Smart Sensing Technology: Opportunities and Challenges

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ABSTRACT: "Smart" sensors with embedded microprocessors and wireless communication links have the potential to change fundamentally the way civil infrastructure systems are monitored, controlled, and maintained. Indeed, a 2002 National Research Council report noted that the use of networked systems of embedded computers and sensors throughout society could well dwarf all previous milestones in the information revolution. However, a framework does not yet exist that can allow the distributed computing paradigm offered by smart sensors to be employed for structural health monitoring and control systems; current algorithms assume that all data is centrally collected and processed. Such an approach does not scale to systems with densely instrumented arrays of sensors that will be required for the next generation of 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.

1 INTRODUCTION

The design, fabrication, and construction of smart structures is 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. Struc-

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tural health monitoring and control systems (SHM/C) represent 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 by domestic and foreign airlines.

The ability to continuously monitor the integrity and control the responses of structures in real time can provide for increased safety to the public, particularly with regard to the aging structures in widespread use today. The capability to mitigate structural dynamic response and prevent structures from reaching their limit states, in addition to the ability to detect damage at an early stage, can reduce the costs and down-time associated with repair of critical damage. Observing, controlling, and/or predicting the onset of dangerous structural behavior, such as “flutter” in bridges, can provide advanced warning to allow for repair or removal of the structure before human lives are endangered. In addition to controlling and monitoring long-term degradation, assessment of structural integrity after catastrophic events, such as earthquakes, hurricanes, tornados, or fires, is vital. This assessment can be a significant expense (both in time and money); for example after the 1994 Northridge earthquake, large numbers of buildings 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/C is clear, with

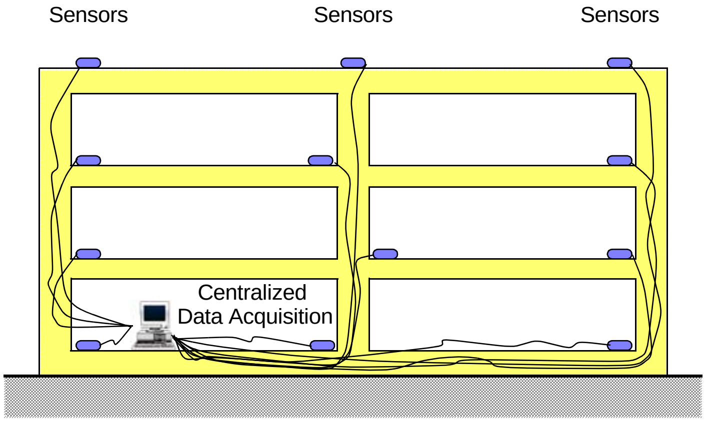

Figure 1. Traditional SHM System using
Centralized Data Acquisition.

the primary goals of such systems being to enhance safety and reliability and to reduce maintenance and inspection costs.

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 other 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 investigated.

Rapid advances in sensors, wireless communication, Micro Electro Mechanical Systems (MEMS), and information technologies have the potential to significantly impact SHM/C. 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-

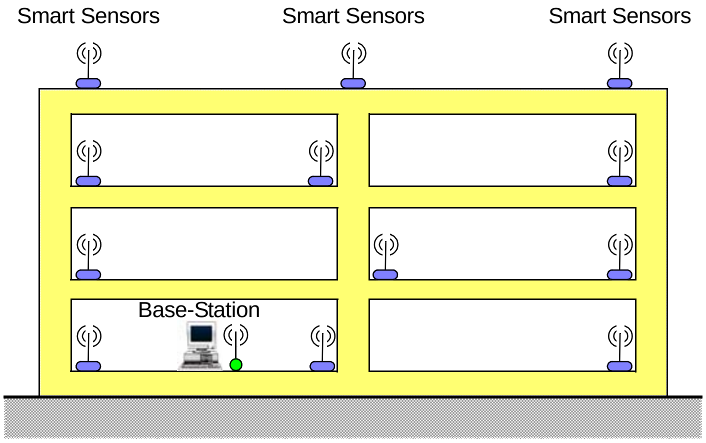

Figure 2. SHM System with Smart Sensors.

diagnosis and self-calibration capabilities, thus reducing that amount of information that needs to be transmitted over the network. Kiremidjian *et al.* (2001) pointed out that pushing data acquisition and computation forward is fundamental to smart sensing and monitoring systems such as illustrated 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.

2 WHAT ARE SMART SENSORS?

To better understand what is meant by a “smart” sensor, first consider the definition of a standard sensor. In general, 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, *etc.*), (ii) signal conditioning and processing (*e.g.*, amplifications, linearization, compensation, and filtering), and (iii) a sensor interface (*e.g.*, the wires, plugs and sockets to communicate with other electronic components) (Kirianaki *et al.* 2002).

As illustrated in Fig. 4, the essential difference between a smart sensor and a standard integrated sensor is its intelligence capabilities, *i.e.*, the on-board microprocessor. The microprocessor is typically used for digital processing, analog to digital or frequency to code conversions, calculations, and interfacing functions, which can facilitate self-diagnostics, self-identification, or self-adaptation (decision making) functions (Kirianaki *et al.* 2002). 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 very large scale integration technology (VLSI) 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/or 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.

Figure 3. Traditional Integrated Sensors.

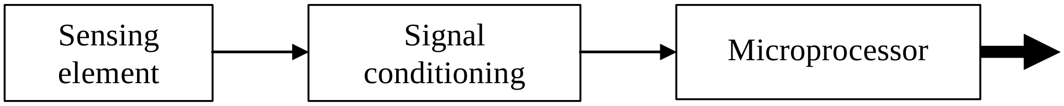

Figure 4. Smart Sensor.

The cost of the smart sensors is also decreasing. Mass production of MEMS and microprocessors for a variety of applications have reduced 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.

To put things in their proper technical perspective, the next section summarizes previous research on wireless sensors and provides a description of the smart sensors developed for civil engineering infrastructure.

3 WIRELESS SENSORS

Wireless global communication is important for facilitating low-cost, densely distributed sensing systems. Wireless radio links have been around for several years. Radio Frequency (RF) links have been utilized in embedded systems for numerous applications, including but not limited to cellular phones, home automation, digital audio players and wireless internet. Recently-developed inexpensive hardware has made it feasible to replace of the cabling in current vibration-based systems with RF links.

Westermo and Thompson (1997) presented a technology using peak strain sensors, which can be used to assess structural health. Their network consisted of three gauges, which, along with a digital junction, were installed on a three-story, wood-frame building. The system was powered by a 12-VDC battery pack; it was intended to routinely interrogate all sensors and store pertinent data or changes on each cycle. To transmit the information, the wireless system was connected to a cellular modem that was set to receive incoming calls from a PC for data downloading or reprogramming.

Pines and Lovell (1998, 1999) discussed an approach using sensors and wireless communication technology to monitor the health of large civil structures remotely using spread-spectrum wireless modems, data communication software, and conventional strain sensors. Their work described examples of condition-based health-monitoring systems that use cellular and through wire for data retrieval. A simple yet inexpensive device was realized and validated on a laboratory test structure at a range of up to approximately 1 mile without loss of communication signal.

Williams et al. (1998) presented a novel idea in which self-sufficient (i.e., generates its own power) wireless sensors were achieved. In their approach, the vibrational energy of the structure was used to power an accelerometer. The feasibility studies on reinforced concrete bridges indicated that the resonant frequency of the electric generator should match the fundamental frequency of the bridge so as to maximize the power generation.

Subramanian (1997) and Varadan et al. (1997, 1998, 1999, 2001) showed the wireless integration of MEMS and surface acoustic wave (SAW) devices employing interdigital transducers (IDT). These devices have a unique advantage in that they do not require an on-board power supply at the sensor location. The acceleration is measured when a wave (produced by a wave generator localized at the base station) is reflected by the sensor; the phase change in the reflected wave is proportional to the acceleration. This sensor has a wide dynamic range. The fabrication of the accelerometer is discussed. The wireless accelerometer provides an attractive opportunity to study the response of a “dummy” in automobile crash tests and may be potentially useful in the deployment of “smart skins” (intelligent fuselage) for aircraft.

Krantz, et al. (1999) presented the Remotely-Queried Embedded Microsensor (RQEM). The objective of this research was to develop a microsensor that could retrieve data from embedded strain gauges. This system consisted of two main parts: the sensor package and the reader. The sensor package consisted of a microsensor (conventional strain gauge), signal conditioner, receiver/transmitter, data encoder, and power supply. The reader consisted of an external antenna coil attached to a Trovan RFID Tag Reader. The measurement occurred when the reader antenna was placed 3 - 12 inches from the embedded sensor.

Lemke (2000) described a remote vibration monitoring system integrated with the internet in order to acquire field data, which was then uploaded to a web server using a wireless connection. The selection of the ground motion transducer with respect to the desired frequency response was discussed. The network was wired, but the transmission from the field site was performed by cellular telephony. Battery power considerations were also studied and the results showed that the system could be dialed just over 5000 times. With a peak transmission every thirty minutes, the system could last for over 200 days.

Oshima et al. (2000) also presented a monitoring system that could be interrogated via a mobile telephone. This system consisted of a photocell, an accelerometer, and a displacement sensor. The sampling frequency was 200 Hz. Experimental results for the structural frequencies and mode shapes were presented that closely agreed with the analytical results. A comparison between a fiber-optic strain sensor and a standard strain gage for crack propagation was presented. A difference of 5–10% in strain measurements between theses sensors was found.

Wang and Liao (2001) presented a wireless signal retrieval system. The difference between this application and the traditional one used is the way that the signal acquisition and transmitting subsystems were tuned to different resonant frequencies through frequency modulation (FM) technology before transmitting. Specifically, the wireless transmitter subsystem composed mainly of the following units: the sensor signal processor, the voltage/frequency (V/F) converter, and the transmitter. The wireless receiver subsystem was mainly composed of the following units: the receiver, the signal processor, the F/V converter, and the low pass filter. An example of a transmission of a sinusoidal wave was presented. The received signal yielded the same frequency content, but the amplitude was increased. The authors claimed that for certain algorithms, this increase in the amplitude of the received signal wasnot a factor. Additionally, they compared the power spectra density of a white noise random signal transmitted through a conventional TX2/ RX2 with that of their wireless system, suggesting that reception of a signal in the range 0–5Hz suffered a sharp decrease in reception and showing that the conventional paradigm was not likely to be effective for monitoring of civil infrastructure.

Evans (2001) provides a very good compendium of the various alternatives that can be used for wireless transmission of data, including free bandwidth frequencies, such as 915 MHz and 2.45 GHz, cellular phone lines, two-way paging, and satellites services. A description of the available sensors, such as the micromachined and force balance accelerometers, is also provided. The author indicates the performance and cost of each one of the wireless devices. Finally, two examples of wireless networks are presented: an application to a highway bridge used to determine damage, and free-field measurements to produce a real-time seismicity map for Oakland, California.

Mita and Takahira (2001) presented a wireless peak strain and displacement sensor. This sensor consisted of a variable capacitor made of an outer cylinder and an inner cylinder, in which the capacitance depended on the overlapping length. In order to retrieve data, a inductor was added to the variable capacitor, creating a resonant circuit. This circuit was excited by a dip meter and a frequency was read (a dip meter is the equipment which measures the frequency of the resonance circuit). A comparison of measurement results between a laser sensor and the peak strain sensor was presented. The agreement of these measurements assured the feasibility and accuracy of the system.

4 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 (1996, 1998), Straser *et al.* (1998), and Kiremidjian *et al.* (1997). This research sought to develop a near real-time damage diagnostic and structural health monitoring system, that evaluates both extreme and long-term structural health. The hardware was designed to acquire and manage the data and the software 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 *et al.* (1997), Lynch *et al*. (2001) demonstrated a proof-of-concept wireless sensor that uses standard integrated circuit components. 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 used the ADXL210 accelerometer making use of the duty cycle modulator that provides 14-bit digital output with an anti-aliased digital signal. In other units, a high performance planar accelerometer is used along with a 16-bit analog to digital (A/D) 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 *et al*. (1997) proposed the Wireless Global Bridge Evaluation and Monitoring System (WGBEMS) to remotely monitor the condition and performance of bridges. WGBEMS used small, self-contained, battery operated transducers, each containing a sensor, a small radio transponder, and a battery. The complete system consisted of a local controller placed off a bridge with 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 used a wide band in the 902 to 928 MHz range.

Brooks (1999) 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

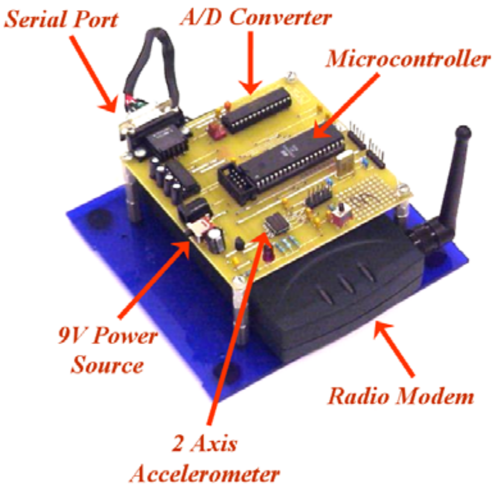

Figure 5. Prototype Smart sensor (Lynch *et al*. 2001).

transmission, local digital processing, preprogrammed decision algorithms, user-defined algorithms, internal self-verification/diagnosis, compensation algorithms, on-board storage, and extensible sensor object models.

Mitchell *et al.* (1999) presented a wireless data acquisition system for health monitoring of smart structures. They developed a micro sensor that used an analog multiplexer 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 used to perform the wireless transmission. Mitchell *et al.* (2001) continued this work to extend cellular communication between the central cluster and the web server, allowing web-control of the network.

Agre, *et al*. (1999) presented a prototype wireless sensor node called "AWAIRS I", shown in Fig. 6. This smart sensor can support bidirectional, peer-to-peer communications with a small number of neighbors. The current device consist of a processor, radio, power supply and sensors (seismic, magnetic and acoustic). Multiple portals for transporting information into or out of the sensor network can be established. They discussed some of the networking problems in a wireless sensor network. This prototype will run approximately 15 hours continuously on two 9V batteries.

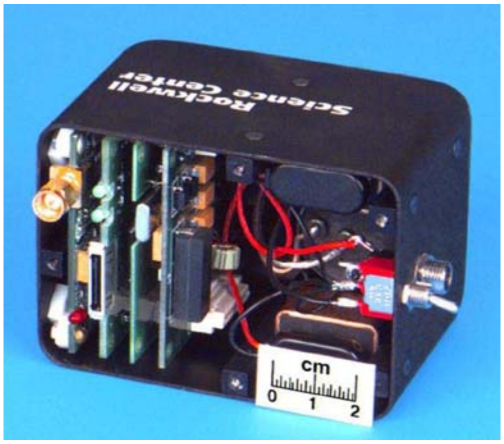

Figure 6. Sensor AWAIRS I (Agre *et al.* 1999).

The time-division multiple access (TDMA) scheme used, allows nodes to turn off their receiver and/or transmitter when they are not scheduled to communicate. This research is in a development phase.

Liu *et al.* (2001) presented a wireless sensor system that includes 5 monitoring stations, each with a 3-axis accelerometer (ADXL05). The stations used an 80C251 microprocessor with a 16-bit A/D converter. Because this network is 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 objective of the recently-created European project of Energy Efficient Sensor Networks (EYES 2002) is to develop the architecture and technology that will enable the creation of a new generation of self-organizing and collaborative sensors. These sensors will be capable of effectively networking together, in order to provide a flexible platform to support a large variety of mobile-sensor network applications.

This 3-year project has the support of Alcatel Center Information and Technology (Alcatel 2004), one of the most important communication solution providers in Europe, with experience in end-to-end networks that will boost reliable communication between sensors.

The architecture of EYES is supported by structure on two levels. The first level deals with the sensors and the network, i.e., internal sensor architecture, distributed wireless access, routing protocols, reliable end-to-end transport, synchronization and localization of nodes. The second level provides distributed services to the application, deals with information collection, lookup, discovery and security. Figure 7 shows a sensor prototype of the EYES project.

EYES will make use of the effort invested in the DataGrid project (DataGrid Project, 2004). The objective of the DataGrid project is to build the next generation of computing infrastructure,

Figure 7. Prototype Smart sensor
(EYES project 2002).

providing intensive computation and analysis of shared large-scale databases. This project includes more than 12 WorkPackages (WP) that deal with middleware, applications and management.

Specifically, EYES will use WP1, WP2, WP3 and WP4. WP1, system architecture (WorkPackage 1, 2004), aims to produce an open framework for flexible development of new applications. WP2, data management (WorkPackage 2, 2004), has been designed to manage and share Petabyte-scale (2^{50} bytes) information volumes. WP3, distributed services (WorkPackage 3, 2004), deals with the service layer, which supports mobile sensor applications. Finally, WP4, proof-of-concept (WorkPackage 4, 2004), whose deliverables will be a proof of concept network that uses more than 100 nodes.

Though, limited technical information has been provided to the public, EYES 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 needed.

5 OPEN ARCHITECTURE OF THE MOTE PLATFORM

An open hardware/software platform for smart sensing applications has recently been developed with substantial funding from the US Defense Advanced Research Projects Agency (DARPA) under the Network Embedded Software Technology (NEST) program. The main idea behind this research is to develop smart dust, or Motes, in which the ultimate goal is to create a low-cost, fully autonomous system within a cubic millimeter volume (Hollar 2000), allowing for the realization of dense sensor arrays. The Mote system consists of four basic components: power, computation, sensors, and communication. It is capable of autonomy and interconnection with other Motes. Besides the advantage of the open hardware/software platform, they have the advantage of small physical size, low cost, modest power consumption, and diversity in design and usage.

The first devices (Hollar 2000) were designed at the University of California at Berkeley by Prof. Kris Pister. The second generation of Motes, called Rene, implemented a modular construction, allowing the use of one unique base with the possibility of various interchangeable sensors. The third generation, called Mica, improved memory capacity and the use of a better microprocessor (4MHz). The most recent devices, Mica2 and Mica2dot, shown in Fig. 8, improved the radio communication (with a tunable frequency radio), and the microprocessor unit (7.3728 MHz). A summary of their characteristics is presented in Table 1.

Table 1: Characteristics of the Mica2 and Mica2dot processor boards

Performance	Mica2	Mica2dot
Flash memory	128K bytes	128 K bytes
Measurement memory	512K bytes	512K bytes
EEPROM	4K bytes	4K bytes
A/D (Channels)	10 bits (8)	10 bits (6)
Center Frequency	433 868/916MHz	433 868/916MHz
Num. of channels of RF	5	8
Data rate	38.4 K baud	38.4 K baud
Outdoor range	300 m.	300 m.

Table 1: Characteristics of the Mica2 and Mica2dot processor boards

Performance	Mica2	Mica2dot
Size	6x3x1 cm	2.5x0.6 cm

The microprocessor can be configured in three different sleep modes: (i) idle, which just shuts off the processor; (ii) power down, which shuts off everything but the watchdog and asynchronous interrupt logic necessary for wake up; and (iii) power save, which is similar to the power down mode but leaves an asynchronous timer running. At peak load, the current system can run about 30 hours on two AA batteries. In the low-power mode, one set of batteries can last for up to a year. The radio consists of a True single chip UHF RF transceiver (CC1000) with frequency range of 300-1000 MHz, that can operate at speeds of up to 76.8 Kbaud. This design allows, through an a internal universal asynchronous receiver-transmitter (UART), the versatility to connect different integrated circuits; *i.e.*, the modularity to support different types of sensors.

Figure 8. Berkeley-Mote (Mica2 and Mica2dot)
Processor Boards.

One of the main benefits of employing the Berkeley-Mote platform for smart sensing research and applications is the availability of a tiny event driven operating system that provides support for efficiency, modularity, and concurrency-intensive operation (Hill 2000; Hill *et al.* 2000). This operating system, called TinyOS, fits in 178 bytes of memory. The entire system is written in a structured subset of the C programming language. Tiny OS has an open architecture that is designed to scale with current technological trends, supporting smaller, more tightly integrated designs, as well as the implementation of software components into hardware.

The Mica2 and Mica2dot platforms can be used along with different types of sensor boards. The available sensors are: accelerometers, magnetometers, microphones, light and temperature sensors, and acoustic actuators. Ultimately, the user can design and manufacture a tailored sensor board according to the needs of the specific application. Currently, researchers can obtain the Berkeley-Mote sensor hardware from Crossbow Technology, Inc. (www.xbow.com), and the latest operating system software can be downloaded from (webs.cs.berkeley.edu/tos/).

The open hardware/software environment provided by the Berkeley-Mote platform leverages the substantial resources that have already been invested by DARPA. Additionally, Intel has recently announced development of the Intel-Mote platform (Kling 2003), with a number of enhancements (see Fig. 9 and table 2). This Mote will fully support TinyOS. The ultimate goal (to be accomplished by 2005) is to develop the Mote in the form of a single microchip with layered components, that will included: sensors, RF MEMS, nonvolatile storage, digital/analog silicon and battery. The

Figure 9. Intel® Mote Prototype.

Table 2: Characteristics of the Intel® Mote Prototype

Performance	Intel® Mote Prototype
Programming memory	64K bytes
Measurement memory	512K bytes
Processor	32 bits (12 MHz)
Center Frequency Data rate	2.4 GHz 723.2/57.6 K baud
Outdoor range	30 m.
Size	3 x 3 cm

present prototype is half the size of the original Berkeley-Mote, provides increased CPU power, for tasks such as location detection and digital signal processing. Other enhancements include security features and more reliable radio links using the bluetooth protocol. The efforts at Intel provide an important indicator of the bright future of this technology

Smart sensors based on the Berkeley-Mote and Intel-Mote platforms will provide the impetus for the development of the next generation of SHM/C systems.

6 PRELIMINARY STUDIES USING THE BERKELEY-MOTE PLATFORM

The Berkeley-Mote platform has been recently used in diverse research fields. Some of the applications includes: robotics (Bergbreiter and Pister 2003), localization (Whitehouse 2002), and environmental monitoring (Mainwaring 2002).

In civil engineering, Kurata *et al.* (2003) presents a study in which the Mica Mote (a previous version of the Mica2), is used as a risk monitoring tool. Two test structures were mounted on a shaking table and subject to the JMA Kobe (NS) earthquake. A Mica and a reference accelerometer were placed at the top of the structures to measure the acceleration. Figures 9 and 10 show the collapse sequence and the associated sensor responses. The Mica was able to detect the damage,

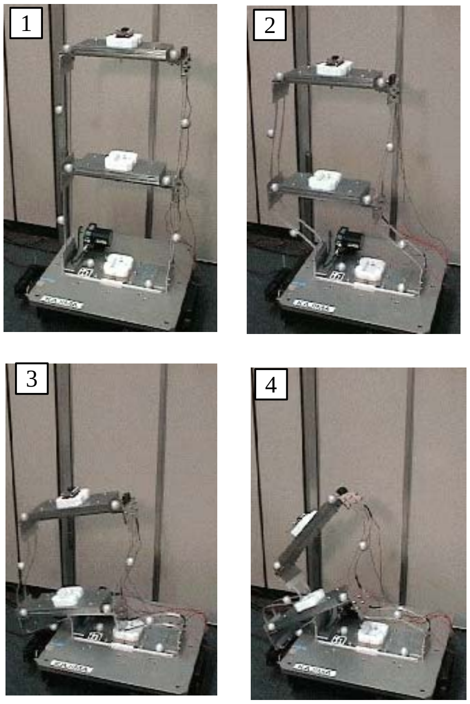

Figure 10. Damage process of test structure (Kurata *et al.* 2003).

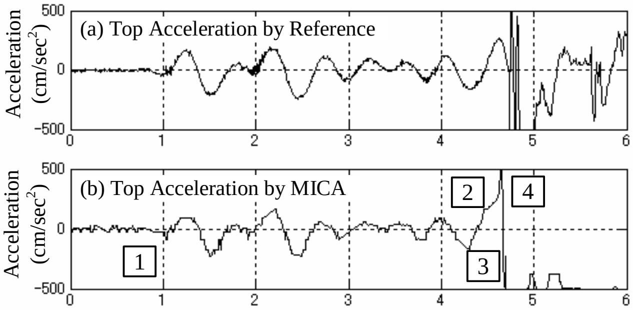

Figure 11. Sensor's records of test structure (Kurata *et al.* 2003).

however data loss during radio transmission and the sensitivity of the accelerometer are identified as limiting factors.

Additionally, a study regarding the performance of the accelerometer ADXL202, when used by the Mica Mote, is presented by Ruiz-Sandoval *et al.* (2003). In this paper, some deficiencies of the ADXL202 are found when measuring low amplitude/frequency signals. A new sensor board called

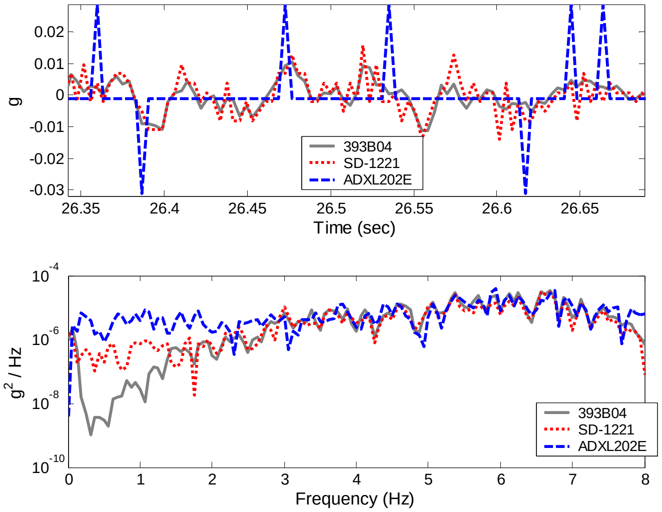

Figure 12. Time and frequency domain plots of acceleration response for a random excitation.(Ruiz-Sandoval *et al.* 2003).

“Tadeo” was developed that includes the high sensitivity accelerometer SD1221 manufactured by Silicon Designs, Inc. (www.siliondesigns.com). Figure 11 shows the performance of Tadeo sensor board compared with a reference accelerometer and the ADXL202. The paper also identified the need for a higher-precision A/D converter for the Mica Mote, in addition to the design of an anti-aliasing filter for the SD1221 accelerometer

The Berkeley-Mote offers a platform research for large number of applications. Specifically, for civil engineering some challenges are exposed. In the next section an analysis of these is described in detail.

7 CHALLENGES AND FUTURE DIRECTIONS

While the opportunities offered by smart sensing for structural health monitoring are substantial (Kurata *et al.* 2003), 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 a hardware and a software perspective. Some directions for future research are also identified.

7.1 Hardware Issues

- *Data Acquisition.* The current A/D converter employed in the Berkeley-Mote platform only has 10-bit resolution, which is inadequate for high-fidelity structural health monitoring applications (Ruiz-Sandoval *et al.* 2003) typically requiring 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 achieve to a precision of 16 μseconds (Kusy and Maroti 2004), the time required for such level of synchronization is of the order of 12 minutes. A less precise, but faster synchronization schemes (Ping 2003) can be used to synchronized within about 2~8 msec. This error can introduce phase delays between sensor measurements. For example, if two Micas are measuring a 5 Hz signal, a 7 msec misalignment in the their clocks will introduce a 12.6 degree phase lag error.

- *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 random delays and significant loss of the data.

- *Limited Bandwidth.* The maximum (wireless) data transmission rate between the Mica2s is 38.4 K baud. Real-time measurements could be hinder without a high speed data transmission rate.

- *Limited Energy.* The Mica2 is battery powered, making power conservation of paramount importance.
- *Security Issues*. To ensure that the information sent through the network is not compromised modified or denied, security in smart sensor enviroments should be taken into account. Authentication schemes, including encryption and decryption of data, as well as assessing the risk of a given environment, should be considered (Nixon, *et al*. 2004).

7.2 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/or mode shapes. A comprehensive view of the existing literature is given in Doebling and Farrar (1999) 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.

A significant impediment to the realization of the vision of massively distributed smart sensors for SHM/C is the lack of a computational framework on which to build new strategies.

- *Distributed Computational Approach*

Recent work by Gao, *et al*. (2004) presents a novel idea for identifying damage using a distributed computing damage detection algorithm. This approach uses an extended version of the Damage Locating Vector (Bernal, 2002) method, which considers the input excitation signal to be unknown, i.e., ambient vibration. Damage is detected using groups of sensors that are organized in a hierarchal manner. The information obtained from each group is sent back to the base station by the selected leader of the group. A numerical example indicates that the algorithm can detect both single and

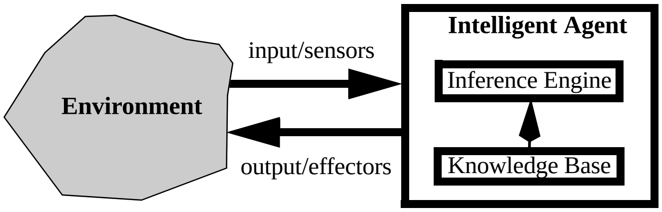

Figure 13. Schematic of Agent-based Framework.

multiple damaged case scenarios. This algorithm is very promising for implementation on a network of smart sensors.

- *Agent-based Framework*

A smart sensor can be viewed as being comprised of two components: a computation/radio transmission component and a sensing one. An alternative classification of these components can be presented as an intelligent and a mechanical component. As such, a smart sensor system can be viewed as a computational *agent* that is capable of flexible autonomous action in order to meet its design objectives. Perhaps the most general way in which the term agent is used is to denote a hardware or software-based computer system that enjoys the properties of autonomy, socialability, reactivity, and pro-activeness. A dense array of smart sensors is a multi-agent system (MAS).

The history of agents can be traced to research on artificial intelligence (AI), object-oriented programming, and concurrent object-based systems, as well as human-computer interface design (Jennings, *et al*. 1998). An *agent* can be define as a gathering of distributed autonomous processes, that each deal with a limited part of the overall problem. Agents are embedded in an environment. They sense and act upon it based on a knowledge base and inference engine (see Fig. 13).

There exists other definitions of agents and extended characteristic definitions. A good compendium of them can be found at Wooldrige and Jennings (1995).

Multi-agent system technologies are playing a critical role in developing effective and efficient problem-solving strategies and methods in large-scale smart sensor networks. MAS technologies provide a framework for building and analyzing such systems and offer specific mechanisms for distributed decision making and coordination in the systems (Weiss 2000). The agent-based view offers a powerful repertoire of tools, techniques, and metaphors that have the potential to considerably improve the way in which people conceptualize and implement many types of software. By structuring such applications as a multi-agent system, the system will have the following advantages: speed-up due to concurrent processing; less communication bandwidth requirements because processing is located nearer the source of information; more reliability because of the lack of a single point of failure; improved responsiveness due to processing, sensing and effecting being co-located; and finally, easier system development due to modularity coming from the decomposition into semi-autonomous agents.

Agents are being used in an increasingly wide variety of applications including: structural control (Hogg and Huberman 1998), air traffic control (Steeb *et al.* 1988), patient care (Huang *et al.* 1995), job shop scheduling (Morley and Schelberg 1993), and transportation management (Fisher *et al.* 1999).

An agent-based architecture provides an important paradigm on which to lay the foundation for smart sensing for SHM/C. Indeed, Liu and Tomizuka (2003) indicated that agent-based sensing is part of the strategic research required to advance sensors and smart structures technology. Focus should be placed on selecting the best architecture, hierarchical interaction, communication, and negotiation methods for the development of a SHM algorithm. Use can be made of the various agent communication languages that have been designed (Mayfield *et al.* 1996; Smith and Cohen 1996).

An effective agent-based computational framework should allow for robust SHM/C algorithm development on a network of smart sensors that can operate within the intrinsic constraints imposed by this environment.

Ruiz-Sandoval (2004) developed an agent-based framework for SHM. Based on the Gaia methodology (Wooldrige *et al.* 2000), this framework was tailored to be used by any descentralized SHM algorithm. A reference implementation using the AR-ARX method (Sohn *et al*. 2001) is presented. The framework was programed with Simulink using the StateFlow tool box (Mathworks 2002). The proposed agent-based framework is shown to be an effective paradigm for implementation of SHM/C algorithms on an array of smart sensors.

8 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 paradigm will 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.

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