Cover page

Title: Validation of an Integrated Network System for Real-Time Wireless Monitoring of Civil Structures

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ABSTRACT

Wireless structural health monitoring (SHM) systems are becoming a convenient and preferred monitoring technology due in part to the elimination of the installation time and costs often associated with traditional tethered systems. However, many challenges associated with developing wireless SHM systems remain. These technical challenges include restricted power consumption, data fidelity during wireless communication, long communication ranges suitable for civil structures, real-time data acquisition from multiple sensing units under limited communication bandwidth, and difficulty in time synchronization.

This paper presents a new integrated real-time wireless SHM system that addresses some of the technical issues described. The proposed system supports real-time data acquisition from multiple wireless sensing units, which can simultaneously collect and analyze data from a heterogeneous set of analog sensors. Low-cost signal conditioning circuits are incorporated to improve the quality of sensor signals. Each wireless sensing unit employs a specially selected wireless transceiver that consumes relatively low power and supports long-distance peer-to-peer communication. An online service platform is developed to allow remote access and graphical display of sensor data in near real-time. The feasibility and reliability of this integrated wireless SHM network system are corroborated by extensive laboratory and field tests.

INTRODUCTION

As a fast-growing research topic, structural health monitoring (SHM) has shown high potential in ensuring the performance and the safety of civil structures [1-2]. In SHM systems, modern sensing technologies are employed to provide accurate measurement of structural responses due to various excitations. These

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measurement results can then be screened by certain damage identification algorithms in order to diagnose damage in the structure.

The data acquisition (DAQ) infrastructure is a fundamental component of any SHM system that collects structural sensor signals. Traditional DAQ modules are wire-based, connecting the sensors with a central data server by running wires throughout the structure. These wire-based DAQ modules usually suffer from installations defined by high costs and long setup times. Typically, a 12-channel wire-based system may cost about $50,000 in the U.S., with half of the expense associated with its installation [3]. Moreover, the installation of wired systems can consume up to 75% of the total testing time for large structures [4].

Recent developments in wireless technologies introduce exciting opportunities in replacing wire-based DAQ modules with wireless units. In wireless SHM systems, wireless communication is used to replace traditional cable communication; therefore, cable installation can be eliminated or minimized. It has been illustrated by Straser *et al*. that wireless SHM systems have great advantages in saving time and cost over cable installations [4]. Lynch *et al*. further demonstrate that many proposed damage identification algorithms can be embedded into units of the wireless sensing network, thereby substantially reducing power-consuming wireless communication, and improving the scalability of the system [5]. Kottapalli *et al*. propose a two-tiered wireless sensor network topology that addresses power consumption, data rate, and communication range limitations of current wireless SHM systems [6]. Other research efforts have also been proposed in developing various wireless SHM systems [7-9], and a survey of current development of wireless SHM systems is given by Lynch *et al*. [10].

Along with the advantages of wireless SHM systems, there also remain some challenges in applying wireless sensing technologies into SHM systems. One major challenge with the hardware design of a wireless sensing unit is the need to optimize power consumption since most wireless sensing units depend on limited battery power. Because of the reduced reliability of wireless communications, robust communication protocols are important to ensure proper information flow in the wireless sensor network. Communication reliability and limited wireless data transfer rates also pose difficulties in realizing real-time and continuous wireless data acquisition.

In previous research, a prototype wireless SHM system has been proposed to address the above problems [11-13]. This paper reports further extension, improvement, and validation of the prototype system. The paper starts with an overview and key performance summary of the current system. Newly incorporated is an online graphical data accessing platform that allows real-time Internet access to the wireless sensor data. Field validation results at the Geumdang Bridge in Icheon, South Korea are then introduced [14]. Towards solving some signal noise problems that were encountered using MEMS accelerometers, a special signal conditioning Printed Circuit Board (PCB) has been designed and fabricated. Validation tests to this signal conditioning circuit board are also presented.

OVERVIEW OF THE PROTOTYPE WIRELESS SHM SYSTEM

Advances in information and communication technologies have greatly facilitated the improvement of SHM systems. The prototype wireless SHM system is designed to provide accurate data acquisition and integrated online services for a wireless sensor network. An overview of the prototype system is illustrated in Figure 1. Each wireless sensing unit can accommodate four analog sensors measuring structural responses. If desired, the sensor data can easily be processed on-board in the wireless sensing unit [5]. A data server is used to organize and collect data from multiple wireless sensing units in the sensor network. The data server also provides Internet connectivity so that sensor data or desired engineering analysis results can be viewed remotely from other computers over the Internet. As discussed in later sections, a signal conditioning circuit is added to filter, amplify and offset the signals from the analog sensors.

The design of the prototype system has been oriented for a large-scale and low-power wireless SHM application in civil structures. Some of the main features of this wireless SHM system are: i) low power consumption while achieving long communication ranges with robust communication protocols for reliable data acquisition, ii) accurate synchronized wireless data collection from multiple analog sensors at a reasonable sampling rate suitable for civil structural applications, iii) considerable local data processing capability at the wireless sensing units to reduce energy consumption and to enhance system scalability, and iv) accommodation of peer-to-peer communication among wireless sensing units for collaborative decentralized data analysis. Key performance characteristics of the wireless sensing units are summarized in Table 1.

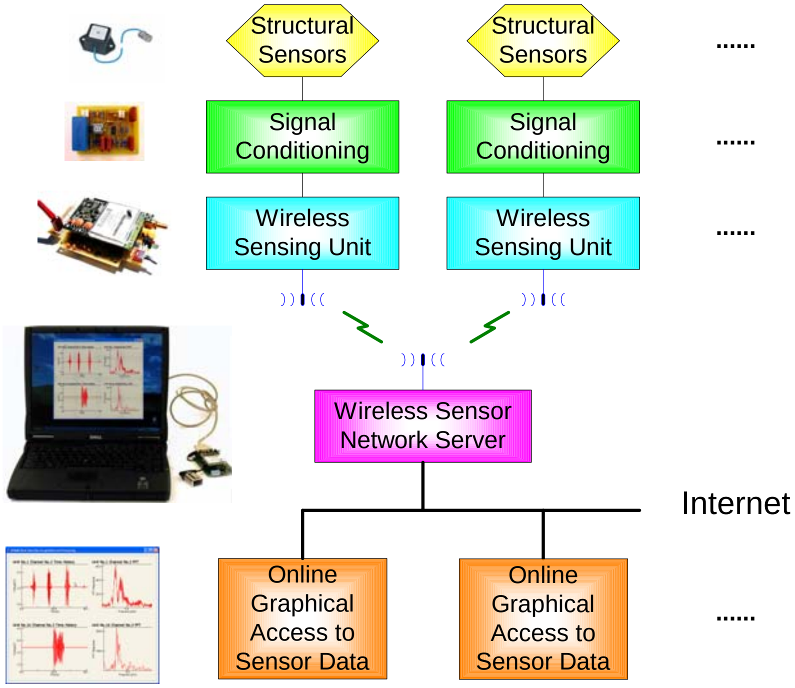


Figure 1. An overview of the prototype wireless SHM system

Table 1. Key characteristics of the wireless sensing unit

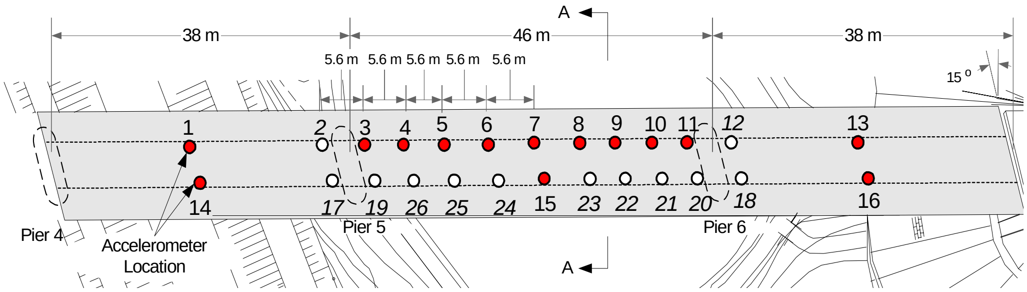
Power Consumption		77mA when active, 100mA when standby (at 5V DC)
Device Size		4.0” x 2.6” x 1.6” (10.2 cm x 6.5 cm x 4.0 cm)
Micro-controller		Atmel ATmega128, 8-bit, 128kB Flash Memory
External SRAM		Cypress CY62128B, 128kB
A/D Converter		Texas Instrument ADS8341, 4-Channel, 16-bit
Wireless Communication With MaxStream 9XCite	*Range*	Up to 300’ (90m) indoor, 1000’ (300m) outdoor
	Transfer Rate	38.4 kbps
	Frequency	902-928 MHz
	Channel Mode	7 channels at Frequency Hopping Spreading Spectrum mode
	Network	Peer-to-peer, broadcast

FIELD VALIDATION TESTS AT GEUMDANG BRIDGE

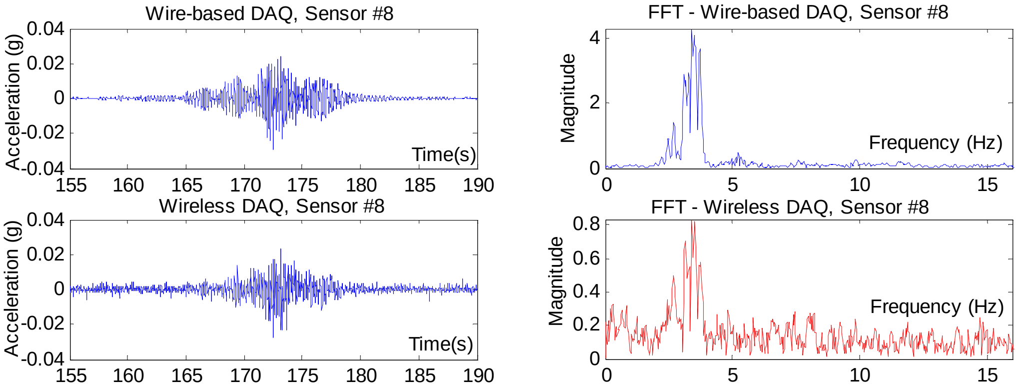
Field validation tests of the prototype wireless SHM system were conducted at Geumdang Bridge in Icheon, South Korea [14]. The Geumdang Bridge, a long-span concrete box girder bridge spanning 122m, is instrumented with two sets of accelerometers attached to both a wired and a wireless monitoring system (Figure 2(a)). Both systems employ accelerometers to measure the vertical acceleration response of the bridge at the 14 solid-dot locations denoted in Figure 2a. The central server (a laptop) of the wireless SHM system is placed at the vicinity of sensor location #9, with a maximum distance of about 60m between the central server and the farthest wireless sensing unit. The piezoelectric accelerometers used by the wire-based monitoring system are PCB393 accelerometers manufactured by PCB Piezotronics. For direct comparison, the wireless monitoring system deploys lower-cost capacitive Piezotronics PCB3801 accelerometers at these locations, with one PCB3801 accelerometer installed side-by-side to each PCB393 accelerometer. PCB393 accelerometers used by the wire-based system have higher sensitivity and lower noise floors; therefore, they are expected to provide better performance than the PCB3801 accelerometers used by the wireless system.

For the wire-based monitoring system, the analog outputs of the PCB393 accelerometers are fed into a 16-channel PCB Piezotronics 481A03 signal conditioning unit. Before being sampled and digitized, the signals are amplified by a factor of 10 using an amplification circuit native to the signal conditioning unit. The wire-based monitoring system is configured to sample the 14 sensor channels at 200Hz. For the wireless monitoring system, the PCB3801 accelerometers are connected directly to the sensing interface of each wireless sensing unit without signal conditioning (the signal conditioning circuit mentioned in the last section was not yet available during the field tests). Due to the limited wireless communication bandwidth and the large number of wireless sensing units that are streaming data simultaneously, the sampling rate of the wireless monitoring system is selected at 70Hz. Over the course of two full days of testing, the designed communication protocol for near-synchronized and continuous real-time data acquisition proves to be highly reliable for the wireless sensor deployment on the bridge structure.

The Geumdang Bridge is kept closed to regular highway traffic while the bridge is excited using trucks of known weight and speed crossing the bridge. Figure 2(b) illustrates the acceleration response of the bridge at sensor location #8 when a 40-ton truck crosses the bridge at 60 km/hr. The figure plots the acceleration time histories collected by the two different systems. There exists a strong one-to-one correspondence in the acceleration response records collected by the two systems. As expected, the acceleration record measured by the wireless monitoring system appears noisier than that collected by the wire-based monitoring system, due to the difference in the accelerometers being used and the signal conditioning in the wired system. The wireless sensing units also perform a 4096-point FFT of the measured acceleration response. The frequency response, as calculated by the wireless sensing unit, is shown in Figure 2(c). If the frequency response is compared to the frequency response calculated off-line using the response data collected by the wire-based monitoring system, the primary response frequency of the bridge can be identified to be 3.6 Hz in both plots. Furthermore, the FFT results from the two systems are very close to each other. The difference in the amplitude of FFT results is mainly caused by the different sampling frequencies used in the two systems.



(a) Plan view showing wired and wireless accelerometers placed for 14 locations



(b) Acceleration data at sensor #8

(c) FFT results at sensor #8

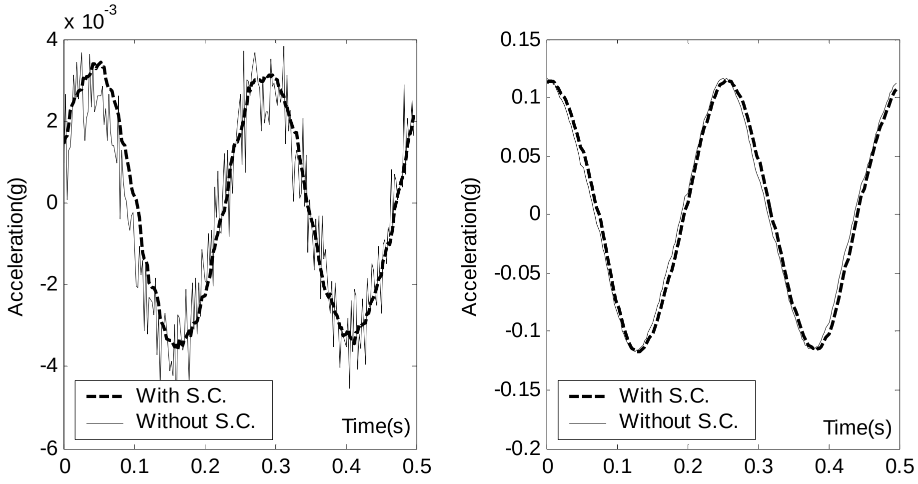
Figure 2. Field validation tests at Geumdang Bridge in Icheon, South Korea

SIGNAL CONDITIONING CIRCUIT DESIGN AND VALIDATION

As shown in the last section, the original sensor signals from the structural response can be weak and noisy. Before feeding these sensor signals into the Analog-to-Digital (A/D) converter of a wireless sensing unit, certain signal conditioning circuits could be used to improve the signal quality. In order to make the prototype wireless SHM system adaptable for noisy sensor signals typical of MEMS accelerometers, a signal conditioning printed circuit board (PCB) has been designed and fabricated. The three major functions of this circuit board are: offsetting, filtering, and amplification.

The reason for offsetting the circuit signal is that the A/D converter of the wireless sensing units takes 0 to 5V input sensor signal. However, this is not always the case for the available sensor signals. For example, some accelerometer signals are 0V when there is no vibration, i.e. the accelerometer signal is fluctuating around 0V when there is vibration. Therefore it is necessary to offset the sensor signal so that the fluctuating signal is within 0 to 5V. In the circuit that has been designed, the conditioned signal is designed to fluctuate around 2.5V, within 0 to 5V. The filtering circuit includes one high-pass filter and one low-pass filter. The high-pass filter is an RC filter with a cut-off frequency of 0.02Hz, and the low-pass filter is a 4-th order Bessel filter with a cut-off frequency of 25Hz. Bessel filter is selected for its property of linear-phase shift in the pass-band frequency range. This linear-phase shift property corresponds to constant time delay for signals in the pass-band, which conserves the waveform in the time domain. The overall amplification of the circuit can be selected by sizing a certain resistor in the circuit. The final PCB circuit board incorporates a 3-position switch, so that three options are provided for the amplification factor (4.9x, 9.5x and 18.5x).

In a validation test of the signal conditioning PCB board, two accelerometers are aligned side-by-side, both measuring the top floor vibration of a 3-story aluminum frame structure located in the laboratory. Signal output from one accelerometer is fed into the A/D converter of a wireless sensing unit directly while



(a) Low vibration amplitude (b) High vibration amplitude

Figure 3. Wireless accelerometer data with and without signal conditioning

the signal from the other accelerometer is fed into the signal conditioning circuit before being sampled by the A/D converter of another wireless sensing unit. For a simple free vibration test, an external force is applied to the top floor of the structure for initial displacement and released. Figure 3(a) presents the sensor data when the vibration amplitude is low, in which case the Signal-to-Noise-Ratio (SNR) is low. It can be observed that the sensor data with signal conditioning is smoother than the data without signal conditioning. Figure 3(b) presents the sensor data when the vibration amplitude is higher. When the SNR is high, the difference between the data collected with and without signal conditioning is almost negligible compared with the signal amplitude.

SUMMARY AND DISCUSSION

This paper presents the design of an integrated software and hardware architecture for a wireless structural health monitoring system. The system supports reliable real-time data collection from wireless sensors with long-range communication in civil structures. An online graphical sensor data access platform has been developed. The implemented prototype system also includes a low-cost signal conditioning PCB board. Both laboratory and field validation tests corroborate the capability and reliability of the prototype system for large-scale deployment in civil structures.

The prototype system can further be improved in a number of areas. With the rapid development in wireless communication technologies, wireless transceivers that support longer communication ranges and higher data rates while consuming less power should be pursued. Improvements can also be made with respect to the embedded software. For example, more advanced communication protocols are needed to organize very-large-scale wireless sensor networks with peer-to-peer connections. Last but not least, additional tests in laboratory and field environment are needed to validate the system, to discover deficiency, and to further refine the design.

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