Structural Health Monitoring Using Wireless Smart Sensor Networks for a Cable-stayed Bridge

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Structural health monitoring (SHM) using wireless smart sensor networks (WSSNs) has been recently received considerable public attention in the field of civil engineering. WSSNs have several attractive features such as on-board computational and wireless communication capabilities, so that the SHM system based on WSSNs can be low-cost, easy to install, and provide effective data management. In this study, WSSNs are realized using a dense array of smart wireless sensor nodes to construct a long-term SHM testbed on an in-service cable-stayed bridge located in Korea (i.e., the second Jindo Bridge). They consist of Imote2s, which are the most recent mote platforms developed by Intel and available at Crossbow, a custom-designed multi-metric sensor boards, base stations, and software provided by the Illinois Structural Health Monitoring Project (ISHMP) Services Toolsuite. In total, 70 wireless smart sensor nodes and two base stations have been deployed to capture the vibration of the bridge excited by traffic and wind loadings. A series of data analyses are performed in both of time and frequency domains. Modal properties of the bridge are identified based on the output-only measurements, and the results are compared with those obtained from the finite element model. It is demonstrated that the proposed WSSNs perform very effectively for SHM of the cable-stayed bridge.

Keywords: Wireless Smart Sensor Network, Structural Health Monitoring, Cable-stayed Bridge, Full-scale Implementation

1 Introduction

The interest in the aging of civil infrastructural systems (e.g., bridges, buildings, pipelines and offshore structures, etc.) in industrialized nations has been increased, because many of them have reached their design life. In order to remain in service, they need to be repaired, retrofitted or replaced. Structural health monitoring (SHM) technology, which provides the means for capturing structural response and assessing structural conditions, can play a key role in increasing their service life, resulting in the considerable research attention to SHM. To date, many SHM systems have been developed, and some of them have been implemented on the full-scale infrastructure, mainly in bridges. However, the cost of...
obtaining the relevant information for SHM on large structures is high (Rice and Spencer 2009). For example, it has been reported that the Bill Emerson Memorial Bridge in USA is instrumented with 84 wired accelerometers with an average cost of over $15K per channel (Celebi 2002), and Tsing Ma Bridge in Hong Kong with more than 600 sensors with an average cost of over $27K per channel (Farrar 2001). If expensive cost of data acquisition systems, such as corresponding signal conditioner, analog filter, and amplifier for each type of sensor, and maintenance cost are additionally considered, then the total cost of a SHM system becomes higher. This high cost is the obstacle to spread the SHM system more widely.

Recently, wireless smart sensors are getting more attention in the field of SHM because they could offer a solution for long-term, scalable SHM of civil infrastructure. They have several distinctive features, which set them apart from traditional wired monitoring systems, such as wireless communication and on-board computing capabilities, resulting in the several merits (e.g., easier installation and efficient data management at a lower cost than traditional wired systems). These features and merits of wireless smart sensors make the scalability of the SHM system to a large network for civil infrastructure possible. Therefore, the evolution of SHM research has shifted away from traditional wired monitoring schemes to wireless smart sensor-based monitoring systems. However, there are several critical issues for realizing the long-term SHM system based on wireless smart sensor networks (WSSNs) to be addressed. This paper presents the deployment and evaluation of a wireless smart sensor system at the second Jindo Bridge. This effort is part of an international collaboration between the USA (University of Illinois at Urbana-Champaign), South Korea (Korean Advanced Institute of Science and Technology (KAIST)), and Japan (University of Tokyo). In this paper, the hardware and software for full-scale deployment are introduced as well as their performance.

2 Wireless Smart Sensor System

2.1 Hardware

The basic configuration of the wireless smart sensor node is an Imote2 with a multi-scale sensing board and a battery board. As the Imote2 has Intel’s PXA271 XScale® processor running at 13-416 MHz and an MMX DSP Coprocessor (Crossbow 2007), it is known as high-performance wireless smart sensor platform. In addition, the imote2 has sufficiently large size of memory for longer measurement as well as on-board computation reaching 256kB SRAM, 32MB FLASH, and 32MB SDRAM.

The multi-scale sensor board that is called SHM-A sensor board, has been designed for monitoring civil infrastructure through the Illinois SHM Project (ISHMP) for monitoring civil infrastructure and is compatible with Imote2 through two basic connectors. This sensor board is capable of capturing 3-axis acceleration, temperature, humidity, light, and external input voltage between 0-3.3V as shown in Figure 1. There developed another board called SHM-W to monitor the wind environment, which is one of the most critical factors that affect the bridge responses and condition in Korea by modifying the SHM-A board to have three external 0-5V input channels to be interfaced with a 3-D ultrasonic anemometer as shown in Figure 1(c).
2.2 Software

In order to acquire and process the sensing data, the software tool suite has been developed. The tool suite (http://shm.cs.uiuc.edu) has been developed by ISHMP to help the civil engineers easily code into the wireless smart sensor nodes (http://shm.cs.uiuc.edu). The tool suite, called ISHMP Services Tool suite, contains basic middleware to provide high-quality sensor data and to transfer the data reliably to the base station via wireless communication as well as a library of numerical algorithms. The tool suite components are categorized into foundation services, tools and utilities, application services, and continuous and autonomous monitoring services. The foundation services provide the fundamental functionalities to measure synchronized sensor data with high confidence (Mechitov et al., 2004). The application services are the numerical algorithms to implement SHM applications on the Imote2, including modal identification and damage detection algorithms. The tools and utilities support network maintenance and debugging. This category has essential services for full-scale monitoring as well as sensor maintenance. Several key services will be explained here: RemoteSensing is the application for the remote data measurement; DecentralizedDataAggregation is the application for remote data measurement and subsequent decentralized on-board computation of the correlation functions of measured data in localized clusters. Imote2Comm is a terminal to interact with a gateway node; RemoteVbat is an application for checking the battery level of remote sensors; and TestRadio is the tool for assessing radio communication quality.

3 Sensor Deployment

3.1 Test-bed

The Jindo Bridges are twin cable-stayed bridges connecting Haenam (a city on the mainland of Korea) with the Jindo Island as shown in Figure 2. Each of these bridges consists of a 344-m main span and two 70-m lateral spans. The 2nd Jindo Bridge has a streamlined steel box girder supported by 60 parallel wire strand (PWS) cables. The 2nd Jindo Bridge is selected as the test bed under the permission of unfettered access by the authority because of (i) the existing SHM system to provide the comparable data with measured one by WSSN and (ii) the complete design and construction documents for full interpretation of the bridge.

3.2 Deployment Plan

The developed hardware and software framework has been deployed on the 2nd Jindo Bridge to validate a large-scale and autonomous SHM system. Since the communication range of Imote2 with an external antenna is about 200m shorter than...
the total length of the bridge, the network was divided into two sub-networks so that the Jindo sub-network consists of 33 nodes with 22 nodes on the deck, 3 nodes on the pylon, and 8 nodes on the cables, and The Haenam sub-network consists of 37 nodes with 26 nodes on the deck, 3 nodes on the pylon, and 7 nodes on the cables. A total of 70 leaf nodes were deployed on the bridge including SHM-A sensor boards to measure 3-axis acceleration and SHM-W board to interface with an anemometer. All the sensors are environmentally hardened as depicted in Figure 4.

Figure 3. Sensor locations (Jang et al., 2010)

3.3 Results and Discussion

Figure 5 shows examples of the ambient acceleration data measured on the deck, pylon, and cable in 3 directions. The amplitudes of the acceleration due to traffic load are found to be large enough for mode extraction, especially for vertical modes (z-axis). The power spectral densities (PSD) of the wireless smart sensor vibration data was compared with that from the existing wired monitoring system. It can be said that modal frequencies look very similar at around 0.44, 0.66, 1.05, 1.37Hz and so on. Modal analysis was also carried as in Figure 7. The mode shapes on the left is identified by modal analysis from measured data and right side is FE model analysis.
4 Conclusions

This paper presents the collaborative research among Korea (KAIST), the US (University of Illinois at Urbana-Champaign), and Japan (University of Tokyo). The novelty of wireless smart sensor system has been deployed on a cable-stayed bridge, the 2nd Jindo Bridge, in South Korea to verify the performance of the system along with its components. Hardware and software of wireless smart sensor node are developed for low-cost and efficient monitoring. SHM-A and SHM-W sensor boards were developed to be interfaced with Imote2 to measure 3-axis acceleration and wind. Besides the hardware, operating software for base stations are also developed for autonomous and effective monitoring of large structures has been developed. After the deployment, it is shown that the wireless smart sensor network can be operated autonomously and efficiently with monitoring strategy. The installed system provided a sufficient and sensitive data to be analyzed resulting in a very accurate modal information similar to FE model.

5 Acknowledgements

This research is supported in part by the National Science Foundation Grant CMS 06-00433 (Dr. S.C. Liu, Program Manager), the Natural Research Foundation in Korea (NRF-2008-220-D00117). The support of the Ministry of Land, Transport and Maritime Affairs in Korea, Daewoo Engineering Co. Ltd., and Hyundai Engineering & Construction Co. Ltd. is also gratefully acknowledged.
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