Key words: Health Monitoring, Civil Infrastructure Systems, Long Span Bridges, Information Technology

Abstract. Mitigating risk due to disasters and managing civil infrastructure systems are intersecting and interacting societal concerns. A coordinated, multi-disciplinary approach is necessary for leveraging technology and innovating both hazard mitigation and infrastructure management. Health monitoring of civil infrastructure systems has emerged as a powerful paradigm for framing and leveraging technologies, especially information technology, promising effective integrated management. Health monitoring by integrated sensing, communication, computing and information systems have been shown to support objective condition assessment, operational management and intelligent transportation systems applications, as well as evaluating the vulnerability of critical infrastructure subjected to hazards and ensuring that the condition of critical civil infrastructure systems and their components are accurately assessed within a short amount of time following incidents, accidents and hazards. Challenges and opportunities in health monitoring are discussed in this paper and an example application to a major long-span bridge is presented.
1 INTRODUCTION

It is generally acknowledged that most critical infrastructure systems have been falling short of providing satisfactory operational performance under everyday demands, and their constructed elements have been appraised to have poor structural conditions (ASCE, 2001 Report Card for America’s Infrastructure). Most experts agree that there is a need to mitigate the shortfall in financing by leveraging technology more effectively. Indeed, the last decade recorded great advances in information technology. The Internet and all other forms of communications and networking have facilitated rapid access to information and computing, overcoming the barriers of distance and time. Parallel developments occurred in experimental and analytical technologies, and especially in many forms of sensing. Integrating communications and computing with sensing promise to have a significant impact on industry and our daily lives (NSF, 2002). Integrated sensing, communication and computation systems are envisioned to have strategic importance for the security of the nation’s civil and engineering infrastructures.

Recent events indicate the need for real-time data and information management systems that provide timely information to emergency managers regarding the conditions of critical infrastructure following disasters. Integrated information and communication systems that take advantage of a GIS platform have been proposed for emergency management (IISIS Project). Health-monitoring systems that integrate real-time sensing, communication and computation together with data and information management have been envisioned for long-span bridges, tunnels and entire regional transportation networks in the realm of next generation’s intelligent transportation systems. Such future health monitoring systems for intelligent transportation networks will collect satellite, aircraft and land-based images and data on weather, traffic, roadway and structural responses, integrate and display the data for on-line, real-time viewing by qualified officials for guiding the public, respond to incidents, support enforcement, and, integrate management.

Transportation health monitoring systems will further take advantage of integrated information systems that will permit officials and engineers to access, review and analyze legacy and recent data and information in addition to real-time data. The data will have many simultaneous modalities, such as satellite images and on-ground streaming-video of traffic and roadway conditions, weigh-in-motion information and critical structural responses including temperatures, accelerations, displacements, tilts and strains. Intermittent and continuous data should be sufficient to evaluate, in real-time, any critical changes in operational safety due to incidents and weather, and structural reliability due to aging, deterioration, damage due to accidents or overloads. These are discussed further in the following. The convergence between transportation health monitoring systems and the real-time damage assessment and emergency response systems envisioned by the disaster mitigation research community are obvious (MEDAT Proceedings, Housner, 1997).

2 DEFINITIONS FOR HEALTH, PERFORMANCE AND HEALTH MONITORING

We define the health of a bridge as its system reliability to possess adequate capacity against any probable demands that may be imposed on it in conjunction with the limit states in Table 1. Performance is a consequence of health, i.e. how the bridge actually meets the reasonable peak-level demands related to utility, operation, serviceability, durability and safety. We note that there has not yet been an adequate discussion for the critical limit-states for defining performance within the civil
engineering community and an ASCE SEI Committee has been recently formed for this purpose (ASCE Official Register, 2001). The recent AASHTO LRFD Code (AASHTO LRFD Bridge Specifications, 1994) definitions for limit-states are limited to some aspects of structural performance only, and they fall short of quantifying lifecycle as well as the expected peak demands or their return periods in each of the critical limit-state categories. To initiate discussion, we venture that the ranges of return periods for peak-demands during the serviceability-durability, safety and conditional limit-state events maybe taken as 25-75 years, 250-500 years and 2500-5000 years, respectively, given the related discussions in the earthquake engineering community for seismic performance.

In reliability analysis it is common to use the “Second Moment Reliability Index $\beta$” as a measure of health or reliability as this relates to the deterministic “Safety Factor” or “Load Rating” most engineers use in practice (Ang. et al. 1975, Enevoldsen, 2001, Frangopol, et al. 2001). For example if Capacity and Demand are independent and normal random variables, $\beta = 0$ corresponds to a Health or 1-$P_f$ of 0.5, $\beta = 3$ corresponds to a Health of 0.999, and $\beta = 4.75$ corresponds to a Health of 0.99999. The latter corresponds to one in a million chance of inadequate capacity.

Engineers often lack sufficient data, especially on peak demands at the ultimate and conditional limit-states, that would be needed to actually quantify the health of an existing bridge. Further, different levels of health for different bridges and for demands at different limit states may be acceptable. For example, a $\beta$ of 3 may be considered quite acceptable for the collapse safety of smaller bridges on secondary roads, but a more stringent $\beta$ of 5 may be necessary for the collapse safety of a major, long-span bridge. Similarly, different $\beta$ would be admissible when evaluating traffic flow capacity, operational safety due to wind and ice, serviceability due to deflection or vibrations, chemical intrusion into a concrete deck, fatigue cracking at a critical weld, safety against element failure, structural system safety, etc.

We define health monitoring as tracking of any aspect of performance or health by reliably measured data and analytical simulations in conjunction with heuristic experience so that we may quantify and bound the health of a bridge for at least the most critical limit state events, in a proactive manner. The concept of health monitoring may be described best in terms of the goals of preventive health management in medicine: anticipate and prevent highly probable, common ailments before they occur; and, diagnose and intercept less common ailments at a sufficiently early stage while they are more curable. The principal advantage is pro-actively intercepting “ailments” before they take their toll. The potential in applying this concept in mature industries such as manufacturing, aerospace, automotive and electronics are well established (Proceedings of the 3rd International Workshop on Structural Health Monitoring, 2001) and the US bridge engineering community has already started to recognize the need for such a concept in view of the perceived “insufficient” condition of a large percentage of the bridges (National Bridge Inventory Data, 1998).

3 LIMITATIONS IN CURRENT PRACTICE

Engineers have been visually inspecting, monitoring and proof testing bridges for Centuries. However, presently health and performance are described based on subjective measures. In addition, defects, deterioration and damage are not discovered until it is possible to visually observe the signs they exhibit at which time these would have taken their toll on health. These shortcomings impact the timeliness, effectiveness and the reliability in any management decision irrespective of any
sophistication in the management process (Chase 1999, Chase 2001). Moreover, even experienced engineers may find visual signs of defects, deterioration and damage and still not be able to diagnose the causative mechanisms, or their impact on reliability and global health. The global health of an entire bridge as a system, inclusive of the performance criteria corresponding to every one of the limit-states in Table 1 is actually what is needed for effective management decisions.

<table>
<thead>
<tr>
<th>Utility</th>
<th>Serviceability &amp; Durability</th>
<th>Safety &amp; Stability of Failure at Ultimate Limit States</th>
<th>Safety at Conditional Limit States</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Impacts</td>
<td>Deformations</td>
<td>Excessive Movements &amp; Settlements</td>
<td>Earthquake</td>
</tr>
<tr>
<td>Social Impacts</td>
<td>Local Deterioration &amp; Damage</td>
<td>Material &amp; Element Failure</td>
<td>Flood</td>
</tr>
<tr>
<td>Cost Parameters</td>
<td>Vibrations</td>
<td>Stability Failure</td>
<td>Fire</td>
</tr>
<tr>
<td>Operational Parameters</td>
<td>Durability</td>
<td>Collapse</td>
<td>Terrorism</td>
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<td>Security</td>
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</tbody>
</table>

Table 1. Critical Limit States and Events Included in the Definition of Health

A recent study was performed by the Federal Highway Administration’s NDE Center on various types of short-to-medium span bridges to establish the reliability of typical visual inspections (FHWA, 2001). This study concluded that at least 56% of the average Condition Ratings derived from visual inspection were incorrect with a 95% probability.

In the case of major long-span bridges, it has been argued that generally more experienced and diligent inspectors are trusted with inspections. However, the effectiveness of visual inspection in reaching all of the critical locations and in finding all of the possible defects becomes especially questionable in the case of very large structures simply because of greater difficulty for access and the impact of geometric scale. The ability of the human eye to scan a 120 feet long member for defects is not the same as scanning a 40 feet long member. In addition, the duration and cost requirements for a thorough inspection of a large, long-span bridge with complex structural systems approach the limits of practicality, effectiveness and feasibility. For example, it has been reported that an in-depth visual inspection of the Brooklyn Bridge in New York required over three months at a cost exceeding $1 Million (Yanev, 2000).

4 THE PROMISE OF FRAMING NEW TECHNOLOGIES WITHIN HEALTH MONITORING

Given the limitations and shortcomings in the current practice, and also given that available bridge program funds permit replacement or upgrade of only a small percentage of the posted and deficient bridges in the National Bridge Inventory (National Bridge Inventory Data, 1998) every year, we need effective strategies for leveraging technology and improving the objectivity, reliability and efficiency in the manner we manage our current investment in highway bridges. Health monitoring may be considered as a new paradigm powerful enough to serve as an overall framework for leveraging technology to impact the practice of bridge engineering. If we are able to make a sufficient number of proper and successful implementations, in the long-term we would accumulate sufficient data and information, gain knowledge and insight for accomplishing (Smith, 2001):

- A data base on as-built properties of various bridge types and the behavior of structural and ancillary systems under environmental and operating loads, and how defects,
aging, deterioration and damage may affect these properties and the lifecycles of typical bridges;

- Improving codes and standards based on relevant, factual and statistically meaningful data, such as the actual bounds of spatial and temporal distributions of loads, load effects and capacities.

- Performance-based engineering based on objective metrics, damage indicators and health and condition indices that may be practically measured;

- Pro-active management of health, i.e. diagnosing and mitigating the circumstances that may eventually lead to unsafe operation, deterioration or damage in a timely manner;

- Effective renewal engineering especially by identifying common defects and root mechanisms that lead to deterioration and mitigating these during renewal;

- Innovation that is not yet codified, such as new materials, fabrication and erection systems, protective systems, etc.

- Integrating operational and maintenance management for improved safety of operation, performance and revenue, especially by clearly understanding and mitigating the adverse impacts of climate, weather and ambient conditions on operational and structural performance;

- Managing emergencies during/following occasional accidents that may affect operation, serviceability and safety, as well as conditional limit-state events such as very rare disasters by effective data and information collection and management tools afforded by health monitoring;

5 TOOLS, APPLICATION SCENARIOS AND STRATEGIES

Given the potential impacts and benefits of health monitoring, we note that it is much more than just a group of technologies. Health monitoring involves the tracking of any aspect of performance or health by reliably measuring data and interpreting this in conjunction with domain specific knowledge and heuristic experience so that the health of a bridge for the limit state events that are of concern and interest may be quantified objectively.

<table>
<thead>
<tr>
<th>Geometry Monitoring</th>
<th>Short-Term Controlled Structural Testing</th>
<th>Localized NDE Methods</th>
<th>Long-Term Monitoring</th>
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<tr>
<td></td>
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<td>Slow-Speed</td>
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<td>Displacements</td>
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Table 2. Experimental Technologies for Bridge Health Monitoring

Health monitoring will involve instrumentation, data acquisition and data analysis, noting that the level of experience and innovation in design, the sophistication in instrumentation, and the quality in data collection and analysis that is required to solve real-life complex infrastructure systems problems
is often far greater than most engineers envision. The experimental technologies that require integrated application for health monitoring are summarized in Table 2. It is not possible to expect an application of only geometry monitoring, or short-term testing, or only NDE to provide a sufficient insight for accomplishing all of the objectives and desired outcomes of health monitoring. We should recognize that health monitoring requires the integration of a considerable number of analytical, experimental and information technologies as well as heuristic knowledge and experience through a well-coordinated multi-disciplinary team effort and within a systems-engineering framework.

The fundamental first step in any health monitoring application is system-identification to conceptualize the bridge system through a physics-based model, such as a geometric-replica high-resolution finite element representation (Aktan et al. 1997, Aktan et al. 1998, Aktan et al. 2000, Farrar et al. 2000). Numerical or neural models may serve for health monitoring of elements or local regions of structures by reducing the problem to statistical pattern-recognition (Soon et al. 2001). Such approaches are valid and useful; however, system-identification and conceptualization of the entire bridge system would be a necessary prelude to such efforts.

The scope of the sensing and data processing, and the frequency of controlled tests for system identification and for calibrating the health monitoring system would depend on the specific objectives of each application. Strategies, constraints and expectations governing possible health monitoring scenarios may differ considerably. For example, the benefits we may expect in designing health monitoring for a new bridge may include diagnosing the rate of intrusion of chemicals into the critical regions of concrete by taking advantage of corrosion sensors embedded at various depths. On the other hand, health monitoring of an existing bridge would more likely be motivated by performance problems or concerns about safety of the as-is structure. Duration of an application is a major parameter depending on the application scenario. In health monitoring of a bridge that is in the design phase, implementation during the construction would enable optimum lifecycle management.

The investment that maybe considered feasible for the health monitoring of a major, unique structure that serves as a lifeline to a major urban area will be quite different from that of a common overpass. However, objective health assessment of large populations of recurring bridge types such as steel-stringer bridges with RC slabs, RC slab bridges, I-or-box-girder bridges with RC slabs, etc. require a different strategy and tools from that of a unique, major bridge. In the former case, we need to take advantage of statistical sampling and clustering to conduct system identification. These studies would permit a generalized behavior of the bridge type. Practical experimental and analytical tools may then be developed for feasibly testing and objectively establishing the health of any and every member of the population as a complement that would provide objectivity to the biannual inspections. Such an approach to health monitoring is analogous to “fleet monitoring” of manufactured systems. The principal challenge would be establishing a statistical sample that would represent all of the critical parameters and their combinations that may affect the health of every single bridge within the entire population. A recent demonstration of the fleet-monitoring approach for re-qualifying the load-capacity rating of T-Beam bridges in Pennsylvania has been carried out as described by Catbas et al (2002).
The duration of health monitoring is another critical variant in any specific application to an existing bridge. Short-term applications at intervals may reveal a snapshot of the operating loads and the corresponding responses of a bridge to assess fatigue-life or to re-qualify posting. Understanding the root causes of any distress signs and establishing the system-reliability of a bridge may require months-to-years of monitoring. If health monitoring is incorporated at the design stage for lifecycle management, we may expect specific benefits:

- Confirming the assumptions made during design and assuring a successful implementation of the design and construction specifications;
- Effective quality control of the material properties, fabrication, transportation, erection and construction, and capturing any significant trapped strains at the end of the construction;
- Documentation of the as-constructed material, element and the entire system properties to serve as a baseline for lifecycle management;
- Characterization of the structure with its foundation and soil in terms of a calibrated analytical model for reliable simulations and load capacity rating;
- Tracking the trapped construction stresses, the loading environment after commissioning and the corresponding movements, strains, tilts, accelerations, displacements and temperatures so that any anomalies in loading or behavior may be detected at an early stage;
- Complementing and directing visual inspections to locations and details that are critical to improve the efficiency and effectiveness of engineers conducting inspection;

If an application is made to an existing bridge, we may expect to accomplish:

- Diagnosing the causes of any distresses or any aspect of performance shortcoming and formulating possible measures for mitigation;
- Establishing remaining fatigue life at fatigue-sensitive and especially fracture-critical details, elements and connections and establish the safety reliability of an aged bridge;
- Whether any changes in codes or loading criteria or use-modes may require retrofit;
- To provide data and serve as a foundation for reliable maintenance, repair or retrofit;
- Analysis of vulnerability against a variety of hazards, eg. Catastrophic accidents, terrorist attack, etc
- Objectively prioritizing replacement in the case of large populations of aging bridges.
Acquiring the right type, mix, frequency and duration of data and designing an optimal sensor suite requires establishing a clear set of objectives and scope for any health monitoring application. A larger number of data channels and higher data acquisition frequencies do not necessarily lead to better health monitoring, in fact obtaining just the right amount of data at just the right time is a necessity for success and data quality assurance may be the single most important issue. Further, health monitoring should not be expected to solve all problems, promoted just on the premise of research. The expected payoff from health monitoring should be carefully evaluated depending on: (a) Whether it is possible to acquire the insight expected from health monitoring by any other, more economical means with a sufficient level of confidence; and, (b) if and how the insight gained by health monitoring will impact the operation and maintenance management decisions and ultimately serve to improve the performance of the bridge.

6 DESIGN AND IMPLEMENTATION PROCESS FOR HEALTH MONITORING OF A MAJOR BRIDGE

The first objective of this paper has been to describe the paradigm of health monitoring with all the associated concepts and expected benefits in terms and examples specific to bridges. This has been presented. The second objective is to outline the steps that are needed for health monitoring of a major bridge, illustrated with an example that the writers have been working on in relation to a long-span bridge. In the case of long-span bridges, health monitoring promises to serve as a vehicle for advancing security surveillance, operations and structural maintenance in one technological leap.

Figure 1: Sensing Systems Distributed Over the Commodore Barry Bridge
Drexel Intelligent Infrastructure Institute researchers have been exploring the opportunities in integrated real-time sensing, communication, computation and information management, i.e. “monitor” systems and one such system is being demonstrated on the Delaware River Port Authority’s Commodore Barry Bridge spanning the Delaware River near Philadelphia. The sensing components of the monitor system on the mile-long Commodore Barry Bridge are summarized in Figure 1, indicating the areas and the mechanisms affecting the bridge that are instrumented, providing 485 channels of on-line data in real-time through an Internet T1 connection.

The basic building blocks of the health monitoring system maybe envisioned as: (a) sensing, data acquisition and control; (b) data processing and information management; and (c) human and organizational interfacing for adoption as a management tool. The data and information processing challenges are very much influenced by the necessity of providing a user-friendly, intuitive and secure interface for the human operators that is the key for organizational acceptance and adoption, naturally the true measure of success.

The following describes the principal steps following in designing and implementing the health monitoring system for the Commodore Barry Bridge:

**Characterization:** This required a thorough review of the design and shop drawings for the bridge, inspection reports and any additional relevant reports or documentation for the bridge to identify the current state of the structure including its performance and maintenance history. A site visit was also performed to visually examine and verify the condition and locations of any special or complex member and connection details, retrofits to the structure, boundary conditions, and to establish access requirements for any instrumentation work.

A 3D FE model of the bridge, shown in Figure 2, was constructed to assist with identifying the critical regions and behavior mechanisms of the bridge’s structural systems and to estimate the limits of the forces, strains, tilts, displacements and accelerations that may be necessary to measure. The FE model is calibrated through system-identification procedures to permit reliable simulations based on the data from a health monitoring implementation. The data needed for system identification of the bridge and subsequent calibration of the FE model were obtained from controlled experiments conducted on the bridge. These experiments included ambient vibration monitoring of the through truss spans and a controlled load test using heavy cranes, one of which is also shown in Figure 2.

The calibrated FE model, which better reflects the true measured behavior of the bridge may serve a number of purposes including: accurate load rating analyses, vibration mitigation studies, vulnerability evaluations, maintenance/retrofit designs, as a benchmark for evaluating future changes in condition, as a foundation for evaluating system reliability and condition indicators for health monitoring, and as a starting point for nonlinear analysis for failure limit state evaluations.
Typical Known and Unknown Phenomena Affecting Performance: The obvious and less-understood phenomena that would be monitored for a successful and long-term health monitoring implementation were determined. It is important to recognize the possible impacts of humidity, wind, temperature, radiation, long-term movements, tilts, slips and settlements on the intrinsic strains and forces. Non-linearity and non-stationary boundary and continuity conditions and energy-dissipation mechanisms are recognized in the design of the health monitoring system, otherwise the reliability in the interpretation of any structural response measurement becomes doubtful.

Measurands, Sensors and Data Acquisition: The individual vectors to be measured are precisely determined and the best sensing-and-data acquisition systems to be integrated for the measurements are selected once the phenomena needing measurement are clearly identified. The individual sensor and data acquisition components are selected from a number proven off-the-shelf sensors, signal conditioning and data acquisition systems based on their physical, electrical and thermodynamic behavior data. It is imperative that these data must be verified through calibration studies as discussed in the following step to permit reliable interpretation of the acquired measurements.

The Commodore Barry Bridge health monitoring system currently is able to integrate the two senses of “vision” and “touch”, the former in the form of streaming digital video images that monitor the traffic moving over critical areas of the bridge and the latter in the form of temperature, displacement, tilt, strain and acceleration measurements distributed as shown in Figure 1.

Sensor and Measurement Calibration Studies: The output of any sensor will include the effects of three primary error sources (mechanical, electronic and thermodynamic) in addition to any “apparent” structural response. For example, a measurement that is desired is often that associated with “stress,” and this may be extracted only after decomposing the output of a sensor into the three possible error components, the apparent response and the desired stress-related response. The operational and behavior characteristics provided by a sensor or data acquisition system manufacturer should be verified and complemented, and installation techniques must be validated through laboratory and field studies taking advantage of measurement calibration systems. These calibration systems incorporate a number of calibration jigs and mechanically transparent systems on which sensors are mounted and which can be subjected to deterministic strain fields, displacements, tilts, and accelerations. The complete measurement system, including its sensors and data acquisition...
hardware and software components should be subject to the full range of anticipated operating conditions, such as those associated with environmental effects, simultaneous interrogation of different sensor types in a range of expected sampling frequencies, cable characteristics and lengths, and other potential sources of noise and interference as part of these calibration studies. Temperature, humidity and radiation controlled environmental chambers permit the study of long-term behavior of sensor-data acquisition systems under simulated field conditions.

**Data acquisition control, synchronization and integration:** The capability to develop network-based integrated control and synchronization of various data acquisition systems have evolved with Internet technologies. The Commodore Barry Bridge health monitoring system permits a combination of continuous, event-based and time-based programmable as well as manually controlled on-line data acquisition modes for interrogating specific sensor clusters. Since data in a long-term health monitoring implementation will be generally obtained over large spatial (kilometers) and temporal spans (years to decades), and along a wide frequency band (various sensors may be interrogated once every quarter hour for ambient temperatures all the way to GHz frequency for acoustic emission sensors), space-time stamping and synchronization of the output from many different data acquisition systems distributed through a bridge is a challenge. Data of different modalities (e.g. image streams vs. a single strain reading) acquired by different systems add to the challenges of accurately time-stamping and synchronizing data.

The sensing system for the Commodore Barry Bridge is interrogated over a local area network, the architecture of which is illustrated in Figure 3. The figure further depicts how the various data acquisition system components are distributed and networked along the bridge. The data acquisition systems are controlled, synchronized and integrated by software developed in Labview. Wind, temperature, radiation and humidity interrogation is done with a data acquisition system from Handar-Vaisala, vibrating-wire based displacement, tilt and strain sensors capture variations in the intrinsic responses over the long-term and are interrogated by a dedicated data acquisition system from Campbell Scientific, Inc., and the cameras are controlled by yet another dedicated system. The high-bandwidth strain, displacement and acceleration sensors for high-speed responses captured over short time increments are interrogated by a system from Optim Electronics, Inc.. *There have been many applications of Interned-based monitoring. The distinction of the system described here is its integrative aspects. Any additional sensors and data acquisition systems based on any operational principle (electrical, mechanical, optical, chemical and combinations) and over any bandwidth, may be integrated into the current system over the network. Wireless operation is a simple step from the current copper-optical fiber network communication mode.*

An authorized operator may take control of the Commodore Barry Bridge health monitoring
system at anytime; however, the system is designed to operate in a programmed mode in which the inputs due to weather and traffic, and the entire set of vibrating-wire sensors are continuously interrogated at low frequency. The high-frequency sensors operate on timed or event-based triggered modes. For example, the system may be triggered to acquire and archive data from a subset of the complete sensor suite on the bridge during the morning and evening rush hours when traffic levels on the bridge are highest, at midnight when traffic levels are very low, when the wind speed reaches a certain threshold value, or when a heavily-loaded truck is detected by the weigh-in-motion system. The frequency and duration of data and image collection, their processing, evaluation and dismissal, archival, presentation to a manager and/or alarm protocols will be eventually transformed to intelligent agents after researchers can more reliably establish the bounds of normality and possible indications or precursors of anomalies in operation or structural behavior.

Data Quality Assurance, Processing and Archival: The architecture of the information systems that have been designed in conjunction with the health monitoring system for the Commodore Barry Bridge is schematized in Figure 4. Clearly, Data quality assurance, processing and archival represent the major information technology related challenge in regards to health monitoring of a major bridge. There are many possible sources of error and uncertainty that can affect the reliability of sensing and data acquisition in the field. Many tests are essential for data quality assurance even after the best possible sensor and data acquisition design, operation, processing and archival practices are followed. In addition to the steps depicted in Figure 3, it is useful to carry out controlled tests as a means of calibrating both the analytical models and the monitor, as discussed earlier related to Characterization. Processing and analysis results need integration with heuristic knowledge for interpreting and assuring the quality of data. Redundancy requirements in the application of sensors, integration of different types of sensors and measurement systems, calibration of the health monitoring system in the field by controlled testing, and, most
importantly, justifying the output of any sensor based on the physics of the measured phenomena are techniques for data quality assurance. Applications of “instrumentation” just to observe an outcome without designing data quality assurance tests and measures often produce unreliable results. Many infrastructure owners have had negative experiences in instrumentation applications if technicians simply instrumented structures often producing too little or too much data for too short or too long without providing an insight and satisfaction to owners. How the entire health monitoring process should be designed in a product-and results-oriented as opposed to a process-oriented manner, so that data does in fact lead to insight for decision-making, is a major challenge.

Data and Information Management In Real-Time: The intrinsic value of health monitoring applications especially for operational and emergency management in conjunction with engineering purposes is realized only by the visual display of critical images and data on-line in real-time (or near real-time). A challenge is in the integration and graphical display design of critical data streams so that users and owners may conceptualize phenomena reflected in the measurements in order to make timely decisions. In many cases, on-line data may have to be compared against recent or legacy data. Quick on-line access to legacy data and analysis engines are needed to take full advantage of real-time data. Integrated information management systems providing on-line data acquisition control and data display, data quality assessment, visualization, analysis and archival capabilities are a required element of health monitoring as discussed further in the following.

Bridge Engineer-Health Monitoring System Interfacing and Decision Making: Health monitoring design should involve the owners and engineers in charge of the operations, maintenance and management of the bridge for maximum benefit. User communication, information and alert protocols, and training and maintenance support needs are major challenges related to monitor-user-organizational interface design.

Figure 5 illustrates the interface designed for viewing real-time images from the bridge and
information from the weigh-in-motion system as well as the weather station. Moreover, the upper left window of this interface permits a user to identify any one of the nearly 500 channels of data from the bridge and view this in real-time together with the images. The possibilities of correlating images and data and further processing for monitoring of various measures of health and performance are striking. More important is the ability to automate detection for immediate and effective response to incidents and to take various proactive measures through smart-signs if adverse driving conditions due to inclement weather and/or roadway conditions maybe emerging.

7 CONCLUSIONS

The promise in integrating and leveraging experimental, analytical and information technologies for bridge condition assessment, load capacity evaluation and maintenance management, in conjunction with operational and emergency management is real and feasible, demonstrated by recent research and applications discussed in this paper. Additional and very successful demonstrations have been described in recent Symposia (Proceedings of SPIE, 2000, 2001, Proceedings of the 3rd, 2nd, and 1st International Workshop on Structural Health Monitoring, 2001, 1999, 1997). Sensor and data acquisition technologies have advanced and are advancing significantly such that the limits of sensing are fast disappearing. Internet architectural standards and associated networking protocols and technologies offer data integration, communication, synchronization, real-time visualization and archival over large distances and very long time durations such as decades. The principal challenges that remain mainly relate to data quality assurance and informaction management, followed by socio-technical barriers. Carrying out a sufficient number of demonstrations that will be acknowledged and recognized as successful by bridge owners and the general bridge engineering community would be the proven path to transforming the state-of-the-practice in bridge management.

We strongly recommend government agencies such as FHWA, NSF and NIST to establish joint programs and initiatives to promote research and further development of health monitoring as a most promising paradigm for infrastructure management.

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