Sandwich Node Architecture for Agile Wireless Sensor Networks for Real-time Structural Health Monitoring Applications

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ABSTRACT

In recent years, wireless sensor network (WSN), as a powerful tool, has been widely applied to structural health monitoring (SHM) due to its low cost of deployment. Several commercial hardware platforms of wireless sensor networks (WSN) have been developed and used for structural monitoring applications [1,2]. A typical design of a node includes a sensor board and a mote connected to it. Sensing units, analog filters and analog-to-digital converters (ADCs) are integrated on the sensor board and the mote consists of a microcontroller and a wireless transceiver. Generally, there are a set of sensor boards compatible with the same model of mote and the selection of the sensor board depends on the specific applications. A WSN system based on this node lacks the capability of interrupting its scheduled task to start a higher priority task. This shortcoming is rooted in the hardware architecture of the node. The proposed sandwich-node architecture is designed to remedy the shortcomings of the existing one for task preemption. A sandwich node is composed of a sensor board and two motes. The first mote is dedicated to managing the sensor board and processing acquired data. The second mote controls the first mote via commands. A prototype has been implemented using Imote2 and verified by an emulation in which one mote is triggered by a remote base station and then preempts the running task at the other mote for handling an emergency event.

Keywords: Sandwich Nodes, SHM, WSN

1. INTRODUCTION

The real-time response is essential for performance of SHM applications as the capability of the monitoring system to catch up sudden events such as earthquakes is of great importance. Unfortunately, one of the main limitations in deploying WSNs is the lack of agility of the network in responding to the sudden events (e.g. Earthquakes). The reason is that the WSN is either in idle mode or transmitting data collected prior to the event. The main goal of this research is to verify the assumption that sensor nodes employing the sandwich-node architecture are capable of being preemptively triggered and set to an emergency mode to capture critical dynamic response of an infrastructure such as a bridge during and after a sudden event in real time. Emergency responsiveness is a critical issue in wireless sensor networks applications such as structure health monitoring (SHM) subject to earthquake excitation and the current architecture of wireless sensor nodes is not capable of reacting instantly to the arrival of an earthquake. Past experience with the current generation of WSNs demonstrated that the earthquake had hit an instrumented bridge and the network completely missed it because it was either in sleep mode or transferring ambient data that was previously collected.

Unlike the conventional sensor node units, the proposed sensing system is capable of instantly reacting to the arrival of an earthquake by a trigger signal. The system will then interrupt its current task, and start collecting earthquake-response data.

In a research project carried out by a research group from the University of California, Berkeley, a wireless sensor network of 320 nodes is installed on the main-span and a tower of the Golden Gate Bridge. After the initial installation phase, the network operated on the bridge from June to

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September 2006, periodically collecting acceleration and temperature data and transmitting them to a base station located inside the south tower (Pakzad et al. 2008). During this 3-month period, at least three earthquakes occurred not far from the bridge, including Glen Ellen shaking on August that has a magnitu[1]de of 4.4 on August 2. 2006. Despite having access to the out-of-site triggering system operated by California Strong Motion Instrumentation Program (CSMIP), the sensor network failed to perform any data collection during all the earthquakes because it was not alert for their arrival; the network was either transmitting ambient vibration data collected prior to the incidence of the earthquake or simply in sleep mode [4] (Cheng and Pakzad, 2009). Most of the research on structural monitoring of the bridges using WSNs is based on periodic collection of ambient data generated by wind and traffic loads, or forced vibration tests using actuators to cause excitations [4, 5, 6, 7, 8, 9] (Maser et al. 1996; Straser and Kiremidjian, 1998; Galbreath et al. 2003; Binns 2004; Lynch et al. 2006; Kim et al. 2007). While this is an important category of structural monitoring, the most insightful and interesting data is that generated by an earthquake, where the structure has significant non-linear behavior and many of its extreme-condition design parameters can be tested. The owners, engineers, and general public may want to know how each element of the structure performs during an earthquake. With the information about how these elements respond to earthquakes, they are able to improve them in the future retrofits/design of that and other bridges.

The limitation of the current generation of WSNs to passive and on-demand monitoring of bridges rather than alert and active triggering can be attributed to the requirement for the network to collect and handle ambient data for continuous monitoring of the bridge. These tasks keep the network busy with data collection and transmission when the network is not in the sleep mode. Some mechanisms are needed to enable prioritization and interruption of these tasks to maintain a dual-functional WSN that can be utilized for both continuous monitoring and earthquake response.

The rest of the paper is organized as follows, in section 2, the typical architecture of state-of-the-art commercial wireless sensor nodes are examined carefully and its architecture deficiency causing the inability in active sensing is analyzed. Then the sandwich node architecture is proposed and depicted in detail. Section 3 includes an implementation of sandwich node prototype and experiment design that evaluates the effectiveness of the prototype.

2. SANDWICH NODE ARCHITECTURE

Sandwich-node is a concept design to remedy the shortcomings of the previous generation of integrated sensing/communication/control devices that have been used for structural health monitoring applications. The proposed node consists of two control/communication motes, a comprehensive sensor board and a single antenna, and can support the prioritization and interruption functionalities as described in the previous section. The improvements in the architecture of the nodes, which result in sandwich-node are based on the design criteria for sustaining an alert and capable WSN for monitoring the response of an infrastructure to earthquake excitations.

2.1 State of the art

Several hardware platforms of WSN have been developed and used for structural monitoring applications [10, 11, 12, 13, 14, 15, 16](Straser and Kiremidjian, 1998; Kottapalli et al. 2003; Aoki et al. 2003; Basheer et al. 2003; Mastroleon et al. 2004; Lynch et al. 2004; Farrar et al. 2005; Wang et al. 2005; Rice et al. 2008).

Figure 1 shows the schematic diagram for the typical design of a node based on integration of a sensor board and a MicaZ mote. In this architecture the sensing units and analog filters and digitization units are housed on a sensor board. The sensor board supports a control and communication unit, which is connected to a bi-directional antenna. In the example presented in Figure 1 the sensors on board consist of four channels of accelerometers and one thermometer (Kim et al. 2006; Pakzad et al. 2005). The board acts in two sensing directions, vertical and transverse. In each sensing direction there is a high-level ADXL 202 channel by Analog Devices to resolve the strong motions of earthquake, and a low-level Silicon Design 1221 for low-level ambient vibrations. Each channel has its own anti alias low-pass filter and a 16-bit analog to digital converter. The mote selected for the node is MicaZ, which has a micro-controller, 512 kB flash memory, and a 2.4 GHz radio-frequency Chipcon CC2420 transceiver that can support commercially available bi-directional antennas.

The performance of this system was evaluated during the deployment of 320 sensors on the Golden Gate Bridge and the results were presented in several reports and publications (Pakzad et al. 2008; Pakzad and Fenves, 2009). This node performed very well for its intended design, periodically collecting large volume of acceleration and temperature data on the bridge and transmitting them to the base station for analysis. The system, however, did not have the capability of interrupting its scheduled task to start a higher priority task.

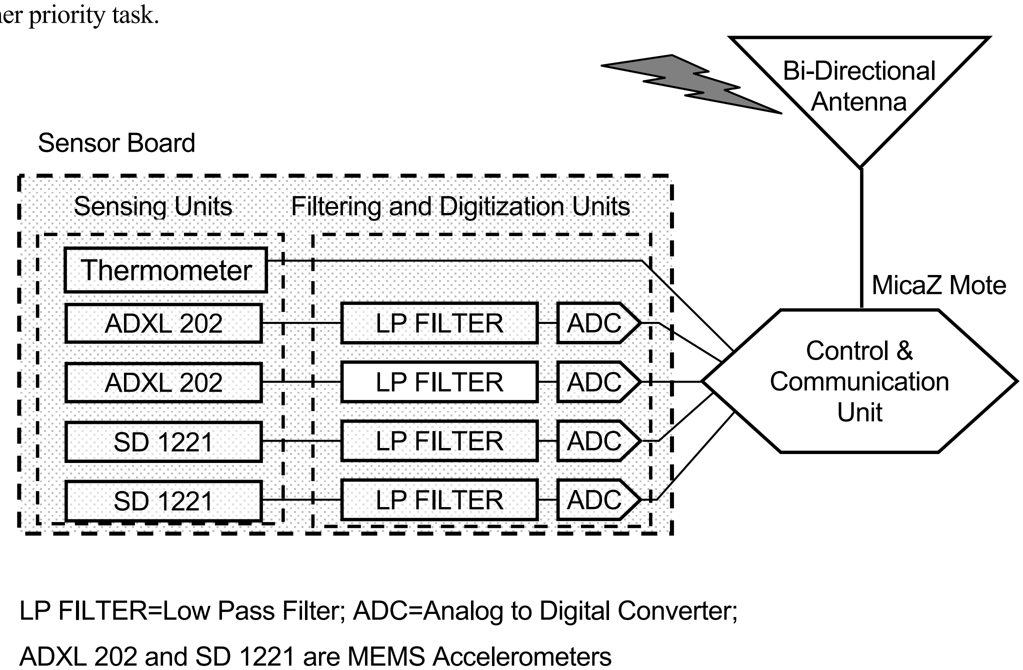


Figure 1. Schematic design of the Berkeley node used on the GGB deployment.

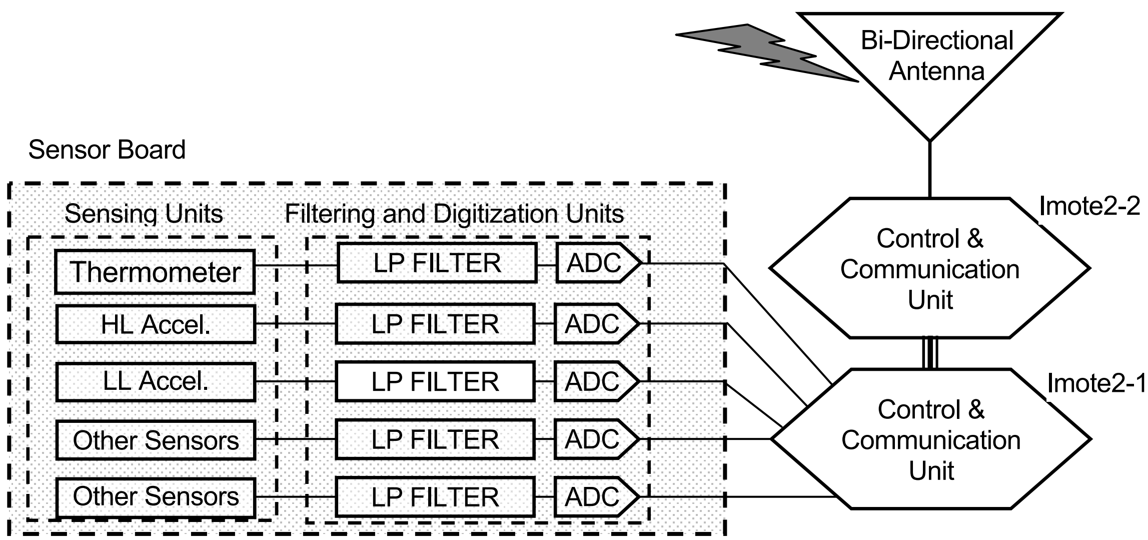
2.2 Sandwich Node Design

The schematic of the proposed design is shown in Figure 2 [17]. The node consists of a sensor board, which has the sensing units, and filtering and digitization units. The sensing units are expandable and can support several types of MEMS sensors and can be customized for the specific application. For earthquake monitoring of bridges, we would include a thermometer to calibrate the measured response to temperature, high-level and low-level accelerometers in multiple directions, and multiple channels of strain gauges. The filtering and digitization unit provides anti alias filters for each sensing channel (e.g. tunable single pole filters) and 16 or 24-bit analog-to-digital converters.

The sensor node supports two Imote2 motes. The first mote is dedicated to managing the control of the sensor board and performing on-board data processing if required (Imote2-1). The second mote is in communication with the first mote through the communication interface to exchange command and data. This mote (Imote2-2) is responsible for maintaining the time-synchronization within the node, communicating data and commands with the network and interpreting and relaying them to the first mote (Imote2-1). These dual control units help increase the computational capability of the node to perform more complicated time- and frequency-domain analysis on the data, maintain alertness in the network by providing accurate time synchronization at each node, and provide accurate clock for fast sampling with small jitter.

3. SANDWICH NODE PROTOTYPE

As described in Section II, the sandwich node features a dual-mote architecture. One mote is connected directly with the sensor board and responsible for sensor board control and data processing. The other mote is connected to the wireless transceiver monitoring the wireless channel for emergency events, which will interrupt the first mote immediately after receiving the incidence of an emergency event. A typical implementation of this sandwich node would include two microprocessors connected together through some interface. The full-featured sandwich node design requires building the node hardware from scratch, which is time consuming and cost ineffective. To save the time and cost while still be able to create and validate an emergency-responsive sandwich node, we currently use an alternative to prototype a sandwich node by integrating two commercial Imote2 together. In the following parts of this section, we will describe the prototype implementation and evaluation in detail.



LP FILTER=Low Pass Filter; ADC=Analog to Digital Converter

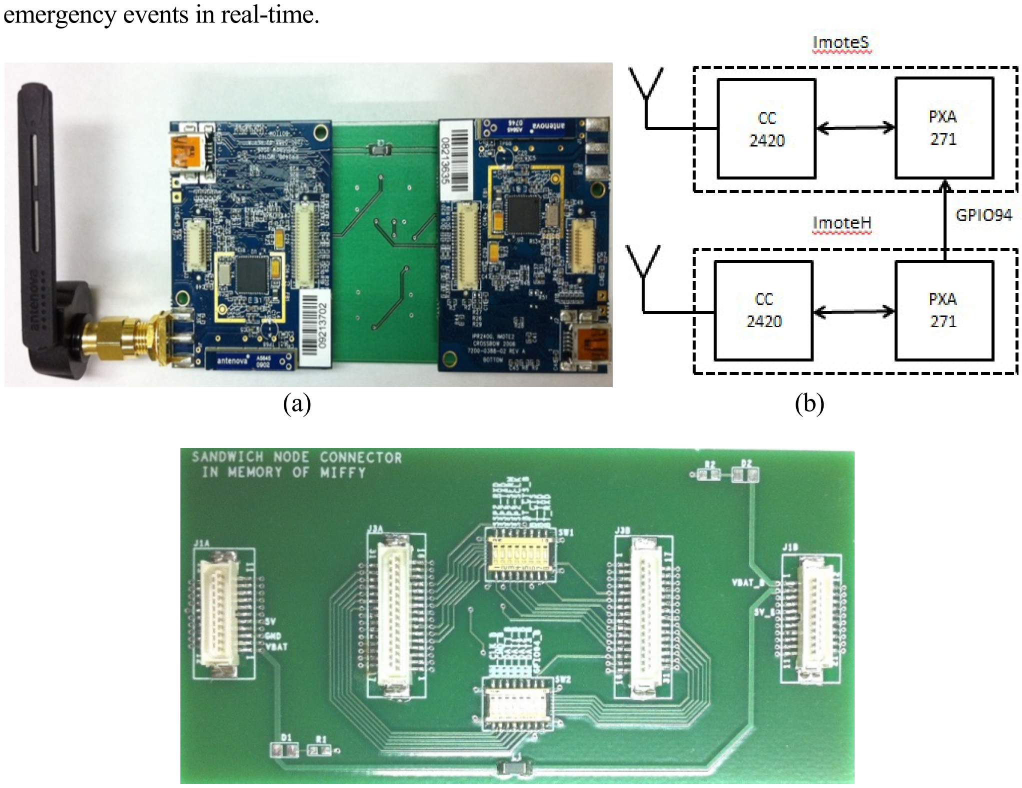
HL Accel.=High-Level MEMS Accelerometer; LL Accel.=Low-Level MEMS Accelerometer

Figure 2. Schematic design of the proposed sandwich-node for earthquake monitoring.

3.1 Sandwich Node Prototype Implementation

The basic idea behind the sandwich node prototype is connecting two Imote2 together and making one controlling the other. As shown in Figure 3, Imote2 is built around a PXA271 Xscale embedded micro processor and a CC2420 wireless transceiver. PXA271 has several serial interfaces and general purpose input/output (GPIO) that can be used to interface with peripherals. In Imote2, these interface pins can be accessed through the 31-pin common connector on the board.

Apart from the interfaces that are utilized by the sensor board, there is still one UART communication port, one serial peripheral interface (SSP) and some GPIOs left for free use. Interfacing two Imote2 through a serial port is a common method in processor interconnections. It allows a data bandwidth ranging from several kilobytes to several megabytes with a few physical wire connections. However, this method complicates the software design as codes that implement the serial communication protocol and device drivers are needed. On the other hand, interfacing two Imote2s with GPIO is a simpler approach both in hardware and software. We choose the later as our interconnection approach for the current prototype. Figure 4 (a) shows the image of sandwich node prototype; (b) is its block diagram and the physical form of the connector board is shown in (c). The connector board provides multiple physical interfaces between the two Imote2s, including GPIO, UART and SPI, which can be selected via switches on the board. Currently, we only use GPIO94 to connect two Imote2s. We denote the controlling Imote2 as ImoteH and the controlled Imote2 with the antenna mounted on (i.e., the left one on the picture) as ImoteS. A GPIO can be configured as input or output pin by the control register in PXA271. When configured as an input, the level transition on the pin can trigger the interrupt of the processor. While in our application, GPIO pin on ImoteS and ImoteH are set in the input mode and the output mode respectively. Wireless transceivers of ImoteS and ImoteH are dedicated for sensing data transmissions and controlling data transmissions. They operate in different frequency bands and thus will not interfere with each other. With this structure and configuration, the sandwich node can respond to emergency events in real-time.



(a) (b)

(c)

Figure 4. (a) Sandwich node prototype based on two Imote2s (b) Block diagram of sandwich node prototype (c) sandwich node connector board

3.2 Sandwich Node Prototype Evaluation

Consider a typical application scenario, in which sandwich nodes are mounted on a bridge running some regular SHM routine such as data collection. Then an earthquake strikes and it will reach the bridge soon. Some remote control station nearby sensed the earthquake wave will first send signals to ImoteH in a wireless control channel indicating the incidence of the earthquake. ImoteH catches this signal and then sends an interrupt signal through GPIO to ImoteS. On receiving the interrupt, ImoteS will stop its current task and switch to an emergency handler function.

In this research, we have established a test environment and designed an experimental application to verify the effectiveness of the sandwich node. As shown in Figure 5, an Imote2 acts as the remote control station and a sandwich node is connected directly to a host PC (i.e. a laptop) through a USB port. In the application, the sandwich node is performing a regular sensing task and the data collected is displayed on the laptop screen. Then at some instant, the remote control station sends an emergency signal via the control channel. The sandwich node receives this signal and switches the task to handle the emergency event. We use a dummy message printing program as the event handler so that a special message is displayed on the screen. In real applications, this special message printing program can be replaced by other programs that handle the emergency event.

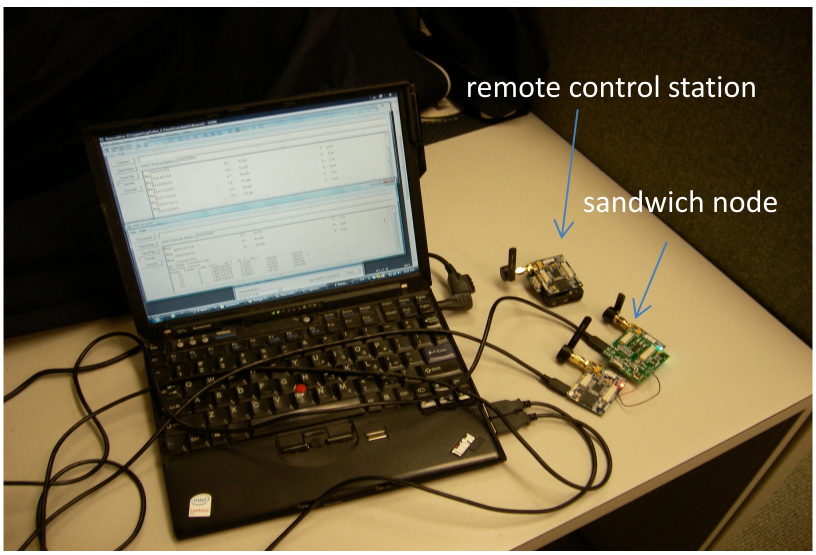


Figure 5. Sandwich node prototype evaluation setup with a remote control station and a sandwich node connected to a host PC

4. CONCLUSION AND FUTURE WORK

In this paper, we survey the architecture of the state-of-the-art commercial sensor nodes such as MicaZ and Imote2 and analyze its inability to respond to emergency events, which is important in structural health monitoring applications such as bridge monitoring. The reason that leads to this drawback lies in the hardware architecture of the senor nodes. Based on this analysis, a new sensor node architecture called sandwich node is proposed. Sandwich node, featuring a dual mote structure with a sensor board, eliminates this flaw by using a control mote to interrupt the other mote that does the regular sensing task when an emergency event happens. Limited by time and cost, we implement a sandwich node prototype based on Imote2 and it can respond to emergency events in real time.

The future improvements of the sandwich node are focused on extending its power and fully utilize the hardware capability. Firstly, bandwidth between two motes can be enhanced. In our sandwich node design, the hardware supports both GPIO and high bandwidth communication ports such as UART and SPI. Due to time limitation, currently the communication between the motes is merely via GPIO, which can only support control message exchanges. So for part of the future work, we will refine the sandwich node prototype by implementing the software to support interconnection between two using serial interface. Secondly, the processing power of the sandwich node is not fully explored. As mentioned in the previous experiment set up, the master node is only used as a means of interrupting the slave node. However, in fact, the master node itself has the same amount of computational capability as the slave node. Thus, it can perform the same computational tasks assigned to slave node to ameliorate its load and enhance the overall performance. For example, time synchronization is a necessary but time-consuming process in almost all WSN applications, which synchronizes all the sensors before they start data sampling tasks. The time needed for synchronization scales with the size of the network, which can easily exceed 10 minutes when the network contains over several hundreds of nodes. This considerably harms the real-time performance of the WSN even it can be timely triggered to catch the unexpected event. This is because the network may not be synchronized at the time of the event, thus has to synchronize first before it is actually ready to acquire data. This issue could be solved by sandwich node as we can program the master node to let it perform time synchronization periodically to keep the network always synchronized. While sudden events happen, the master node interrupts the slave node, and then sends the pre-calculated synchronization packets to the slave node so the slave node can directly start data sampling.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. Pakzad, S.N., Fenves, G.L., Kim, S., and Culler, D.E. 2008. Design and Implementation of Scalable Wireless Sensor Network for Structural Monitoring. ASCE J. of Infrastructure Engineering, 14(1):89-101.
2. Dorvash, S., Pakzad, S. N., Labuz, E., Chang, M., Li, X. and Cheng, L. 2010. Validation of a Wireless Sensor Network using Local Damage Detection algorithm for Beam-Column Connections. in Smart Structures and Materials, San Diego, CA.
3. Cheng, L. and Pakzad, S, Agility of Wireless Sensor Networks for Earthquake Monitoring of Bridges, the Sixth International Conference on Networked Sensing Systems (INSS'09), Carnegie Mellon University, Pittsburgh, USA, June 17 - 19, 2009.
4. Maser, K., Egri, R., Lichtenstein, A. and Chase, S. (1996). “Field Evaluation of a Wireless Global Bridge Evaluation and Monitoring System.” Proceedings of the 11th Conference on Engineering Mechanics, Fort Lauderdale, FL, Vol. 2, 955–958.
5. Straser, E. G. and Kiremidjian, A. S. (1998). “A Modular, Wireless Damage Monitoring System for Structures,” Technical Report 128, John A. Blume Earthquake Engineering Center, Stanford University, Stanford, CA.
6. Galbreath, J. H., Townsend, C. P., Mundell, S. W., Hamel, M. J., Esser, B., Huston, D., and Arms, S. W. (2003). “Civil Structure Strain Monitoring with Power-efficient, High-speed Wireless Sensor Networks,” in Proceedings of the 4th International Workshop on Structural Health Monitoring, Stanford, CA, September 15–17, 1215–1222.
7. Binns, J. (2004). “Bridge Sensor System Delivers Results Quickly,” Civil Engineering, Vol. 74, No. 9, 30–31.

8. Lynch, J.P. and Loh, K.J. (2006). "A Summary Review of Wireless Sensors and Sensor Networks for Structural Health Monitoring." The Shock and Vibration Digest, 38(2): 91-128.
9. Kim, S., Pakzad, S.N., Culler, D., Demmel, J.,Fenves, G.L., Glaser, S. and Turon, M. (2007). "Health Monitoring of Civil Infrastructures Using Wireless Sensor Networks." Proceedings of the 6th International Conference on Information Processing in Sensor Networks (IPSN 2007), Cambridge, MA.
10. Kottapalli, V. A., Kiremidjian, A. S., Lynch, J. P., Carryer, E., Kenny, T.W., Law, K. H., and Lei, Y. (2003). "Two-tiered Wireless Sensor Network Architecture for Structural Health Monitoring," in Smart Structures and Materials, San Diego, CA, March 3–6, Proceedings of the SPIE, Vol. 5057, 8–19.
11. Aoki, S., Fujino, Y., and Abe, M. (2003). "Intelligent Bridge Maintenance System Using MEMS and Network Technology," in Smart Systems and NDE for Civil Infrastructures, San Diego, CA, March 3–6, Proceedings of the SPIE, Vol. 5057, 37–42.
12. Basheer, M. R., Rao, V., and Derriso, M. (2003). "Self-organizing Wireless Sensor Networks for Structural Health Monitoring," in Proceedings of the 4th International Workshop on Structural Health Monitoring, Stanford, CA, September 15–17, 1193–1206.
13. Mastroleon, L., Kiremidjian, A. S., Carryer, E., and Law, K. H. (2004). "Design of a New Powerefficient Wireless Sensor System for Structural Health Monitoring," in Non-destructive Detection and Measurement for Homeland Security II, San Diego, CA, March 16–17, Proceedings of the SPIE, Vol. 5395, 51–60.
14. 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 Operational Power Efficiency," Smart Materials and Structures, Vol. 13, No. 4, 800–810.
15. Wang, Y., Lynch, J. P., and Law, K. H. (2005). "Wireless Structural Sensors Using Reliable Communication Protocols for Data Acquisition and Interrogation," in Proceedings of the 23rd International Modal Analysis Conference (IMAC XXIII), Orlando, FL, January 31 – February 3.
16. Rice, J.A., Mechitov, K.A., Spencer, B.F. and Agha, G.A. (2008). "A Service-Oriented Architecture for Structural Health Monitoring using Smart Sensors." Proceedings of the 14th World Conference on Earthquake Engineering, October 12-17, 2008, Beijing, China.
17. Zi Wang, Shamim N. Pakzad, and Liang Cheng, "Sandwich node architecture for task preemption in wireless sensor networks for structural health monitoring applications." Proceedings of the 8th International Workshop on Structural Health Monitoring, September 13-15, 2011. Stanford University, Standford, CA.