Sensor network application framework for autonomous structural health monitoring of bridges

Edward Sazonov[a], Kerop Janoyan [b], Ratan Jha[c]
[a] Dept. of Electrical and Computer Engineering
[b] Dept. of Civil and Environmental Engineering
[c] Dept. of Mechanical and Aeronautical Engineering
Clarkson University, 8 Clarkson Ave, Potsdam, NY, 13699

ABSTRACT

Life cycle monitoring of civil infrastructure such as bridges and buildings is critical to the long-term operational cost and safety of aging structures. Nevertheless, there is no commonly accepted and recognized way to perform automated monitoring of bridges. One of the important issues is the cost of the data acquisition subsystem and its installation and maintenance costs, which are tightly connected to the choice of monitoring methodology.

The presented application framework includes: first, Wireless Intelligent Sensor and Actuator Network (WISAN) as an inexpensive way to perform data acquisition for the tasks of structural health monitoring; second, a vibration-based SHM method for bridges; and third, a fully autonomous SHM system for bridges, ambient-energy-powered and minimally dependent of human involvement.

Design of the sensor network reflects the particularities of the application: proactive rather than reactive nature of the data streams; fault-tolerant architecture ensuring protection from extreme events; and real-time data acquisition capabilities. Other issues include operating a massive array of heterogeneous sensors, achieving a low cost per sensor, cost and sources of energy for the network nodes, energy-efficient distribution of the computational load, security of communications and coexistence in the ISM radio bands.

The modal SHM methods under consideration are the method of modal strain energy with fuzzy uncertainty management, method of damage index and a method based on Hilbert-Huang transform. Modal identification through ambient vibrations is performed though auto-regressive moving average models.

The final step in the monitoring methods is the determination of bridge deterioration rate and prediction of its remaining useful life based on measurements provided by the sensor network and modal methods used. The deterioration curves are generated at both the element and bridge levels and are compared to existing inspection-based methods.

Keywords: wireless sensor networks, structural health monitoring, ambient vibrations, autonomous systems, modal strain energy, deterioration rate, life-cycle monitoring.

1. INTRODUCTION

Life cycle monitoring of civil infrastructure such as bridges and buildings is critical to the long-term operational cost and safety of aging structures. Knowledge of the structure's health, load bearing capacity, and remaining life is the primary goal of any strategy of Structural Health Monitoring (SHM). Bridges constitute the most vulnerable element of the transportation infrastructure. An out-of-service bridge creates economic losses both for the bridge users (in terms of traffic delays and detours) and for the bridge and road operators. At the end of 2003, the Federal Highway Administration (FHWA) has listed 27 percent of the country's 591,000 bridges as structurally deficient or functionally obsolete, in terms of dimensions, load or other characteristics (FHWA, 2003).

Repair and replacement of the structurally deficient components based on the results of objective evaluation of the bridge status can significantly reduce money spent on maintenance. The key is to have a low cost and reliable way to evaluate structural integrity, identify deteriorated structural components and quantify changes in terms of the load capacity and remaining service life estimates. This goal can be accomplished by a system that is capable of performing continuous health monitoring and evaluation of bridges and could complement FHWA-mandated periodic visual inspections of the bridges

At the present time there is no commonly accepted and recognized way to perform automated monitoring of bridges. One of the important issues is the cost of the data acquisition subsystem and its installation and maintenance costs, which are tightly connected to the choice of monitoring methodology. Lynch et al. (2003) reported the costs over $300,000 per bridge ($5000 per sensor) to install a monitoring system with 60 accelerometers in California and the cost of the 600-channel monitoring system for Tsing Ma Suspension bridge to be over $16 million, or over $27,000 per channel.

The high costs of instrumentation can be alleviated by employing the concept of a highly distributed, networked data acquisition system such as a wireless sensor network, consisting of many inexpensive low-power nodes. However, the full potential even of a low-cost SHM system can only be achieved if it requires minimal human involvement in reviewing periodic reports produced by the system and responding to alarms. Every step of data processing starting from data acquisition up to computing remaining life estimates has to be automated and performed by a computer without human involvement, i.e. perform a fully automatic decision support.

2. DESIRED FEATURES OF THE SHM SYSTEM

The design of an autonomous SHM system should follow a global view on the system as a complex and tightly integrated sequence of information processing, where each step depends on the desired features of the SHM system and defines methods to be used. Therefore, desired features should be defined as the first step of the design and application process.

In the proposed SHM system, we are targeting the following features:

1. The SHM system should utilize low-cost equipment and sensors, have low installation and maintenance costs. Ideally, the cost of an installed system should constitute 1-2% of the structure's cost.
2. Massive arrays of heterogeneous should be employed on the structure, collecting a variety of information from the structural components.
3. The system should be easily configured to be used with various types of bridges with different structural geometry and independent of used construction materials.
4. Data collected from the sensor arrays should be processed in a streamlined, fully automatic manner, with the final result being a periodic report delivered to the monitoring agency over inexpensive, commonly available and reliable data link. The system should be able to raise alarms in case of extreme events, pronounced and rapid changes in structure's condition and major equipment malfunctions.
5. The system should function unattended for prolonged periods of time (years), provide for self-diagnostic capabilities and easy repairs.
6. To be fully autonomous, the SHM system should not utilize wired power for data acquisition and, most importantly, damage detection and localization, i.e. it should utilize ambient energy for these goals.

To satisfy stated requirements, we are proposing a sensor-network-based application framework of structural health monitoring of bridges. Utilization of a sensor network addresses cost and power requirements. Installation costs for wireless sensors are much lower then for wired systems. At a low price tag per sensor, repair by replacement is a viable and inexpensive way to maintain the system. With a low-power design (Sazonov et al 2004), a networked sensor will consume very little energy and can utilize harvesting of ambient energy (vibration, solar, wind, etc.) for powering of the data acquisition and network communications, eliminating the need for periodic battery changes.

Modal-based damage detection and localization methods allow monitoring of various types of bridges and construction materials. Being driven by ambient excitation these methods can perform monitoring of structure excited only by passing traffic and wind, therefore enabling truly autonomous monitoring not dependent on external, dedicated excitation sources. Modern low-power general purpose computers (such as notebook computers) possess enough computing power to perform the full cycle of information processing directly on site, while being powered by a solar cell or a wired source. Processing the information from the damage detection and localization method as well as from auxiliary sensor, methods of computational intelligence such as neuro-fuzzy systems allow connecting damage and sensor information to element-level and bridge-level health reports. These periodic reports will be emailed to the monitoring agency via an inexpensive cellular link or a satellite link in places with no cellular coverage.

The general structure of the proposed system is shown in Fig. 1. The following sections of this paper present more details on the proposed Wireless Intelligent Actuator and Sensor Network (WISAN), damage detection and localization from ambient vibrations and estimating remaining service life of a bridge.

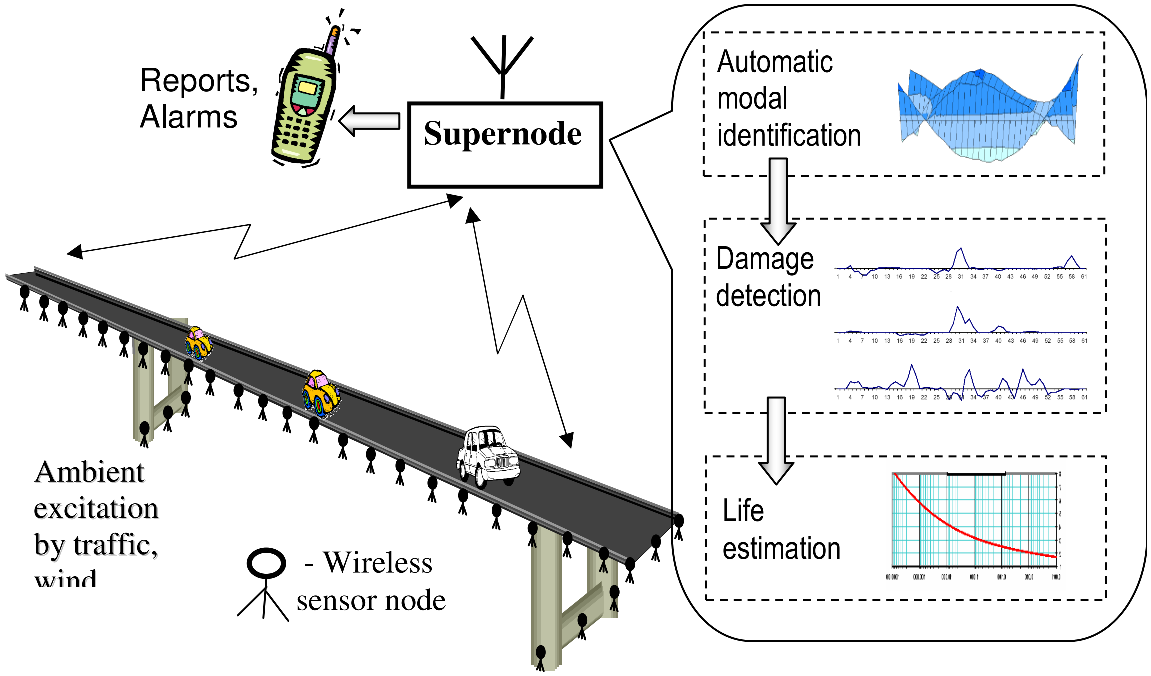

Fig 1. General structure of the proposed system.

3. WIRELESS INTELLIGENT SENSOR NETWORK

Utilization of a sensor network for long-term SHM is performed in an attempt to minimize cost and maximize utility of the system as a whole. Therefore, the sensor network design should be closely tied-in with the design of the monitoring methodology and do not necessarily follow the concepts formulated for other applications.

The key differences include: proactive rather than reactive nature of the data streams, where data is collected from multiple sensors at a constant rate rather than reflecting events or changes in values; the fault-tolerant architecture ensuring protection from extreme events and making the system insensitive to loss of one or multiple nodes does not assume such node losses under normal operating conditions; and real-time data acquisition capabilities require not only timestamping and prompt delivery of messages, but closing the feedback loop directly on a sensor node.

The design issues include minimization of power consumption by a sensor node, so it can be powered by harvested energy; accounting for coexistence with other devices functioning in the Industrial, Scientific and Medical (ISM) range of radio frequencies; guaranteeing reliable and secure way of communication in a network containing a large number of nodes; performing energy-efficient distribution of computational load and providing on-sensor intelligence supporting the monitoring methodology; enabling self-localization of the sensor nodes for easy configuration of the network.

The Wireless Intelligent Sensor and Actuator Network (WISAN, “the sensor network”) is designed with the goal of continuous structural health monitoring in mind. The design of the network conforms to the requirements stated in the previous section and provides a sound foundation for practical implementation of health monitoring systems for bridges.

The sensor nodes are built around an ultra-low-power microcontroller MSP430F1611 from Texas Instruments (TI 2004). A 2.4Ghz module CC2420 from Chipcon (Chipcon 2004) is used for the IEEE 802.15.4 compatible network interface. The CC2420 is a low-power, low-cost, IEEE 802.15.4 compliant transceiver designed for RF applications in the 2.4 GHz unlicensed ISM band. The transceiver module provides 16-channel direct sequence spread spectrum modem with 2 Mchips/s and 250 kbps effective raw data rate, low power consumption (RX: 60 mW, TX: 52 mW), effective range 10 to 75 meters, programmable output power, hardware MAC encryption and authentication (AES-128), signal strength indicator and battery monitor.

The low power consumption of sensor nodes enables truly autonomous and continuous operation from an energy-harvesting device. In practical terms, a virtually maintenance-free SHM system could be created by utilization of electro-mechanical or piezo-electrical power generating devices for powering of the WISAN nodes.

Selection of the 802.15.4-compatible protocol for the physical and data link layers of the network protocol also resolves the issues with electromagnetic compatibility, reliability and security. The radio frequency (channel) allocation for 802.15.4 devices foresees the coexistence in the presence of other popular network protocols, such as 802.11 (WiFi). The communications between sensor nodes can be made secure through Advanced Encryption Standard (AES) encryption and authentication.

The signal strength meter located in the Chipcon RF interface module allows implementation of localization capabilities in the sensor nodes by performing cross-node measurements of signal strength.

WISANs architecture provides flexibility and fault-tolerance through two-tier cluster organization (Sazonov et al 2004). Each cluster head collects data from the sensor nodes and passes it on to a supernode, where data processing takes place (Fig.1). For many small-scale bridges the network will contain a single cluster head / supernode.

4. THE MONITORING METHODOLOGY

Dynamics based SHM can provide a quantitative global damage detection method that can be applied to complex structures. A recent paper by Chang et al. (2003) reviews health monitoring methods for civil infrastructure.

The basic idea in most dynamics-based SHM is that changes in physical parameters (mass, stiffness, damping) cause changes in structural properties (natural frequency, mode shape, modal damping) hence damage can be determined by changes in dynamic properties. However, standard modal properties represent a form of data compression and modal properties are independent of excitation amplitude, frequency, and location. Lower frequency modes tend to capture global response, but damage is typically a local phenomenon and local response is captured by higher frequency modes. The task of damage detection by finding shifts in resonant frequencies or changes in structural mode shapes is further compounded by changes in these characteristics due to environmental factors (temperature, moisture, etc.).

We are investigating several methods to bring out their relative advantages and disadvantages. The first two methods are similar conceptually, but differ in treating noise and uncertainty of the real-world systems. First is the method of modal strain energy combined with a fuzzy expert system (Sazonov et al, 2002) and second is the method of damage index (Kim and Stubbs, 2002). Both methods utilize the modal data extracted through structural identification over several measurements performed under the same environmental and load conditions.

Modal parameter identification with the aid of ARMA (auto-regressive moving average) models leading to a state space formulation of the structural dynamic equations of motion assumes that the dynamic behavior of the structure can be described by a stationary, infinite order, linear, dynamical system. The input forces from the natural excitations may be in the form of white or colored noise, mixed with harmonics and non-stationary noise. At Clarkson University, we have successfully implemented an advanced algorithm for identification of structures using ARMA models and discrete time state space formulation (He and Jha, 2004). The ARMA model allows analysis of linear systems based on output measurements, while the input is an unknown uncorrelated random signal.

Another method under investigation is based on advanced signal processing for damage detection and localization. Historically, structural vibration signals have been analyzed as frequency response using Fourier transform or as energy-frequency-time response using short-time Fourier transform. A novel method, known as Hilbert-Huang Transform (HHT) (Huang et al., 1998), produces instantaneous frequencies as functions of time that give sharp identifications of imbedded structures. The final presentation of the results is an energy-frequency-time distribution, designated as the Hilbert spectrum. This means we obtain the instantaneous frequency and energy defined locally, rather than the global frequency and energy defined by traditional Fourier Transform. Also, Fourier analyses are valid for problems involving linear systems with periodic or stationary response. However, the Fourier analysis has little physical sense for nonlinear systems and/or non-stationary response. We have conducted a comparative study of vibration signal analysis using short-time Fourier transform and Hilbert-Huang transform to gain an insight into their benefits (Jha et al., 2004). The HHT spectrum is more sensitive to the dynamic energy-frequency distribution and it is capable of capturing the difference in the structural response caused by damage. The short time Fourier transform indicates the natural frequency changes, but fails to capture the magnitude changes.

5. CONDITION ASSESSMENT AND LIFE CYCLE MONITORING

The ultimate goal of the damage detection scheme is to assess the bridge’s condition and determine its remaining useful or service life. Currently, State and metropolitan planning organizations turn to Bridge Management Systems (BMS) to provide them with a systematic approach to bridge programming. However, the deterioration rates are extrapolated from visual inspection data and are highly subjective and prone to human errors. Rational bridge deterioration rate information based on measured performance response data would provide a cogent basis for condition assessment of bridges.

The two BMS software that are most frequently used today are PONTIS (Golabi et al., 1993) and BRIDGIT (Hawk and Small, 1998). Both systems attempt to predict the remaining life of a bridge by generating life cycle curves using empirical (visual inspection) data input in the BMS routines. In PONTIS, originally funded by the FHWA, a population of bridges is represented on a network level by the individual bridge elements (deck, girder, bearings, etc.) with field inspection data providing numerical condition states for each element. The prediction model, a probabilistic second order Markovian chain, is applied at the network level, estimating the proportion of each bridge element that is expected to deteriorate in the next inspection cycle. A rank order of the bridge element condition states in any inspection cycle leads to an application at the bridge level. BRIDGIT, another popular BMS developed under the National Cooperative Highway Research Project (NCHRP) 12-28(2), is similar to PONTIS in that a Markovian prediction model is applied at the element level. The primary difference between the two systems lies in the optimization model, which is more bridge specific in BRIDGIT and that it addresses the issue of element interaction more extensively than PONTIS.

Deterioration curves could also be generated at both the element and bridge system levels based on measured performance data then compared to those produced by various BMS software. Element-level parameters determined could be used to generate condition ratings for the individual structural elements. The input parameters will include damage report information, such as location and magnitude of change in damage, as well as environmental factors such as temperature. These element ratings would be input into the existing BMS models through general mapping from a physical order to a logical order. The mapping scheme would take measured performance information and relate them to the existing inspection-based rating description tables (such as number of cracks, location of damage, etc.). The generated curves would also act as a baseline for comparison in the case when only damage detection measurements are available for computation of the final bridge deterioration curve. A knowledge-based expert system that can be defined analytically must be used to perform the mapping of input parameters supplied to the BMS.

6. IMPLEMENTATION

Design of the Wireless Intelligent Sensor and Actuator Network is currently being developed under a grant from New York State Energy Research and Development Authority (NYSERDA). Fig. 2 shows a prototype of the WISAN modules.

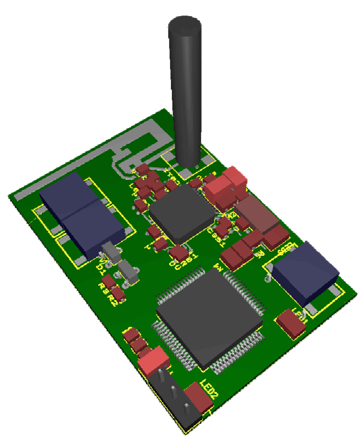

Fig. 2. A prototype of the WISAN nodes.

7. CONCLUSIONS

The presented application framework concept of a sensor network for autonomous structural health monitoring addresses the synergetic issues of integrating a sensor network with a vibration-based SHM method and subsequent estimation of the remaining life.

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