Source: *Proceedings of the 4th International Workshop on Structural Control and Monitoring*, New York City, NY, USA, June 10-11, 2004.

Overview of Wireless Sensors for Real-Time Health Monitoring of Civil Structures

J. P. LYNCH

ABSTRACT

Wireless monitoring has emerged in recent years as a promising technology that will greatly impact the field of structural health monitoring. This paper is a summary of research efforts that have resulted in the design of numerous wireless sensing unit prototypes explicitly intended for implementation in civil structures. Wireless sensing units integrate wireless communications and mobile computing with sensors to deliver a sensor platform inexpensive to install in large-scale structures. Collocating computational power with sensors is a distinct feature of the wireless sensing paradigm that allows sensors to self-interrogate measurements for signs of structural damage. The paper concludes with a discussion on the future research needs that can further advance wireless sensing as a viable substitute for traditional wire-based structural monitoring systems.

INTRODUCTION

Civil structures are large-scale systems that are required to withstand the loads man and nature can impose upon them. Safety is a paramount issue that needs to be considered during the design process of these complex structural systems. Many proven methods are available that can assist structural owners and facility managers to ensure the safety of their structures. Visual inspections are widely used to inspect structures for outward signs of distress, but can be labor-intensive and dependent upon the inspector's judgment. Also available is a large collection of non-destructive evaluation (NDE) technologies including acoustic emission, ultrasonic testing, and radar tomography. NDE methods are localized in scope and require knowledge of probable damage locations. Permanent monitoring systems can also be employed to continuously monitor the response of civil structures to external loads. The availability of global structural response data from permanent monitoring systems has fueled the growth of the field of structural health monitoring. One shortcoming of such systems lie in their dependence on extensive lengths of coaxial wires for the transfer of sensor measurements, thus driving up their installation and maintenance costs.

The declining cost of electronic, computing and communication technologies,

---

Jerome Peter Lynch, Assistant Professor, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109-2125

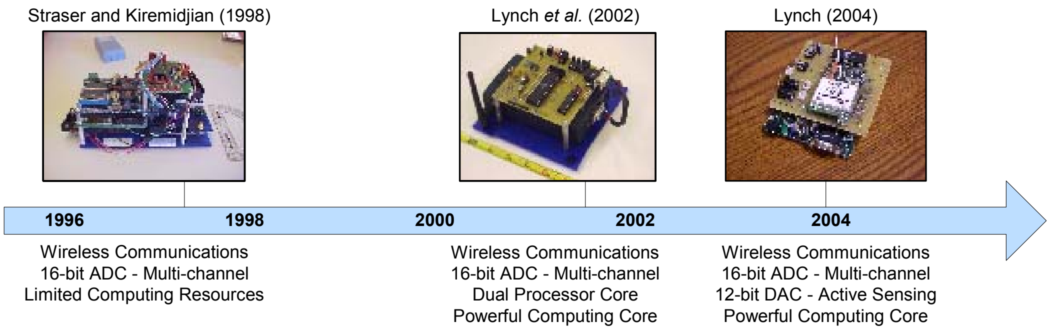

Figure 1. Evolution of wireless sensing units designed for structural monitoring

coupled with growing capabilities at rates espoused by Moore's Law [1] has led to the emergence of mobile computing technologies that are rapidly changing society. The development of wireless sensors is an integral part of the mobile computing revolution; wireless sensors act as miniature computing nodes that can monitor physical systems in which they are installed. The limitations of current structural monitoring technologies have prompted researchers to explore the use of wireless sensors for performing many of the tasks associated with monitoring civil structures. Initial excitement surrounding the adoption of wireless sensors in structural monitoring systems was based on the prospect of reducing the high costs associated with installing extensive lengths of coaxial wires in large civil structures. Straser and Kiremidjian [2] were the first to propose the integration of wireless radios with sensors to reduce the cost of structural monitoring systems. Lynch [3] has extended the functionality of wireless sensors by integrating sophisticated microcontrollers with them to enable sensor-based execution of embedded engineering algorithms. Since the initial exploration of wireless sensing solutions for structural monitoring, the field has fully blossomed into a viable tool that the structural engineering community can use to acquire empirical performance data of their structures from which the onset of structural distress could be identified.

This paper will review the state-of-the-art in the field of wireless structural monitoring. In particular, the design of various wireless sensor units that have been explicitly designed for monitoring the behavior of civil structures, is discussed. With sufficient computational resources coupled with sensors, a number of engineering analyses have already been embedded in the core of wireless sensors for real-time interrogation. The algorithms validated during laboratory and field validation studies are presented in detail. The paper concludes with a discussion of the future research opportunities that exist in further advancing the capabilities of wireless sensor networks and the role they may play in monitoring civil structures.

WIRELESS SENSING UNITS FOR STRUCTURAL MONITORING

Wireless sensing units represent the building block from which wireless structural monitoring systems can be formed. They must be capable of acquiring response measurements from sensors installed in a structure and to reliably communicate those measurements to other sensors and system data repositories. With the cost of microcontrollers declining, the functionality of the monitoring system can be improved by the implementation of data analysis capabilities within the wireless sensing nodes themselves. To attain the demanding performance levels that civil structures impose on the monitoring system, a top down design strategy is taken. To keep costs down, the design of wireless sensors are done with commercially available off-the-shelf components.

Since Straser and Kiremidjian [2] first proposed the integration of wireless communications with sensors, wireless sensing unit designs have rapidly matured. Figure 1 highlights the evolution of wireless sensing units for structural monitoring with their corresponding performance features highlighted. The hardware designs of these wireless sensing units closely mirror the operational tasks the units will assume within the structural monitoring system. To collect response measurements from sensors, sensing interfaces are needed to accurately convert analog sensor outputs into high resolution digital formats (often 16-bits or higher). The sensing interfaces are designed to be sensor transparent permitting the interface of any type of analog sensor with the wireless sensing units. To date, sensors employed with wireless sensing units include microelectromechanical system (MEMS) accelerometers, strain gages, linear displacement transducers and MEMS gyroscopes, just to name a few.

To accomplish the important task of data interrogation, microcontrollers are chosen to serve as the core of the wireless sensing unit designs. The computational core of the Straser and Kiremidjian wireless sensing unit consisted of a low-power 8-bit Motorola 68HC11 microcontroller [2]. The 68HC11 microcontroller is capable of managing the operation of the unit (collect and wirelessly transmit data) but lacks sufficient resources for executing sophisticated processing algorithms. To address this limitation, a wireless sensing unit design by Lynch [3] proposes the use of a dual microcontroller core. First, a low-power 8-bit Atmel AVR microcontroller is added to the core to perform the data collection and wireless communication tasks. This low-power microcontroller is always powered on, but draws little power from portable power supplies. A second microcontroller, a 32-bit Motorola PowerPC, is added to the core to accomplish the task of executing sophisticated engineering analyses. Since this microcontroller requires more power from portable power supplies than the AVR microcontroller, the PowerPC is kept in an off state and is powered on only when data interrogation is necessary. The dual processor core has been proven effective in providing sufficient computational resources with the wireless sensing unit without placing additional demands on the power source to be used for powering the wireless sensing unit in the field.

After data has been locally stored and processed, a wireless communication channel is needed to transfer data to the wireless network of sensing units. The large dimensions of civil structures require node to node communication ranges of over 150 meters. To provide resilience to channel interference, multi-path reflection, and path losses, spread-spectrum frequency-hopping wireless radios are typically selected for integration with the designs of wireless sensing units. Many wireless radios have been used with success including the Proxim ProxLink, Proxim RangeLAN2 and MaxStream 9XCite wireless radios. All three radios operate on the unregulated FCC industrial, scientific and medical (ISM) bands and have communication ranges of over 150 meters inside heavily constructed structures.

More recently, Lynch *et al.* [4] has extended the role of the wireless sensing unit in structural monitoring systems. A new sensing unit is proposed that is capable of actuating a number of monitoring and control technologies. To actuate, an actuation interface has been designed using a four-channel 12-bit digital-to-analog converter (DAC) capable of sample rates as high as 100 kHz. Termed a wireless active sensing unit, the unit can command active sensors to enhance the unit's ability to screen a structure for indicators correlated to damage. A recent validation study of the wireless active sensing unit employed piezoelectric pads mounted to the surface of structural plates. The unit commanded the piezoelectric pads to excite elements with Lamb waves, record the corresponding element responses, and interrogate the input-output response data for signs of crack damage. Wireless active sensing opens many exciting opportunities including the use of the unit to incorporate well proven NDE technologies within global structural monitoring systems.

To validate the use of wireless monitoring in real civil structures, a structural monitoring system consisting only of wireless sensing unit prototypes was successfully used to monitor the Alamosa Canyon Bridge in New Mexico. The monitoring system was used to record the bridge response to excitations applied during forced vibration testing. The wireless sensing unit also executed embedded fast Fourier transforms (FFT) to accurately identify the primary modal frequencies of the bridge during testing [5].

EMBEDDED ENGINEERING ANALYSES

The judicious selection of hardware components only represents the first-step in the design of wireless sensing units. Equally necessary is software to be embedded in the units' computational cores to manage their operation and interrogate response measurements in near real-time. In particular, tremendous interest surrounds wireless sensing units because of their potential use to autonomously screen response measurements for signs of structural damage. Wireless sensing units can also play important roles in system identification studies of structures and in structural control systems.

As summarized by Table 1, a number of different engineering analyses have been encoded for autonomous execution by wireless sensing units. Fast Fourier transforms (FFT) have been coded using the computationally efficient Cooley-Tukey algorithm [6]. FFTs can play an important role in identifying the primary modal frequencies of structures. For example, wireless sensing units installed in the Alamosa Canyon Bridge were successfully used to identify the bridge's first three modal frequencies [5]. To illustrate the ability of wireless sensing units to provide real-time feedback of the health of structures, a damage detection method proposed by Sohn and Farrar [7] has been explored. This approach uses the standard deviation of the residual error of an autoregressive with exogenous input (ARX) time series model as the sensitive feature from which damage can be detected. The embedded AR-ARX damage detection method has proven reliable when tested using a laboratory lump mass model that has been intentionally damaged. A particularly powerful feature of the AR-ARX time series approach is its ability to identify damage in the vicinity of a sensor node by only analyzing the node's response data. Without requiring the sharing of response time-histories between sensing units, the computational autonomy of the wireless sensing unit is preserved. The incorporation of damage index models that use structural drift responses to identify the amount of damage sustained by reinforced concrete and high performance fiber reinforced cementitious composite (HPFRCC)

Table 1. SUMMARY OF EMBEDDED ENGINEERING ANALYSES

Algorithm	Domain	Validation Structure
Fast Fourier Transform (FFT)	▪ System ID ▪ Damage Detection	▪ Alamosa Canyon Bridge ▪ 5DOF Shear Structure
Autoregressive Models (AR)	▪ System ID	▪ Alamosa Canyon Bridge ▪ 5DOF Lab Structure
AR-ARX Damage Detection Pattern Recognition Method	▪ Damage Detection	▪ Lump-Mass Structure
Damage Index Models	▪ Damage Detection	▪ Cement Coupling Beam ▪ Cement Bridge Pier
Wavelet Transforms (WT)	▪ System ID ▪ Damage Detection ▪ Data Compression	▪ Compression of 5DOF Shear Structure Time-History Data
Huffman Coding	▪ System ID ▪ Damage Detection ▪ Data Compression	▪ Compression of 5DOF Shear Structure Time-History Data

elements has also been embedded in wireless sensing units. A wireless sensing unit integrated with an HPFRCC coupling beam tested under reverse cycle loading was capable of predicting the failure of the beam.

Performing data interrogation at the wireless sensor is prudent from an energy standpoint [8]. Wireless radios often consume the most power in the wireless sensing unit design. As such, wireless communication of raw time-history records would represent an inefficient use of limited battery resources. In lieu of transmitting raw time-history data, the wireless sensing unit is used to first interrogate the data to distill a small number of indicators that could then be wirelessly transmitted. For example, damage detection algorithms could be used to determine if damage is present and the wireless channel reserved for transmitting only if damage was or was not found. Studies have been performed to assess the amount of battery power that is preserved by first interrogating response data. Using the AR-ARX damage detection method proposed by Sohn and Farrar [7], the wireless sensing unit was able to extend the life of a limited supply battery back by more than double [8]. In those instances where it is necessary to transmit the time-history data, lossless data compression using wavelet transforms and Huffman coding tables has been successful used to first compress data so that use of the wireless channel is minimized.

CONCLUSIONS

Many challenges still lie in the way of improving the capabilities of wireless sensors. The power consumption characteristics of current prototype designs are still too high to consider battery power an attractive power source. Identifying the wireless communication components as the largest power consumer, research is already under way to integrate 802.15.4 compliant (Zigbee) radios with the wireless sensing units. Zigbee is the first wireless protocol standard that is designed exclusively for wireless sensor networks. As such, the protocol is written with power in mind; Zigbee consumes a fraction of the power needed for other wireless protocols such as Bluetooth and 802.11 variants. A multi-disciplinary research effort is underway at the University of Michigan's Center for Wireless Integrated

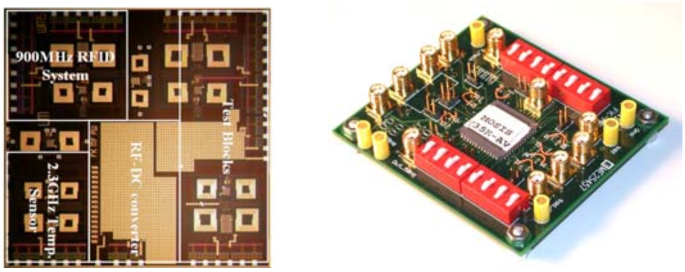

Figure 2. Remotely powered sensor/transponder IC (courtesy Prof. Michael Flynn)

Microsensors to incorporate 802.15.4 radios within a small-scale wireless sensing platform that is incredibly low-power. The center is also producing an exciting array of wireless sensor platforms including radio frequency identification (RFID) sensors as presented in Figure 2.

The role of the wireless sensing unit can also be further extended to tackle problems beyond structural health monitoring. The technology can be used in the design of structural control systems. Wireless active sensing units that command actuators are being employed to control the displacement of laboratory test structures. The performance of wireless communication technologies challenge the classical approach to the design of control systems with range, latencies and data loses still major issues to address.

ACKNOWLEDGEMENTS

This research has been partially funded by the National Science Foundation and Los Alamos National Laboratory. Collaboration with Profs. Kincho Law and Anne Kiremidjian at Stanford University if greatly appreciated.

REFERENCES

1. Moore G. E. 1968. “Cramming More Components onto Integrated Circuits.” *Proceedings of the IEEE*, 86(1): 82-85.
2. Straser, E. G. and A. S. Kiremidjian. 1998. *A Modular Wireless Damage Monitoring System for Structures*. Report No. 128, John A. Blume Earthquake Engineering Center, Stanford, CA.
3. Lynch, J. P. 2002. *Decentralization of Wireless Monitoring and Control Technologies for Smart Civil Structures*. Report No. 140, John A. Blume Earthquake Engineering Center, Stanford, CA.
4. Lynch, J. P., Sundararajan, A., Law, K. H., Sohn, H., Farrar, C. R. 2004. “Design of a Wireless Active Sensing Unit for Structural Health Monitoring.” *Proceedings of the 11th Annual International Symposium on Smart Structures and Materials,* San Diego, CA, March 14-18, 2004.
5. Lynch, J. P., Law, K. H., Kiremidjian, A. S., Carryer, E., Farrar, C. R., Sohn, H., Allen, D., Nadler, B. and Wait, J. 2002. "Laboratory and Field Validation of a Wireless Sensing Unit Design for Structural Monitoring," *Proceedings of US-Korea Workshop on Smart Structural Systems,* Pusan, Korea, August 24-25, 2002.
6. Press, W. H., S. A. Teukolsky, W. T. Vetterling and B. P. Flannery. 1992. *Numerical Recipes in C: The Art of Scientific Computing*. Cambridge: Cambridge University Press.
7. Sohn, H. and C. R. Farrar. 2001. “Damage Diagnosis Using Time Series Analysis of Vibration Signals,” *Smart Materials and Structures*, 10(3): 446-451.
8. Lynch, J. P., Sundararajan, A., Law, K. H., Kiremidjian, A. S. and Carryer, E. 2004. "Embedding Damage Detection Algorithms in a Wireless Sensing Unit for Attainment of Operational Power Efficiency," *Smart Materials and Structures*, IOP, 13(4): 800-810.