaluated with much higher accuracy and confidence.

Using SHM techniques makes it possible to retrieve information about the status of individual elements of a bridge. Since every component requires unique maintenance work, maintenance operations can be scheduled more specifically and efficiently. Also, once individual deterioration and maintenance models are available for each critical node, a network reliability analysis can be conducted within the bridge components, in order to determine the most critical ones (parallel/series). This can allow more efficient maintenance planning.

As a result, it is expected to reduce overall cost of maintenance, extend lifetime and safety of bridges by using combination of SHM and Probabilistic Life-Cycle Assessment methods. The proposed bridge management system will be an integrated approach of maintenance planning with probabilistic optimization supported by collection and analysis of data by health monitoring. The system can extend to include other bridges for network-level management planning (Estes and Frangopol, 1999, Farhey, et al., 2000, Imai and Frangopol, 2001, Kong and Frangopol, 2003).

5 CASE STUDY: INFORMATION MANAGEMENT SYSTEM FOR FDOT

An ongoing project with Florida Department of Transportation (FDOT) focuses on the bridge management system and its integration with health monitoring technologies. Information exchange among FDOT divisions, namely, Structures, Maintenance and Operations groups is being investigated in order to detect deficiencies in the communication mechanisms among these groups. These three branches have overlapping operation fields and data needs; however, lack of information sharing among those was reported, resulting in retrieval of incompatible or duplicate data. Data storage is by means of various formats, so collected data is not readily accessible by other groups, or even by the same group. This is an example of lateral information flow hindrance, where groups on the same managerial level are concerned.

FDOT is divided into 8 district regions, as shown in Figure 7, where inspection and maintenance tasks are undertaken by district offices. District offices have developed diverse practices of bridge data collection and management, being disoriented by numerous sensor and data acquisition technologies, while having no standardized specification or guide to follow for health monitoring applications. In addition to the difficulties in data collection and assessment of district bridges, incompatible data generated by different district offices are creating bigger problems in the headquarter office, in terms of making comparative evaluations for bridges from different districts.

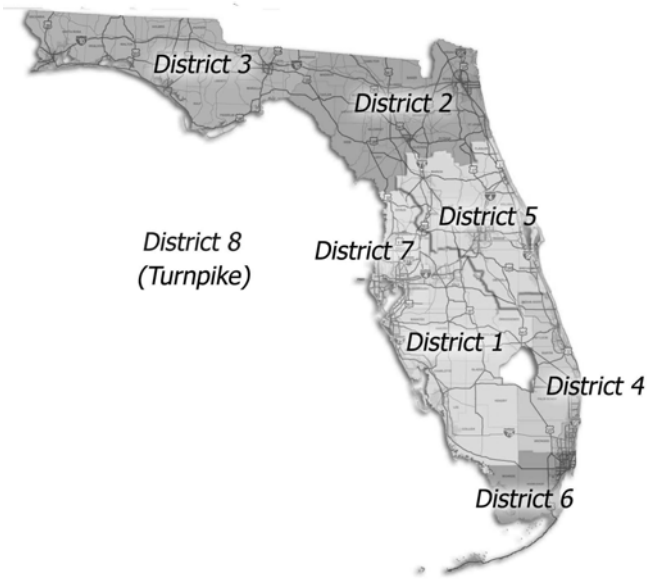

Figure 7. FDOT District Regions Map

Florida bridges also include 98 movable bridges, complex structures having machinery for opening a portion of the bridge, to allow the passage of ships or other traffic through the bridge. The majority of movable bridges are of bascule type, having interior spans called "leaves" that rotate upward and away from the centerline of the river, providing clear passage for river traffic (Figure 8). Movable bridges are the most problematic ones to maintain and repair. Their maintenance cost is about ten times more per sq.ft of bridge. Rehabilitation budgets of movable bridges amount many times those of fixed bridges. Movable bridges are inspected closely for all aspects of deterioration, since their deterioration rate is much faster than fixed bridges, and any malfunctioning will inevitably cause long delays. On-site maintenance personnel keep the mechanical components serviced continuously, since they are the most critical parts of functioning.

Figure 8. Movable Bridge Examples (Bascule Type)

Structural properties are also watched closely for frame misalignment, support damage, weld deterioration, corrosion, scouring, erosion washouts and so on. Also, other common problems are the electrical limit switches that control the sequence of bridge opening and closing procedures, where missing one switch causes the procedure to stop and a long time to detect the location of the problem and fixing it, causing long vehicle queues (Buxton-Tetteh, 2004).

Design of a new framework is necessary to be able to incorporate health monitoring data into bridge management and decision making process, and to serve as an efficient information storage and access site, where data is directly logged and shared, and all information is available to FDOT parties up to their level of authorization. An integrative database system is being developed and proposed for achieving an integrated bridge management system. The basic user interface is summarized below in Figure 9, illustrating the main categories of the software operation. The web-based system is to offer a graphical and user-friendly interface, where districts and bridges of concern can be selected from map views. The software in development is being designed with a mixture of state-of-the-art web, database and programming development software, and including latest security considerations.

Real-time modules and specific instrumentation to replace the current electrical system prone to malfunctions can also help reduce movable bridge breakdowns and long delays. In addition to offering advanced management tools with optimization analyses, integrated monitoring of instrumentation can also increase the efficiency of operation of movable bridges. Therefore, movable bridges can also be assigned 'Bridge Operation' component within this scheme, with which the operation of the bridge can be tracked real time.

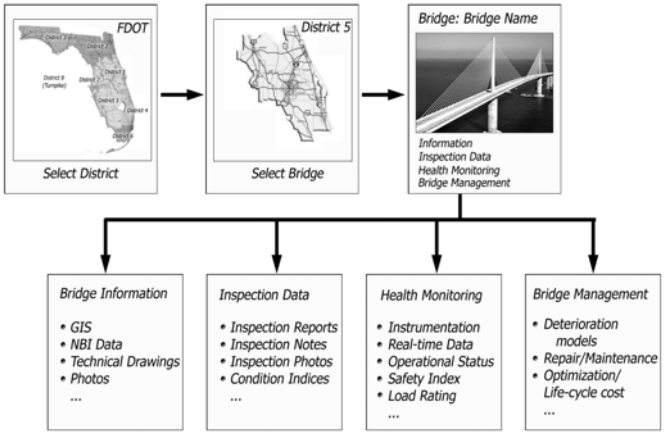

Figure 9. Bridge Management Database Schema for FDOT

In addition to storing regular inspection data, the database will also contain instrumentation data obtained through the sensor network, incorporating analysis algorithms for deriving safety indices and other health indicators. Real-time health monitoring will be allowed for bridges with continuous instrumentation, therefore keeping the supervisors aware of possible drops in safety level due to any kind of distress as environmental forces or wearing effects. After an extreme event like a hurricane where several structures within the network are affected to different levels, an instantaneous condition assessment will be invaluable for prioritizing repair interventions and determining safe routes for evacuation.

The software is also going to include the latest bridge management methods in the 'Bridge Management' component. Probabilistic deterioration models will be derived from health monitoring data to come up with realistic and reliable prediction models, instead of using the information from visual inspections. Probabilistic network analyses will be run using the indices for individual bridge components to determine the overall safety of the bridge, accumulation of which will result in deterioration rates with very high certainty compared to current methods based on visual inspection methods or assumptions. Life-cycle maintenance cost analyses will be run using bridge deterioration models and effects and unit costs associated with each action, optimum maintenance plans will be drawn for given bridge lifetime, minimizing the total cost and assuring certain safety levels. This will be an ultimate tool for high-level management of bridges allowing trade-off analysis and budget decisions with maximum efficiency.

6 CONCLUSIONS

As health monitoring methods are becoming more frequent and common, state departments of transportation are tackling with the problems of utilizing these new technologies without proper standardization and guidance, as well as managing the huge information flow, to incorporate the benefits of the new technology into their operation schemes. Focusing on investigating the characteristics, current practices and common problems for Florida DOT and its bridge network, this study is aimed at combining all aspects of bridge management with latest health monitoring technology, providing;

1 Standardization of instrumentation, data collection and evaluation procedures
2 Information storage, management and sharing system (integrated database)
3 Combination of bridge health condition data with maintenance, repair and replacement (MRR) planning; high-level decision-making tools

Current investigation and development of new methods and software are carried out with experimental investigation and validation using laboratory models utilizing the state-of-the-art sensor and health monitoring technology.

7 ACKNOWLEDGEMENTS

This study is conducted with the support of Florida Department of Transportation (FDOT). The authors would like to thank Messrs. Marc Ansley, Richard Kerr, Richard Long, John Harris and Ms Elizabeth Birriel of FDOT for their valuable feedback and guidance. Professor Dan M. Frangopol's recent visit to UCF and his guidance in the areas of reliability analysis and maintenance management are greatly appreciated. Finally, the help and support of Ms. Elisa Bishop and other student members of the SHM research group in CEE/UCF are to be acknowledged.

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