STRUCTURAL HEALTH MONITORING USING SMART SENSING TECHNOLOGY

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Abstract- Smart" sensors with embedded microprocessors and wireless communication links have the potential tofundamentally change the way civil infrastructure systems are monitored, controlled, and maintained. Indeed, a 2002 National Research Council Report noted that the use of networked systems ofembedded computers and sensors throughout society could well dwarf all previous milestones in theinformation revolution. However, a framework does not yet exist that can allow the distributed computingparadigm offered by smart sensors to be employed for structural health monitoring and control The design, fabrication, and construction of smart structures are one of the ultimate challenges to engineering researchers today. Because they form the essence of system intelligence, one of the cores of smart structures technology centers around innovative sensors and sensor systems. Structural health
monitoring (SHM) represents one of the primary applications for new sensor technologies. Indeed, much attention has been focused in recent years on the declining state of the aging infrastructure in the U.S., as well as to the limitation of their responses during extreme events (such as wind and earthquakes). These concerns apply not only to civil engineering structures, such as the nation's bridges, highways, and buildings, but also to other types of structures, such as the aging fleet of aircraft currently in use bydomestic and foreign airlines. The ability to continuously monitor the integrity of structures in real-time can provide for increased safety
to the public, particularly for the aging structures in widespread use today. The ability to detect damage at an early stage can reduce the costs and down-time associated with repair of critical damage. Observing and predicting the onset of dangerous structural behavior, such as flutter in bridges, can allow for
advance warning of such comportment and commencement of removal of the structure from service for the protection of human life. In addition to monitoring long term degradation, assessment of structural integrity after catastrophic events, such as earthquakes, hurricanes, tornados, or fires, is vital. These
assessments can be a significant expense (both in time and money), as was seen after the 1994 Northridge earthquake with the numerous buildings that needed to have their moment-resisting connections inspected. Additionally, structures internally, but not obviously, damaged in an earthquake may be in great danger of collapse during aftershocks; structural integrity assessment can help to identify such structures to enable evacuation of building occupants and contents prior to aftershocks. Furthermore, after natural disasters, it is imperative that emergency facilities and evacuation routes, including bridges and highways, be assessed for safety. The need for effective SHM is clear, with the primary goals of such systems being to enhance safety and reliability and to reduce maintenance and inspection costs.

systems,current algorithms assume that all data is centrally collected and processed. Such an approach does notscale to systems with densely instrumented arrays of sensors that will be required for the next generationof structural health monitoring and control systems. This paper provides a brief introduction to smart sensing technology and identifies some of the opportunities and associated challenges.

Index Terms- SHM, MEMS

I. INTRODUCTION

To efficaciously investigate both local and global damage, a dense array of sensors is envisioned for large civil engineering structures. Such a dense array must be
designed to be scalable, which means that the system performance does not degrade substantially or at all as the
number of components increases. In the conventional approach using wired sensors (see Fig. 1), the shear number of accompanying wires, fiber optic cables, or physical transmission medium may be prohibitive,
particularly for structures such as long-span bridges or tall buildings. Consequently, global communication in a
wireless fashion that will facilitate low-cost, densely distributed sensing has been distributed.
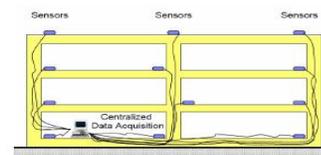

Figure 1. Traditional SHM System
using Centralized Data Acquisition.

Rapid advances in sensors, wireless communication, Micro Electro Mechanical Systems (MEMS), and information technologies have the potential to significantly impact SHM. To assist in dealing with the large amount of data that is generated by a monitoring system, on-board processing at the sensor allows a portion of the computation to be done locally on the sensor's embedded microprocessor. Such an approach provides for an adaptable, smart sensor, with self diagnosis and self-calibration capabilities, thus reducing that amount of information that needs to be transmitted over the network. Kiremidjian pointed out that pushing data acquisition and computation forward is fundamental to smart sensing and monitoring systems such as are in Fig. 2, but represents a radical departure from the conventional instrumentation design and computational strategies for monitoring civil structures.

Following an introduction to smart sensing, some of the opportunities, as well as the challenges offered by this new technology, are presented.
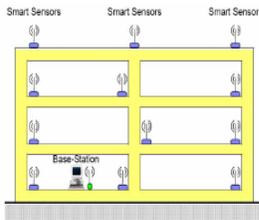

Figure 2. SHM System with Smart Sensors.

1.1 Importance of SHM

SHM has been a growing priority for the civil engineering infrastructure as the country's roads and bridges become older and need more maintenance attention. There are several SHM methods, but many prove to be time consuming and expensive. Efficient SHM for bridges and pavements will aid engineers in identifying developing distresses and in scheduling maintenance early. "The bridge management systems of the future must be based upon better information, better knowledge, better technology, and improved decision support tools,

1.2 WHAT ARE SMART SENSORS?

A sensor is a device that is designed to acquire information from an object and transform it into an electrical signal. As shown in Fig. 3, a traditional integrated sensor can be divided into three parts:

(i)   The sensing element (e.g., resistors, capacitor, transistor, piezo-electric materials, photodiode.

(ii)   Signal conditioning and preprocessing (amplifications, linearization, compensation, and filtering).

(iii)   A sensor interface (e.g., the wires, plugs and sockets to communicate with other electronic components.

As illustrated in Fig. 4, the essential difference between a smart sensor and a standard integrated sensor is its intelligence capabilities, The microprocessor is typically used for digital processing, analog to digital or frequency to code conversions, calculations, and interfacingfunctions, which can facilitate self-diagnostics, self-identification, or self-adaptation (decision making) function
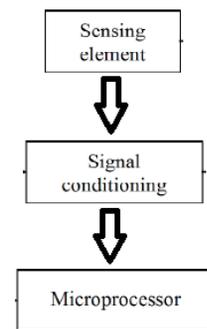

Figure 4. Smart Sensor

It can also decide when to dump/store data, and control when and for how long it will be fully awake so as to minimize power consumption. The size of smart sensors has been decreasing with time. The use of MEMS has made possible the dream of having ubiquitous sensing and in particular small "smart" sensing. MEMS devices are manufactured using vary large scale integration technology and can embody both mechanical and electrical functions. MEMS can be used in an environment to both sense and actuate. Sensing requires that a physical or chemical phenomenon be converted to an electrical signal for display, processing, transmission, and recording. Actuation reverses this flow and converts an electrical signal to a physical or chemical change in the environment. The main advantage brought by this technology and its design paradigm to applications is miniaturization. MEMS features are typically on the scale of microns (10–6 m). MEMS devices can be found in a wide-range of applications from accelerometers for airbag deployment to electronic particle detector that helps for nuclear, biological, and chemical inspection. The cost of the smart sensors is also decreasing. Mass production of MEMS and microprocessors for a variety of applications have reduce their cost to a levels of tens of dollars, and with their increasing popularity, costs may be reduced to fractions of a dollar. The

improvement in the technologies for other important components, such as memory, radio transmitters, and batteries, will allow more capable and long lasting devices, reducing their maintenance cost. Finally, all smart sensors to date are wireless, with data transmission based on radio frequency (RF) communication. There exist several protocols for transmitting data. One of the most popular is Bluetooth, a short-range radio technology aimed at simplifying communication among Net devices, as well as between devices and the internet. Most of these sensors envision using low radiated power to avoid the

heavy costs associated with certifying the sensor with the FCC. Therefore, a smart sensor as define herein has four important features: (i) on-board Central-Processing- Unit (CPU), (ii) small size, (iii) wireless, and (iv) the promise of being low-cost. The next sections summarize previous research on smart sensors developed for civil engineering infrastructure, present results using one particular smart sensor, and discus opportunities and challenges to the widespread use of this technology.

II.   SMART SENSORS FOR MONITORING CIVIL INFRASTRUCTURE

Some of the first efforts in developing smart sensors for application to civil engineering structures were presented by Straser, and Kiremidjian. This research sought to develop a near real-time damage diagnostic and structural health monitoring system that evaluate both extreme and long-term structural health. The SHM system was designed to acquire, manage the data, and to facilitate damage detection diagnosis. They proposed a network that provided ease of installation, low per unit cost, portability, and broad functionality. The sensor unit consists of a microprocessor, radio modem, data storage, and batteries. To save battery life, most of the time the sensor unit is in a sleep mode, periodically

checking its hardware interrupts to determine if there are external events that require attention. Building on the work of Kiremidjian, Lynch demonstrated a proof of concept wireless sensor that utilized standard integrated circuit
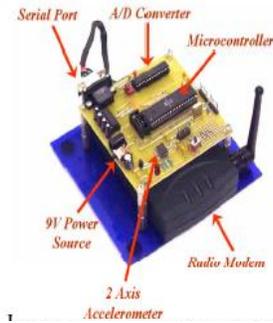
components.

Figure 5.Phototype smart senser.

This unit consists of an 8-bit ATmel microcontroller with a 4 MHz CPU that can accommodate a wide range of analog sensors. The communication between the sensors is done via a direct sequence spread spectrum radio. Some units use the 14-bit digital output with an anti-aliased digital signal of the ADXL210 accelerometer. In other units, a high performance planar accelerometer is used along with a 16-bit analog to digital converter. The whole system can be accommodated within a sealed unit roughly 5" by 4" by 1" in size (see Fig. 5). The sensor unit has been validated through various controlled experiments in the laboratory. Maser proposed the Wireless Global Bridge Evaluation and Monitoring System (WGBEMS) to remotely monitor the condition and performance of bridges. This system used small, self contained, battery operated transducers, each possessing a sensor, a small radio transponder, and a battery. The complete system consisted of a local controller placed off the bridge and several transducers distributed throughout the bridge. The data collection at the transducer involves signal conditioning, filtering, sampling, quantization, and digital signal processing. The radio link uses a wide band in the range 902 to 928 MHz. Brooks emphasized the necessity of migrating some of the computational processing to the sensor board, calling them Fourth-generation sensors. This generation of sensors will be characterized by a number of attributes: bi-directional command and data communication, all digital transmission, local digital processing, preprogrammed decision algorithms, user-defined algorithms, internal self verification/ diagnosis, compensation algorithms, on-board storage, and extensible sensor object models. Figure 5. Prototype Smart Sensor Mitchell presented a wireless data acquisition system for health monitoring of smart structures. A micro sensor was developed in which an analog multiplexer was used to allow data from multiple sensors to be communicated over a single communication channel. The data was converted to a digital format before

transmission using an 80C515CO microcontroller. A 900 MHz spread spectrum transceiver system, capable of transmitting serial data at the rate of 50Kbps, was employed to perform the wireless transmission. Mitchell continued this work to extend cellular communication between the central cluster and the web server, allowing web-based control of the network. Agre, presented a prototype wireless sensor node called
"AWAIRS I"

Figure 6. Sensor AWARIS (Agre [13]).

This smart sensor can support bidirectional, peer-to-peer communications with a small number of neighbors. The current version of this device consists of a processor, radio, power supply and sensors . Multiple portals for transporting information into or out of the sensor network can be established. This prototype
is capable pf continuous operation for approximately 15 hours on two 9V batteries. The time-division multiple access scheme used allows nodes to turn off their receiver andtransmitter when they are not scheduled tom communicate. This research is still in the development phase. mLiu presented a wireless sensor system that includes 5 monitoring stations, and each with a 3-axis ADXL05 accelerometer. The stations used an 80C251 microprocessor with a 16-bit A/D converter. Because this network was sensing continuously, transmission of data to the base station could present collisions. To avoid this problem, a direct sequence spread spectrum radio with long pseudo noise code was used to distinguish each substation. Experimental verification was provided. The recently created European project of Energy Efficient Sensor Networks (EYES [15]) has the objective to develop the architecture and technology that will enable the creation of a new generation of selforganizingand collaborative sensors. These sensors will be capable of effectively network together, so as to provide a flexible platform for the support of a large variety of mobile sensor network applications. This 3-year project has the support of Alcatel Center Information and Technology , one of the most important communication solution providers

in Europe, with experience in end-to-end networks that will boost a reliable communication between sensors. The architecture of EYES is supported by two-level structure. The first level deals with the sensors and the network. The second level provides with distributed services to the application. Figure 7 shows a sensor prototype of the EYES project.
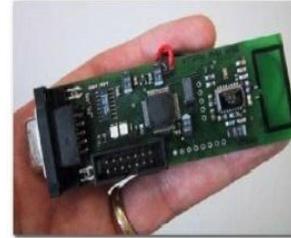

Figure 7. Prototype Smart sensor
(EYES project [15]).

EYES project will use the efforts invested in the Data Grid Project . The Data Grid Project has the objective to build the nest generation of computing infrastructure, providing intensive computation and analysis of shared large-scale databases. This project includes more that 12 Work Packages that deal with middleware, applications and management. Specifically, EYES will use WP2: data management. WP2 has been designed to manage and share Petabyte-scale (250 bytes) information volumes. One of the deliverable will be a proof of concept network that uses more than 100 nodes. Unfortunately, no technical information has yet been provided to the public. Nevertheless, EYES project is definitely something to watch for in the near future. While substantial research has been undertaken to develop smart sensors for civil engineering applications, all of the previously mentioned systems are of a proprietary nature. To effectively move the technology forward, an open hardware/software platform is necessary.
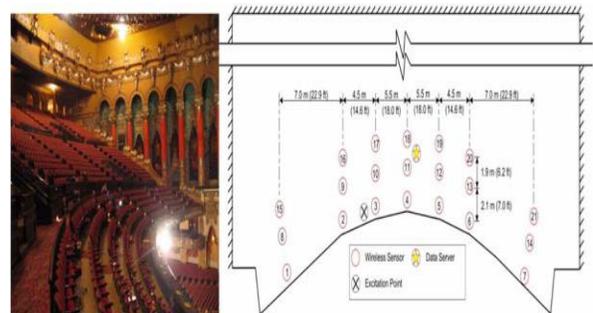

Figure 8. Historic theatre balcony with locations of wireless sensors, an excitation point, and a data server.
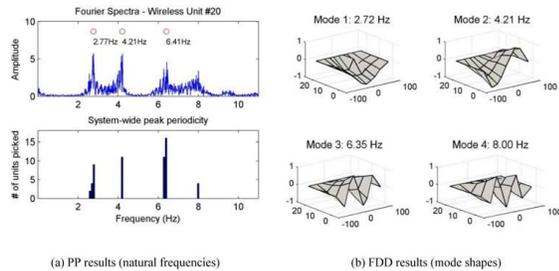
(a) PP results (natural frequencies)   (b) FDD results (mode shapes)

Figure 9. Results of embedded modal identification technique determined by in-network data processing

III. CHALLENGES AND FUTURE DIRECTIONS

The field of SHM will continue to grow. SHM has applications in many fields, such as the aerospace and automotive industries. A study in 2005, funded by the Wisconsin Highway Research program, was conducted by the Center for Transportation Research and Education (CTRE) at Iowa State University (ISU) on the types of smart monitoring technologies available and what technologies will be available in the future. The emerging technologies mentioned are fiber optic sensors, MEMS, wireless sensors for corrosion monitoring, wireless communication, data processing, and data management. Some of these technologies depend on other emerging technologies. For example, it is necessary to have efficient data processing and management for a MEMS to operate in the way designers intend. The Wisconsin Highway Research program study also revealed that current use of actual smart systems was not widespread throughout state DOT agencies . As MEMS and wireless technologies improve, more sensor systems will be added to the list of "smart" sensor monitoring systems. The envisioned future for MEMS is to integrate microsensors, microactuators, and microelectronics and other technologies onto a single microchip, which will enable the development of smart products and the realization of complete "systems-on-a-chip." While the opportunities offered by smart sensing for structural health monitoring are substantial a number of critical issues need to be addressed before this potential can be realized. This section discusses some of the constraints under which smart sensing applications must be developed from both hardware, and software perspective. Some directions for future research are also identified.

3.1 Hardware Issues

Data Acquisition. The current A/D converter employed in the Berkeley-Mote platform only has a 10-bit resolution, which is inadequate for high fidelity structural health monitoring applications whichtypically requires a 16-bit resolution. The Intel Mote has a modular design that allows for higher-resolution A/D converters to be developed/implemented.

• Synchronization:- Although synchronization can be achieved to a precision of 16 μs, the time required for such level of synchronization is of the order of 12 minutes. A less precise, but faster synchronization schemes can be used to synchronize sensors within about 2~8 ms.This error can introduce phase delays between sensor measurements.

• Limited memory:-The Mica2 has only 128 Kbytes of memory for instructions, and only 512 Kbytes on flash memory and 4 Kbytes of memory EEPROM, placing severe constraints on data storage and algorithm implementation.
• Data Transmission:- The Mica2 cannot simultaneously send/receive data. In a massively distributed sensor network, this limitation, combined with the Mica2's limited power, processing, and memory resources, may result in a significant bottleneck. Moreover, transmission collisions can result in randomdelays and the losses of up to 30% of the data.

• Limited Bandwidth:-The maximum data transmission rate between the Mica2s is 38.4 Kbaud. Real-time measurements could be hindered without a high speed data transmission rate.

• Limited Energy:- The Mica2 is battery powered, making power conservation of paramount importance.
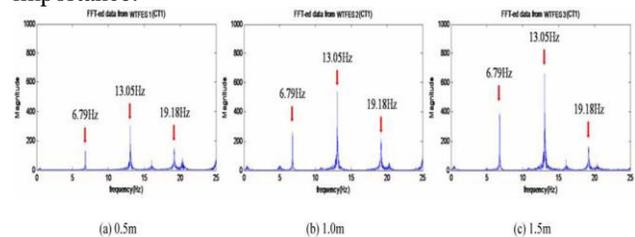

(a) 0.5m   (b) 1.0m   (c) 1.5m

Figure 10. Fourier spectra of accelerations at different sensor locations and natural frequencies obtained by a peak picking algorithm.
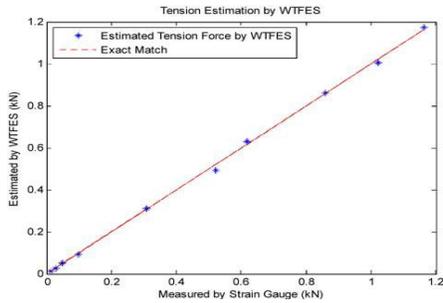
Figure 11. Comparison of the estimated tension forces by WTFES with those measured by stain gauge.

3.2 Software Issues

Relatively complex algorithms for monitoring and control of structures have been developed and implemented in the laboratory. Many researchers have focused on the development of SHM algorithms for estimating damage based on dynamic structural characteristics, such as natural frequencies, damping ratios, and mode shapes. A comprehensive view of the existing literature is given in Doebling where more than 600 references are cited. However, algorithms developed to date assume real-time, central-processing of the data - they cannot be implemented directly in the distributed computing environment employed by smart sensors.

IV.CONCLUSIONS

This paper provided a brief introduction to smart sensing technology, identifying a number of the opportunities, as well as some of the associated challenges. Smart sensors based on the Mote paradigmwill provide the impetus for development of the next generation of structural health monitoring systems, opening new horizons for research and development. Multi-agent system technology offers a computational framework for new algorithms implementation.
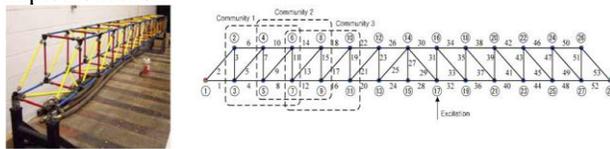

(a) 3-D truss structure   (b) Nodes, elements, and local sensor communities: Sensors at Nodes 2-11

Figure 12. Experimental setup for a 3-D truss and locations for sensors and excitation.

REFRENCES

1. Aoki, S. Fujino, Y., and Abe, M. (2003). "Intelligent bridge maintenance system using MEMS and network technology," Proc. SPIE Conf., 5057, San Diego, CA, USA.

2. Brincker, R., Zhang, L., and Anderson, P. (2001). "Modal identification of output-only systems using frequency domain decomposition," Smart Materials and Structures, 10 (3), pp. 441-445.

Celebi, M. (2002). Seismic Instrumentation of Buildings (with Emphasis of Federal Buildings). Technical Report

No. 0-7460-68170, United States Geological Survey, Menlo Park, CA, USA. Cho, S., Lynch, J. P. and Yun, C B. (2008). "Development of a low-cost automated tension estimation system for cablestayed bridges," Proc. ASME Conf. Smart Materials, Adaptive Structures & Intelligent Systems, Ellicott City, MD, USA.

Chung, H-C., Enomoto, T., Shinozuka, M., Chou, P., Park,

3. C., Yokoi, I., and Morishita, S., (2004). "Real-time visualization of structural response with wireless MEMS

sensors," Proc. 13th world conf. Earthquake Engineering, Vancouver, BC, Canada.

4. Farrar, C. R. (2001). Historical Overview of Structural Health Monitoring. Lecture Notes on Structural Health

Monitoring Using Statistical Pattern Recognition, Los Alamos Dynamics, Los Alamos, NM, USA. Farrar, C. R., Allen, D. W., Ball, S., Masquelier, M. P., and Park. G,. (2005). "Coupling sensing hardware with data

interrogation software for structural health monitoring," Proc. 6th Int'l Symp. Dynamic Problems of Mechanics,

Ouro Preto, Brazil.

5. Gao, Y. and Spencer Jr., B. F. (2008). "Structural health monitoring strategies for smart sensor networks,"

Newmark Structural Engineering Laboratory report Series 011.

6.James, G. H., Carne, T. G., and Lauffer, J. P. (1993). "The natural excitation technique for modal parameter extraction from operating wind turbine," Report No. SAND92-1666, UC-261, Sandia National Laboratories. Kim, 7. B. H., Park, T., Shin, H. and Yoon T. Y. (2007). "A comparative study of the tension estimation methods for

cable supported bridges," International Journal of Steel Structures, 7 (1), pp. 77-94.

8.Levis, P., Madden, S., Polastre, J., Szewczyk, R., Whitehouse, K., Woo, A., Gay, D., Hill, J., Welsh, M.,Brewer, E., and Culler, D. (2005). TinyOS: An Operating System for Sensor Networks. Ambient Intelligence, Weber, W., Rabaey, J.M., Aarts, E., Eds.

115-148, Springer, Berlin, Heidelberg.