HEALTH MONITORING FOR CIVIL INFRASTRUCTURE

A. ELGAMAL, J.P. CONTE, AND M. FRASER

Department of Structural Engineering, University of California, San Diego
9500 Gilman Drive, La Jolla, CA 92093-0085, USA

S. MASRI

Department of Civil Engineering, University of Southern California
Los Angeles, CA 90089-2531

T. FOUNTAIN AND A. GUPTA

San Diego Supercomputer Center, University of California, San Diego
9500 Gilman Drive, La Jolla, CA 92093-0505, USA

M. TRIVEDI

Department of Electrical and Computer Engineering, University of California, San Diego
9500 Gilman Drive, La Jolla, CA 92093-0407, USA

M. EL ZARKI

School of Information and Computer Science, University of California, Irvine
Irvine, CA 92697-3425

ABSTRACT: Internet technologies are increasingly facilitating real-time monitoring of Bridges and Highways. The advances in wireless communications for instance, are allowing practical deployment for large extended systems. Sensor data, including video signals, can be used for long-term condition assessment, traffic-load regulation, emergency response, and seismic safety applications. Computer-based automated signal-analysis algorithms routinely process the incoming data and determine anomalies based on pre-defined response thresholds. Upon authentication, appropriate action may be authorized for maintenance, early warning, and/or emergency response. In such a strategy, data from thousands of sensors can be analyzed with real-time and long-term assessment and decision-making implications. Addressing the above, a flexible and scalable (e.g., for an entire Highway system, or portfolio of Networked Civil Infrastructure) software architecture/framework is being developed and implemented. This framework will network and integrate on-line real-time heterogeneous sensor data, database and archiving systems, computer vision, data analysis and interpretation, numerical simulation of complex structural systems, visualization, probabilistic risk analysis, and rational statistical decision-making procedures. Such a decision-support system contributes to the vitality of our economy, as rehabilitation / renewal / replacement / maintenance of this infrastructure is estimated to require expenditures in the Trillion-dollar range nationwide (in addition to Homeland security/natural disaster concerns). An evolving project portal (http://healthmonitoring.ucsd.edu) currently depicts some elements of the envisioned integrated health monitoring analysis framework.

CONDITION OF CIVIL INFRASTRUCTURE

The deterioration of the civil infrastructure in North America, Europe and Japan has been well documented and publicized. In the United States, 50 percent of all bridges were built before the 1940's and approximately 42 percent of these structures are structurally deficient[1-3].

Since the occurrence of the 1994 Northridge, California, earthquake and the 1995 Kobe, Japan, earthquake, there has been a quantum jump in the number of civil structures that have been instrumented for monitoring purposes. Furthermore, plans are underway to install a variety of strong-motion vibration sensors in many civil structures (in some cases many hundreds of sensors in a single structure). Clearly, the main issue that is facing the structural health monitoring community is not the lack of measurements per se, but rather how to measure, acquire, process, and analyze the massive amount of data that is currently coming on-line (not to mention the terabytes of streaming data that will inundate potential users in the near future) in order to extract useful information concerning the condition assessment of the monitored structures.

RESEARCH FRAMEWORK

The overall research framework addresses development of: (1) networked sensor arrays, (2) a high-performance database with data cleansing and error checking, data curation, storage and archival, (3) computer vision applications, (4) tools of data analysis and interpretation in light of physics-based models for real-time data from heterogeneous sensor arrays, (5) visualization allowing flexible and efficient comparison between experimental and numerical simulation data, (6) probabilistic modeling, structural reliability and risk analysis, and (7) computational decision theory. In order to satisfy these requirements, this research is making use of recent advances in (1) high-performance databases, knowledge-based integration, and advanced query processing, (2) instrumentation and wireless networking, (3) computer vision and related feature extraction algorithms, and (4) data mining, model-free and model-based advanced data analysis, and visualization.

An integrated system is being built to achieve the above-mentioned objectives. This system integrates all tasks from sensor configuration, data acquisition and control, to decision-making and resources allocation.

Database Research

The complexity of data sources (including real-time sensor and video streams, and the output of physics-based and statistical models), and the need to perform advanced real-time and off-line analyses (often requiring the integration of real-time sensor data with simulation model output) necessitates a scaleable high-performance computational infrastructure. The San Diego Supercomputer Center (SDSC) Data Mining group is focusing on key enabling technologies for advancing the state-of-the-art in data and knowledge management infrastructure, including (1) middleware toolkits for application and database integration and (2) data modeling, integration and complex query processing to provide query support to the structural analyst who may wish to retrieve stored or computed information from a single data source, or from a virtual data source constructed by integrating multiple actual data sources. These technologies will be employed in the development of a high-performance data management, analysis and interpretation system for civil infrastructure monitoring. This system will integrate sensors, databases, modeling, analysis, visualization and simulation tools, and provide access to various application interfaces (e.g., reliability and risk assessment, event response) through a secure portal.

Sensor Network

A significantly new research challenge is the need to integrate multiple sensor streams to develop local and global health-state indicator variables that need to be queried and monitored by the system. The indicators may be defined as user-specified aggregates (or other functions) over instantaneous values of several data streams, over pre-computed aggregates covering one or more sensors. The participants of this project have significant prior work in the development of information integration systems[4]. The sensor network consists of a dense network of heterogeneous sensors (e.g., strain gages, accelerometers, cameras, potentiometers, … etc.). In addition, the network must be easy to deploy, scalable – allowing for progressive deployment over time, and must allow for local processing and filtering of data, remote data collection, accessibility and control. Using a ubiquitous and inexpensive wireless communication technology to create Fixed Sensor Area Networks (FSANs) will accelerate the extensive deployment of sensor technology[5].

Computer Vision

Visualization is often the first step in data exploration, enabling scientists and decision makers to exploit the pattern recognition capabilities of the human visual system. Visualizations of sensor measurements, features extracted from measurements (e.g., modal strain energy distribution), and simulation results provide visual interpretations of infrastructure status and behavior.

It is anticipated that computer vision will become a primary and routine sensing technique within any health monitoring framework. Broader impacts of the computer vision research include the areas of rescue and crisis management systems, traffic flow analysis and modeling, intelligent transportation and telematics systems, and surveillance and security of public spaces[6].

As a novel aspect of our research, a load database extracted from video data is being created. For video data, the database will record the types and positions of load objects at specific time instants (e.g., cars and trucks crossing a bridge). This will be stored as spatially indexed valid-time temporal data coming from the video analysis engine. It will be converted to a load by a video data wrapper process, which will return for each array element of the structure an estimated load at the time instant. In this context, many cameras and potentially different types of video sensors are involved. For this reason, a promising investigation to systematically develop frameworks, models, and algorithms for fusion of such data derived from video is being undertaken.

Damage Detection and Data Analysis

This research includes tasks aimed at evaluating, calibrating and applying several promising approaches for detecting small structural changes or anomalies and quantifying their effects all the way up to the decision making process. These approaches include:

- Damage detection on the basis of influence coefficients. This method uses a time-domain identification procedure to detect structural changes on the basis of noise-polluted measurements. Application of the identification procedure under discussion yields the optimum value of the elements of equivalent linear system matrices (influence coefficients). By performing the identification task before and after potential structural changes (damage) in the physical system have occurred, quantifiable changes in the identified mathematical model may be detected by analyzing the probability density functions of the identified system matrices.

- Damage Detection Using Neural Networks. Among the structure-unknown (model-free) identification approaches that have been receiving growing attention recently are neural networks[7]. Not only do neural networks not require information concerning the phenomenological nature of the system being investigated, they also have fault tolerance, which makes them a robust means for representing model-unknown systems encountered in the real world.

- Structural Health Monitoring Using Statistical Pattern Recognition. These methods include primarily model-based and model-free statistical pattern recognition methods[8, 9]. Structural health monitoring methods based on statistical pattern recognition classify the structure in various damage states based on the statistical difference between features extracted (via signal processing, parameter estimation, or some other technique) from the measured responses of the structure in the undamaged and damaged states. A promising model-based damage identification method consists of updating (e.g., Bayesian) the parameters of a physics-based nonlinear finite element model of the monitored structure using response measurement and possibly input data.

- Reliability and Risk Analysis. The model updating methodology based on a nonlinear physics-based model of the monitored structure will be used not only as a tool for tracking the health of the structure, but also as a basis to assess the reliability of the structure in performing as expected under uncertain current and future loads. Reliability of the structure against various potential limit-states can be evaluated using a probabilistic mechanics-based model of the structure and a probabilistic representation of current and future load effects and deterioration effects. The combination of probabilistic non-destructive structural health monitoring techniques and computational methods of reliability analysis provides a powerful tool to continuously monitor competency of the structure under consideration [10].

- Probabilistic Modeling and Computational Decision Theory. Probabilistic networks (or Bayesian probabilistic networks) provide a comprehensive framework for modeling and analyzing uncertainties[11]. Although there have been numerous developments in this field, there are still a number of challenges in extending the theory and tools to address a larger range of applications, including the incorporation of background knowledge into the model-building process, providing large-scale database support for probabilistic modeling and decision support, and relating probabilistic modeling to other mathematical and statistical methods (e.g., using probabilistic nets to model parameter uncertainty in physics-based models).

- Physics-based Modeling and Simulation. The computational engine for mechanics-based modeling and analysis of bridge systems will include use of OpenSees[12]. OpenSees (Open System for Earthquake Engineering Simulation) is an open source software framework to simulate the response of structural and geotechnical systems to earthquake and dynamic loads in general. The object-oriented framework of OpenSees allows the structural response simulation to be factorized into independent classes such as model building, finite elements, constitutive material models, boundary conditions and constraints, solution strategies, equation solvers, time integration algorithms, and recorders emulating sensors.

CURRENT RESEARCH EFFORTS

The universe of damage detection scenarios likely to be encountered in realistic civil infrastructure applications is very broad and encompassing. Among the numerous considerations which influence the choice and effectiveness of a suitable method are: variety of materials of construction, level of damage and deterioration of concern, type of sensors used, nature of the instrumentation network, extent of available knowledge concerning the ambient dynamic environment, spatial resolution of the sensors, configuration and topology of the test structure, sophistication of available computing resources, complexity of the detection scheme, degree of a priori information about the condition of the structure, selected threshold level for detecting perturbations in the system condition, and depth of knowledge concerning failure modes of the structure.

Demonstration applications based on bridge field testbeds are currently being developed. These will allow researchers interested in structural health monitoring to exercise the developed framework using real life application examples and to contribute to enhancing the "toolkit" of methods supported by the framework. Current efforts include:

- Work begun concurrently in several areas to build the envisioned high-performance software system infrastructure required for this project. A project portal to connect and integrate the various project components (http://healthmonitoring.ucsd.edu) was established using Web Services for portability and extensibility. Current interactive website content includes a database for the health monitoring of the UCSD Powell Laboratory test-bed composite deck panels, allowing users to browse the database for recorded sensor and video data, and image feature extraction from recorded video, to determine the direction, size, and type of traffic passing over the bridge decks.

- Work towards establishing large-scale databases via the new IBM SDSC Regatta computer (http://www.npaci.edu/online/v7.6/DataStar_03-19.html), and the TeraGrid Project (http://www.teragrid.org/ and http://www.npaci.edu/online/v7.1/tgrid.html). The complexity of data sources, (including real-time sensor and video streams, and the output of physics-based and statistical models), and the need to perform advanced real-time and off-line analyses (often requiring the integration of real-time sensor data with simulation model output) necessitates a scaleable high-performance computational infrastructure. This system will exert heavy demands on memory requirements (for the online database required for real-time integration with incoming sensor data, and for the execution of the structural simulations, and the various data mining routines). In preparation Microsoft SQL and IBM DB2 are in use. Data Fusion of Video images, extracted features, and sensor data (strains) has been implemented. Real time data streaming protocols and real time data analysis in the time and frequency domains are being developed.

- Wireless Sensor Network Research exploring Bluetooth and Ultra Wide Band (UWB) technologies[5] is underway. Communicating with sensors has long been limited either to wired connections or to expensive, proprietary wireless communication protocols. Using a ubiquitous and inexpensive wireless communication technology to create Fixed Sensor Area Networks (FSANs) will accelerate the extensive deployment of sensor technology. A topology formation scheme was proposed that not only takes into account the traffic generated by different sensor nodes but also the associated link strengths, buffer capacities and energy availability. Such an arrangement would allow for scalability to include any number of sensors at any point of time, robustness against link breakdowns and node failures, and self healing, re-configuration of the system. Discussions for indoor and outdoor experimental setups are ongoing towards large-scale implementation on a spatially extended Civil Structure (or along a Highway artery).

- Use of Video for monitoring load and correlation to recorded sensor data (structural strain, displacement, and acceleration measurements), for data mining and system identification purposes. Pilot experiments have been conducted to develop such a synchronized database of video images, extracted features, and sensor measurements. Using video sequences from a distributed array of cameras, quantitative information about vehicles, such as size, type, location, and velocity can be provided, which can indirectly give an idea about the magnitude of the loads. The information thus obtained can then be integrated with the corresponding measured strains (Figure 1).

- Data Mining and System Identification algorithms are being applied to civil infrastructure (bridge) damage detection scenarios. Neural Networks and Support Vector Machine algorithms are under investigation. As a first step, we are exploring different data mining methodologies within a relatively "clean" environment of data generated by a computational model of an actual existing bridge. It was decided to focus on a typical seismic damage mechanism (formation of a weak "plastic hinge" zone at the pier base), and introduce a weakened zone at each pier base corresponding to loss of original stiffness randomly in the range of 10%-50%. This computational exercise generated a wealth of data akin to that from actual measurements, allowing us to embark on a data mining investigation. For example, the above-mentioned data is used with the Support Vector Machine (SVM) induction algorithm, and thereafter, the performance of SVM-generated models is evaluated based on additional damage data from the computational model. These preliminary tests have shown that the predictive strength of these algorithms in detecting damage location is satisfactory. However, more research is still needed before applying this technique to real world problems.

- Investigations of sensor network deployment on a large Bridge are underway. Led by Professor Masri, the Vincent Thomas Bridge (VTB), Long Beach, CA, is being considered as an example of such an appropriate Civil Engineering Structure. Large-scale computational finite element modeling is also underway (Figure 2). Modeling of moving traffic loads on Bridges is being addressed using the large Finite Element Code ADINA. Other Bridges in California and Oregon are also being considered for possible deployment of a Fiber Optic sensor network, in collaboration with our industry partner Blue Road Research (http://www.bluerr.com/).

SUMMARY AND CONCLUSIONS

An integrated analysis framework will foster the development of practicable structural health monitoring methodologies as well as the discovery of new physical knowledge in the area of deterioration (sudden or progressive) of civil infrastructure systems. The experimental studies being conducted will develop new monitoring methodologies to augment conventional approaches, thereby improving the reliability of structural damage detection and condition assessment methods. The intended technical and theoretical research will advance the frontiers of nonlinear system identification and modeling, thus facilitating the development of robust approaches for quantification and reduction of risk.

Not only will this research lead to a versatile integrated framework for condition assessment and damage detection under normal operating conditions, but will also be beneficial in providing rapid response (in virtually real time) due to sudden dynamic loads or terrorist acts. For large structures or extended structural networks, such a computer-based framework is simply a necessity.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Information Technology Research (ITR) Grant No. 0205720.

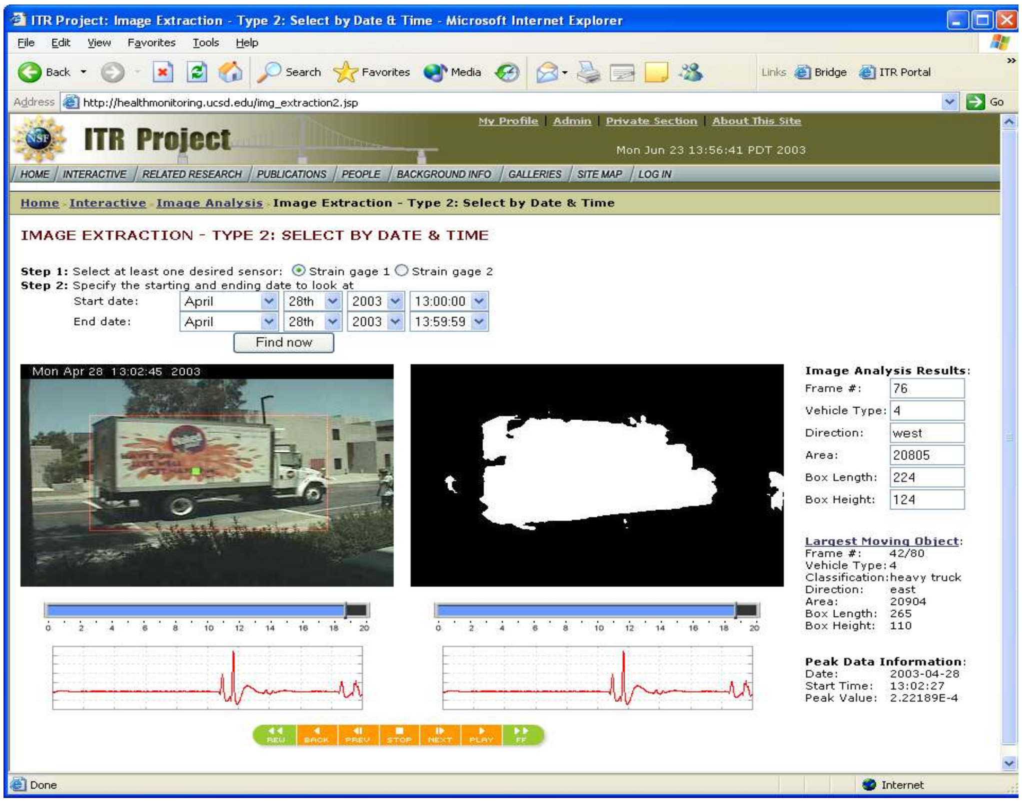

Figure 1. Sample of Data Fusion from ITR Portal (http://healthmonitoring.ucsd.edu) depicting integration of time-synchronized sensor data and video.

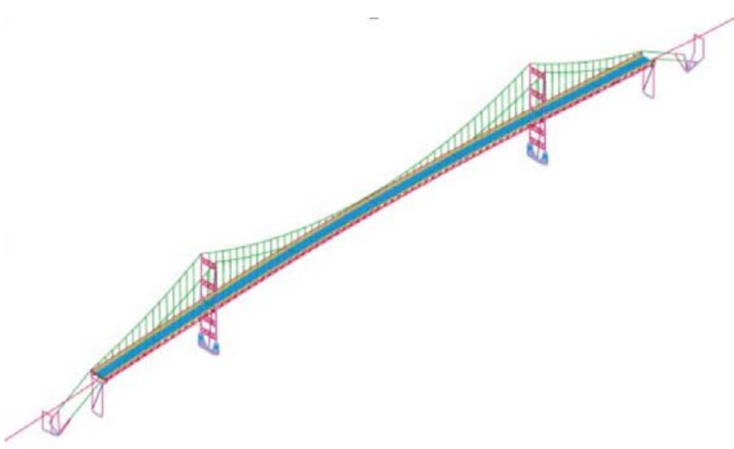

Figure 2. Finite Element Model of the Vincent Thomas Bridge

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