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#### Abstract

This paper presents the results of international cooperative researches on smart wireless sensors and SHM of civil structures among KAIST, the University of Michigan, and the University of Illinois at Urbana-Champaign. At first, the state-of-art in the smart wireless sensor technology is reviewed. The subsystems of a smart wireless sensor are discussed, and available wireless sensor platforms developed in the academia and industries are reviewed. Then three smart wireless SHM systems developed by the present authors are applied to SHM of various types of civil structures in this study. The first example is a distributed modal identification system using a smart wireless sensor platform, which is applied to the modal identification of a balcony structure in a historic theatre. The second one is a low-cost and autonomous wireless tension estimation system for cable-stayed bridges, which is employed for modal identification and tension estimation of a stay cable. The last one is an autonomous decentralized SHM system, which is applied to damage detection on a 3-D steel truss structure.

Keywords: smart wireless sensor, wireless sensor network, structural health monitoring, modal identification, damage detection

## 1. Introduction

The civil structures are often exposed to severe loadings during their lifetime, especially at extreme events like earthquake and typhoon, which causes serious concerns on the integrity of the structures that is closely related to the public safety. Tragic disasters on the civil structures, like collapses of bridges or buildings, often accompany a large number of casualties as well as social and economic problems, thus most of the industrialized countries are on the verge of increasing their budget for structural health monitoring (SHM) of their major civil infrastructures. The SHM system often offers an opportunity to reduce the cost for the maintenance, repair, and retrofit throughout the life-cycle of the structure.

In the conventional SHM system, the expensive cost for purchase and installation of the SHM system components,

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such as sensors, data loggers, computers, and connecting cables, is a big obstruction. To guarantee that measurement data are reliably collected, SHM systems generally employ coaxial wires for communication between sensors and the repository. However, the installation of coaxial wires in structures is generally very expensive and laborintensive. For example, it was reported that a SHM system installed in a tall buildings generally cost in excess of \$US5000 per sensing channel (Celebi, 2002). As SHM systems grow in size (as defined by the total number of sensors), to assess the current status of the structure accurately, the cost of the monitoring system can grow much faster than at a linear rate. For example, the cost of installing about 350 sensing channels on Tsing Ma Suspension Bridge in Hong Kong was estimated to have exceeded \$8 million (Farrar, 2001). If the maintenance cost of the SHM system, which will be increased as the system gets older, is also considered, the total cost may be increased exponentially. This limitation on economical realization of SHM system may prevent installation of large number of sensors enough to assess the accurate status of a large civil structure, if the big budget for the SHM system is not secured.

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Recently, smart wireless sensor has been considered as

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an alternative tool for economical and accurate realization of structural health monitoring system. Smart wireless sensor is an emerging sensor with the following essential features: on-board micro-processor, sensing capability, wireless communication, battery powered, and low cost (Nagayama, 2007). When many sensors are implemented on a SHM system for a sizable civil structure, wireless communication between sensors and data repository seems to be attractive in the aspects of the cost. Dense arrays of low-cost smart wireless sensors have the potential to improve the quality of the SHM dramatically using their onboard computational and wireless communication capabilities. These wireless sensors provide rich information which SHM algorithms can utilize to detect, locate, and assess structural damage caused by severe loading events and by progressive environmental deterioration as well as economical realization of SHM system. Information from densely instrumented structures is expected to result in the deeper insight into the physical state of the structural system.

This paper presents the results of international cooperative researches on smart wireless sensors and SHM of civil structures among KAIST, the University of Michigan, and the University of Illinois at Urbana-Champaign. At first, the state-of-art in the smart wireless sensor technology is reviewed. The subsystems of a smart wireless sensor are discussed, and available wireless sensor platforms developed in the academia and industries are reviewed. Then three smart wireless SHM systems developed by the present authors are applied to SHM of various types of civil structures in this study. The first example is a distributed modal identification system using a smart wireless sensor platform, WiMMS, developed by Zimmerman and Lynch (Zimmerman et al., 2008). The system is applied to the modal identification of a balcony structure in a historic theatre. The second one is a low-cost and autonomous wireless tension estimation system for cable stayed bridges using WiMMS (Cho et al., 2008). Modal identification and cable tension estimation have been carried out on a stay cable at a laboratory. The last one is an autonomous decentralized SHM system, which consists of (1) Imote2, a commercial wireless sensor platform developed by Intel and available from Crossbow, (2) middleware services for time synchronization and hardware/ software interaction, (3) a distributed computing strategy using a hierarchical network topology, and (4) a stochastic damage locating vector method. This system has been developed by Spencer's group at University of Illinois at Urbana-Champaign (Nagayama et al., 2007, Nagayama et al., 2008). Validation test have been carried out for damage detection on a 3-D steel truss structure.

### 2. Smart Wireless Sensor Technology

### 2.1. Subsystems of smart wireless sensor

Generally, a smart wireless sensor is composed of three or four functional subsystems; such as sensing interface, computational core, wireless transceiver, and for some, an actuation interface (Lynch, 2006). The sensing interface includes an interface to which sensors can be connected and an analog-to-digital converter (ADC). The computational core generally consists of a microcontroller for the computational tasks, a random access memory (RAM) to stack the measured and processed data, and a flash memory with software programs for the system operation and data processing. The wireless transceiver is an integral component of the wireless system, which is composed of a RF radio modem and antenna to communicate the processing information with other wireless sensors and to transfer the processed data to a remote data server.

When a structure is monitored using a smart wireless sensor, the performance and functionality of each subsystem must be carefully selected considering the structural type, quantities to monitor, sensor locations, and environment of the structure. For a case of vibration-based monitoring algorithm, an ADC with 16-bit or higher conversion resolution is preferred due to small amplitudes of the vibration signals, and the wireless transceiver must have enough transmission range for stable wireless communication. If the embedded software requires long-time history data and high computational power, the microcontroller and peripheral RAM must have large data bus and memory space. For acoustic or ultrasonic NDE, high sampling capability of the ADC is required.

### 2.2. Available smart wireless sensor platforms

As interest in the smart wireless sensors is increasing in the civil, mechanical, and aerospace engineering fields, a number of smart wireless sensor platforms have been developed in academia and industries as shown in Figure 1. Straser and Kiremidjian (1998) first proposed a design of a low-cost wireless modular monitoring system (WiMMS) for civil structures by integrating a microcontroller with a wireless radio. Lynch et al. (2001) have improved the WiMMS with emphasizing the power of the computational core. The WiMMS platform has been improved further by Wang et al. (2005) with implementing a software which allows multiple threads (e.g. processing or trasmitting data while collecting data) to be executed simultaneously to fully utilize the computational power of the wireless sensor. Aoki et al. (2003) have proposed remote intelligent monitoring system (RIMS) designed for the purpose of SHM of bridges and infrastructures. The RIMS employs high-clock microcontroller, 3-axis MEMS piezoresistive accelerometer, and internet-based wireless modem to control the system via ethernet protocol. Chung et al. (2004) have developed a wireless sensor platform (DuraNode) for monitoring of bridges and buildings. DuraNode has a special feature in addition to the wireless sensor platforms, which also enables the wired internet data communication for building structures with an established Local Area Network (LAN). Farrar and Allen (2005) have developed a smart wireless sensor platform, called Husky, which performs a series of damage detection algorithms by



(a) WiMMS (Straser et al., 1998)



(d) RIMS (Aoki et al., 2003)



(g) MICA2 Mote (Crossbow)



(b) WiMMS (Lynch et al., 2001)



(e) Husky (Farrar et al., 2005)





(c) WiMMS (Wang et al., 2005)



(f) DuraNode (Chung et al., 2004)



(i) Imote2 (Intel)

bow) (h) Imote (Intel) Figure 1. Various smart wireless sensor platforms.

interacting with a damage detection algorithm package (DIAMOND II) written in Java.

Besides the smart wireless sensor platforms developed in the academia, a number of commercial smart wireless sensor platforms have been also developed for SHM applications in the industies. Mote, which is initially developed at the University of California-Berkeley and subsequently commercialized by Crossbow (Zhao and Guibas, 2004), may be the most famous commercialized platform. The major reason of Mote's popularity is that it is an open source wireless sensor platform with both its hardware and software (TinyOS) designed available to the public (Lynch et al., 2006). Mote has been successively revised to Imote and Imote2 by Intel. The Imote2 may be the most powerful and promising smart wireless sensor platform built with 32 bit XScale processor with a RAM of 32 MB and a flash memory of 32 MB, and an integrated radio with a built-in 2.4 GHz antenna (Crossbow, 2008).

Recently, Nagayama and Spencer (2008) have been working on the realization of monitoring and autonomous performance evaluation of full-scale bridges using a network of Imote2s. A new sensor board for Imote2 that is tailored to the requirements of SHM applications has been designed (Rice *et al.*, 2008a), and an open-source software library for SHM applications of Imote2, Illinois SHM Services Toolkit (<u>http://shm.cs.uiuc.edu/software.html</u>), has been developed with a service oriented architecture to allow easy implementation of SHM algorithms on smart sensor networks (Nagayama *et al.*, 2008 and Rice *et al.*, 2008b).

For more detailed information on the smart wireless sensor platforms, it is recommended to refer the papers by Lynch *et al* (2006 and 2007).

## 3. Applications of Smart Wireless Sensor to Shm of Civil Structures

# 3.1. Distributed modal identification using a WiMMS 3.1.1. Distributed modal identification scheme

The extraction of the modal information, such as modal frequencies and mode shapes, from sensor data is very important for the assessment of the structural performance and the calibration of the analytical design model. In an attempt to merge the modal identification methods into a state of the art wireless sensing paradigm, the peak picking (PP) method and the frequency domain decomposition (FDD: Brinker *et al.*, 2001) technique is modified for use within a distributed (i.e. decentralized) wireless sensing network (Zimmerman *et al.*, 2008).

The PP method is relatively easy to decentralize and

implement in a wireless sensing network. First, an acceleration time history data is collected at each sensor node and converted to a frequency response function (FRF) using the embedded fast Fourier transform (FFT) algorithm. Each node then picks the largest peaks from its FRF by scanning for frequencies at which the value of the FRF is significantly and consistently higher than the values of the FRF at surrounding frequencies. By tabulating the periodicity at which a given frequency has been picked by sensor nodes on the network, the central node in the wireless sensor network can infer a subset of reasonable modal frequencies from the original PP data without losing modal informations due to possible positioning of sensors at the nodal points of the structure.

For a wireless network of sensors with a limited size of memory capacity as WiMMS, an alternative decentralized FDD is developed (Zimmerman *et al.*, 2008). At first, a set of acceleration time history data giving consistent natural frequencies are collected for each sensor node, and the embedded PP algorithm is employed to look for the system-wide natural frequencies. Once the results have been shared among the nodes in the network, every node transmits its FFT results to the next node in a predetermined chain to construct a power spectral density (PSD) matrix for two nodes at each natural frequency. After performing singular value decompositions (SVD) on all of the PSD matrices with two degree of freedom, a set of two-node mode shapes can be extracted at each natural frequency. Finally, all of the two-node mode shapes are transmitted to the central node, where they are combined to form the full mode shapes of the global system.

### 3.1.2. Experimental structure and results

A historic theatre, located in the southeastern Michigan in the US, was selected as a test structure to validate the embedded decentralized algorithms using a wireless sensor network. The front section of the main balcony was instrumented using the WiMMS units (Wang *et al.*, 2005). Twenty-one units were installed in a seven-bythree grid, with seven units distributed evenly across the span of the balcony in each of rows 1, 3, and 5 as shown in Fig. 2. Attached to each wireless unit was either a PCB Piezotronics 3801D1FB3G capacitive accelerometer or a Crossbow CXL02LF1Z capacitive accelerometer oriented to monitor the vertical acceleration of the balcony.

A set of fifteen nearly identical tests were carried out using impulse loadings generated by a single person (weighing 82 kg) performing a heel drop. The objective of the tests was to validate the performance of the proposed distributed identification methods for modal frequencies and mode shapes using the embedded



Figure 2. 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 3. Results of embedded modal identification technique determined by in-network data processing.

		Natural Frequency (Hz)				MAC			
Method	Run #	Mode 1	Mode 2	Mode 3	Mode 4	Mode 1	Mode 2	Mode 3	Mode 4
Centralized FDD (off-line)	1	2.734	4.163	6.335	7.946	1.000	1.000	1.000	1.000
Peak Picking (embedded)	2	2.727	4.210	6.349	7.996	-	0.949	0.937	0.779
	3	2.734	4.135	6.342	8.020	0.825	0.678	0.427	0.817
	4	2.772	4.144	6.396	7.929	0.990	0.973	0.869	0.944
Decentralized FDD (embedded)	5	-	-	-	-	0.957	0.985	0.961	0.840
	6	-	-	-	-	0.988	0.943	0.821	0.373
	7	-	-	-	-	0.994	0.984	0.630	0.960

Table 1. Summary of modal identification results obtained using embedded methods

processing capabilities residing on a spatially distributed network of wireless sensor nodes. The results obtained from the present method are shown in Fig. 3 and Table 1, and compared with the results from an offline centralized FDD analysis. It can be seen that the proposed embedded methods yield the modal parameters very comparable to those obtained using the traditional offline analysis.

# 3.2. Estimation of cable tension force using a WiMMS 3.2.1. Wireless tension force estimation system for cable structures

Cable tension force is one of the most important structural parameters for the SHM of cable-stayed bridges during construction and operation. In this study, smart wireless sensor technology is combined with a vibrationbased tension force estimation method (Kim *et al.*, 2007). A low-cost and automated wireless tension force estimation system (WTFES) is developed. The hardware consists of a smart wireless sensor (WiMMS) developed by Wang *et al.* (2005), a commercial MEMS accelerometer to measure the acceleration time-history of a stay cable, and a signal conditioning circuit with three primary functions; signal amplification, mean-shifting, and antialias (band-pass) filtering. The WiMMS is composed of a multi-channel 16-bit analog-to-digital converter (ADC), a 8-bit microcontroller, a 128 kB memory, and a 900 MHz wireless transceiver. The cable tension is estimated using the vibration-based method developed by Zui *et al.* (1996), which consists of 7 formulas relating the natural frequencies to the cable tension force under various sagging conditions. The formulas are embedded onto the computational core of the smart wireless sensor. To extract natural frequencies from the measured acceleration data without human intervention, an automated peak picking algorithm is also developed with consideration of typical properties of the natural frequencies of cables (Cho *et al.*, 2008).

### 3.3.2. Validation test and results

To validate the proposed automated wireless tension force estimation system, a series of laboratory tests were carried out on a cable installed at a laboratory as shown in Fig. 4. Tests were performed for 10 different cable tension forces with corresponding cable sags. The tension forces of the cable in the tests were measured by a strain gauge installed at the lower end of the cable to be used as the references of the tension force estimation. Impact loads were applied at arbitrary locations on the cable. Acceleration time-histories were captured by 3 MEMS accelerometers installed at different locations on the cable



Figure 4. Experimental setup for a stay cable and sensor locations.



Figure 5. Fourier spectra of accelerations at different sensor locations and natural frequencies obtained by a peak picking algorithm.



Figure 6. Comparison of the estimated tension forces by WTFES with those measured by stain gauge.

as shown in Fig. 4. The sampling frequency was 50 Hz, and the duration of each record is about 80 sec.

Figure 5 shows example Fourier spectra of the accelerations at 3 sensor locations along with the natural frequencies obtained by the peak picking algorithm. It is shown that the estimated natural frequencies by the automated peak picking algorithm exactly match to the large peaks inferred as the natural frequencies of the cable. The estimated tension forces from the tests were compared with the measured tension forces using the strain gauge in Fig. 6. It can be found that all the estimated tension forces are in excellent agreement with the real values measured by the strain gauges.

# 3.3. Autonomous decentralized SHM system using Imote2

# 3.3.1. Distributed computing strategy and system development

An autonomous decentralized SHM system has been developed based upon the distributed computing strategy (DCS) proposed by Gao and Spencer (2008). The DCS prescribes a distributed implementation of vibration-based damage detection algorithms. The present SHM system utilizes Imote2 hardware (Crossbow, 2008), TinyOS (Levis *et al.*, 2005), middleware services (Nagayama *et al.*, 2008), a hierarchical network topology, and a newly developed damage detection algorithm (Nagayama *et al.*, 2007). Imote2s were programmed to form a hierarchical network consisting of a manager node, cluster head nodes, and leaf nodes (see Fig. 7). One of the nodes in each cluster is assigned as the cluster head, which organizes communication and data processing within the community. In addition, the cluster head communicates with the other cluster heads of the neighboring communities.

The programmed operations are summarized Fig. 8. At the beginning, all the necessary parameters such as node ID, sensor installation directions, and sampling duration are input to the network from the base station and forwarded to the leaf nodes through the manager node. All the Imote2s participate in time synchronization using the corresponding middleware service. Using precise timestamps of samples, the Imote2s apply resampling on the measured data to obtain the synchronized measurement data accurately. Then correlation functions are estimated from the synchronized data in a distributed manner employing the model-based data aggregation (Nagayama et al., 2005, Nagayama et al., 2008). The cluster head multicasts its own measurement data as the reference signal to the leaf nodes. All the member nodes estimate correlation functions between the reference signal and their own data. The correlation functions are then collected at the cluster heads and further processed for the free vibration characteristics using the natural excitation technique (NExT: James et al., 1993). The cluster heads perform the modal identification and damage localization employing eigensystem realization algorithm (ERA) and stochastic damage locating vector (SDLV) method. In the SDLV method, the damage is localized by detecting a member of which the normalized accumulated stress becomes below the predetermined threshold value. The SDLV damage detection results of the adjacent clusters are then shared among their respective cluster heads to evaluate the damage. The clusters overlap so that each structural element is shared by more than one cluster. If neighboring cluster heads in the clusters sharing the damaged element consistently locate the damage, then the



Figure 7. System architecture.

damage detection results are reported to the base station and the cluster heads switch to sleep mode. If the results are inconsistent, the damage detection process is repeated.

### 3.3.2. Experimental verification

This implementation has been experimentally verified on a three-dimensional truss structure located in the Smart Structures Laboratory at the University of Illinois at Urbana-Champaign as shown in Fig. 9a (SSTL- <u>http://sstl.cee.uiuc.edu</u>). The truss is excited vertically with a 100-Hz band-limited white noise excitation at Node 17 using a magnetic shaker. Ten Imote2s are mounted at Nodes 2-11 on the left size of the truss to measure the accelerations in three directions. Six Imote2s mounted on six front panel nodes of two consecutive bays of the truss constitute a local sensor community, or a cluster, that monitors structural damage within the bays: for instance, Nodes 2-7 for Community 1. Ten Imote2s in total make three overlapping sensor communities as shown in Fig. 9b.

A horizontal element numbered '8' on the lower cord is replaced with an element of 52.7% reduced cross-section to simulate damage to the truss. Model-based data aggregation is then performed in each cluster to estimate correlation functions in a distributed manner. The modal parameters identified from the correlation functions



Figure 8. Implementation flow chart.

before and after the element replacement are input into the SDLV algorithm to locate the simulated damage. Fig. 10 shows the normalized accumulated stress calculated by three adjacent cluster heads. The Imote2s in two local sensor communities (1 and 2) successfully detected Element 8 as damaged, indicated by a normalized accumulated stress below the predetermined threshold.

Upon completing calculation of the normalized accumulated stresses, the three cluster heads exchange their damage detection results to assess whether consensus has been achieved. Because consistency is reported on Element 8, the results are reported to the base station. Autonomous judgment on damage elements among cluster heads is thus materialized and experimentally verified.

## 4. Concluding Remarks

This paper presents a review of the current state-of-art in the smart wireless sensor technology. The subsystems of a smart wireless sensor are discussed, and available wireless sensor platforms developed in the academia and industries are reviewed. Then three smart wireless SHM systems developed by the present authors are applied to SHM of various types of civil structures in this study.

The first example is a distributed modal identification system using a smart wireless sensor platform, WiMMS, in which a decentralized FDD is developed for a wireless



(a) 3-D truss structure

(b) Nodes, elements, and local sensor communities: Sensors at Nodes 2-11

Figure 9. Experimental setup for a 3-D truss and locations for sensors and excitation.



Figure 10. Accumulated normalized stress on each truss element.

sensor network with a limited memory capacity. The system has been successfully applied to the modal identification of a balcony structure in a historic theatre. The second one is a low-cost and autonomous wireless tension estimation system for cable stayed bridges using the same WiMMS. Validation of the system has been successfully carried out for modal identification and cable tension estimation on a stay cable at a laboratory. The last one is an autonomous decentralized SHM system, which consists of (1) Imote2, a commercial wireless sensor platform developed by Intel and available from Crossbow, (2) middleware services for time synchronization and hardware/software interaction, (3) a distributed computing strategy using a hierarchical network topology, and (4) a stochastic damage locating vector method. Validation test has been carried out on a 3D steel truss structure.

Though the smart wireless sensor technology has been rapidly improving, there still remain serious limitations in hardware, software, and energy supply technology. Hardware issues to be improved may be wireless communication range, data transmission rate, and highfrequency sampling capability. However, it is expected that hardware problems may be solved relatively fast owing to the speedy advance of electronics technology. Software technology for the full utilization of the hardware and for the complete assessment of structural health has been progressing slower than the hardware technology. It requires multidisciplinary researches among the engineers in civil, mechanical, electrical, and computer science engineering to facilitate the software developments for wireless SHM. The battery technology is improving much slower than the others. Many researchers are currently working for increasing the battery life, such as optimized wireless sensor network to reduce power consumption, improved wireless communication technology, and energy harvesting. Therefore, further technological improvements are still required for the smart wireless sensor technology in order to become an economical and reliable tool for SHM of large and complex structural systems.

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