Wireless Sensing Technologies for Civil Infrastructure Monitoring and Management

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ABSTRACT

Ensuring the safety of civil infrastructures is of utmost importance to society. Research and developments in Structural health monitoring (SHM) systems aim to monitor and to diagnose the conditions of a structure. With recent advances in wireless communication technology, wireless networks can potentially offer a low-cost alternative to traditional cable-based structural monitoring systems. Another advantage of a wireless system is the ease of relocating structural sensors, thus providing a flexible and reconfigurable system architecture. This paper describes the development of a prototype wireless structural sensing system. This integrated hardware and software system is designed and implemented using low-cost off-the-shelf electronic components. Hardware drivers, data streaming protocols, and computational algorithms are embedded in the wireless sensor nodes to provide the basic functionalities for structural monitoring applications. Laboratory and field validation tests have been conducted to illustrate the acquisition, management and processing of high quality sensor data collected by the wireless system.

1. INTRODUCTION

As civil structures are subject to loads and other environmental effects, the condition of many civil infrastructure systems is deteriorating. For example, nearly 42% of the bridges in the United States were reported to be structurally deficient and below established safety standards [1]. To protect the public, current U.S. federal requirements necessitate local transportation authorities to visually inspect the entire inventory of well over 580,000 highway bridges biannually [2]. However, visual inspection can only consider damage that is visible on the surface of the structure and can be highly subjective. A recent study by the U.S. Federal Highway Administration (FHWA) revealed that visual inspections can lead to wide variability on the condition ratings assigned by trained inspectors, even for an intentionally damaged bridge [3]. With visual inspections both costly and labor intensive, low cost sensing systems that can quantitatively assess the integrity and remaining life of a structure are desirable [4]. As a complimentary and promising alternative to visual inspections, structural health monitoring (SHM) systems have been proposed to predict, identify and locate the onset of structural damage [5, 6]. Smart sensor technologies are employed to assist in identifying subtle structural abnormality based on measured structural responses [7].

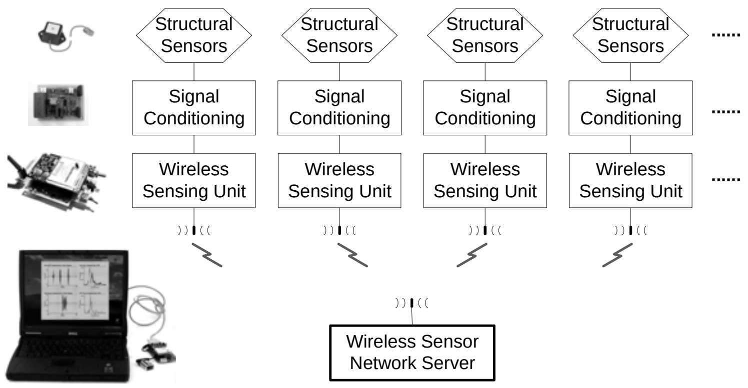
A necessary element of a SHM system is the data acquisition (DAQ) system used to collect sensor measurements. Current commercial DAQ systems typically employ cables to transmit sensor data to the central data repository. Installing extensive lengths of cables can consume over 75% of the total SHM system installation time [8]. In the U.S., the cost of installing a monitoring system in buildings can exceed a few thousand dollars per sensing channel [9]. As structural size grows and the number of sensing nodes rises, the installation cost and time for wired systems increase significantly. For example, the instrumentation of the three major bridges in Hong Kong (Tsing Ma Bridge, Kap Shui Mun Bridge, and Ting Kau Bridge) with over 1000 sensors consumes 36 km of copper cable and 14 km of fiber optic cable, and the installation has taken over a year [10].

Recent developments in microelectromechanical systems (MEMS) and wireless communications have introduced new opportunities to reduce the installation costs of structural monitoring systems [11, 12]. MEMS technology has led to the development of sensors that are low cost, low power, compact, and easy to install. Wireless technology allows for transmitting sensor measurements without the need for cables. The use of wireless communications as a means for eradicating cables within a SHM system has been demonstrated by Straser and Kiremidjian [8]. Lynch et al. [13] explored the concept of embedding data interrogation algorithms directly onto wireless sensing units. Many research efforts in developing wireless sensing platforms for structural health monitoring have been reported [14-23]. A comprehensive review of wireless sensors and their adoption in structural health monitoring has been reported by Lynch and Loh [24].

This paper describes the design, implementation, and validation of a wireless structural sensing system [25-28]. Section 2 introduces the hardware and software design of the wireless sensing units. Hardware modules that provide functionalities for communication, sensing and computing are described. A three-layer software architecture is designed to support the microcontroller peripherals, hardware component drivers and application software routines. Sections 3 to 5 describe a series of validation tests for the wireless structural sensing system. The results from a laboratory test using a 3-story structure and field tests upon two bridge structures are presented. This paper is concluded with a brief summary and discussion in Section 6.

2. DESIGN OF THE WIRELESS SENSING SYSTEM

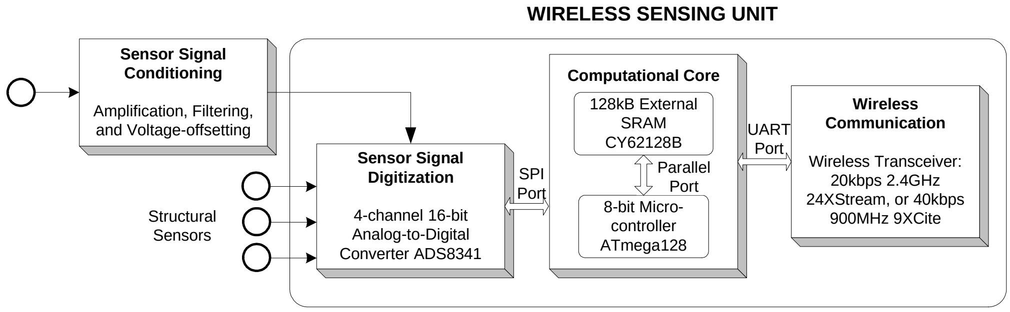
Wireless sensing units are the building blocks of a wireless structural sensing system. For the prototype system, each wireless unit is designed to be able to collect sensor data, communicate with other units, and perform engineering analyses. Through the wireless communication channels, these individual units form a sensing network. As shown in Fig. 1, a simple star-topology network is adopted for the prototype wireless sensing system. The system includes a server and multiple wireless sensing units that interface with structural sensors, signal conditioning modules. Any desktop or laptop computer connected with a compatible wireless transceiver can be used as the server. The server is responsible for: (1) commanding all the corresponding wireless sensing units to perform data collection or interrogation tasks; (2) synchronizing the internal clocks of the wireless sensing units; (3) receiving data or analysis results from the wireless network; and (4) storing the data or results. The server also provides Internet connectivity so that sensor data or analysis results can be viewed remotely from other computers over the Internet. This section describes the hardware components of the wireless sensing unit and the embedded software design for the microcontroller in the wireless unit [25].



<Figure 1> Overview of the prototype wireless structural sensing system

2.1. HARDWARE DESIGN OF THE WIRELESS SENSING UNIT

Fig. 2 shows the overall hardware design of the prototype wireless sensing unit, and an optional off-board signal conditioning module. The basic wireless sensing unit consists of three functional modules: sensor signal digitization, computational core, and wireless communication. The auxiliary sensor signal conditioning module assists in amplifying, filtering, and offsetting analog sensor signals prior to digitization. The sensing interface converts analog sensor signals into digital data which is then transferred to the computational core through a high-speed Serial Peripheral Interface (SPI) port. Besides a low-power 8-bit Atmel ATmega128 microcontroller, external Static Random Access Memory (SRAM) is integrated with the computational core to accommodate local data storage and analysis. The computational core communicates with a wireless transceiver through a Universal Asynchronous Receiver and Transmitter (UART) interface.



<Figure 2> Functional diagram detailing the hardware design of the wireless sensing unit

The prototype wireless sensing unit is judiciously designed for applications in civil structures. Some of the main design objectives are: (1) low power consumption while achieving long communication ranges with robust communication protocols for reliable data acquisition; (2) accurate synchronized wireless data collection from multiple analog sensors at a reasonable sampling rate suitable for civil structural applications; (3) high-precision analog-to-digital conversion; (4) local data processing capability at the wireless sensing units to reduce energy consumption and to enhance system scalability; and (5) peer-to-peer communication among wireless units for collaborative decentralized data analysis. The key parameters of the prototype wireless sensing unit are summarized in Table 1. The rest of this section describe the three functional modules, the signal conditioning module, the power consumption performance, and the hardware packaging of the wireless sensing unit.

Table 1. Key performance parameters of the wireless sensing unit

Design Parameter	**Specification**	
Computing Core		
Microcontroller	8-bit RISC architecture, up to 16MIPS throughput at 16MHz	
Flash Memory	128K bytes	
Internal SRAM	4K bytes	
External SRAM	128K bytes	
EEPROM	4K bytes	
Power Consumption	30mA active, 55µA standby	
Wireless Transmission	*9XCite*	*24XStream*
Operating Frequency	ISM 902-928 MHz	ISM 2.4000 - 2.4835 GHz
Data Transfer Rate	38.4 kbps	19.2 kbps
Communication Range	Up to 300' (90m) indoor, 1000' (300m) at line-of-sight	Up to 600' (180m) indoor, 3 miles (5km) at line-of-sight
Power Consumption	55mA transmitting, 35mA receiving, 20µA standby	150mA transmitting, 80mA receiving, 26µA standby
Sensing Interface		
Sampling Precision and Rate	16bit, Up to 100kHz	
Analog Sensor Channels	4	
Others		
Unit Size	$10.2 \times 6.5 \times 4.0$ cm^3	

2.1.1. SENSOR SIGNAL DIGITIZATION MODULE

The main component of the sensor signal digitization module is a 4-channel 16-bit analog-to-digital (A/D) converter, Texas Instruments ADS8341. Each wireless sensing unit can accommodate signals from up to four analog structural sensors (e.g. accelerometers, velocity meters, strain gages, among others). The 16-bit A/D resolution is sufficient for most applications in structural sensing. One requirement from the ADS8341 A/D converter is that the sensor signal should be between 0 and 5V. The highest sampling rate supported by this A/D converter is 100 kHz, which is much higher than the sampling frequency typically needed for monitoring civil structures. This rate determines that each sampling execution takes only 10 μs. Therefore, the A/D conversion can be finished swiftly through the timer interrupt service of the microcontroller (ATmega128), without disrupting the execution of wireless communication or data processing programs. Continuous wireless sensor data collection can thus be supported by this prototype wireless sensing system.

2.1.2. COMPUTATIONAL CORE

A low-cost 8-bit microcontroller, Atmel ATmega128, is selected as the computational core of the wireless unit. The ATmega128 microcontroller contains 128kB of reprogrammable flash memory for the storage of embedded software, which, based on laboratory and field experiments, is sufficient to incorporate a wide variety of structural monitoring algorithms. The microcontroller also contains 4kB of nonvolatile Electronically Erasable Programmable Read-Only Memory (EEPROM) for data storage. One Serial Peripheral Interface (SPI) and two Universal Asynchronous Receiver and Transmitter (UART) interfaces are provided by the ATmega128 to facilitate communication with other hardware components. The timer and interrupt modules of the ATmega128 are employed for executing routines that need to be precisely timed, e.g. sampling sensor data at specified frequencies.

The microcontroller also contains 4kB Static Random Access Memory (SRAM) for storing stack and heap variables, which as it turns out, is often insufficient for the execution of embedded data interrogation algorithms. To address this issue, an external 128kB memory chip, Cypress CY62128B, is incorporated. Hardware and software procedures are implemented to bypass the 64kB memory address space limitation of the ATmega128, to ensure that the full 128kB address space of the CY62128B can be utilized. The external memory is sufficient for executing many sophisticated damage identification algorithms on a large quantity of sensor data.

2.1.3. WIRELESS COMMUNICATION MODULE

The wireless communication module provides the interface for the unit to exchange data with other wireless units, or a data server with a wireless transceiver attached. Sufficient communication reliability, range, and data transfer rate are needed to employ the wireless units in civil structures. On the other hand, the wireless module, which is the most power-consuming component of a typical wireless sensing unit, should not consume too much battery power while active. Certain trade-offs are necessary to balance the requirements for better performance and for low power consumption. Wireless frequency allocation regulated by the government is another factor that should be considered while selecting wireless transceivers. The wireless sensing unit is designed to be operable with two different wireless transceivers: 900MHz MaxStream 9XCite and 2.4GHz MaxStream 24XStream. Pin-to-pin compatibility between these two wireless transceivers makes it possible for the two modules to share the same hardware connections in the wireless unit. This dual-transceiver support affords the wireless sensing unit to be usable in different countries. The data rate, communication range and power consumption of the two transceivers are provided in Table 1 (see http://www.maxstream.net for details). Both transceivers support peer-to-peer and broadcasting communication modes, which allow flexible information flow in the wireless sensor network.

2.1.4. POWER CONSUMPTION

Power consumption is another important issue to consider when selecting the hardware elements and communication modules of a wireless sensing unit. While power consumption should be minimized, it must not be done at the expense of the functionalities needed by the wireless sensing unit. The power consumed by the wireless sensing unit is a function of the voltage and the amount of electrical current supplied to each component. All the hardware components are internally referenced at 5V. Estimation of the active and standby electrical current for each component of the wireless sensing unit is listed in Table 2. When in active mode, the wireless sensing unit collects, interrogates or wirelessly transmits sensor data. In contrast, the hardware components consume minimal amount of electrical current when they are in standby mode.

Table 2. Approximate current consumption of the wireless sensing unit

Component	Active Current	Standby Current
A/D converter ADS8341 (at 100 Hz)	1mA	1μA
Micro-controller ATmega128 (at 8MHz)	15mA	40μA
SRAM CY62128B	15mA	15μA
Support electronics	1mA	24μA
Complete wireless sensing unit	77mA	100μA

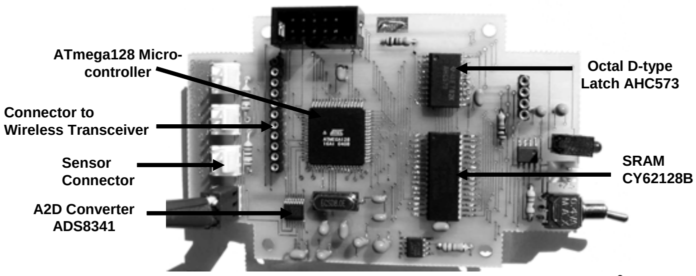
It can be seen that the wireless transceiver consumes the greatest amount of electrical power when active which indicates the importance of minimizing the use of the wireless communication channel as a means of preserving battery energy. Conservative estimations for the power consumption of the wireless units using the 9XCite and 24XStream transceivers are summarized in Table 3. Under fully-active continuous operation, the expected life expectancy, T_{active}, of the sensing unit with five ordinary lithium AA batteries (Energizer L91) lasts about a day. For the standby mode with duty lifecycle usage of the battery allows batteries' life expectancy, $T_{standby}$, to last more than 3 years. If it is assumed that the system is active for 10 minutes each day for data collection and transmission, the life expectancy of the wireless sensing unit, $T_{10\min-\text{active}-\text{per}-\text{day}}$, is estimated to be about half a year. Because of the difference in power consumption and communication range, the life expectancy of a wireless unit with the 24XStream transceiver is shorter than a unit using the 9XCite transceiver.

Table 3. Estimated life expectancy of the wireless sensing unit in days

Life Expectancy	Unit with 9XCite	Unit with 24XStream
T_{active}	1.57	0.82
$T_{standby}$	1208	1140
$T_{10\min-\text{active}-\text{per}-\text{day}}$	190	107
$T_{5\min-\text{active}-\text{per}-\text{day}}$	329	197

2.1.5. UNIT PACKAGING

A simple two-layer printed circuit board (PCB) is designed and fabricated. As shown in Fig. 3(a), the PCB has a dimension of 9.7 × 5.8 cm^2, which may be further reduced using a multi-layer circuit design. Fig. 3(b) shows that the PCB, wireless transceiver, and batteries can be stored within an off-the-shelf weatherproof plastic container, which has a dimension of 10.2 × 6.5 × 4.0 cm^3. Each packaged unit, including the five AA batteries, weighs about 0.38 kg. Each packaged unit acts as an autonomous node capable of collecting, processing, and wirelessly transmitting data to other sensing units and the central server.



(a) PCB of the wireless sensing unit (9.7 × 5.8 cm^2)

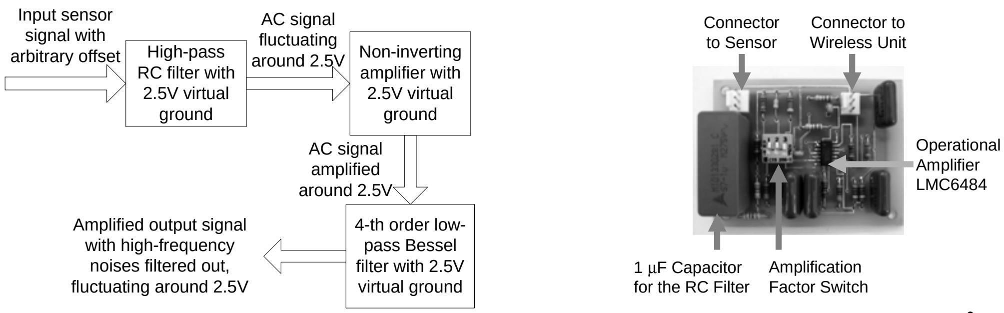

(b) Packaged unit (10.2 × 6.5 × 4.0 cm^3)

<Figure 3> Pictures of the wireless sensing unit

2.1.6. SENSOR SIGNAL CONDITIONING MODULE

For field applications, a wireless sensing system must be capable of recording both ambient and forced vibrations. With ambient vibrations typically defined by small amplitudes, a high-resolution (16-bit or higher) A/D converter is normally needed by a structural sensing system. The placement of the low-cost 16-bit ADS8341 A/D converter leaves the A/D vulnerable to electrical noise present in the circuit. From experimental tests, the effective resolution for the A/D channels is found to be about 13-bit, which is likely insufficient for sampling low-amplitude vibration data. Additionally, for the ADS8341 A/D converter, the sensor signals must be within 0 to 5V. A signal conditioning module is thus designed to amplify signals, filter out noises, and shift sensor signals within range.

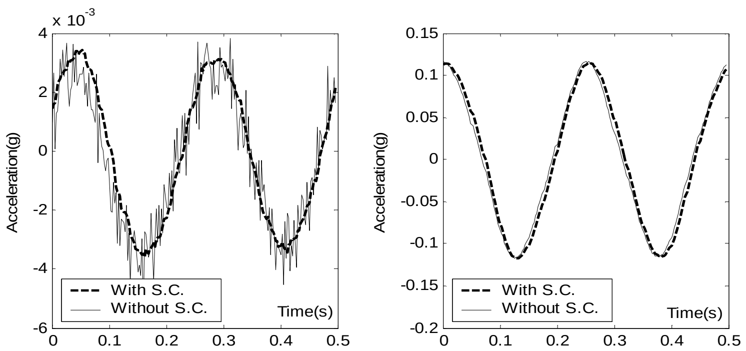
Sensor signals are fed into the signal conditioning module prior to A/D conversion. Fig. 4(a) shows the filtering circuitry that consists of a high-pass resistor-capacitor filter with a cutoff frequency of 0.02Hz and a low-pass fourth-order Bessel filter with a cutoff frequency of 25Hz. The linear-phase shift property of the Bessel filter ensures a constant time delay for signals in the pass band, thus maintaining the signal waveform in the time domain. Fig. 4(b) shows the signal conditioning board that includes hardware components for the filtering, offsetting, and amplification functions.



(a) Functional Diagram of the Circuits (b) PCB board (5.0 × 6.5 cm^2)

<Figure 4> Sensor signal conditioning module

To illustrate, Fig. 5 shows two acceleration time histories measured by two accelerometers placed side by side. The signal from one accelerometer is processed by the signal conditioning module before being fed into the A/D converter, while the signal from the other accelerometer is fed into the A/D converter directly. As shown in Fig. 5(a), when the vibration amplitude is lower (~4mg), in which case the Signal-to-Noise-Ratio (SNR) is low, the sensor data with signal conditioning is much smoother than the data without signal conditioning. When the vibration amplitude is higher (~0.1g), i.e. when the SNR is high, the difference between the data collected with and without signal conditioning is almost negligible with respect to the signal amplitude, as shown in Fig. 5(b).

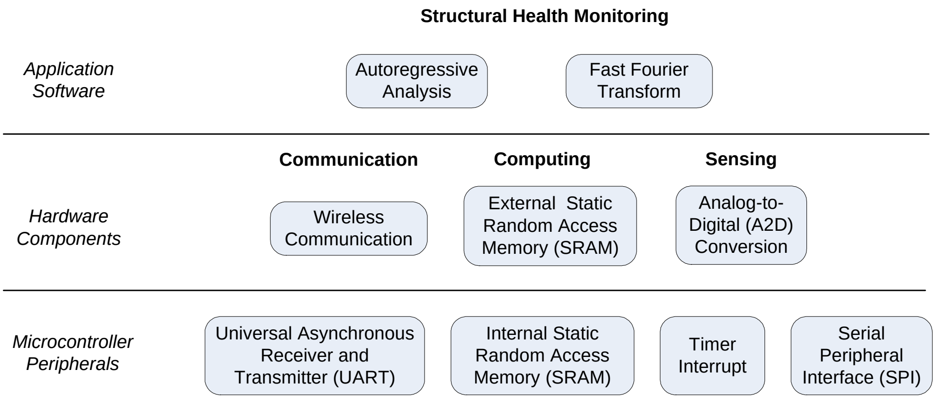


(a) Low vibration amplitude (b) High vibration amplitude

<Figure 5> Acceleration data with and without signal conditioning (S.C.)

2.2. SOFTWARE ARCHITECTURE OF THE WIRELESS SENSING UNIT

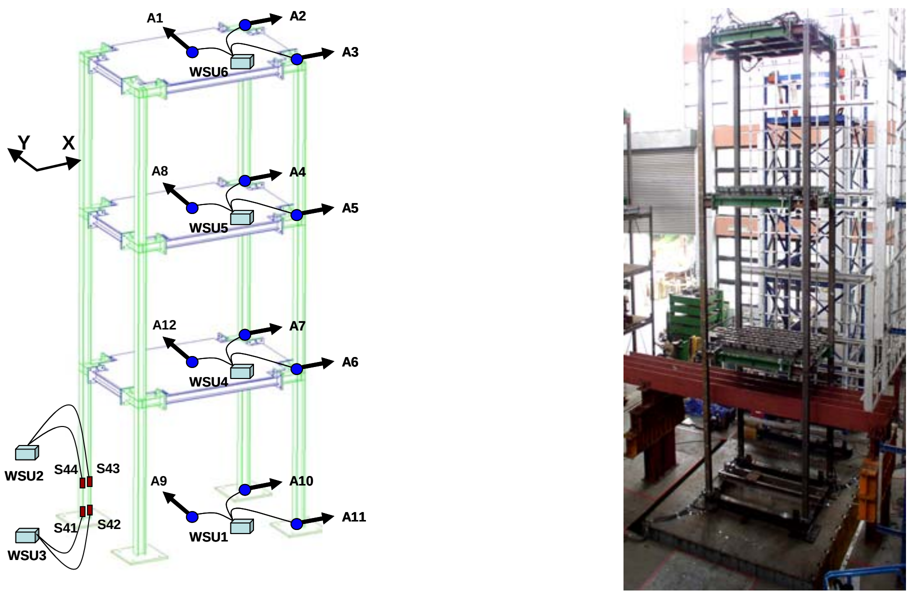
To achieve various functionalities for structural sensing, embedded software for the ATmega128 microcontroller is required. The embedded software can be written in a high-level C programming language, compiled into binary instructions, and preloaded into the nonvolatile flash memory of the microcontroller. When the wireless unit is powered on for normal operation, the microcontroller automatically starts executing the embedded instructions. The software design of the wireless sensing units follows a three-layer structure as shown in Fig. 6. At the bottom level are the software modules that manage the basic peripherals of the microcontroller and serve as building blocks in developing drivers for other hardware components. Embedded modules in this layer include byte-by-byte communication drivers through the UART (Universal Asynchronous Receiver and Transmitter) and SPI (Serial Peripheral Interface) ports, timer interrupt functions, and internal memory management. The middle layer consists of software drivers that manage other onboard hardware components. These software modules build on top of the microcontroller peripherals and include drivers for the wireless transceiver, the external memory and the A2D converter. In the top level layer, by utilizing the hardware drivers for communication, computing and sensing, software programs can be implemented to support various structural health monitoring applications. A number of engineering algorithms, such as Fast Fourier Transform (FFT) and autoregressive (AR) analysis, have been implemented and embedded in the wireless units. Onboard data processing helps save energy resources by reducing wireless transmission of large amounts of raw sensor data. With the application software executing in the wireless unit, each unit acts as an autonomous node in a wireless sensing network. This architecture of distributed sensing and computing represents a new paradigm in structural sensing, as opposed to traditional centralized systems.



<Figure 6> Software layers of the ATmega128 microcontroller in the wireless sensing unit

3. LABORATORY VALIDATION TEST AT NCREE, TAIWAN

To verify the performance of the wireless structural sensing system, laboratory and field tests have been conducted [26-28]. This section describes a large-scale shake table test conducted in collaboration with researchers at the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan in June 2005 [26]. As shown in Fig. 7, the three-story single-bay steel frame structure mounted on a shake table has a 3m-by-2m floor area and a 3m inter-story height. H150x150x7x10 I-section elements are used for all columns and beams with each beam-column joint designed as bolted connections. Each floor is loaded with concrete blocks and has a total mass of 6,000kg. The test structure is mounted on a 5m-by-5m shake table capable of applying base motion in 6 independent degrees-of-freedom. For the tests, a set of wired sensors connecting to a cable-based data acquisition system are placed side-by-side to all the wireless accelerometers and strain gages as shown in Fig. 7(a). For the wired system, Setra141-A accelerometers (with acceleration range of ±4g and a noise floor of 0.4mg) and 120Ω metal foil strain gages are employed. Multiple Pacific Instrument Series 5500 data acquisition chassis are used in the wired system. Each chassis can sample 16 channels of sensor data at a maximum rate of 30 kHz. Throughout the validation tests, a sampling rate of 200Hz is used by the wired system.



(a) Instrumentation strategy (b) Shake table setup

<Figure 7> Three-story steel-frame structure in NCREE

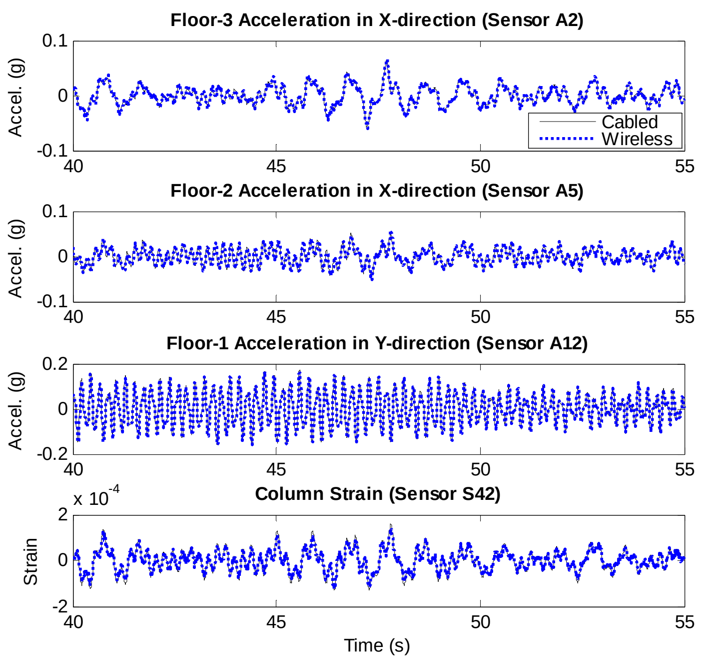
As shown in Fig. 7(a), the test structure is instrumented with a wireless network consisting of 6 wireless sensing units. Due to local frequency band requirements, the MaxStream 24XStream wireless transceiver operating at 2.4GHz spectrum is employed for the wireless sensing unit. The instrumentation strategy of the wireless sensing system is to record both the acceleration response of the structure as well as the strain measurements at the base column. Each wireless sensing unit is responsible for the three accelerometers instrumented on a floor. For example, wireless sensing unit WSU6 is used to record the data from three accelerometers on the top floor: A1, A2 and A3. This configuration of accelerometers is intended to capture both the longitudinal and lateral responses of each floor, as well as any torsion behavior.

The accelerometers employed with the wireless sensing units are the Crossbow CXL01LF1, CXL02LF1, and CXL02LF1Z accelerometers (see Table 4). Additionally, four metal foil strain gages with nominal resistances of 120Ω and a gage factor of two are mounted on two of the base columns. A wheatstone bridge amplification circuit is used to convert the changes in gage resistance into voltage signals [29]. As shown in Fig. 7, two wireless sensing units (WSU2 and WSU3) are dedicated to record the strain measurements with each unit connecting to two gages.

Table 4. Parameters of the accelerometers used in the NCREE laboratory test

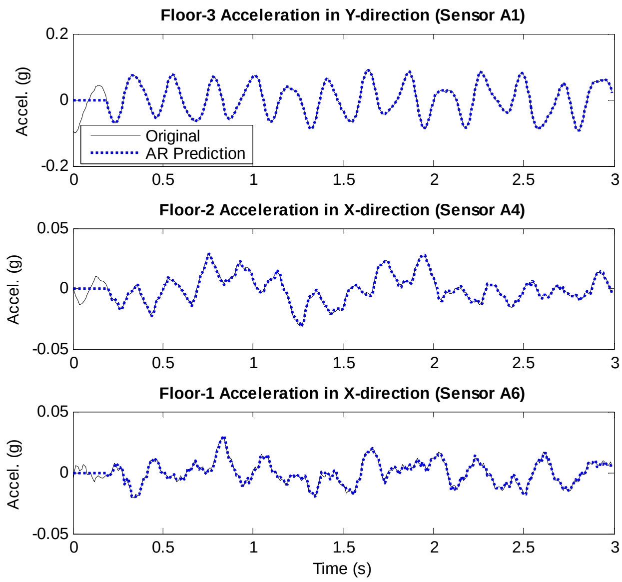
Specification	**CXL01LF1**	**CXL02LF1 / CXL02LF1Z**	**Setra141-A**
Sensor Type	Capacitive	Capacitive	Capacitive
Maximum Range	±1 g	±2 g	±4 g
Sensitivity	2 V/g	1 V/g	0.125 V/g
Bandwidth	50Hz	50Hz	260Hz
RMS Resolution (Noise Floor)	0.5 mg	1 mg	0.4 mg
Minimal Excitation Voltage	5 VDC	5 VDC	5 ~ 15 VDC

Ambient white noise and seismic excitations, including El Centro (1940), Kobe (1995), and Chi-Chi (1999) earthquake records, were applied to excite the test structure [26]. The results shown in Fig. 8 are based on a 90-second bi-directional white noise excitation of 1m/s and 0.5m/s standard deviation velocities in the X and Y directions respectively. The sampling rate for the wireless system is chosen to be 100Hz. As shown, the time history responses for both acceleration and strain measurements recorded by the wired and wireless sensing system are identical which indicate the high accuracy of the wireless sensor data. Due to the relatively high amplitude of the sensor signal, the signal conditioning module is not necessary and has not been employed in these tests.



<Figure 8> Comparison between wireless and wired sensor data for the 3-story structure

To illustrate the utilization of the on-board microcontroller for data interrogation, an autoregressive (AR) time series model that has been proposed for damage detection applications is implemented on each wireless sensing unit [30, 31]. During the tests, the wireless sensing units are commanded to automatically determine the optimal AR model that fits the collected sensor data and to transmit the model coefficients to the central server. Fig. 9 shows the acceleration time history reconstructed using 20 AR model coefficients as compared with the directly recorded raw time history data at sensor locations A1, A4, and A6. As shown in the plots, the reconstructed time history using the AR model can accurately predict the response of the structure. That is, with the microcontroller, useful computations can be performed on the wireless sensing unit, and the amount of data (in this case, the AR coefficients) that need to be transmitted in real time can be significantly reduced.

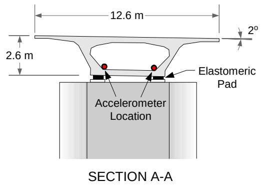


<Figure 9> Comparison between original wireless sensor data and the AR predictions

4. FIELD VALIDATION TESTS AT GEUMDANG BRIDGE, SOUTH KOREA

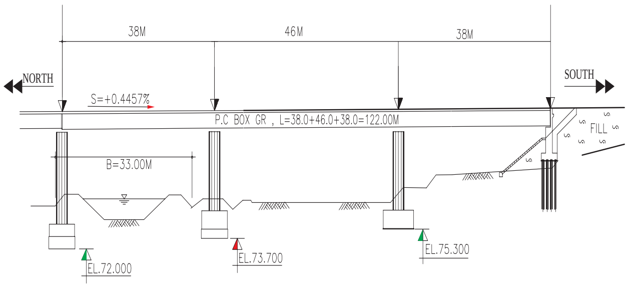
Field validation tests are also conducted to illustrate the use of the wireless units under real operating environments. This section describes the field validation tests conducted at Geumdang Bridge in Icheon, South Korea, in collaboration with researchers at the Korea Advanced Institute of Science and Technology (KAIST) in July 2005 [27]. One convenient feature of this testing venue is that the Korea Highway Corporation has the ability to open or close the two-lane test road and to reroute traffic [32]. The Geumdang Bridge has a total span of 273m, and is designed using two different section types. The northern portion is constructed with four independent spans (with span lengths of 31m, 40m, 40m and 40m respectively), each of which is designed using a 27cm concrete deck supported by four pre-cast concrete girders. The validation test is performed on the southern portion of the Geumdang Bridge. As shown in Fig. 10, the southern portion of the bridge is constructed with a continuous 122m long post-tensioned box girder. The depth of the box girder is

2.6m, and the width of the bridge deck is about 12.6m. The southern portion is subdivided into three sections (38m, 46m, and 38m, respectively) which are supported by the abutment and the three piers.

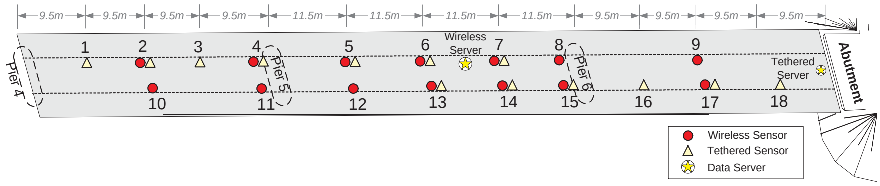


(a) Section view of the girder.

(b) Side view picture of the bridge.



(c) Elevation view on the southern portion of the bridge.



(d) Plan view of the accelerometer locations on the Geumdang Bridge

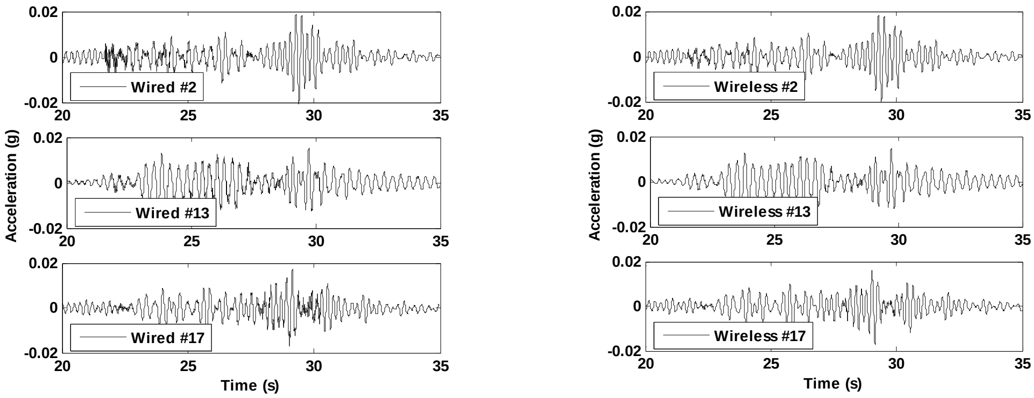
<Figure 10> Illustration of Geumdang Bridge in Icheon, South Korea

In this field test, a total of 14 accelerometers are deployed in the wireless system (Fig. 10(d)). A laptop connected with a MaxStream 9XCite transceiver, located at around the middle of the bridge and at the vicinity of sensor location #6, is employed to collect sensor data from all the 14 wireless sensing units. Furthermore, 13 accelerometers are instrumented with the wired system. As shown in Table 5, the accelerometers used in the wired system are high-precision piezoelectric accelerometers Piezotronics 393B12, and the accelerometers used in the wireless system are the MEMS accelerometers Piezotronics PCB3801 with lower precision. The PCB393 accelerometers used by the wire-based system have a very low noise floor of only 50μg and a high sensitivity of 10V/g and are well suited for use in ambient vibration applications. For the PCB3801 accelerometers used by the wireless system, the sensor signal conditioning module described earlier was employed to amplify sensor signals and filter signal noise. The signal conditioning module includes a low-pass fourth-order Bessel Filter with a cutoff frequency at 25Hz to remove high-frequency sensor noises and an amplification of sensor signal up to 20 times before being digitized by the wireless sensing unit. Within the box girder, there are a number of vertical stiffener diaphragms within the box girder that attenuate the wireless signal between the wireless sensing units. The installation of the wireless sensing system takes only about couple hours.

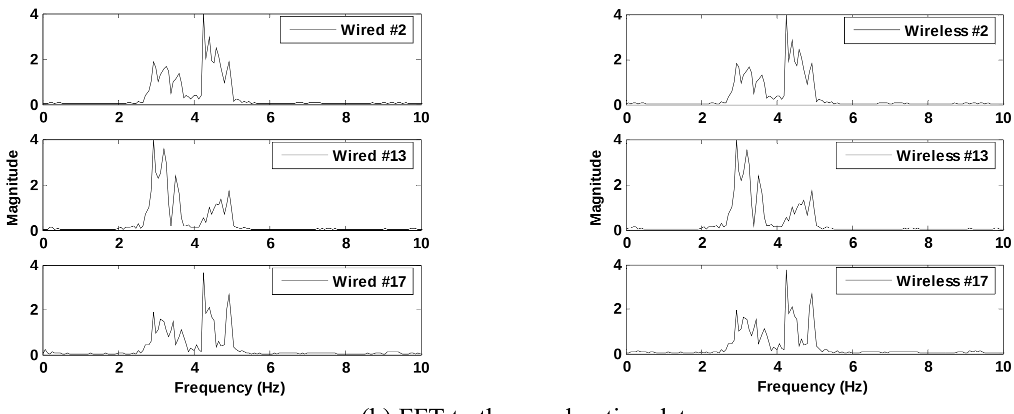
Table 5. Parameters of the accelerometers used at the Geumdang Bridge test

Specification	PCB393 (Wired System)	PCB3801 (Wireless System)
Sensor Type	Piezoelectric	Capacitive
Maximum Range	± 0.5g	± 3g
Sensitivity	10 V/g	0.7 V/g
Bandwidth	2000 Hz	80 Hz
RMS Resolution (Noise Floor)	50 μg	500 μg
Minimal Excitation Voltage	18 ~ 30 VDC	5 VDC

Vibration tests are conducted by driving a 40-ton truck at set speeds to induce structural vibrations into the system. For all the tests conducted, the wireless sensing system proves to be highly reliable using the designed communication protocol and automatically recovers from occasional wireless transmission failures. The same sampling rate of 200Hz is employed by both the wired and the wireless system. Fig. 11 shows the acceleration data recorded at sensor locations #2, #13, and #17 when the truck was crossing the bridge at 60km/h. The recorded output by the wireless system has the precision identical to that offered by the commercial wired system. With the embedded 4096 point FFT algorithm, the frequency response can be calculated onboard by the wireless units. As shown in Fig. 11, the first three dominant frequencies can easily be identified as 3.0, 4.3 and 5Hz, which are very close to the bridge natural frequencies previously published [32].



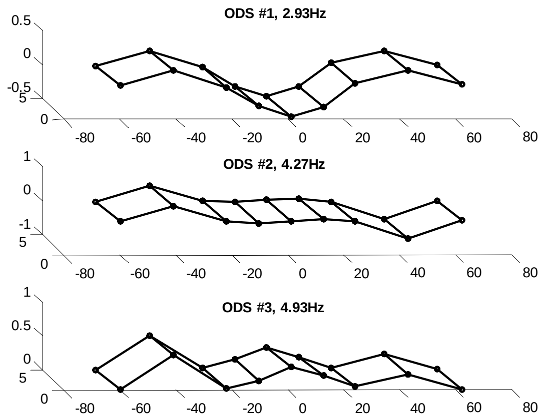
(a) Vertical acceleration of Geumdang Bridge when a 40 ton truck crossed at 60 km/hr



(b) FFT to the acceleration data

<Figure 11> Measured acceleration time-history and the FFT for the Geumdang Bridge test

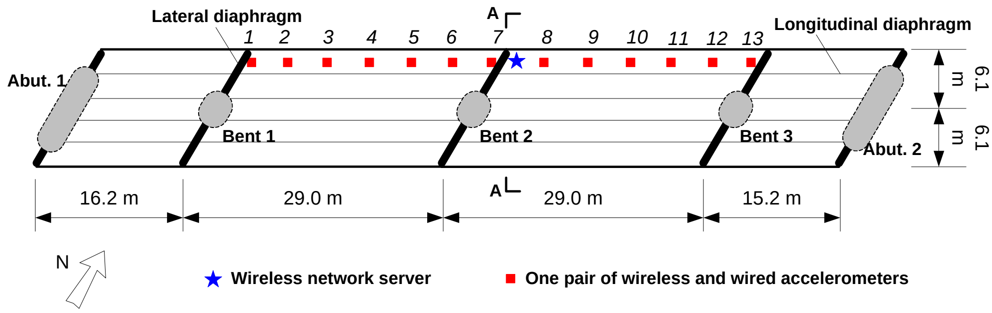
Once the dominant frequencies are determined, the complex numbers of the Fourier transform in the interested frequency range are wirelessly transmitted to the central server, so that the operating deflection shapes (ODS) of the bridge under the truck loading can be computed. Fig. 12 shows the ODS for the first three dominant frequencies extracted from the wireless data. The ODS shapes are not exactly the bridge mode shapes but are typically good approximations to the mode shapes.



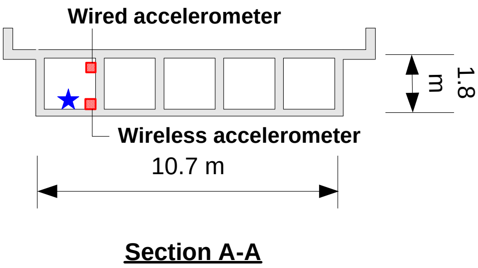
<Figure 12> Operating deflection shapes (ODS) of the Geumdang Bridge

5. FIELD VALIDATION TESTS AT VOIGT BRIDGE, SAN DIEGO, CA

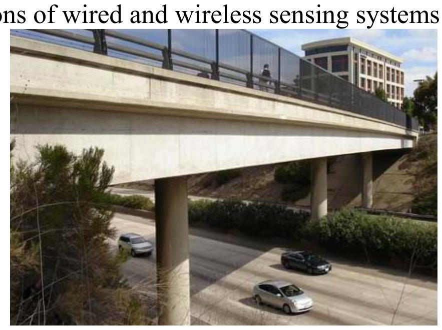
In collaboration with researchers at the University of California at San Diego (UCSD), another field validation test for the wireless structural sensing system was conducted at Voigt Bridge located on the UCSD campus [28]. The bridge is a concrete box girder highway bridge that carries traffic over Interstate 5. The two-lane bridge is about 89.4m long and consists of four spans (Fig. 13). The bridge deck has a skew angle of about 32º, with the concrete box-girder supported by three single-column bents. Over each bent, a concrete lateral diaphragm with a thickness of about 1.8m is located for stiffening the girder and could potentially pose challenges for the transmission of wireless signals within the box girder. Longitudinally, the box girder is partitioned into five cells running the length of the bridge. As a testbed project for structural health monitoring research, a sophisticated wire-based system has been installed in the northern-most cells of the Voigt Bridge by researchers at UCSD [33]. The wire-based system includes accelerometers, strain gages, thermocouples, humidity sensors, and a video camera. Twenty capacitive accelerometers are installed in the northern most bridge cell, spaced about 4.5m apart, to measure the vertical vibration along the bridge. Data from the wired sensors are collected by a data acquisition system installed in the north-west corner of the bridge. Upon collection, the data can be accessed over the Internet using a Wi-Fi setup near the bridge. This wired data acquisition system serves as the baseline for validating the performance of the prototype wireless structural sensing system.



(a) Plan view of the bridge illustrating sensor locations of wired and wireless sensing systems



(b) Deployment the accelerometers



(c) Side view of the bridge over Interstate 5

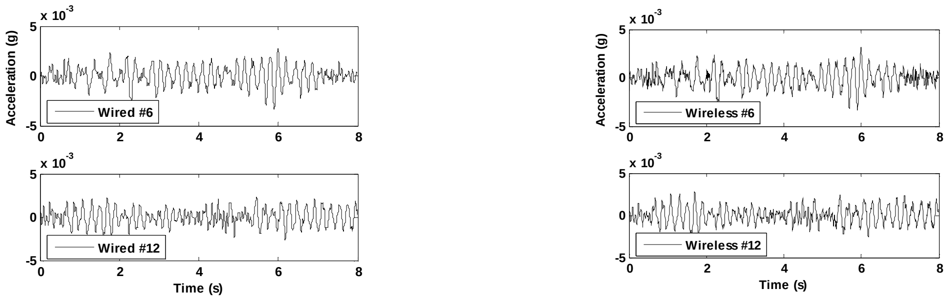
<Figure 13> Voigt Bridge on the campus of the University of California, San Diego, CA

To validate the wireless structural sensing system, thirteen accelerometers interfaced to wireless sensing units are installed within the two middle spans of the bridge to measure vertical vibrations. One wireless sensing unit (associated with one signal conditioning module and one accelerometer) is placed immediately below the accelerometer associated with the permanent wired monitoring system (Fig. 13(b)). While the wired accelerometers are mounted to the cell walls, wireless accelerometers are simply mounted on the floor of the girder cells to expedite the installation process. At locations #3, 4, 5, 9, 10, and 11 as shown in Fig. 13(a), PCB Piezotronics 3801 accelerometers are used for both the wired and the wireless systems. At the other seven locations, Crossbow CXL01LF1 accelerometers are used with the wired system, while Crossbow CXL02LF1Z accelerometers are used with the wireless system. Table 6 summarizes the key parameters of the three types of accelerometers. Signal conditioning modules are used for filtering noise, amplifying and shifting signals for the wireless accelerometers. Sampling frequencies for the wire-based system and the wireless system are 1,000 Hz and 200 Hz, respectively. The installation and calibration of the wireless sensing system, including the placement of the 13 wireless sensors, takes about an hour. The MaxStream 9XCite wireless transceiver operating at 900MHz is employed.

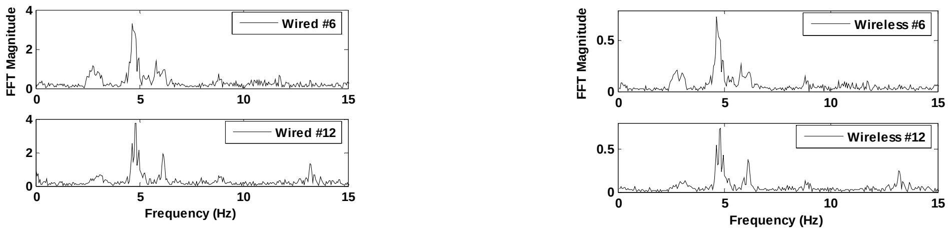
Table 6. Parameters of the accelerometers used at the Voigt Bridge test

Specification	**PCB3801**	**CXL01LF1**	**CXL02LF1Z**
Sensor Type	Capacitive	Capacitive	Capacitive
Maximum Range	± 3g	± 1g	± 2g
Sensitivity	0.7 V/g	2 V/g	1 V/g
Bandwidth	80 Hz	50Hz	50Hz
RMS Resolution (Noise Floor)	0.5 mg	0.5 mg	1 mg
Minimal Excitation Voltage	5 ~ 30 VDC	5 VDC	5 VDC

Fig. 14(a) and Fig. 14(b) show the time history data and the Fourier spectra at locations #6 and #12, collected by the wire-based and wireless sensing systems when a vehicle passes over the bridge. A close match is observed between the data collected by the two systems. The FFT results using the data collected by the wired system are computed offline, while the FFT results for the wireless data are computed online in real-time by the wireless unit. Because the sampling frequency of the wired system is five times higher than that of the wireless system, the magnitude of the Fourier spectrum for the wired system is also about five times higher than those for the wireless system.



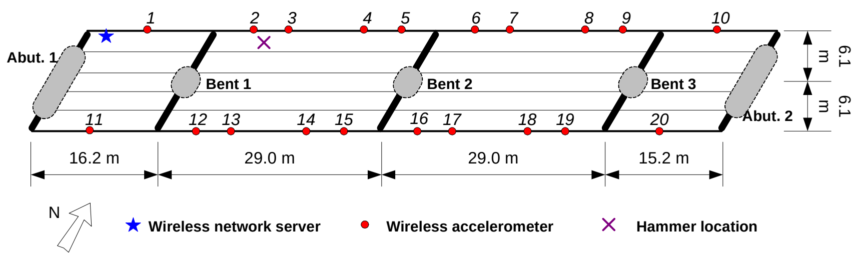
(a) Comparison between wired and wireless time history data



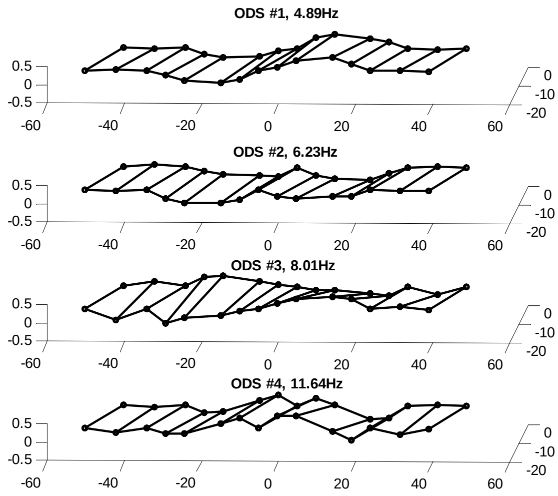
(b) Comparison between FFTs computed offline by a computer and online by the wireless sensing units

<Figure 14> Comparison between wired and wireless data for the Voigt Bridge test

One attractive feature of the wireless sensing system is that the sensors can be re-configured easily. To determine the operating deflection shapes of the bridge deck, twenty wireless sensors and the wireless network server are moved and mounted on the bridge sidewalks (Fig. 15). A hammer excitation test is then conducted on the bridge deck. DIAMOND, a modal analysis software package, is used to extract the operating deflection shapes of the bridge deck [34]. Under hammer excitation, the operating deflection shapes at or near a resonant frequency should be dominated by a single mode shape [35]. Fig. 16 shows the first four dominant operating deflection shapes of the bridge deck using wireless acceleration data. The ODS #1, #2, and #4 show primarily flexural bending modes of the bridge deck; a torsional mode is observed in ODS #3.



<Figure 15> Wireless accelerometer deployment for the ODS analysis to Voigt Bridge



<Figure 16> Operating deflection shapes of Voigt Bridge extracted from wireless sensor data

6. SUMMARY AND DISCUSSION

In this paper, the integrated hardware and software design of a prototype wireless sensing system has been described. Laboratory test using a 3-story structure and field tests upon two bridge structures are presented to illustrate the functionalities of the prototype wireless structural sensing system. These tests have validated the following system features: (1) operational robustness and fidelity of wireless sensing data while employing the wireless sensing system in both laboratory environment and in actual civil structures, (2) the embedded computing capability of the wireless units, (3) the performance of the specially designed signal conditioning module, and (4) easy re-configurability of the wireless sensor network topology. Besides the validation tests presented, the prototype wireless sensing system has also been employed at the Gi-Lu Cable-Stayed Bridge in Taiwan [36], the Fox Theatre Balcony in Michigan, USA [37], the WuYuan Steel Arch Bridge, Xiamen, China [38] and other civil infrastructures. This research has demonstrated the applicability of wireless technology for structural sensing applications. Research continues to deploy and to improve the prototype system for other civil infrastructures. The use of the wireless sensing system for structural control applications is currently being investigated [39].

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