Wireless Sensor Advances and Applications for Civil Infrastructure Monitoring

B.F. Spencer, Jr. and Chung-Bang Yun (Editors)
The Newmark Structural Engineering Laboratory (NSEL) of the Department of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign has a long history of excellence in research and education that has contributed greatly to the state-of-the-art in civil engineering. Completed in 1967 and extended in 1971, the structural testing area of the laboratory has a versatile strong-floor/wall and a three-story clear height that can be used to carry out a wide range of tests of building materials, models, and structural systems. The laboratory is named for Dr. Nathan M. Newmark, an internationally known educator and engineer, who was the Head of the Department of Civil Engineering at the University of Illinois [1956-73] and the Chair of the Digital Computing Laboratory [1947-57]. He developed simple, yet powerful and widely used, methods for analyzing complex structures and assemblages subjected to a variety of static, dynamic, blast, and earthquake loadings. Dr. Newmark received numerous honors and awards for his achievements, including the prestigious National Medal of Science awarded in 1968 by President Lyndon B. Johnson. He was also one of the founding members of the National Academy of Engineering.

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This technical report is a reprint of the articles that appeared in the June issue of the Journal of Smart Structures and Systems on Wireless Sensor Advances and Applications for Civil Infrastructure Monitoring that was edited by Billie F. Spencer, Jr. and Chung-Bang Yun. To promote wider distribution of this timely collection of papers, the Editor-in-Chief of the Journal, Prof. Chang-Koon Choi, has generously allowed its publication in the Newmark Structural Engineering Laboratory Report Series.

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Foreword

For most industrialized nations, the annual expenditure on civil infrastructure amounts to between 8-15% of their GDP. This investment is only likely to increase, with spending on system rehabilitation outpacing the growth in expenditures on system expansion. Indeed, recent catastrophic failures have focused public attention on the declining state of the aging infrastructure. These concerns apply not only to civil engineering structures, such as bridges, highways, and buildings, but to other structures such as the aging aircraft fleet commercial airlines currently in use as well. Improving and modernizing our infrastructure is critical to ensuring our safety and security and maintaining economic vitality.

Structural Health Monitoring (SHM) using wireless sensor technology (WST) has emerged as a promising solution to challenges associated with the declining state of aging civil infrastructure. Successful implementation of long-term, continuous, and automated SHM using WST is expected to improve public safety, increase structural reliability, enhance inspection quality, and reduce maintenance costs. Moreover, such SHM systems can aid in lifetime monitoring of future construction projects and help to assess emergency facilities and evacuation routes, including bridges and highways, in a timely manner after natural disasters.

Today, research advances in WST are coming at an unparalleled pace, many leading to a number of full-scale implementations. As a result, publication of a special issue of the Journal of Smart Structures and Systems that collects this material together is quite timely and important.

This special issue on *Wireless Sensor Advances and Applications for Civil Infrastructure Monitoring* is organized into two main categories. The first 13 articles address the use of wireless smart sensors to monitor a variety of civil infrastructure. The subsequent 5 articles focus on impedance and guided waves based SHM using wireless piezoelectric sensors.

Finally, we would like to thank all of the authors for their valuable contributions and the reviewers for their time and effort in providing many valuable suggestions and comments. We particularly wish to express our gratitude to Dr. Shih-Chi Liu of National Science Foundation, USA and Professor Chang-Koon Choi of KAIST, Korea for their support and encouragement in the preparation of this special issue.

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## Table of Contents

Flexible smart sensor framework for autonomous structural health monitoring ..........423
   Jennifer A. Rice, Kirill Mechitov, Sung-Han Sim, Tomonori Nagayama,
   Shinae Jang, Robin Kim, Billie F. Spencer, Jr., Gul Agha, and Yozo Fujino

Structural health monitoring of a cable-stayed bridge using smart sensor technology:
   deployment and evaluation .................................................................439
   Shinae Jang, Hongki Jo, Soojin Cho, Kirill Mechitov, Jennifer A. Rice,
   Sung-Han Sim, Hyung-Jo Jung, Chung-Bang Yun, Billie F. Spencer, Jr.,
   and Gul Agha

Structural health monitoring of a cable-stayed bridge using wireless smart sensor
   technology: data analyses .................................................................461
   Soojin Cho, Hongki Jo, Shinae Jang, Jongwoong Park, Hyung-Jo Jung,
   Chung-Bang Yun, Billie F. Spencer, Jr., and Ju-Won Seo

Reliable multi-hop communication for structural health monitoring ......................481
   Tomonori Nagayama, Parya Moinzadeh, Kirill Mechitov, Mitsushi Ushita,
   Noritoshi Makihata, Masataka Ieiri, Gul Agha, Billie F. Spencer, Jr.,
   Yozo Fujino, and Ju-Won Seo

Rapid-to-deploy reconfigurable wireless structural monitoring systems using
   extended-range wireless sensors ..........................................................505
   Junhee Kim, R. Andrew Swartz, Jerome P. Lynch, Jong-Jae Lee,
   and Chang-Geun Lee

Development and deployment of large scale wireless sensor network
   on a long-span bridge ........................................................................525
   Shamim N. Pakzad

Non-invasive acceleration-based methodology for damage detection and assessment
   of water distribution system ...............................................................545
   Masanobu Shinozuka, Pai H. Chou, Sehwan Kim, Hong Rok Kim,
   Debasis Karmakar, and Lu Fei

Experimental validation of a multi-level damage localization technique
   with distributed computation .............................................................561
   Guirong Yan, Weijun Guo, Shirley J. Dyke, Gregory Hackmann, and Chenyang Lu

Wireless operational modal analysis of a multi-span prestressed concrete bridge
   for structural identification ..............................................................579
   Matthew J. Whelan, Michael V. Gangone, Kerop D. Janoyan, Neil A. Hoult,
   Campbell R. Middleton, and Kenichi Soga
Wireless sensor networks for permanent health monitoring of historic buildings .......... 595
Daniele Zonta, Huayong Wu, Matteo Pozzi, Paolo Zanon, Matteo Ceriotti, Luca Mottola, Gian Pietro Picco, Amy L. Murphy, Stefan Guna, and Michele Corrà

Wireless sensor networks for underground railway applications: case studies in Prague and London .............................................................. 619
Peter J. Bennett, Kenichi Soga, Ian Wassell, Paul Fidler, Keita Abe, Yusuke Kobayashi, and Martin Vanícek

Design, calibration and application of wireless sensors for structural global and local monitoring of civil infrastructures .............................................................. 641
Yan Yu, Jinping Ou, and Hui Li

Multi-scale wireless sensor node for health monitoring of civil infrastructure and mechanical systems .............................................................. 661
Stuart G. Taylor, Kevin M. Farinholt, Gyuhae Park, Michael D. Todd, and Charles R. Farrar

Ultra low-power active wireless sensor for structural health monitoring ....................... 675
Dao Zhou, Dong Sam Ha, and Daniel J. Inman

Development of a low-cost multifunctional wireless impedance sensor node .................. 689
Jiyoung Min, Seunghee Park, Chung-Bang Yun, and Byunghun Song

Autonomous smart sensor nodes for global and local damage detection of prestressed concrete bridges based on accelerations and impedance measurements .................. 711
Jae-Hyung Park, Jeong-Tae Kim, Dong-Soo Hong, David Mascarenas, and Jerome Peter Lynch

Concrete structural health monitoring using piezoceramic-based wireless sensor networks .............................................................. 731
Peng Li, Haichang Gu, Gangbing Song, Rong Zheng, and Y.L. Mo

A wireless guided wave excitation technique based on laser and optoelectronics ........... 749
Hyun-Jun Park, Hoon Sohn, Chung-Bang Yun, Joseph Chung, and Il-Bum Kwon
Flexible smart sensor framework for autonomous structural health monitoring

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Abstract. Wireless smart sensors enable new approaches to improve structural health monitoring (SHM) practices through the use of distributed data processing. Such an approach is scalable to the large number of sensor nodes required for high-fidelity modal analysis and damage detection. While much of the technology associated with smart sensors has been available for nearly a decade, there have been limited numbers of full-scale implementations due to the lack of critical hardware and software elements. This research develops a flexible wireless smart sensor framework for full-scale, autonomous SHM that integrates the necessary software and hardware while addressing key implementation requirements. The Imote2 smart sensor platform is employed, providing the computation and communication resources that support demanding sensor network applications such as SHM of civil infrastructure. A multi-metric Imote2 sensor board with onboard signal processing specifically designed for SHM applications has been designed and validated. The framework software is based on a service-oriented architecture that is modular, reusable and extensible, thus allowing engineers to more readily realize the potential of smart sensor technology. Flexible network management software combines a sleep/wake cycle for enhanced power efficiency with threshold detection for triggering network wide operations such as synchronized sensing or decentralized modal analysis. The framework developed in this research has been validated on a full-scale bridge in South Korea.

Keywords: smart sensor network; structural health monitoring; full-scale bridge monitoring; service-oriented architecture; Imote2.

1. Introduction

Civil infrastructure is the foundation of our society and has a widespread impact on the quality of our daily lives. Monitoring the safety and functionality of the world’s buildings, bridges and lifeline systems, is critical to improving maintenance practices, minimizing the cost associated with repair and ultimately improving public safety. Structural health monitoring (SHM) provides the means for capturing structural response and assessing structural condition for a variety of purposes. For example, the information from an SHM system can be used to fine-tune idealized structural models, thereby allowing more accurate prediction of the response due to extreme loading conditions, such
as an earthquake. SHM also can be used to characterize loads in situ, which can allow the detection of unusual loading conditions as well as validate the structure’s design. In addition, real-time monitoring systems can measure the response of a structure before, during and after a natural or man-made disaster, that can be used in damage detection algorithms to assess the post-event condition of a structure.

Gaining a clear understanding of structural behavior to allow a reasonable assessment of its as-built condition requires high-fidelity sensor data to build accurate models (Nagayama et al. 2007). In addition, potentially problematic structural changes, such as corrosion, cracking, buckling, fracture, etc., all occur locally within a structure. It is expected that sensors must be in close proximity to the damage to capture the resulting change in response while sensors further from the damage are unlikely to observe measurable changes. To achieve an effective monitoring system that is capable of generating informative structural models and detecting critical structural changes, a dense array of sensors is required. Due to the cost of deployment and the potential for data inundation, such a dense instrumentation system is not practically realized with traditional structural monitoring technology.

Advances in wireless technology and embedded processing have made much lower-cost wireless smart sensor networks (WSSNs) an attractive alternative to wired, centralized data acquisition (DAQ) systems. The majority of the work using wireless smart sensors for structural monitoring has focused on using the sensors to emulate traditional wired sensor systems (Arms et al. 2004, Pakzad et al. 2008, Whelan and Janoyan 2009). As these systems require that all data be sent back to a central DAQ system for further processing, the amount of wireless communication required in the network can become costly in terms of excessive communication times and the associated power it consumes as the network size increases. For example, a wireless sensor network implemented on the Golden Gate Bridge that generated 20 MB of data (1600 seconds of data, sampling at 50 Hz on 64 sensor nodes) took over nine hours to complete the communication of the data back to a central location (Pakzad et al. 2008).

WSSNs leverage onboard computational capacity on the wireless sensors to allow data processing to occur within the network, as opposed to at a central location. By implementing data processing techniques, such as modal analysis or damage detection algorithms, in such a distributed manner, the amount of communication that occurs within the network can be reduced, while providing usable information on the structural condition (Nagayama and Spencer 2007). WSSNs employing decentralized computing offer a scalable solution that has the potential to dramatically improve SHM efforts.

In recent years, researchers have made progress toward addressing the inherent roadblocks to realizing SHM application that utilize WSSNs. Nagayama and Spencer (2007) successfully implemented a distributed WSSN SHM system on a laboratory scale truss structure. To date, the hardware and software required for SHM have yet to be integrated to achieve a framework that is suitable for autonomous monitoring and distributed data management on a full-scale structure employing a dense network of sensors.

The objective of this research is to provide an enabling WSSN framework to address issues that have limited their effectiveness for SHM systems. In particular, the development of flexible, multi-metric sensors for use in WSSNs with user-selectable anti-aliasing filters to produce high-quality data appropriate for SHM applications and the development and validation of an enabling, open-source software framework that is modular and adaptable are presented. The integration of these software and hardware components has resulted in a flexible framework that enables autonomous, full-scale implementations of SHM systems.
2. High-fidelity WSSN data acquisition

The successful utilization of WSSNs for structural monitoring relies on their ability to capture data that provides a reasonable representation of the physical response. Some of the inherent characteristics associated with wireless smart sensors have made high-fidelity data acquisition a challenging undertaking. This section presents the development of sensor hardware and data acquisition software designed specifically for a broad range of SHM applications. This sensor hardware interfaces with the Imote2 smart sensor platform, the only commercially available smart sensor platform that is well-suited to the demands of such applications. Until now, the vibration sensors that have been widely available for smart sensor platforms, and in particular the Imote2, have lacked user-selectable anti-aliasing filters, flexibility in the choice of sensing parameters, sample rate accuracy, and temperature correction.

2.1 Smart sensor platform

The smart sensor platform used in this research is the Imote2 (Fig. 1). The Imote2 is built around Intel's low-power X-scale processor (PXA27x). The scalability of the processor speed based on application needs allows for increased performance without a significant increase in overall power consumption. The onboard memory of the Imote2 is another feature that sets it apart from other wireless sensor platforms and allows its use for the high-frequency sampling and computationally intense data processing required for dynamic structural monitoring. It has 256 KB of integrated SRAM, 32 MB of external SDRAM and 32 MB of flash memory (Crossbow Technology 2007a).

TinyOS (www.tinyos.net) is the open-source operating system used on many smart sensors (Levis et al. 2005), including the Imote2. TinyOS only supports two types of executions: tasks and hardware event handlers. This concurrency model makes programming in TinyOS complicated, as it requires the use of many small event handlers and does not support real-time scheduling, making control of execution timing difficult. Hardware event handlers can preempt the execution of a task. Nagayama et al. (2006) discuss the potential effects of this limitation as it pertains to achieving synchronized sensing in a WSSN and some methods for overcoming it. In particular, an uncertain delay in the start of sensing due to the lack of strict timing control is an issue that must be addressed if synchronized sensing is to be achieved.

The Imote2 provides a flexible platform for a range of sensing applications. The sensors used

Fig. 1 Imote2 top and bottom view (left) and stacked on battery board with antenna (right)
with the Imote2 are interfaced to the main board via two connectors in a stackable configuration. The Imote2 does not have an onboard analog-to-digital converter (ADC) and therefore is only compatible with digital inputs, specifically I2C (Inter-Integrated Circuit: a two-line serial data bus that supports multiple data channels) and SPI (Serial Peripheral Interface: a four-wire digital bus that typically only supports a single data channel). The Imote2’s flexible sensor interface allows its users to tailor sensor boards to their application.

2.2 SHM-A sensor board

Vibration-based SHM requires sensed data that well represents the physical response of the structure both in amplitude and phase. The measurements must have ample resolution to characterize the structural response and must be recorded with a consistent sample rate that is synchronized with other sensed data from the structure. Whether the data is used to perform modal analysis, system identification or vibration-based damage detection, these aspects of the data quality must be met so that reasonable results may be achieved (Nagayama et al. 2007). To be used in SHM applications, the sensor hardware that interfaces with the Imote2 must provide such high-fidelity data.

The only commercially available accelerometer sensor board that interfaces with the Imote2 (ITS400C sensor board, Crossbow Technology 2007b) was evaluated to determine its appropriateness for SHM applications by Nagayama et al. (2006). The results demonstrated the need for a sensor board with higher resolution and more accurate sampling rates designed specifically for SHM applications. To meet this need, the design of a newly developed Structural Health Monitoring Accelerometer (SHM-A) board is presented with its experimental verification. The SHM-A board provides user-selectable sampling rates and anti-aliasing filters for a broad range of applications. The components of the SHM-A board have been selected to meet the requirements of vibration-based SHM applications, specifically with respect to data quality and the demands of achieving synchronized sensing.

The key component of the SHM-A board is the Quickfilter QF4A512 ADC and signal conditioner with programmable sampling rates and digital filters (Quickfilter Technologies 2007). The SHM-A board interfaces with the Imote2 via SPI I/O and has a three-axis analog accelerometer for vibration measurement. A block diagram of the components of the SHM-A sensor board is given in Fig. 2. Fig. 3 shows three views of the board. The details of the board components will be discussed in subsequent paragraphs.

![Fig. 2 Block diagram of SHM-A Rev 4.0](image-url)
Flexible smart sensor framework for autonomous structural health monitoring

The ST Microelectronics LIS344ALH capacitive-type MEMS accelerometer (STMicroelectronics 2008), with DC to 1500 Hz measurement range, was chosen for the SHM-A board. This type of accelerometer utilizes the motion of a proof mass to change the distance between internal capacitive plates, resulting in a change of output voltage in response to acceleration. Kurata et al. (2006) investigated several commercially available MEMS accelerometers in the context of structural monitoring applications and found that the ST Microelectronics accelerometer had better performance than other comparably priced sensors. Though MEMS accelerometers are available with lower noise levels, the ST Micro accelerometer offers an excellent price/performance ratio. In addition, it provides three axes of acceleration on a single chip. The specifications for the accelerometer are given in Table 1. If lower noise characteristics are required for a specific application, a higher-cost accelerometer, such as the SD1221 (Silicon Designs 2007) or the Si-Flex SF1500S (Colibrys 2007), could be incorporated into the board design with appropriate measures to accommodate higher power requirements.

According to the datasheet noise density values for the accelerometer, the expected corresponding $RMS$ noise over a 20-Hz bandwidth is 0.10 - 0.13 mg for the $x$- and $y$-axes and 0.13 - 0.26 mg for the $z$-axis. One hundred SHM-A boards were tested to determine their noise performance and their calibration constants (scale and offset). The sensors were placed flat on a desk and data was collected at 50 Hz (with a cutoff frequency of 20 Hz) for 1.5 minutes with no external excitation. Additional tests were conducted with 8 sensor boards at a 1000-Hz sample rate with a cutoff frequency of 250 Hz to assess the higher frequency performance. To ensure that the desk was not vibrating, simultaneous measurements were taken with a low-noise seismic accelerometer (PCB 393C).

The average measured $RMS$ vibration level was 0.29 mg for the $x$- and $y$-axes and 0.67 mg for the $z$-axis. The higher noise levels in the $z$-axis appear to be intrinsic to the most recent ST Micro accelerometer revision (LIS344ALH) which exhibits higher $1/f$ noise characteristics (higher noise at

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axes</td>
<td>3</td>
</tr>
<tr>
<td>Measurement range</td>
<td>±2 g</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.66 V/g</td>
</tr>
<tr>
<td>Power supply</td>
<td>2.4 V to 3.6 V</td>
</tr>
<tr>
<td>Noise density, $x$- and $y$-axes</td>
<td>22 - 28 μg/Hz</td>
</tr>
<tr>
<td>Noise density, $z$-axis</td>
<td>30 - 60 μg/Hz</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-40 to 85°C</td>
</tr>
<tr>
<td>Supply current</td>
<td>0.85 mA</td>
</tr>
</tbody>
</table>

Fig. 3 SHM-A sensor board: top (left), bottom (middle) and perspective (right)

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lower frequencies) along that axis; this noise was not observed in the previous versions of the accelerometer. The x- and y-axes should be used as the primary measurement axes when possible.

The Quickfilter QF4A512 programmable signal conditioner (Quickfilter Technologies 2007) employs a versatile four-channel, 16-bit resolution ADC. Each channel has a selectable gain (up to 8x), an analog anti-aliasing filter, individually selectable sampling frequencies and individually programmable digital FIR filters (up to 512 filter coefficients). The primary reasons for the selection of the QF4A512 are its ability to achieve un-aliased signals regardless of the measurement bandwidth (outlined in detail in the following paragraph) and the option to implement high-coefficient FIR filters on each sensor channel. Although the power consumption of the QF4A512 is higher than other products, this drawback is offset by the added features and power management approaches discussed later in this paper. The key features of the QF4A512 are summarized in Table 2.

The QF4A512 performs oversampling, filtering and decimation to achieve two purposes in the digitization of the measured signal. The first purpose of oversampling is to improve the resolution of the output by decreasing the noise from quantization error. The resolution of the ADC dictates the smallest measurable increment that can be resolved. Quantization introduces a constant level of noise energy which is uniformly distributed over the measured bandwidth. The higher the sampling frequency, the wider the frequency range over which the noise energy is distributed. Because the energy of the noise is constant, increasing the Nyquist frequency lowers the amplitude of the noise. When a digital decimation filter is applied to the oversampled signal, the noise energy above the new Nyquist frequency is eliminated, thereby improving the resolution of the signal. A 4-times oversampling rate lowers the quantization noise floor by 6 dB or the equivalent of achieving one additional bit in resolution.

The QF4A512 provides variable anti-aliasing filters by following the unaliased, oversampled signal with digital filtering and decimation. The analog anti-aliasing filters are 3rd order Bessel filters with a cutoff frequency of 500 kHz. While this cutoff frequency may seem high for structural monitoring applications, with bandwidths of interest typically below 20 Hz, it is set to ensure that aliasing is avoided when the signal is digitized at the much higher oversampling rates that are used (e.g., 12.5 MHz) without limiting the final measurement bandwidth. The digital decimation filters are Cascaded-Integrator-Comb (CIC) filters, working in combination with the Cascaded-Integrator Halfband (CIH) filters to ensure that the integrity of the signal is maintained upon decimation to the

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>Value</th>
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<tbody>
<tr>
<td>Channels</td>
<td>Single or double ended</td>
<td>4</td>
</tr>
<tr>
<td>Signal-to-Noise Ratio (SNR)</td>
<td>$f_s = 2$ kHz</td>
<td>82 dB</td>
</tr>
<tr>
<td></td>
<td>$f_s = 2$ MHz</td>
<td>69 dB</td>
</tr>
<tr>
<td>Throughput (w/40 MHz SPI bus rate)</td>
<td>1 channel active</td>
<td>1.47 Msps</td>
</tr>
<tr>
<td></td>
<td>4 channels active</td>
<td>390 ksps</td>
</tr>
<tr>
<td>Nominal Resolution</td>
<td></td>
<td>16 bits</td>
</tr>
<tr>
<td>Effective Number of Bits (ENOB)</td>
<td>$f_s = 2$ kHz</td>
<td>13.2 bits</td>
</tr>
<tr>
<td></td>
<td>$f_s = 2$ MHz</td>
<td>11.2 bits</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>Quiescent</td>
<td>2.0 mW</td>
</tr>
<tr>
<td></td>
<td>Power down</td>
<td>0.96 mW</td>
</tr>
<tr>
<td></td>
<td>$f_s = 1$ kHz, 1 channel</td>
<td>84.8 mW</td>
</tr>
<tr>
<td></td>
<td>$f_s = 1$ kHz, 4 channels</td>
<td>230.4 mW</td>
</tr>
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final user-specified sampling frequency. This combination of filters provides excellent amplitude
response while preserving a linear phase response (Hogenauer 1981). This method of oversampling,
filtering and decimation to remove aliasing is common for PC-based analyzer systems. After the
signal is downsampled to the effective sampling rate, the user-defined FIR filters (low-pass, high-
pass or band-pass) are applied to further reduce noise and preserve the bandwidth of interest for the
particular application.

A software driver for the SHM-A board was developed in TinyOS. The purpose of the driver is to
control the functions of the QF4A512, such as loading the filter coefficients, allocating memory,
time-stamping, writing data, etc. At the beginning of sensing, the driver first initializes the ADC and
then triggers the sampling to start. During sampling, the samples are released from the QF4A512
and written to the Imote2 buffers as two-byte signed integers (16-bit).

Tests were conducted to calibrate each channel of the accelerometer. The SHM-A board mounted
on an Imote2 was placed on an accelerometer calibration frame which ensured a level measurement
surface. Measurements were taken with the board oriented so that signals corresponding to -1 g, 0 g
and +1 g were measured for each of the measurement axes. The results provided the necessary
calibration constants (DC offset and scale) which can be directly implemented in the sensing
application.

In addition to the static calibration, dynamic calibration testing was conducted on a bench-scale
shake table alongside a wired reference sensor to evaluate the sensor boards at frequencies above
the DC (static) response. Focus was placed on the lower frequency range of 0 to 20 Hz range as
well as higher frequencies up to 250 Hz. The results of the dynamic tests were in agreement with
the static calibration tests. There is some challenge in verifying the performance of the SHM-A
sensor board below 1 Hz due to limitation in the motion of the shake table and the presence of
typical 1/f noise in the accelerometer output. The result is some discrepancy between the reference
sensor and the SHM-A board. More detail on the calibration results may be found in Rice and
Spencer (2009) and the datasheet for the SHM-A sensor board (http://shm.cs.uiuc.edu/files/SHM-

The environmental sensors on the SHM-A board include a digital light sensor and a digital
combination temperature/humidity sensor. Initial sensor board test results exhibited large drifts in
the mean value of the acceleration data over time, even when the sensor was stationary. Subsequent
investigation revealed that the drift was due to the temperature sensitivity of the mean value of the
accelerometer in response to self-heating of the sensor board caused by the operation of the Imote2
processor and the QF4A512 ADC. To address the mean value drift of the accelerometer output
resulting from temperature changes, onboard temperature compensation has been implemented in
software. By simultaneously measuring the temperature and the acceleration, the direct relationship
between the self heating of the board and the accelerometer output can be determined. This correction
factor is built into the driver and automatically accounted for during sensing. The temperature
sensors were not individually calibrated; performing calibration of the temperature sensors may
yield more accurate temperature correction results.

2.3 Unified sensing

In addition to the previously described hardware components, specific software components have
been implemented to ensure accurate data sampling while maintaining memory efficient operation.
The Unified Sensing service provides a convenient, general-purpose application programming interface,
replacing the standard TinyOS sensing interface for the Imote2 and extending its functionality to include precise time-stamping of the data and providing transparent support for a variety of sensor boards, including the SHM-A board. The complete and self-contained data representation employed in *Unified Sensing* makes it easy to pass around and modify the data without hard-coding connections between components that use only parts of this data. This approach facilitates data being passed directly to the application services described in the following section. More detail on the *Unified Sensing* service can be found in Rice *et al.* (2010).

3. WSSN software development framework

SHM applications implemented on WSSNs require complex programming, ranging from network functionality to algorithm implementation. Software development is made even more difficult by the fact that many smart sensor platforms employ special-purpose operating systems, such as TinyOS, without support for common programming environments. Although TinyOS is widely used for WSSN applications, it is a very challenging environment for non-programmers to develop network control and application software. The embedded system expertise required to develop SHM applications has limited the use of WSSN technology for monitoring of civil infrastructure.

3.1 Service-oriented architecture

A common approach to the issue of software complexity is to divide the software system into smaller, more manageable components. Service-oriented architecture (SOA) has been proposed as a way to use this design philosophy in building dynamic, heterogeneous distributed applications (Singh and Huhns 2005, Tsai 2005). Services, in SOA terminology, are self-describing software components in an open or modifiable distributed system. The description of a service, called a contract, lists its inputs and outputs, explains the provided functionality, and describes non-functional aspects of execution (e.g., resource consumption). An application built using SOA consists of a number of linked services within a middleware runtime system that provides communication and coordination between them. Data is passed among the services in a common format and the services do not require knowledge of its origin. Different applications can be built from the same set of services, depending on how they are linked and on the execution context (Gu *et al.* 2005). This approach provides support for dynamic, highly adaptive applications without the need to revisit and adapt the implementation of each service for each new application. SOA has the potential to address the challenges inherent to designing complex and dynamic WSSN applications (Liu and Zhao 2005, Mechtitov *et al.* 2007).

An attractive aspect of SOA is that it separates the tasks undertaken in WSSN application development. In sensor networks used for structural monitoring, the application designer is likely to also be the application user, having expertise in SHM applications and the desired output of the network, but limited knowledge on network programming and the hardware-software interface. As such, it is important for the less complex, high-level design of the application and the domain-specific algorithms used by the services to be separated from the often more complex, low-level infrastructure necessary to make the WSSN work. SOA in WSSNs makes it possible to compose and deploy complex applications through a user interface suitable for non-programmers, potentially accelerating the use of WSSNs of SHM applications.
Flexible smart sensor framework for autonomous structural health monitoring

The Illinois Structural Health Monitoring Project (ISHMP), a collaborative effort between researchers in civil engineering and computer science at the University of Illinois at Urbana-Champaign, has sought to tackle the complexity associated with creating WSSN applications by developing a software framework based on the design principles of SOA. This framework provides a suite of services implementing key middleware infrastructure necessary to provide high-quality sensor data and to reliably communicate it within the sensor network, as well as number of commonly used numerical algorithms. This framework is intended to allow researchers and engineers to focus their attention on the advancement of SHM approaches without having to concern themselves with low-level networking, communication and numerical sub-routines. This software is open-source and available for public use at http://shm.cs.uiuc.edu/software.html.

The service-based software framework provides an open-source software library of customizable services for, and examples of, SHM applications utilizing WSSNs. SHM middleware services and distributed damage detection algorithms reported in Nagayama and Spencer (2007), along with a collection of tools, utilities and algorithms, have been implemented to enable efficient development of flexible and robust SHM applications on WSSNs. Additional services that enable autonomous network operation have also been included in the software toolsuite, as described in Section 4.

3.2 ISHMP toolsuite

The components of the service-based framework provided by the ISHMP Toolsuite can be divided into three primary categories: (1) foundation services, (2) application services and (3) tools and utilities. In addition, a library of supporting numerical functions that are common to many SHM algorithms is provided including fast Fourier transform (FFT), singular value decomposition (SVD), eigenvalue analysis, etc. In the description of the services that follows, leaf nodes are defined as the nodes that comprise the sensor network while the gateway node is the Imote2 that is connected to the base station PC that operates the network. The network topology that is utilized varies from application to application. More information on these applications and the topologies they employ can be found in Sim and Spencer (2009) and Rice et al. (2010).

The foundation services implement the functionality required to support the application and other services. When used together, one of the primary purposes of the foundation services is to enable applications acquire synchronized data from a network of sensors. The foundation services include network time synchronization (TimeSync), the previously described Unified Sensing, reliable communication of both short messages and long data records (ReliableComm), and a service that supports the reliable dissemination of network commands (RemoteCommand).

The application services provide the numerical algorithms necessary to implement SHM applications on the Imote2s and may also be used independently. For each application service, an application module to test the algorithm on both the PC and the Imote2 has been developed. The applications services include synchronized sensing (SyncSensing), correlation function estimation (CFE), the Eigensystem Realization Algorithm (ERA), Stochastic Subspace Identification (SSI), Frequency Domain Decomposition (FDD), and the Stochastic Damage Locating Vector method (SDLV).

Documentation is provided for each service and test application within their respective directories in the ISHMP software package. This documentation gives details on requirements and formats of the inputs and outputs for each service.

The tools and utilities are used for network testing and debugging and are necessary in any large-scale or long-term WSSN deployment to evaluate the network conditions at the structure, determine
appropriate values of adjustable system parameters, and assess power consumption and longevity
issues. Included are utilities for resetting nodes remotely, measuring battery voltage, and changing
the radio channel and power for gateway and leaf nodes.

The application tools can be categorized as either those operating on a single node (typically the
gateway node) or those that operate on multiple, distributed leaf nodes. The single-node application
tools include a gateway node sensing tool (*LocalSensing*), a terminal program for interfacing the
base station PC with the gateway Imote2 (*imote2comm*), and a numerical service that simulates the
identification of potential structural damage locations from injected acceleration data (*TestServices*).

The distributed nature of the multi-node application tools requires careful scheduling and
coordination of network tasks, making them more susceptible to failure if any of the nodes in the
network malfunctions. Efforts have been made to ensure that the applications continue to operate
even when one or more of the nodes in the network exhibit unexpected behavior. The distributed
applications tools include a tool to test the raw bi-directional communication between a sender and
a group of receiving nodes (*TestRadio*), a flexible network-wide synchronized sensing application
(*RemoteSensing*), and a sample application that demonstrates a decentralized approach to SHM data
collection and aggregation (*DecentralizedDataAggregation*, Sim and Spencer 2009).

All of the services introduced here are described in more detail in Rice et al. (2010). Sim and
Spencer (2009) provide instructions and examples for creating applications using the ISHMP Toolsuite.

4. Autonomous monitoring

Three critical deployment issues drive the WSSN software that is presented in this section: 1) continuous
and autonomous monitoring, 2) efficient power management and 3) data inundation mitigation. While
these may appear to be conflicting goals, careful application design can meet the
requirements for all three. The solution is to implement a network that is only minimally active
during non-critical structural response, but becomes fully active to measure higher response levels.
The software presented in the previous section lays the groundwork for full-scale, autonomous
monitoring of civil infrastructure however, it does not address these concerns that arise when
moving from a laboratory setting to a full-scale deployment.

Ideally, full-scale WSSN deployments should require minimal external interaction after some
initialization involving the establishment of network operation parameters, unless instructed otherwise
by the network administrator. Special care must be taken in the design of the application software to
ensure a continuous and autonomous operating scenario is achieved while maintaining power
efficiency. These measures can be divided into three categories: schedule-based operations, trigger-
based operations and safeguard features. This section presents software developments in each of
these categories that, when integrated, enable full-scale, autonomous network operation.

4.1 Sleep cycling

In a traditional wired sensor implementation, power management is of little concern. The sensors
can remain active at all times and thus have the ability to be interrogated at any time to acquire
data. Unlike wired systems, one of the most critical features of a successful WSSN deployment is
the implementation of careful power management strategies. A common approach to achieving
significant energy savings in sensor network applications is to allow the sensor nodes to sleep
during periods of inactivity while waking periodically to listen for instructions (Ye et al. 2002, Wang and Xiao 2006). The Imote2 allows the processor to be put into a deep sleep mode, whereby only the clock component of the processor is supplied power; all other components are powered down. Fig.4 illustrates the power savings associated with the deep sleep mode relative to other operations of the sensor node. When the node is in the deep sleep state, it cannot send data or receive commands via the radio or the serial ports, and the LEDs do not function. Effectively, the node has no power until the sleep time expires.

While it may seem advantageous to keep the leaf nodes in the deep sleep mode for extended periods of time to save power, this approach limits the ability of the gateway node to access the network at random to send inquiries or initiate network operations. To take advantage of the power savings of the deep sleep mode, while still allowing the gateway node access to the leaf nodes, a sleep/wake cycle service called SnoozeAlarm has been implemented. When SnoozeAlarm operates on the leaf nodes (i.e., they are in the SnoozeAlarm mode), they sleep for a set period of time and then wake up for a relatively short period of time, during which they can listen and receive message. The ratio between the time spent awake and the sum of sleep time and the awake time is the SnoozeAlarm duty cycle. For optimal power saving, the duty cycle should be minimized while still allowing a long enough listen time to receive and process commands (>500 ms). The actual overall power savings associated with the use of SnoozeAlarm is dependent on the application in which it is implemented.

The SnoozeAlarm wakeup command provides an efficient method for waking a network of leaf nodes in SnoozeAlarm mode. The ReliableComm protocol for broadcasting messages to a group of leaf nodes is only successful if all of the destination nodes respond with an acknowledgement in a set period of time, thus limiting its use for waking the network. Instead, the network is woken in a serial manner using successive unicast commands from the gateway node to individual leaf nodes in the network. The gateway node cycles through the list of sleeping leaf nodes, sending a wakeup command to one node in the list each time a preset time-out timer fires. When a leaf node sends back an acknowledgement, thus indicating it received the message and is remaining awake, it is removed from the list of nodes to wake up and added to the list of nodes that have been successfully woken. This process continues until all nodes are awake or until a time-out timer expires.
4.2 Threshold triggering

One approach to ensure that important occurrences are captured by the sensor network is to designate a subset of the network to sense data on a more frequent basis than the rest of the network and provide alerts (Hui et al. 2003, Wang and Xiao 2006). In this research, the Threshold Sentry tool allows a subset of the leaf nodes to act as sentry nodes, in addition to their duties as leaf nodes. ThresholdSentry is setup on the gateway node by specifying the IDs of the leaf nodes that comprise the sentry network, the interval at which they will be asked to sense data, the duration of the data check on each sentry node, the sampling parameters for the data check, and the threshold value used for comparison in the data check. If a sentry node determines that the threshold value has been exceeded during its observation time, it sends an alert message to the gateway node. Upon receipt of the flag, the gateway node makes the decision on the next actions to implement in the network, such as waking the remaining nodes and initiating RemoteSensing. The current implementation of ThresholdSentry utilizes acceleration measurements; however other triggers, such as strain levels or wind speed, may be incorporated into the application.

The selection of sentry nodes and their threshold values should be made such that the threshold is exceeded often enough for adequate structural monitoring, but not an excessive number of times at the risk of data inundation and higher power consumption levels. Because a single threshold value is used for all sentry nodes, the nodes selected as sentry nodes should measure similar levels of vibration to ensure consistency in the events that trigger the network. For example, on a long-span bridge, the nodes located near the support piers are expected to experience much lower vibration levels than those near the mid-span of the bridge. Sentry nodes both of these locations and would exceed the threshold under very different loading circumstances.

The temporal resolution of the sentry node wakeup events is a user-defined parameter that is based on the structure being monitored, the amount of data that is required from the network and power constraints of the sentry nodes. The sentry nodes are identical to the leaf nodes in hardware and functionality. Since they wake up more often than leaf nodes to carry out sentry sensing, they will use more power. The more sentry nodes that are utilized and the less often they wake up, the more the burden of sentry sensing can be shared, thus reducing the levels of additional power usage.

The current implementation of ThresholdSentry used in conjunction with RemoteSensing allows the network to capture the occurrence of longer-duration, lower-frequency events such as high wind; however, it does not support capturing short-term, transient events such as an earthquake. The time required to wake the network and perform time synchronization prior to the collection of data would cause such events to be missed. In future network development, the network wakeup time could be reduced using a propagating wakeup message with optimized communication parameters and the order of data collection and synchronization could be switched to facilitate faster initiation of sensing.

4.3 Autonomous network operation

Achieving an autonomous SHM implementation on a network of smart sensors requires a high-level application to coordinate each of its components in response to various events. AutoMonitor has been developed to provide this functionality. AutoMonitor is present on the gateway node and serves the purpose of maintaining the RemoteSensing and ThresholdSentry parameters and coordinating the associated network tasks.
AutoMonitor is initiated via an input file that sets the parameters for each of the tasks it coordinates. Once started, it requires no additional input from the user. The selection of most of these parameters is highly application-dependent and will take a period of adjustment and refinement to optimize for each case. Many of these parameters have power consumption implications; their effect on power management must be carefully considered. Jang et al. (2010) describes the selection of these parameters for the long span bridge deployment described in the following section.

After the input file containing all of the necessary parameters is read, AutoMonitor initiates ThresholdSentry. AutoMonitor employs a timer and a counter to limit the number of RemoteSensing events that occur in a particular time period. When the gateway node receives the alert message that the threshold has been exceeded on a sentry node, it first checks whether the maximum number of RemoteSensing events in the set time period has been reached. If maximum has been reached, ThresholdSentry is resumed. If not, AutoMonitor sends a command to wake the network and initiate RemoteSensing. After RemoteSensing completes and all of the data is transferred ThresholdSentry is reinitiated.

The software components presented in this section enable continuous operation of WSSNs for SHM applications outside of the laboratory setting. This software allows critical structural response to be captured while maintaining low-power network operation the majority of the time. The AutoMonitor network management application coordinates the operation of ThresholdSentry, SnoozeAlarm and RemoteSensing to ensure autonomous and continuous functionality of the network. More details on the software implementation may be found in Rice and Spencer (2009).

5. Framework integration

The software and hardware developed in this research were validated on a cable-stayed bridge (the 2nd Jindo Bridge) in South Korea. This deployment is part of a trilateral collaboration between South Korea (KAIST), Japan (University of Tokyo) and the USA (University of Illinois at Urbana-Champaign). The purpose of the deployment is to demonstrate the suitability of the Imote2 smart sensor platform, the SHM-A sensor board, and the ISHMP software for the full-scale SHM of a bridge. The Jindo Bridges (Fig. 5) are twin cable-stayed bridges that connect Jindo Island to the far southwestern tip of the Korean Peninsula near the town of Haenam (Fig. 6). The older span finished

Fig. 5 Twin Jindo Bridges connecting Jindo Island with the Korean Peninsula with the 2nd Jindo Bridge on the left
construction in 1984 and the newer span (the 2nd Jindo Bridge) was completed in 2005. The 2nd Jindo Bridge, the subject of this study, is on the left in Fig. 5.

The primary goal of the Jindo Bridge deployment is to realize the first large-scale, autonomous network of smart sensors utilized for SHM. This deployment is expected to highlight the challenges and opportunities associated with such a large scale test-bed and thus provide rich information for researchers and engineers interested in achieving a similar SHM system. For the research presented in this paper, the primary goals of the deployment are to validate the performance of the SHM-A sensor board for full-scale testing and validate the autonomous network operation software.

In total, 70 Imote2 leaf nodes with SHM-A sensor boards have been installed on the Jindo Bridge. Currently, the network has been in continuous operation for over four months with the primary deployment challenges associated with software parameter optimization. The SHM-A sensor board has successfully captured ambient traffic loading with peak acceleration ranging from less than 5 mg to over 30 mg. Further analysis of the data resulted in the successful identification of the first twelve modes of vibration on the deck, as well as tension forces of 10 cables with large tensile stresses. More detail on the Jindo Bridge deployment, including the implementation of renewable power sources, the selection and implication of various network parameters, and the analysis result of measured data can be found in Jang et al. (2010) and Cho et al. (2010).

6. Conclusions

The research presented in this paper has laid the foundation for autonomous implementations of WSSNs for full-scale SHM of large structures. The flexible framework encompasses the necessary hardware, software and implementation considerations to enable distributed SHM strategies in a wide range of applications. The result of this research is a road map for achieving autonomous, full-scale WSSN applications to improve infrastructure monitoring practices.

The autonomous network management software implemented on a network of Imote2 smart sensors employing the SHM-A sensor board has enabled the ongoing large-scale deployment on the 2nd Jindo Bridge in South Korea. The AutoMonitor application has successfully managed the network...
by running ThresholdSentry to trigger network-wide synchronized sensing when it is necessary while limiting unnecessary or undesired data acquisition events. Thus far, the 2nd Jindo Bridge deployment has tested the limits of single-hop WSSN implementations with reasonable success and has already provided a wealth of information and insight into the critical issues that are still being addressed as part of the ongoing study. The results from this bridge represent the first autonomous, large-scale deployment of a WSSN for structural monitoring.

Acknowledgments

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Structural health monitoring of a cable-stayed bridge using smart sensor technology: deployment and evaluation

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Abstract. Structural health monitoring (SHM) of civil infrastructure using wireless smart sensor networks (WSSNs) has received significant public attention in recent years. The benefits of WSSNs are that they are low-cost, easy to install, and provide effective data management via on-board computation. This paper reports on the deployment and evaluation of a state-of-the-art WSSN on the new Jindo Bridge, a cable-stayed bridge in South Korea with a 344-m main span and two 70-m side spans. The central components of the WSSN deployment are the Imote2 smart sensor platforms, a custom-designed multimetric sensor boards, base stations, and software provided by the Illinois Structural Health Monitoring Project (ISHMP) Services Toolsuite. In total, 70 sensor nodes and two base stations have been deployed to monitor the bridge using an autonomous SHM application with excessive wind and vibration triggering the system to initiate monitoring. Additionally, the performance of the system is evaluated in terms of hardware durability, software stability, power consumption and energy harvesting capabilities. The Jindo Bridge SHM system constitutes the largest deployment of wireless smart sensors for civil infrastructure monitoring to date. This deployment demonstrates the strong potential of WSSNs for monitoring of large scale civil infrastructure.

Keywords: structural health monitoring; wireless smart sensor network; cable-stayed bridge; deployment; evaluation.

1. Introduction

Civil infrastructure systems such as bridges, buildings, pipelines and offshore structures are valuable national assets that must be maintained to ensure economic prosperity and public safety. Many bridge structures in modern countries have reached their design life and will need to be replaced or retrofitted to remain in service. Indeed in the United States, more than 149,000 bridges are structurally deficient or functionally obsolete according to the 2006 report from the Federal Highway Administration (FHWA 2009). Thus, the ability to assess the structural condition and possibly
increase the service life has been pursued widely by researchers. The enabler is structural health monitoring (SHM) – data measurement, system identification and condition assessment. To date, numerous SHM methodologies and systems have been proposed, and some of them have been applied on the full-scale bridge structures: e.g., the Alamosa Canyon Bridge (Doebling et al. 1997), the I-10 Bridge (Todd et al. 1999), the Hakuscho Bridge in Japan (Abe et al. 2000), the Bill Emerson Memorial Bridge in Missouri (Celebi et al. 2004), and the Tsing Ma Bridge in Hong Kong (Wong 2004), to name a few. Though these examples demonstrated the significant potential of SHM, the cost of obtaining the relevant information for SHM on large structures is high (Rice and Spencer 2009). For example, the Bill Emerson Memorial Bridge is instrumented with 84 accelerometer channels with an average cost per channel of over $15 K, including installation.

Wireless smart sensors offer a solution for long-term, scalable SHM of civil infrastructure by providing easier installation and efficient data management at a lower cost than traditional wired monitoring systems. Specifically, the wireless sensor unit used for the monitoring system discussed herein possesses multiple sensor channels and costs less than $500 USD each, including solar power harvesting devices. Moreover, installation time and effort is significantly less than the wired counterpart. Also, wireless smart sensors have on-board computation capability that can help to mitigate the problem of data inundation that is intrinsic to densely instrumented structures. These features of wireless smart sensors help to ensure the scalability of the SHM system to a large network necessary for long-span bridges.

Several researchers have employed wireless smart sensors to monitor bridge structures (Lynch et al. 2006, Nagayama and Spencer 2007, Kim et al. 2007, Pakzad 2008, Jang et al. 2009), providing important insight into the opportunities and challenges for WSSN technology for long-term monitoring. Critical issues identified include: (i) power management, (ii) energy harvesting, (iii) fault tolerance, (iv) autonomous operation, and (v) environmental hardening. To address these research challenges, an international test bed employing a cable-stayed bridge in South Korea was developed.

This paper reports on the deployment and evaluation of a state-of-the-art WSSN on the Jindo Bridge. This effort is part of a trilateral 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). The test bed bridge has a 344-m main span and two 70-m side spans, connecting mainland South Korea with Jindo Island across the sea. The main components of the WSSN deployment are the Imote2s (Crossbow Technology 2009), custom-designed multimetric sensor boards, base stations, and software provided by the ISHMP Services Toolsuite (Rice and Spencer 2009). Although the functionality and the stability of each component has been previously verified by a series of experiments both at the laboratory scale and for small full-scale bridges, various factors at the monitoring site make this deployment quite challenging and will be discussed in this paper. In total, 70 sensor nodes and two base stations have been deployed to monitor the bridge using an autonomous SHM application with excessive wind and vibration triggering the system to initiate monitoring. Finally, the performance of the system has been evaluated in terms of hardware durability, software stability, power consumption and energy harvesting options.

2. Bridge description

The Jindo Bridges are twin cable-stayed bridges connecting Haenam on the mainland with the
Jindo Island (see Fig. 1). The Jindo Island is the third largest island in South Korea, and Haenam, which is located in the south-west tip of the Korean peninsula. Each of these bridges consists of three continuous spans, with a 344-m central main span and two 70-m side spans.

The original Jindo Bridge, constructed in 1984 by Hyundai Engineering & Construction Co., Ltd., was the first cable-stayed bridge in South Korea. The width of the bridge is 11.7-m, the design traffic velocity is 60 km/hr, and the design live load is based on AASHTO HS-20-44 (DB-18). The second Jindo Bridge was constructed in 2006 by Hyundai Engineering & Construction Co., Ltd., Daelim Industrial Co., Ltd. and Namhei Co., Ltd. The width of the second bridge is 12.55 m, the
traffic design velocity is 70 km/hr, and the design live load is based on AASHTO HS-20-44 (DB-24, DL-24). It has a streamlined steel box girder supported by 60 high-strength steel cables connected to two pylons. The structural drawing of the bridge is shown in Fig. 2.

Both bridges have existing SHM systems based on wired sensors. The first Jindo Bridge has 38 strain gages, four inclinometers, two anemometers, two seismic accelerometers, five uniaxial capacitive accelerometers, and 15 uniaxial piezoelectric accelerometers. The second Jindo Bridge has 15 thermometers, 15 strain gages, four biaxial inclinometers, two string pots, two laser displacement meters, 24 Fiber Bragg Grating sensors, 20 uniaxial capacitive accelerometers, two biaxial force balance type accelerometers, and three triaxial seismic accelerometers. Among two bridges, the second Jindo Bridge is selected as the test bed for this research, for two primary reasons: (i) the existing SHM system is quite versatile, including accelerometers and fiber optic sensors and (ii) the design and construction documents are more complete.

3. Bridge monitoring system

3.1 Hardware

The wireless smart sensor is the key element of the bridge monitoring system. Two hardware configurations are employed: a gateway node attached to the base station PC, and battery-operated leaf nodes at remote locations to the base station. Because the wind excitation is the major source of bridge vibration, two types of sensor boards have been employed: the SHM-A sensor board to measure vibrations and the SHM-W sensor board to measure signals from an anemometer. To evaluate the potential for long-term deployment, solar panels and rechargeable batteries have been installed on selected nodes.

3.1.1 Smart sensor nodes

Each smart sensor unit consists of an Imote2, an IBB2400CA battery board, and the SHM-A multi-scale sensor board. The Imote2 is a high-performance wireless smart sensor platform, having Intel’s PXA271 XScale® processor running at 13-416 MHz and an MMX DSP Coprocessor (Crossbow Technology 2007). The memory size is increased significantly from the previous generation of motes, having 256 kB SRAM, 32 MB FLASH and 32 MB SDRAM, which enables longer measurements, as well as the on-board computation. The IBB2400CA battery board is designed to power the Imote2 using three 1.5-volt batteries.

The SHM-A sensor board has been designed for monitoring civil infrastructure through the Illinois SHM Project, an interdisciplinary collaborative effort by researchers in civil engineering and computer science at the University of Illinois at Urbana-Champaign (Rice et al. 2010). The tri-axial accelerometer employed is the ST Microelectronic’s LIS344ALH, which has a range of ±2 g. The analog acceleration signals from the accelerometers are digitized by the Quickfilter QF4A512, which has a 4-channel, 16-bit Analog to Digital Converter (ADC) and programmable signal conditioner with user-selectable sampling rates and programmable digital filters. The resolution of the ADC is 16 bit, and the noise levels of the accelerometer are 0.3 mg for the x- and y-axes and 0.7 mg for the z-axis. The SHM-A board also contains temperature, humidity and light sensors. An additional analog input allows this board to measure data from many other types of sensors such as anemometers and strain gages. Four sampling frequencies (10, 25, 50, 100 Hz) have been pre-programmed on the
SHM-A board for this bridge monitoring application; however, the sampling rate can be chosen nearly arbitrarily by designing appropriate filters for the QF4A512. The components of the SHM-A sensor board are identified in Fig. 3. More details can be found in (Rice et al. 2010).

Two hardware configurations of smart sensor nodes are required for the wireless communication and sensing: a gateway node for sending commands and receiving wireless data from the network, and the battery-powered nodes remote to the base station. The gateway node consists of an Imote2 stacked on an IIB2400 interface board connected to the base station PC via a USB/UART port. The leaf nodes consist of an SHM-A sensor board and Imote2 stacked on the battery board as shown in Fig. 4. To increase the communication range, both nodes are equipped with an Antenova gigaNova Titanis 2.4 GHz external antenna (Antenova 2009). The sensor nodes are placed in environmentally hardened enclosures to endure the harsh environment at the Jindo Bridge site.

3.1.2 Wind monitoring system: modified SHM-A board with anemometer

The Jindo Island is located in Haenam, one of the windiest regions in South Korea with several typhoons each year. A cable-stayed bridge like the Jindo Bridge is sensitive to such strong wind; thus, an important objective of this study is monitoring the wind and the associated dynamic responses of the bridge.

A 3-D ultra-sonic anemometer has been incorporated into the WSSN for reliable wind monitoring of the Jindo Bridge. Because of its high resolution (wind speed: 0.01 m/s, wind direction: 0.1 degree) and good accuracy (wind speed: ±1%, wind direction: ±2 degrees), the RM Young Model 81000 anemometer was chosen (see Fig. 5(a)). The durability of ultra-sonic anemometers makes them well-suited for long-term operation in harsh environment. Moreover, the anemometer’s analog voltage outputs, ranging from 0 to 5V, can be easily accommodated by the SHM-A board with...
small modifications.

The SHM-W board is developed by modifying the SHM-A board to have three external 0-5V input channels and one acceleration channel. The wind speed (channel 1), horizontal and vertical wind directions (channels 2 and 3) are measured through analog input interface connectors on the SHM-W board as shown in Fig. 5(c). Because the SHM-W board also uses the QFA512-based sensor board, it uses the same software drivers as the SHM-A board; as a result, the wind data is acquired precisely synchronized with the acceleration data from the SHM-A board. Another modification for SHM-W board is that it is adjusted so that the full range of the 0-5V inputs is utilized, resulting in better resolutions for the wind data.

3.1.3 Energy harvesting with solar panels

While battery power provides a convenient and readily-available solution for WSSNs, the drawback is that regular battery replacements are required for long-term deployments. From this perspective, energy harvesting is important for long-term operation of the wireless SHM systems. Roundy _et al._ (2004) compared the power densities of available harvesting sources such as sunlight, thermal gradient, human motion, vibration and acoustic noise, etc. As shown in Table 1, the power density of the solar cells is the largest, showing the potential to increase the network lifetime to longer than one year. Therefore, solar panels and rechargeable batteries have been chosen as energy harvesting/power system and installed on several leaf nodes at locations where battery replacement is difficult.

The Imote2 can be powered by rechargeable batteries using the Power Management Integrated Circuit (PMIC) (Miller and Spencer 2009). The PMIC can be connected directly to Lithium-Ion or Lithium-Polymer batteries without a protection diode; the diode can be bypassed with an additional zero-ohm resistor (R1). To allow the current from solar panel to flow into the battery, the nCHARGE-EN pin, which is a control switch to decide battery options, should be pulled low with

<table>
<thead>
<tr>
<th>Harvesting technology</th>
<th>Power density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar cells (outdoors at noon)</td>
<td>15 mW/cm²</td>
</tr>
<tr>
<td>Piezoelectric (shoe inserts)</td>
<td>330 μW/cm³</td>
</tr>
<tr>
<td>Vibration (small microwave oven)</td>
<td>116 μW/cm³</td>
</tr>
<tr>
<td>Thermoelectric (10 °C gradient)</td>
<td>40 μW/cm³</td>
</tr>
<tr>
<td>Acoustic noise (100 dB)</td>
<td>960 nW/cm³</td>
</tr>
</tbody>
</table>
Structural health monitoring of a cable-stayed bridge using smart sensor technology

Considering the range of input power that the Imote2 can support (4.6–10 V, up to 1400 mA), the SPE-350-6 solar panel from Solarworld (9 V-350 mA) shown in Fig. 7(a) was employed. A Powerizer lithium-polymer rechargeable battery (Powerizer 2009) was selected, which reaches up to 4.2 V when fully charged. This system has 10,000 mAh capacity (half of that of D-cell batteries), will allows this system to supply power to the Imote2 for an extended period without recharging.

3.2 Software: ISHMP services toolsuite

The Illinois SHM Project developed a suite of services, denoted the ISHMP Services Toolsuite, that implements key middleware functionality to provide high-quality sensor data and to transfer the data reliably to the base station via wireless communication across the sensor network, and a library of numerical algorithms. This open-source software is available at http://shm.cs.uiuc.edu/software.html. More detailed information regarding this software can be found in Rice et al. (2010).

The toolsuite components are categorized into foundation services, application services, tools and utilities, and continuous and autonomous monitoring services. The foundation services provide the fundamental functionalities to measure synchronized sensor data reliably (Mechitov et al. 2004,
Nagayama and Spencer 2007, Rice et al. 2008). 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. The key features of these services include RemoteSensing, a remote data measurement application; DecentralizedData Aggregation, data measurement and on-board computation to calculate the correlation functions for decentralized local groups; imote2comm and autocomm, an automatic terminal tool to interact between the base station PC and a gateway node; Vbat, a command for checking a leaf node’s battery level; TestRadio, a tool for assessing radio communication quality, and many others.

The continuous and autonomous monitoring service critical for this deployment is AutoMonitor, an autonomous SHM network management application, which combines RemoteSensing, ThresholdSentry, and SnoozeAlarm (Rice and Spencer 2009). SnoozeAlarm is a strategy that allows the network to sleep most of the time, thus improving energy efficiency and allowing long-term system deployment. To wake the network for an important event, the ThresholdSentry application defines a specified number of the leaf nodes as sentry nodes. The sentry nodes wake up at predefined times and measure a short period of acceleration or wind data. When the measured data exceeds a pre-defined threshold, the sentry node sends an alarm to the gateway node, which subsequently wakes the entire network for synchronized data measurement. In this way, AutoMonitor enables the automatic, continuous monitoring with reduced power consumption.

The AutoMonitor application employs multiple threshold levels for the Jindo Bridge SHM system. When a single threshold level is used to define the maximum number of events during given period, if the threshold level is too high, the data measurements would rarely if ever occur. If too small a threshold level is used, the number of events can be exhausted with small structural responses, hence possible strong vibrations during remaining period cannot be captured. The multiple threshold levels, having separate maximum number of events, make it possible to measure both rare but strong responses and frequent but low-level ambient vibration during a given period, which enables more effective SHM.

Another feature of the AutoMonitor application is a wind threshold sentry. The wind sentry node is equipped with SHM-W sensor board with ultrasonic anemometer. Strong winds, such as those that occur during typhoons, induce large structural responses. Therefore, the wind sentry will trigger network sensing when the velocity exceeds a threshold. In this deployment, both vibration- and wind-based sentry nodes have been installed for the AutoMonitor application. In summary, the final software version is the AutoMonitor application having both data measurement and on-board computational functionality, a multiple threshold triggering strategy using vibration/wind sentries pursuing energy efficiency using SnoozeAlarm.

4. Deployment of the SHM system

The developed hardware and software framework has been deployed on the Jindo Bridge to realize the first large-scale, autonomous, WSSN-based SHM system. Due to the harsh environment at the site, the delicate electrical components of the SHM system have been hardened to prevent corrosion, overheating, or other damage. Also, many verification and optimization steps have been required to extend the laboratory-scale SHM system to a full-scale deployment for a long-span bridge structure. The details of the hardening and optimization process are provided in this section.
4.1 Network topology

The network topology is carefully determined to ensure reliable network sensing for the Jindo Bridge. The major factors to define the network topology are the size of network, the communication range, etc. The total length of the bridge is 484 m, the communication range of Imote2 with external antenna is ~200 m, and the number of sensor nodes in network is 70. Considering the range and the communication time, the network was divided into two sub-networks: one on the Jindo side and the other on the Haenam side.

The Jindo sub-network consists of 33 nodes with 22 nodes on the deck, three nodes on the pylon, and eight nodes on the cables. The Haenam sub-network consists of 37 nodes with 26 nodes on the deck, three nodes on the pylon, and seven nodes on the cables. Each sub-network is controlled by a base station located on the concrete piers supporting the steel pylons of the first Jindo Bridge. These locations were chosen to achieve consistent line-of-site communication with leaf nodes.

4.2 Base station

4.2.1 Components of base station

Because the base station provides access to the WSSN, it is critical to the performance of the entire network. The base station controls the network by 1) sending messages to the leaf nodes, 2) storing the transmitted data from the WSSN, 3) processing received data and 4) transferring the data to the remote server via internet. To achieve these functions, the base station is composed of an industrial-grade PC running Windows XP Professional OS, an uninterrupted power supply (UPS) backup, a gateway node and an environmentally hardened enclosure as shown in Fig. 8.
An industrial-grade PC AAEON AEC-6905 was adopted as a base station for its fan-less architecture, protecting it from dust and moisture. The UPS backup APC ES550 protects the base station components from an unexpected electric surges and outages. The gateway node is consisted of an Imote2 stacked with an interface board for interactive serial communication and SHM-A sensor board and 2.4 GHz 5 dBi dipole antenna as shown in Fig. 9. A wired internet line was installed to the PC with an ADSL internet modem to provide remote access to base station, to control the WSSN, and to download the measured data.

Software for remote control and data download is installed on the base station. On the top of basic OS and anti-virus software, the key components of software are Cygwin and the autocomm executable application for interfacing with the gateway node, the VNC (Virtual Network Computing) server for remote desktop control, and an FTP (File Transfer Protocol) server to remotely download the measured data.

4.2.2 Environmental concerns and solutions

The environmental solution for stability of the base stations is provided when it is exposed to environmental load such as sunlight, rain, snow, fog and typhoon. The site of the Jindo Bridge is often subject to high humidity due to frequent fog and harsh winds. To protect electric components from damage, ABS enclosures were employed to house the base stations. This industrial-grade PC was found to radiate significant heat, which results in shut down of the PC by drastically increasing the temperature inside the enclosure. To address this problem, the enclosure was modified to include two-way ventilation as shown in Fig. 10. All ventilation openings have anti-bug nets and rain-protection brackets, and the exhaust fan is connected to a temperature sensor inside the enclosure. If the temperature in the enclosure is over 35 °C, the fan will automatically turn on. In addition, the power cable, the USB cable to the gateway node, and the LAN cable to the wired internet line pass through the enclosure wall via cable glands. This enclosure with the ventilation system has provided effective and stable operation of the base station.

Fig. 10 Ventilation enhancements for base station enclosure
4.3 Smart sensor nodes

4.3.1 Environmental hardening and sensor installation

The leaf nodes were also placed in environmentally hardened enclosures. Water-tight PVC enclosures were employed protecting from moisture as well as not interfering with radio communication as shown in Fig. 11. The battery board is modified to employ three D-cell batteries instead of standard AAA batteries. The nominal voltage of both a single AAA and a single D-cell battery is 1.5V, while the capacity of an alkaline D-cell battery is 20,000 mAh, versus 1,200 mAh for an AAA alkaline battery; thus, enabling significantly longer network operation. The size of the enclosure is primarily dependent on the size of the batteries.

To increase the radio communication range, the Imote2 has been modified to use an external antenna (Linderman et al. 2010; Antenova gigaNova Titanis 2.4 GHz external antenna (Antenova 2009). The external antenna is mounted to the enclosure and then connected to the Imote2 with an antenna extension cable. The sensor unit is mounted separately from the battery holder. The bottom of the battery board is attached on the enclosure using the Scotch® Exterior Mounting Tape.

The smart sensor nodes for the deck, pylons and cables are mounted using different methods. The leaf nodes on the deck are mounted upside down on the bottom side of deck using magnets. The leaf nodes on the pylons also employed the magnets for attachment. This magnet is one-directional and has 10 kg holding capacity (Fig. 12(a)). Using two magnets on the bottom of each enclosure, the secure connection between the sensor enclosure and the bridge steel surface is ensured. In addition, the magnets are surrounded by double-sticky Styrofoam panel with the thickness of the
magnet, to prevent the vibration due to the vortex-shedding in the gap between the enclosure and structure surface (see Fig. 12(b)). This approach reduces the installation time and effort under the deck; however, the magnet-based method is not feasible for the cable sensors due to round surface. Therefore, the leaf nodes on the cables are mounted using two U-bars and aluminum mounting plate as shown in Fig. 11(c). Because these nodes are directly exposed to sun light, the stainless steel cover is employed to protect the PVC enclosure.

4.3.2 Software setup and verification

Two software configurations have employed to prepare the smart sensor nodes. The gateway nodes have been programmed with the AutoMonitor application to control the autonomous monitoring of the network. The leaf nodes have been programmed with the RemoteSensing, which combined with TestRadio, and DecentralizedDataAggregation (Sim and Spencer 2009). In the AutoMonitor application, users can decide whether raw acceleration data or correlation functions using decentralized estimation from the local groups are returned to the base station by selecting either RemoteSensing or DecentralizedDataAggregation, respectively.

The software performance using a large network of wireless smart sensor nodes have been previously verified both in the laboratory and field environments after programming the nodes. After loading the software, a number of autonomous monitoring application tests were conducted to check the performance both in the laboratory and the field. The purpose of these tests is to verify the long-term network stability under various operation scenarios with 40 nodes. During the tests, basic communication parameters were modified to accommodate the large network size.

Fault tolerance features for robustness of the software have also developed because a human operator cannot constantly monitor the state of the monitoring system. To this end, the AutoMonitor application provides several features, including: (1) sending the network wake-up command repeatedly, as in some cases a node can return to the sleep mode soon after waking up, (2) skipping over unresponsive nodes after a short timeout when sending commands or receiving data, and (3) rebooting the leaf nodes in case of failures of component services that may leave the node in an inconsistent state and prevent further operation. Additionally, the AutoMonitor application coordinates with its component services (SnoozeAlarm, ThresholdSentry and RemoteSensing) to handle internal errors in those services in a consistent manner. After the software setup and verification was completed, all leaf nodes were deployed on the bridge at the locations indicated in Fig. 14.

4.3.3 Communication range tests for sensor placement

![Communication range test](image)

Fig. 13 Communication range test (73 sensors tested)
Because single-hop communication was used for this deployment, radio communication tests were conducted on-site using the TestRadio application to measure the packet reception rates at various communication distances. During the communication range tests, the gateway node was located at the Haenam side pylon and the leaf nodes were gradually moved out to the mid-span. The number of sensors which were unresponsive to the TestRadio request from the gateway node was counted as shown in Fig. 13. In total, 73 Imote2s were tested and five nodes were found to be unresponsive and subsequently replaced. At the mid-span at 172 m, 23 Imote2s were found to communicate effectively. Based on these radio communication tests, sensors location were optimized as shown in Fig. 14.

4.3.4 Optimal antenna direction

The antenna orientation is optimized based on the influences of network environment to determine optimal network performance. The antennas should be co-linear, to ensure optimal radio communication. The electric field component in the desired orientation is referred to as the co-polarized field and any field in the perpendicular (undesired) direction is referred to as the cross-polarized field (Linderman et al. 2010). Optimizing the antenna orientation is not a simple problem for large WSSNs because elevations of sensors are different for those under the deck, at the side of the pylon, on the top of the pylon and the cable nodes. The antenna direction of the gateway node is critical to reliable communication with all leaf nodes. Therefore, the antenna for the gateway node and all leaf nodes are oriented perpendicular to the longitudinal axis of the bridge and parallel to the ground as shown in Fig. 15. In this manner, all sensors can communicate with the gateway node efficiently. This configuration has been verified through communication tests.

5. Communication parameter optimization

The communication parameters have been optimized to operate the large WSSN on a long-span
Table 2 Software parameters for the Jindo Bridge deployment

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameter</th>
<th>Initial state</th>
<th>Updated state</th>
</tr>
</thead>
<tbody>
<tr>
<td>RemoteSensing</td>
<td>Number of RemoteSensing events</td>
<td>1 per day</td>
<td>4 per day</td>
</tr>
<tr>
<td></td>
<td>Time synchronization wait time</td>
<td>30 sec</td>
<td>30 sec</td>
</tr>
<tr>
<td></td>
<td>SENSING START DELAY</td>
<td>15,000</td>
<td>50,000</td>
</tr>
<tr>
<td></td>
<td>NODE SENSING START DELAY</td>
<td>1,000</td>
<td>1,500</td>
</tr>
<tr>
<td></td>
<td>Sampling frequency</td>
<td>50 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td></td>
<td>Channels sampled</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Number of data points</td>
<td>1,000</td>
<td>5,000</td>
</tr>
<tr>
<td>Snooze Alarm</td>
<td>SnoozeAlarm wake/listen time</td>
<td>750 ms</td>
<td>750 ms</td>
</tr>
<tr>
<td></td>
<td>SnoozeAlarm sleep time</td>
<td>15 sec</td>
<td>15 sec</td>
</tr>
<tr>
<td></td>
<td>SnoozeAlarm duty cycle</td>
<td>4.76%</td>
<td>4.76%</td>
</tr>
<tr>
<td>ThresholdSentry</td>
<td>ThresholdSentry check interval</td>
<td>20 min</td>
<td>10 min</td>
</tr>
<tr>
<td></td>
<td>ThresholdSentry Sensing time</td>
<td>10 sec</td>
<td>10 sec</td>
</tr>
<tr>
<td></td>
<td>Threshold value for vibration sentry</td>
<td>10 mg</td>
<td>10 mg, 50 mg</td>
</tr>
<tr>
<td></td>
<td>Threshold value for wind sentry</td>
<td>N/A</td>
<td>3 m/sec, 8 m/sec</td>
</tr>
<tr>
<td>Watchdog Timer</td>
<td>Period</td>
<td>10 min</td>
<td>60 min</td>
</tr>
<tr>
<td></td>
<td>Update</td>
<td>1 min</td>
<td>60 min</td>
</tr>
</tbody>
</table>

bridge in terms of RemoteSensing, DecentralizeDataAggregation, SnoozeAlarm, ThresholdSentry and Watchdog Timer. Table 2 shows the list of the network parameters and values for the initial state and the updated state. First of all, the number of times that the RemoteSensing application can be run is updated from once per day to four times a day. The primary concern for the number of measurement events is the power consumption. After pre-deployment with the initial parameters, it was found that the maximum number of the measurement events could be increased to four times a day without significantly increasing the power consumption of the WSSN.

The communication waiting times are important for successful operation of RemoteSensing with large networks of smart sensors. There are four steps in RemoteSensing: (1) network time synchronization, (2) sending measurement parameters from the gateway to leaf nodes, (3) data collection and (4) transferring data back to the gateway node and saving the data on the base station. The first communication wait time is for time synchronization. The second wait time is the time required to
send the sensing parameters to all of the nodes in the network. This total wait time is expressed by

\[ T = S_c + n \cdot S_n \]  

(1)

where, \( S_c \) is a constant wait time, \( S_n \) is a short nodal wait time for each sensor denoted as, and \( n \) is the number of sensors. These two parameters are increased in the updated state considerably because the communication took a longer time for the long distances between the leaf nodes.

The data measurement parameters include the sampling frequency, the measurement directions, and the number of data point for each channel. 10,000 data points are measured in three directions at 10 Hz.

The \textit{SnoozeAlarm} parameters include the duration of the wake/listen time and the sleep time. The sleep time can be chosen based on the target excitation. For Jindo Bridge, loading from strong winds from typhoons having a duration of several hours to a day is significant. For such excitations, waking the network up within several minutes of a trigger event is quite reasonable. To accommodate this, the deep sleep interval is set to 15 seconds, and the wakeup time to listen for commands is 750 ms. With this setup, the wake up time for the entire network was in the range of 1–5 minutes based on the radio communication conditions.

The \textit{ThresholdSentry} parameters include the number of sentry nodes used in the network. The number of sentry nodes for this deployment is three for Haenam side and two for Jindo side. The sentry checks the acceleration level frequently to catch large vibration due to strong winds. The sentries are set to wake up every 10 minutes and measure the acceleration for 10 seconds. The threshold values for the vibration sentry are 10 mg and 50 mg, so that large vibration events more than 50 mg should be recorded. For the wind sentry, the thresholds are 3 m/sec and 8 m/sec to measure both the usual state of wind-induced vibration (3-4 m/sec) and stronger wind vibration events.

Finally, a \textit{Watchdog Timer} is used to reset the nodes to ensure the network reliability in the case of a node hanging due to some unexpected error. The Watchdog update time is the waiting time before the processor resets the node when the node gets hung up. Using this setup, an indefinite hang-up of nodes may be avoided. The Watchdog period should be longer than the measurement duration so that the Watchdog timer does not interrupt the measurement and reset the leaf nodes. The Watchdog update was set to one minute, and the Watchdog timer period is set to 10 minutes during the initial state, because the network sensing takes less than 10 minutes. This is updated to 60 minutes and 60 minutes respectively for the updated state to measure longer data with increased distances of sensor distribution.

6. Evaluation of the SHM system

6.1 Hardware performance

The hardware components including smart sensor nodes base stations and the anemometer with many installation details have shown reliable performance during this deployment. One of the biggest enablers of the deployment on the Jindo Bridge is the SHM-A sensor board. The resolution of the sensor board is ~0.3 mg and adequate to measure the bridge vibration in the range of 5–30 mg. The programmable sampling frequency features are critical to capture major natural frequencies of the bridge under 1 Hz as opposed to ITS400CA basic sensor board (MEMSIC 2010) support higher sampling frequency than 280 Hz. Furthermore, the modified SHM-A board with an anemometer, the
SHM-W sensor board, has reliably measured the wind information; however, the horizontal component of the wind direction is not measured by channel 2 of the SHM-W board because of a hardware malfunctioning problem on the anemometer.

The two base stations have been functioning reliably for four months, enabling stable remote monitoring of the Jindo Bridge and communication with each gateway node. When checking the condition of the inside of the base station enclosure after four months of operation, it was confirmed that it has successfully protected the computer from overheating and the harsh environment.

The enclosures for the leaf nodes have also performed well. The inside of sensor enclosure was dry and the temperature was acceptable. The magnet-based attachment has proven to be an excellent solution for the Jindo Bridge because all leaf nodes have been attached firmly for four months.

6.2 Software performance

The AutoMonitor application has shown stable performance after appropriate optimization of the sensing and radio communication parameters. All software is operating reliably and remotely desktop using a VNC® server. RemoteSensing and DecentralizedDataAggregation work successfully with optimized communication parameters.

The ambient vibration data at the Jindo Bridge has been acquired from the WSSN. One sample of recorded data has shown in Fig. 16, of which levels are ~8 mg, ~40 mg, ~5 mg for the deck, cable and pylon, respectively.

The power spectral densities (PSD) of the vibration data have been investigated. Fig. 17(a) shows the PSDs of the deck vibrations at the mid span, quarter span and at the pylon. The PSD magnitude of deck sensors near pylon is almost zero; however, the other two sensors at the mid span and the quarter span show significant energy around 0.44, 0.66 and 1.03 Hz, implying the natural frequencies of the bridge. Fig. 17(b) shows the comparison between the PSD from the existing wired sensor at the quarter span and the PSD from the deployed wireless sensor at the same location. Though the wired sensor data was measured in 2007 and the wireless sensor data was measured in 2009, most natural frequencies agree well with the previous data.

Fig. 18 shows the PSD from six cables sensors and from the pylon sensors the one in the side and at the top. For the cable sensors, the consistent peaks are shown around 0.44, 0.66, 1.03 Hz for all sensors and different peaks for various cables in other frequency regions. The natural
frequencies of the pylon sensor in the side (1) and of the one at the top are different. Detailed modal analysis and detailed cable tension estimation is described in the companion paper in this issue (Cho et al. 2010).

6.3 Wind speed and direction

The wind speed and direction has been successfully measured using the 3D ultra-sonic anemometer at the mid span. The outputs of the SHM-W sensor board are raw voltage measurements from the anemometer. This data have been converted to the wind speed and voltage using the anemometer sensitivity. The data are synchronized with vibration data measured by SHM-A sensor board. Fig. 19 shows example data. In this sample data, the wind speed was 4-6 m/sec and the direction is zero degrees to the longitudinal direction of the bridge.
Fig. 20 shows the operating time for the RemoteSensing application in terms of various phases for different requested sample sizes. In total, three axes of accelerations were measured at 50 Hz from 23 sensor nodes. In this specific deployment, the communication time sending data back to the gateway node has been measured. Although the total communication time depends on various environmental and communication factors, the communication time shows a linear relationship with the number of requested data points as shown in Fig. 20. Based on this result, the total communication time to acquire 30,000 points from 46 sensor nodes of two networks is about 30 minutes.

6.4 Power consumption

The battery voltage levels for all nodes in both sides have been recorded for two months as shown in Fig. 21. The average initial voltage of the three D-cell batteries on each sensor nodes was 4.6 V, and the average on board voltage reading using RemoteVbat command was 4.2 V. The on board voltage reading is 0.3–0.4 V less than the actual battery voltage because of the diode drop on the battery board to prevent damage due to incorrect installation of the batteries. From 8/27/09 to 9/8/09, the parameters stored in FLASH on each Imote2 were uploaded many times to optimize
network performance, which is a power demanding procedure. After 9/8/09, the AutoMonitor application has run continuously to measure the data. During this period, the power consumption has been approximately linear. The minimum onboard voltage for sensing is 3.4 V. The power consumption depends on the frequency of data measurement, data length, and sleeping parameters. Based on once-a-day measurement with the network parameters mentioned in Table 2, three D-cell batteries can operate about two months.

6.5 Energy harvesting strategy using solar power

In total, eight sensor nodes employ solar panels and rechargeable batteries. Five of the solar powered sensor nodes are on the cables, two on the pylons, and one on the deck. Fig. 22 shows the voltage of the solar rechargeable batteries during monitoring. The voltage levels of the rechargeable

![Graph showing charging status of solar rechargeable batteries on Jindo Bridge SHM system](image)

**Fig. 22** Charging status of solar rechargeable batteries on Jindo Bridge SHM system
battery have maintained around 4.15 V, which confirms that the charging process of the solar power system is working well. However, the solar powered node located under the deck (Haenam side, node 6) shows a continuous decrease in the voltage level. The reason for the decrease is that it only can receive indirect reflected sunlight, because its orientation is downward. Either a more sensitive solar panel, reorienting the panel, or another type of energy harvesting system should be considered for sensors located under the deck in the next deployment.

7. Conclusions

A state-of-the-art SHM system using a WSSN has been successfully deployed on the Jindo Bridge in South Korea to verify the performance of the system and to serve as a driver for advancement of smart sensor technology. The Imote2 has been selected as the wireless sensor platform to use along with custom-designed SHM-A and SHM-W sensor boards. An autonomous structural monitoring system has been developed employing a threshold detection strategy and an energy-efficient sleeping mode to extend the network lifetime. Solar powered nodes have been employed to investigate the possibility of energy harvesting to power the sensor network.

In total, 70 sensor nodes have been installed, divided into two sub-networks to decrease the communication time and because of the limit of the radio communication range. All sensors are carefully located based on radio communication capability determined by extensive radio communication tests. The measured data shows a good agreement with data from the existing wired system, which verifies that the data quality of the WSSN is reliable. Successful deployment of this WSSN demonstrates the suitability of the Imote2 smart sensor platform, the SHM-A sensor board, and the ISHMP software for full-scale, continuous, autonomous SHM.

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Structural health monitoring of a cable-stayed bridge using smart sensor technology


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Structural health monitoring of a cable-stayed bridge using wireless smart sensor technology: data analyses

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Abstract. This paper analyses the data collected from the 2nd Jindo Bridge, a cable-stayed bridge in Korea that is a structural health monitoring (SHM) international test bed for advanced wireless smart sensors network (WSSN) technology. The SHM system consists of a total of 70 wireless smart sensor nodes deployed underneath of the deck, on the pylons, and on the cables to capture the vibration of the bridge excited by traffic and environmental loadings. Analysis of the data is performed in both the time and frequency domains. Modal properties of the bridge are identified using the frequency domain decomposition and the stochastic subspace identification methods based on the output-only measurements, and the results are compared with those obtained from a detailed finite element model. Tension forces for the 10 instrumented stay cables are also estimated from the ambient acceleration data and compared both with those from the initial design and with those obtained during two previous regular inspections. The results of the data analyses demonstrate that the WSSN-based SHM system performs effectively for this cable-stayed bridge, giving direct access to the physical status of the bridge.

Keywords: wireless smart sensor network; cable-stayed bridge; structural health monitoring; modal identification; cable tension estimation.

1. Introduction

Jang et al. (2010) describes field deployment of structural health monitoring (SHM) system using wireless smart sensor technology on a cable-stayed bridge in Korea (the 2nd Jindo Bridge). A total of 70 wireless smart sensor nodes are installed with high spatial density on the bridge, facilitating measurements of 3-axis acceleration underneath of the deck, on two pylons, and on the cables. Using two base stations, measurement has been carried out during the past 4 months using an autonomous monitoring system based on the SHM framework proposed by Rice et al. (2010). Overall performance of the system has been evaluated in terms of hardware durability, software stability, power consumption and harvesting (Jang et al. 2010).

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The next generation of SHM systems must move from the *nice-to-have* to the *need-to-have* paradigm that is essential and beneficial for structure operation and maintenance (Fujino et al. 2009). To date, wireless smart sensing technology has been studied in depth by many researchers for monitoring large civil infrastructures; however, only a few full-scale deployments have been realized, most of which were for demonstration purposes only. For example, Weng et al. (2008) reported a monitoring campaign to determine the modal properties of the Gi-Lu cable-stayed Bridge in Taiwan using 12 wireless sensing units interfaced to velocity meters. Various sensor configurations (i.e., on the deck only or both on the deck and cables) were considered to identify the modal properties of the global structure, as well as cable tension forces. Pakzad et al. (2008) instrumented a total of 64 wireless sensor nodes on the deck, one of the towers, and several cables of the Golden Gate Bridge. A pipeline multi-hop communication protocol was successful to collect the measured data, which was utilized to evaluate the performance of the wireless sensor network, as well as to identify modal properties of the bridge. Both of these efforts were short-term demonstration projects.

This paper assesses the performance of the wireless SHM system installed at the 2nd Jindo Bridge by analyzing the measured acceleration data. This cable-stayed bridge in Korea is a structural health monitoring (SHM) international test bed for advanced wireless smart sensors network (WSSN) technology. First, a finite element (FE) model is constructed based on an in-depth study of the detailed drawings and design documents, and validated using the acceleration data from the existing wired monitoring system on the bridge. The acceleration data collected from the current wireless smart sensor network (WSSN) at two base stations (Haenam-side and Jindo-side) are subsequently analyzed. Two output-only modal identification (ID) methods are used to extract the modal properties of the bridge from the ambient acceleration data of the deck and the pylons. The extracted modal properties from both modal ID methods are validated by comparing with each other and with those from the FE analysis. Tension forces are estimated on 10 of the bridge’s stay cables using data collected from the sensor nodes mounted on the cables. The estimated tension forces are compared both with those used in the initial design and with those obtained during the regular inspections in 2007 and 2008. Finally, a discussion is provided regarding the efficacy of the monitoring strategy utilizing the WSSN for comprehensive SHM of the cable-stayed bridge.

2. Finite element model of Jindo Bridge

2.1 Construction of finite element model

Prior to the sensor deployment, a finite element (FE) model of the 2nd Jindo Bridge is constructed for validation of the analysis results of the measured data based on detailed drawings and design documents. A commercial structural analysis software, MIDAS/CIVIL (MidasIT 2009), is used. The bridge’s main box girder is modeled by 128 frame elements with 6 different sectional properties. Additional masses are appended to the girder to represent the pavement, guard rails, water supply pipes, curbs and diaphragms. Each of two pylons is modeled by 110 frame elements with 7 different sectional properties. The spread footings of the pylons are on the stiff rock and thus modeled as fixed boundary conditions. The cables are modeled by truss elements with Ernst equivalent elastic moduli to consider the nonlinear effect caused by self-weight of cables with resulting tension forces and sag (Ernst 1965). Fig. 1 shows the resulting FE model of the 2nd Jindo Bridge.
2.2 Validation of the finite element model

A preliminary validation of the FE model is achieved by comparing the computed modal properties with those extracted from acceleration responses measured in 2007 using the existing
Soojin Cho et al.

wired monitoring system. Fig. 2 shows the first six mode shapes evaluated from the FE model, including longitudinal, lateral, vertical and torsional modes. The first 10 natural frequencies of the vertical modes are obtained as 0.442, 0.647, 1.001, 1.247, 1.349, 1.460, 1.586, 2.115, 2.139 and 2.561 Hz. Fig. 3 shows the power spectral density (PSD) of a vertical acceleration record, which contains vertical and torsional mode information, measured at a quarter span of the deck in 2007. The first 3 peak frequencies (i.e., 0.440, 0.659 and 1.050 Hz) are in very good agreements with the FE analysis results, while the higher modal frequencies are larger than the FE results. The differences in these higher modes are within 16%, which shows the general validity of the FE model; however, updating of the FE model may increase the efficacy of the model for comprehensive SHM of the bridge.

3. Wireless smart sensor network and measured data

3.1 Wireless smart sensor network

The 2nd Jindo Bridge at the southern tip of the Korean peninsula has been established as an international SHM test bed for advanced wireless smart sensor network (WSSN) technology (see Fig. 4). This trilateral collaborative research effort between Korea (KAIST), the USA (University of Illinois at Urbana-Champaign), and Japan (University of Tokyo) constitutes the largest deployment of wireless smart sensors to date for monitoring civil infrastructure. A detailed description of this test bed can be found in Rice et al. (2010) and Jang et al. (2010); for completeness, a brief synopsis is provided here.

A total of 70 wireless smart sensor nodes (leaf nodes) are installed on the 2nd Jindo Bridge. To facilitate efficient data collection, the 70 nodes are divided into two sub-networks: 37 nodes on the Haenam-side and 33 nodes on the Jindo-side, as shown in Fig. 5. 49 nodes are installed under the deck, with additional six nodes on the two pylons and 15 nodes on the stay cables. Each leaf node is comprised of an Imote2, a multi-scale sensor board including a tri-axial accelerometer, and a battery board with three D-cell batteries; the components are all housed in environmentally hardened plastic enclosures. Two base stations are located at the tops of two pylon bases of the 1st Jindo Bridge adjacent to the 2nd Jindo Bridge to secure the line-of-sight wireless transmission path between leaf nodes and gateway nodes of base stations. Each base station is composed of an
industrial-purpose PC, a gateway node, and an ADSL modem to connect the PC to the internet. The gateway node broadcasts commands to the leaf nodes in its sub-network, collects measured data, and stores it on the PC. For efficient management of the battery power, ordinary leaf nodes are normally in a deep-sleep state, periodically waking to listen for network alerts. Such alerts are provided by the Sentry nodes, which are programmed to wake up and measure the data at predefined times; when the measured wind velocity and acceleration responses exceed prescribed threshold levels the network is alerted and network-wide data collection is initiated. The wind speed threshold is set at 3 m/s, whereas the acceleration threshold is set at 10 mg during normal operation. For each network-wide measurement instance, 500 seconds of data is taken using a 10-Hz sampling rate (i.e., 5000 samples); anti-aliasing filters are employed with a 4-Hz cutoff frequency (Rice et al. 2010).

3.2 Measured acceleration data

The coordinate system of the global structure and cables is priorly determined in Fig. 6 to help readers for direction of the measured data. Fig. 7 shows examples of the ambient acceleration data
measured on the deck and the pylons in the three global coordinate directions. The amplitudes of the acceleration due to automobile traffic on the bridge are found to be large enough for mode extraction, especially for the vertical modes ($Z$-axis). Fig. 8 shows examples of the ambient acceleration data measured on 2 cables. Similar to the deck vibration, the cable vibration in $Z_c$-axis (usually
referred as “vertical” or “in-plane” vibration in many literatures) is much larger than the other vibration components in $X_c$- and $Y_c$-axis. The cable-vibration amplitudes are also found to be sufficiently large for mode extraction, which will be used for estimation of the cable tension forces as described in a subsequent section.

4. Output-only modal identification

Modal properties such as natural frequencies, mode shapes and modal damping ratios play key roles for SHM of bridges. For example, they are used for evaluating the structural integrity (Koo et al. 2008), assessing aerodynamic stability (Jain et al. 1998), calibrating the baseline finite element model (Yun 2001), and vibration control of deck and cables (Koshimura et al. 1994, Li et al. 2007). To analyze the ambient (or operational) acceleration data excited by ambient sources, such as wind and traffic, output-only modal identification methods are required. The output-only modal identification methods are based on the assumption that input is broadband Gaussian random process. In this study, two output-only modal identification methods are employed using the ambient vibration data. They are the frequency domain decomposition (FDD) and stochastic subspace identification (SSI) methods. For completeness, a brief outline of the methods is included in this section.

4.1 Theory of output-only modal identification methods

4.1.1 Frequency domain decomposition method

The FDD method (Brinker et al. 2001) starts by constructing and decomposing the PSD matrix for the measured data via the singular value decomposition (SVD)

$$ S_{yy}(\omega) = U(\omega)\Sigma(\omega)V^T(\omega) $$

where $y$ is the measurement vector; $S_{yy}(\omega)$ is the PSD matrix; $\Sigma$ is the diagonal matrix containing the singular values ($\sigma_i(\omega)$) in descending order; and $U$ and $V$ are unitary matrices containing the left and right singular vectors. Due to the symmetry of $S_{yy}(\omega)$, $U$ is equal to $V$. The magnitudes of the singular
values indicate the relative level of vibration at the corresponding frequencies. The peaks in the plot of
the 1st singular value versus frequency can be interpreted as natural frequencies of the structure, while
the corresponding 1st singular vectors at these frequencies can be interpreted as the associated mode
shapes. Thus, the natural frequencies can be estimated by the conventional peak picking method using
the 1st singular value function.

4.1.2 Stochastic subspace identification method
The SSI method (Overschee and De Moor 1993, Peeters and De Roeck 1999) starts from the state
space representation for the equations of motion assuming a linear time-invariant system

\[ \mathbf{x}(k+1) = A\mathbf{x}(k) + \mathbf{w}(k) \]
\[ \mathbf{y}(k) = C\mathbf{x}(k) + \mathbf{v}(k) \]  

(2)

Where \( \mathbf{x}(k) \) is the state vector at time \( t = k\Delta t \); \( \mathbf{y} \) is the observation vector at time \( t = k\Delta t \); \( A \) is the discrete
state matrix; \( C \) is the observation matrix; and \( \mathbf{w}(k) \) and \( \mathbf{v}(k) \) are the process and measurement noises
which are assumed to be uncorrelated Gaussian random sequences.

The cross correlation matrix of the observation can be written as

\[ R_y = E[\mathbf{y}(k+i)\mathbf{y}^T(i)] = CA^{-1}EC[\mathbf{x}(i+1)\mathbf{y}^T(i)] = CA^{-1}G \]  

(3)

Then, the Hankel matrix can be composed of a series of the cross correlation matrices, which can
be decomposed into an observability matrix (\( \mathcal{O}_n \)) and an extended controllability matrix (\( \mathcal{C}_n \)) as

\[
\begin{bmatrix}
R_n & \cdots & R_{n+1} \\
\vdots & \ddots & \vdots \\
R_{n+1} & \cdots & R_{n+2}
\end{bmatrix}
= \begin{bmatrix}
CG & \cdots & CA^{n-1}G \\
\vdots & \ddots & \vdots \\
CA^{n-1}G & \cdots & CA^{n+1}G
\end{bmatrix}
\begin{bmatrix}
\mathcal{O}_n \\
\vdots \\
\mathcal{C}_n
\end{bmatrix}
\]  

(4)

If \( H_{n,n+2} \) is decomposed by SVD as

\[
H_{n,n+2} = U_1 \Sigma_1 U_2^T \approx U_1 \Sigma_1 V_1^T
\]  

(5)

The observability matrix can be obtained as

\[
\mathcal{O}_n = U_1 \Sigma_1^{1/2}
\]  

(6)

From Eq. (6), the following relationship can be established, from which the discrete state matrix
\( A \) can be obtained using the pseudo-inverse technique

\[
\mathcal{O}_{n-1}^+ = \mathcal{O}_{n-1}^{-1}A
\]  

(7)
From the discrete state matrix $A$ the eigenvalue ($\lambda_i$) and eigenvector ($\psi_i$) can be obtained, from which the natural frequencies ($\omega_i$) and mode shapes ($\phi_i$) can be obtained from the following relationships

$$\lambda_i = \frac{\ln(\lambda_i)}{\Delta t}$$

$$\phi_i = C \psi_i$$

where $\lambda_{ci} = \frac{\ln(\lambda_i)}{\Delta t}$ is the $i^{th}$ eigenvalue of continuous system; $\Delta t$ is the sampling time; $\xi_i$ is the modal damping ratio; and asterisk (*) denotes complex conjugate.

SSI requires the system order $n$ to be determined a priori. In this study, a stabilization chart is used to find a suitable system order with the criterions provided by Yi and Yun (2004). The stabilization chart shows the stable modes as a function of increasing system order $p$. To construct the stabilization chart, noise modes are identified and discarded for each system order $p$. To the end, the natural frequencies, modal damping ratios, and modal assurance criterion (MAC) values of the modes for the system of order $p$ with those from the system of order $p$-1 (adjacent system orders) is estimated.

First, mode for which the modal damping ratio is determined to be larger than 0.5 is classified as a noise mode and discarded. Among the non-noise modes, stable modes are classified when the normalized differences of natural frequencies, and modal damping ratios with the system at the system order $p$-1 are less than 0.01 and 0.2, respectively, and when MAC value is larger than 0.95.

### 4.2 Results of modal analysis

#### 4.2.1 Identified modal properties from individual WSSN

Modal analyses are carried out on the two sets of data obtained from Haenam- and Jindo-side WSSNs using the two previously described output-only modal identification methods. Because the WSSNs are not synchronized to each other during the measurement, the data from each WSSN are analyzed independently, and then combined subsequently. To obtain the PSD matrix for the FDD method, each 5000 point acceleration data record is processed using a 1024 point FFT, employing 50% overlap and a Hanning window using the Matlab CPSD command.

Fig. 9 shows the stabilization charts for SSI plotted along with the 1$^{st}$ singular values of FDD. Using SSI, 12 stable modes and 3 noise modes (NC1-3) are identified at a high system order ($n$>60) in the frequency range of 0-3 Hz. The resonant frequencies are found to have good agreements with the peak frequencies from FDD. Table 1 gives descriptions of the identified modes; Tables 2 and 3 and Figs. 10 and 11 show the natural frequencies and mode shapes determined by SSI and FDD, respectively, from the two WSSNs. The results from different modal identification methods are found to be consistent to each other. Note that the noise modes can be attributed to two malfunctioning leaf nodes (D-HE12 and D-JE7 - see Fig. 5) with unexpected noises at 0.82 Hz, 1.64 Hz and 2.46 Hz.

Several modes (DL1, DV2, DT1 and PB1 - see Table 1) are found undetected by FDD. In Figs. 10 and 11, some mode shapes extracted by FDD show un-smooth shapes at a few sensor locations, while those by SSI are generally smooth. If longer acceleration records were collected, the modal properties of both FDD and SSI would be in better agreement. However, the SSI method can reduce significantly the amount of data, and thus transmission time, processed in a large-scale WSSN. The present results show that SSI with a system order greater than 60 yields reasonable results.

In Table 2, the identified natural frequencies are compared with those obtained from both the wired monitoring system and the FE analysis. The identified natural frequencies show excellent agreements.
with the frequencies obtained from the wired monitoring system in 2007. The results are also found to be in good agreement with the FE analysis through the 3\textsuperscript{rd} vertical mode, while those for the higher modes are generally larger than the FE results. However, the differences are found to be within 16%.

Table 1 Modes extracted by output-only modal identification (0-3Hz)

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Main member</th>
<th>Mode Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DL1</td>
<td>Deck</td>
<td>1\textsuperscript{st} longitudinal mode</td>
</tr>
<tr>
<td>2</td>
<td>DV1</td>
<td>Deck</td>
<td>1\textsuperscript{st} vertical mode</td>
</tr>
<tr>
<td>3</td>
<td>DV2</td>
<td>Deck</td>
<td>2\textsuperscript{nd} vertical mode</td>
</tr>
<tr>
<td>4</td>
<td>DV3</td>
<td>Deck</td>
<td>3\textsuperscript{rd} vertical mode</td>
</tr>
<tr>
<td>5</td>
<td>DV4</td>
<td>Deck</td>
<td>4\textsuperscript{th} vertical mode</td>
</tr>
<tr>
<td>6</td>
<td>DV5</td>
<td>Deck</td>
<td>5\textsuperscript{th} vertical mode</td>
</tr>
<tr>
<td>7</td>
<td>DV6</td>
<td>Deck</td>
<td>6\textsuperscript{th} vertical mode</td>
</tr>
<tr>
<td>8</td>
<td>DT1</td>
<td>Deck</td>
<td>1\textsuperscript{st} torsional mode</td>
</tr>
<tr>
<td>9</td>
<td>DV7</td>
<td>Deck</td>
<td>7\textsuperscript{th} vertical mode</td>
</tr>
<tr>
<td>10</td>
<td>DV8</td>
<td>Deck</td>
<td>8\textsuperscript{th} vertical mode</td>
</tr>
<tr>
<td>11</td>
<td>PB1</td>
<td>Pylon</td>
<td>1\textsuperscript{st} bending mode</td>
</tr>
<tr>
<td>12</td>
<td>DV1</td>
<td>Deck</td>
<td>9\textsuperscript{th} vertical mode</td>
</tr>
<tr>
<td>-</td>
<td>NC1-NC3</td>
<td>-</td>
<td>Noise mode from two malfunctioning nodes</td>
</tr>
</tbody>
</table>

Fig. 9 Comparison of stabilization chart of SSI with the 1\textsuperscript{st} singular values of FDD
4.2.2 Combination of modes from two sensor networks
The modal properties from each WSSN are combined to provide the global information for SHM. To construct the global mode shapes, least-square method is applied to knit the modes together at the four overlapped reference nodes at mid-span (see Fig. 12). Examples of the combined mode shapes are compared with those from the FE analysis in Fig. 13. The MAC values of 0.943-0.986 between the respective modes demonstrate the excellent agreement in the results, reinforcing the exceptional performance of the WSSN. The software is currently under development for synchronization of two separated base stations and expected to be implemented on the 2nd Jindo Bridge in the near future. The decentralized data aggregation (Sim et al. 2010) and decentralized processing (Jeong and Koh 2009) appropriate to monitoring of the cable-stayed bridge is destined to be implemented with the help of one base station as well.

5. Estimation of cable tension forces

5.1 Description of cable properties
The 2nd Jindo Bridge has a total of 60 parallel wire strand (PWS) stay cables. The bridge is symmetric along the longitudinal as well as the lateral directions. Each pylon holds 30 cables; 15 cables on each of east and west sides. The cables are categorized into 4 groups with different cross sections (i.e.: $\phi 7\times139$, $\phi 7\times109$, $\phi 7\times73$, and $\phi 7\times151$) as shown in Fig. 14. The above designations indicate the number of 7 mm diameter steel wires in a cable. High-damping rubber dampers are installed on cable anchors to reduce the wind-induced cable vibration.

Among the 15 cables instrumented by wireless smart sensor nodes, 10 east-side cables are selected to estimate the tension forces due to the collocation of wired sensors as well as their large tension levels, as shown in Fig. 14. Table 3 shows the general properties of the cables. The effective lengths of the cables are obtained from the work by Park et al. (2008). Note that the leaf nodes...
Fig. 10 Mode shapes from SSI (solid line) and FDD (dashed line): Haenam-side, on 9/8/2009
Structural health monitoring of a cable-stayed bridge using smart sensor technology: data analyses

Fig. 11 Mode shapes from SSI (solid line) and FDD (dashed line): Jindo-side, on 9/11/2009

(a) DL1 (SSI only)  (b) DV1
(c) DV2  (d) DV3
(e) DV4  (f) DV5
(g) DV6  (h) DT1 (SSI only)
(i) DV7  (j) DV8
(k) PB1 (SSI only)  (l) DV9

Fig. 11 Mode shapes from SSI (solid line) and FDD (dashed line): Jindo-side, on 9/11/2009
monitoring the cables are mounted approximately 3 m above the deck to facilitate access to the nodes; for this location, the rubber dampers do not affect significantly the response of the cable.

5.2 Vibration method for cable tension estimation

Given the importance of cables for the global integrity of a cable-stayed bridge, continuous monitoring of cable tension forces is prudent to assess cable degradation and anchorage slippage (Cho et al. 2010). In this study, the cable tensions are estimated using the identified natural frequencies. For this purpose, the tension force and the natural frequencies can be related as (Park et al. 2008)

\[
\left( \frac{f_n}{n} \right)^2 = \frac{T}{4mL_{\text{eff}}^2} + \frac{EI\pi^2 n^2}{4mL_{\text{eff}}^4} = a + bn^2
\]

where \( T \) is cable tension force; \( n \) is the order of the dominant modes; \( f_n \) is the frequency of \( n \)-th dominant modes; \( m \) is unit mass of the cable; and \( L_{\text{eff}} \) is the effective length of the cable. A regression can be performed between \( (f_n/n)^2 \) and \( n^2 \) to obtain the intercept \( a \) and slope \( b \) in Eq. (9); subsequently, \( T \) can be determined as

\[
T = 4mL_{\text{eff}}^2 a
\]

Fig. 8 shows two examples of the measured acceleration data from on tri-axial accelerometers on the cables of Jindo side. Fig. 15 shows the Fourier amplitude spectra (FAS) for the cable motions along with the FAS for deck motions. Fig. 15 indicates that of the many peaks apparent in the FAS
Fig. 13 Mode shapes identified from the data (left) and from the FE analysis (right)

(a) DV1 (MAC: 0.957)
(b) DV2 (MAC: 0.986)
(c) DV3 (MAC: 0.975)
(d) DV6 (MAC: 0.949)
(e) DV9 (MAC: 0.943)

Fig. 14 Arrangement of stay cables and wireless sensors on cables (sensor numbers in parentheses)

for the vertical cable vibration, some can be associated with the deck motion owing to deck-cable interaction, particularly in the vertical direction.
However, the FAS for the lateral cable vibration do not contain so many peaks related to the deck motion. Because of the circular cross-section, slenderness and small sag of the stay cable, the modal properties of the cable are very similar in the vertical and lateral directions. Hence, in this study, the natural frequencies of the cables are extracted from vertical vibration with complementary use of Table 3 Properties of the cables monitored

<table>
<thead>
<tr>
<th>Cables</th>
<th>HC4, JC4</th>
<th>HC6, JC6</th>
<th>HC9, JC9</th>
<th>HC13, JC13</th>
<th>HC15, JC13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable type</td>
<td>(7 \times 151)</td>
<td>(7 \times 151)</td>
<td>(7 \times 73)</td>
<td>(7 \times 109)</td>
<td>(7 \times 139)</td>
</tr>
<tr>
<td>Elasticity (tonf/mm(^2))</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Area (mm(^2))</td>
<td>5811.0</td>
<td>5811.0</td>
<td>2809.0</td>
<td>4195.0</td>
<td>5349.0</td>
</tr>
<tr>
<td>Length (m)</td>
<td>97.10</td>
<td>65.00</td>
<td>83.17</td>
<td>141.76</td>
<td>174.15</td>
</tr>
<tr>
<td>Effective length (m)</td>
<td>95.38</td>
<td>63.33</td>
<td>79.01</td>
<td>136.87</td>
<td>169.69</td>
</tr>
<tr>
<td>Unit mass (ton/m)</td>
<td>0.00486</td>
<td>0.00486</td>
<td>0.00236</td>
<td>0.00354</td>
<td>0.00448</td>
</tr>
<tr>
<td>Design cable sag (mm)</td>
<td>256.0</td>
<td>96.0</td>
<td>221.0</td>
<td>537.0</td>
<td>809.0</td>
</tr>
<tr>
<td>Design tension force (tonf)</td>
<td>237.0</td>
<td>271.0</td>
<td>90.0</td>
<td>160.0</td>
<td>202.0</td>
</tr>
<tr>
<td>Allowable tension force (tonf)</td>
<td>470.0</td>
<td>470.0</td>
<td>227.0</td>
<td>339.0</td>
<td>433.0</td>
</tr>
</tbody>
</table>

Fig. 15 Fourier spectra of acceleration data on the deck and cables (Jindo-side, on 9/11/2009)

However, the FAS for the lateral cable vibration do not contain so many peaks related to the deck motion. Because of the circular cross-section, slenderness and small sag of the stay cable, the modal properties of the cable are very similar in the vertical and lateral directions. Hence, in this study, the natural frequencies of the cables are extracted from vertical vibration with complementary use of
the lateral vibration components. The first five identified frequencies for two cables are: 0.645, 1.294, 1.948, 2.598, and 3.247 Hz for Cable JC15 with Node C-JE8, and 0.772, 1.514, 2.275, 3.027 and 3.789 Hz for Cable JC13 with Node C-JE7. The natural frequencies are found to be almost proportional to the order of modes \((n)\), which is a dynamic characteristic of a slender cable with little bending and sag effect (Irvine 1981, Cho et al. 2010).

5.3 Interaction between deck and cables

Fig. 15 shows that the 1\textsuperscript{st} frequency of Cable JC15 with Node C-JE8 is very close to the frequency of the 2\textsuperscript{nd} vertical mode of the deck, while the 3\textsuperscript{rd} frequency of Cable JC13 with Node C-JE7 is very close to the frequency of the 8\textsuperscript{th} vertical mode of the deck. If the frequency of oscillation of the deck and/or tower falls in the neighborhood of the frequencies of the lower modes of a stay cable, the stay cable may be subjected to large vibration (Pinto da Costa et al. 1996). Such interaction between deck/pylon and cable vibration in the lower frequency range has been reported by Caetano et al. (2008) on the International Guadiana cable-stayed bridge in Portugal and by Weng et al. (2008) on the Gi-Lu cable-stayed bridge in Taiwan. This phenomenon, called as parametric excitation, is generally difficult to avoid in long-span bridges with many cables. However, if the cable vibration levels are found to be significant, cable dampers may be introduced to mitigate the response.

5.4 Estimated cable tension forces

Based on the identified dominant frequencies, the tension forces for the 10 cables are estimated as shown in Fig. 16. The estimated tension forces for the cables show consistency with respect to the monitoring periods. In Table 4, the averages of the estimated tension forces are compared with those obtained from two previous regular inspections in 2007 and 2008, as well as those from the
Table 4 Comparison of estimated tension forces with those from previous regular inspections in 2007 and 2008

<table>
<thead>
<tr>
<th>Cables (East-side)</th>
<th>Estimated tension forces (tonf)</th>
<th>Initial design values (tonf)</th>
<th>Maintenance thresholds (tonf)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present WSSNs in 2009 (averaged)</td>
<td>Previous inspections in 2007</td>
<td></td>
</tr>
<tr>
<td></td>
<td>in 2008</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haenam-side</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC4</td>
<td>274.0 (2.04)*</td>
<td>262.7</td>
<td>246.2</td>
</tr>
<tr>
<td>HC6</td>
<td>294.7 (-3.19)*</td>
<td>304.6</td>
<td>271.8</td>
</tr>
<tr>
<td>HC9</td>
<td>89.3 (0.90)*</td>
<td>86.9</td>
<td>87.6</td>
</tr>
<tr>
<td>HC13</td>
<td>170.2 (3.00)*</td>
<td>164.0</td>
<td>163.6</td>
</tr>
<tr>
<td>HC15</td>
<td>224.9 (2.18)*</td>
<td>219.9</td>
<td>204.8</td>
</tr>
<tr>
<td>Jindo-side</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JC4</td>
<td>254.0 (1.30)*</td>
<td>245.1</td>
<td>245.9</td>
</tr>
<tr>
<td>JC6</td>
<td>274.5 (-1.09)*</td>
<td>282.0</td>
<td>271.5</td>
</tr>
<tr>
<td>JC9</td>
<td>88.5 (2.15)*</td>
<td>85.5</td>
<td>88.2</td>
</tr>
<tr>
<td>JC13</td>
<td>154.3 (2.33)*</td>
<td>148.3</td>
<td>164.1</td>
</tr>
<tr>
<td>JC15</td>
<td>216.8 (0.14)*</td>
<td>214.1</td>
<td>201.3</td>
</tr>
</tbody>
</table>

*The differences from regular inspection in 2008 are shown in the parentheses.

initial design, and those from the maintenance thresholds which are 60% of allowable tension forces of the cables (ATMACS 2008). The current estimations are found to be very close to the tension forces from two previous inspections with less than 4% difference. The tension forces of 8 cables have increased slightly with time, while those of 2 cables (HC6 and JC6) supporting the side spans have slightly decreased. The estimated cable tension forces are generally larger than the initial design values (10% at maximum) except JC13. All cable tension values are well within the maintenance thresholds, indicating that the cables are in safe operation.

6. Conclusions

This paper analysed the data collected from the 2nd Jindo Bridge, a cable-stayed bridge in Korea that is a structural health monitoring (SHM) international test bed for advanced wireless smart sensor network (WSSN) technology. A FE model of the bridge has been constructed based on its detailed drawings. Modal properties of the bridge were evaluated using two different output-only identification methods: FDD and SSI. Tension forces for 10 selected cables were also derived from the ambient acceleration data using a vibration method. The results of data analyses are summarized as follows:

1) Modal properties of the bridge were successfully determined from the ambient acceleration measurements obtained from the WSSNs using both FDD and SSI. The natural frequencies identified using the WSSNs were found to be in excellent agreement with those previously obtained using the existing wired sensors. The extracted mode shapes show excellent agreements with those from the FE analysis. SSI with high system order (larger than 60) is found to be very appropriate for extracting the modes without extensive amounts of data.

2) The frequencies of the higher modes of the FE model are found to differ from the identified values by less than 16%, which indicates the need for updating of the FE model.

3) The interaction between the deck and cables must be considered carefully to obtain accurate estimates of the natural frequencies of the cables, which are used for tension force estimation. To
this end, complementary use of the lateral vibration data of the cables was shown to be beneficial, because they are less sensitive to the deck motion.

4) The estimated tension forces for the 10 cables were very close to those from 2 previous regular inspections (i.e., less than 4% difference).

Finally, a substructural damage identification method for a cable-stayed bridge is now under development, with full utilization of the decentralized computing capabilities of the wireless smart sensor nodes. In this approach, substructural modal information for the deck/pylon and cable tension forces is combined to provide a comprehensive assessment of the structural integrity of the bridge.

Acknowledgements

This work was supported by the Korea Research Foundation Grant funded by the Korean Government (MEST) (NRF-2008-220-D00117), the National Science Foundation Grant CMS 06-00433 (Dr. S.C. Liu, Program Manager), and Smart Infrastructure Technology Center (SISTeC) at KAIST. Their financial supports are greatly appreciated. Additionally, cooperation of the Ministry of Land, Transport and Maritime Affairs in Korea, Daewoo Engineering Co. Ltd. and Hyundai Construction Co. Ltd. are gratefully acknowledged.

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ATMACS (2008), Consulting for the measurement systems for integrated entrusted management of long-span bridges (The 1st and 2nd Jindo Bridges) (in Korean), Sungnam, Gyunggi-do, Korea.
Reliable multi-hop communication for structural health monitoring

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Abstract. Wireless smart sensor networks (WSSNs) have been proposed by a number of researchers to evaluate the current condition of civil infrastructure, offering improved understanding of dynamic response through dense instrumentation. As focus moves from laboratory testing to full-scale implementation, the need for multi-hop communication to address issues associated with the large size of civil infrastructure and their limited radio power has become apparent. Multi-hop communication protocols allow sensors to cooperate to reliably deliver data between nodes outside of direct communication range. However, application specific requirements, such as high sampling rates, vast amounts of data to be collected, precise internodal synchronization, and reliable communication, are quite challenging to achieve with generic multi-hop communication protocols. This paper proposes two complementary reliable multi-hop communication solutions for monitoring of civil infrastructure. In the first approach, termed herein General Purpose Multi-hop (GPMH), the wide variety of communication patterns involved in structural health monitoring, particularly in decentralized implementations, are acknowledged to develop a flexible and adaptable any-to-any communication protocol. In the second approach, termed herein Single-Sink Multi-hop (SSMH), an efficient many-to-one protocol utilizing all available RF channels is designed to minimize the time required to collect the large amounts of data generated by dense arrays of sensor nodes. Both protocols adopt the Ad-hoc On-demand Distance Vector (AODV) routing protocol, which provides any-to-any routing and multi-cast capability, and supports a broad range of communication patterns. The proposed implementations refine the routing metric by considering the stability of links, exclude functionality unnecessary in mostly-static WSSNs, and integrate a reliable communication layer with the AODV protocol. These customizations have resulted in robust realizations of multi-hop reliable communication that meet the demands of structural health monitoring.

Keywords: wireless smart sensors; multi-hop communication; structural health monitoring; reliability; dense instrumentation.

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1. Introduction

Objective evaluation of structural performance can facilitate effective and efficient maintenance of aging infrastructure. Comprehensive understanding of structural behavior is fundamental to such evaluation. Nevertheless, conventional approaches to capture structural dynamic behavior have limitations which current technological advances may overcome. Sensing devices are becoming smaller, less expensive, more robust, and highly precise, allowing collection of high-fidelity data with dense instrumentation employing multi-metric sensors. Wireless smart sensor networks (WSSNs) leverage these advances to offer the potential for dramatic improvements in the capability to capture structural dynamic behavior and evaluate the condition of structures. WSSNs can be employed for medium- and long-term monitoring of structural condition, as well as for shorter-term investigative structural monitoring campaigns to diagnose specific problems.

Structural health monitoring (SHM) systems based on WSSN offer many advantages over conventional wired systems, particularly for large civil infrastructure (Nagayama and Spencer 2007, Rice et al. 2010, Jang et al. 2010); however, WSSN implementation for such purposes has challenges. In addition to the sensing issues discussed in Nagayama and Spencer (2007), communication issues emerge which are not manifested in other WSSN applications that consider collection of small amounts of data in open environments, e.g., environmental monitoring and target tracking (Mainwaring et al. 2002, Luo et al. 2006). Radio communication on and around structures made of concrete or steel components is usually complicated due to radio wave reflection, absorption, and other phenomena that result poor reception. Moreover, sensor nodes are frequently installed in partially- or completely- obscured areas, such as between girders. These facts, combined with the sheer size of typical civil infrastructure, often make direct communication with the base station impractical.

Multi-hop communication, together with appropriate packet-loss compensation, addresses these issues by successively routing the communication through intermediate nodes, which are sufficiently close to employ direct single-hop communication. Multi-hop communication is comprised of two main phases: (i) the routing phase discovers desirable path(s) between source and destination; (ii) the data transport phase uses the constructed path(s) to deliver data. Many routing and transport protocols have been proposed for ad hoc wireless networks; however, these protocols are not designed specifically for structural health monitoring applications and do not necessarily provide the desired functionality.

The remainder of this article is organized as follows. Application specific characteristics of multi-hop communication are first presented, and multi-hop communication application scenarios are discussed. Then, a brief survey of multi-hop communication approaches is presented, along with the rationale for selecting the AODV routing protocol. Subsequently, two complementary approaches for reliable multi-hop communication are proposed, both utilizing the AODV protocol and acknowledgement-based reliable communication (Nagayama and Spencer 2007). The first approach, termed herein General Purpose Multi-hop (GPMH), features flexibility to accommodate a variety of communication patterns involved in decentralization to reduce communication requirements, while the other approach, termed herein Single-Sink Multi-hop (SSMH), aims to achieve efficient data collection from a dense array of sensor nodes. These two approaches are described in detail and their advantage and disadvantages are discussed.
2. Communication requirements for SHM applications

In the design of large-scale SHM systems, application-specific characteristics and requirements must be considered. The WSSN deployment on the Jindo Bridge (Jang et al. 2010, Cho et al. 2010) has provided critical insight into the necessary design features for a reliable multi-hop communication protocol. Following a brief description of the Jindo Bridge deployment, these features, as well as possible communication usage patterns, are summarized.

2.1 Jindo Bridge SHM project

The primary goal of the Jindo Bridge SHM project has been to realize the first large-scale, autonomous WSSN for structural health monitoring, taking advantage of the advanced computational capabilities of the Imote2 nodes (Crossbow Technology 2009). The second Jindo Bridge, opened in 2006 and connecting the southwestern tip of the Korean Peninsula and the Jindo Island (see Fig. 1), is the target of this study. This three-span, continuous, steel box-girder cable-stayed bridge has a length of 484 m (70 + 344 + 70) m and a width of 12.55 m. The two pylons are 89 m high. The acceleration responses of the bridge under traffic and wind loads are investigated employing the Imote2s and the SHM-A sensor boards (Crossbow Technology 2007, Rice and Spencer 2009).

The initial goals of this study were to investigate issues related to long-term monitoring, which...
involves permanent instrumentation and periodic monitoring. As shown in Fig. 2, 70 sets of Imote2s and sensor boards were installed on the girders, cables and pylons. Two gateway nodes are installed on the two pylons of the first Jindo Bridge and are connected to two base station computers, which are accessible through a wired Ethernet connection; remote users can send commands to the sensor network to start sensing, collect data and examine sensor node status. Also, sensors are installed with a set of autonomous monitoring software. Several sentry nodes monitor the vibration level and wake up the other nodes as needed. Sensor installation locations were selected so that all the nodes are in single-hop range from the two gateway nodes at the respective base stations. Changes in structural performance can be examined through modal, structural and statistical analyses performed automatically by the WSSN.

Short-term monitoring campaigns were also considered in this study, where quick and easy sensor deployment, measurement and removal are performed in one or a few days. Such monitoring campaigns are frequently employed for investigative studies, to examine chronological changes of structural performance, or to confirm structural behaviors after construction, structural retrofit, and extreme loading events such as earthquakes. To this end, from 21 to 34 Imote2s and sensor boards were deployed on the top side of the bridge deck over the three spans; acceleration responses were recorded, and forwarded to the gateway node connected to the base station computer. The wireless monitoring campaign was repeated by several people on a daily basis to gain insight into usability issues. While sensor installation on the top side of the bridge deck allows for quick deployment, handrails and other objects resulted in a complex communication environment and limited radio communication range; these tests informed the development of the multi-hop communication software described herein.

Further information regarding the Jindo Bridge SHM project can be found in Jang et al. (2010) and Cho et al. (2010).

2.2 WSSN application specific characteristics

A number of critical issues emerged in the course of the Jindo Bridge project. While many of the concerns were identified during the initial design phase, their relative importance and magnitude did not become apparent until the deployment and testing phase.

2.2.1 Large data size

Communication in most WSSN applications involves exchanging commands and limited amounts of data, both of which are typically small enough to be encapsulated in single packets. However, structural monitoring applications need to transfer large amounts of dynamic measurement data, which must be divided into a large number of packets. Each sample data point is typically 2 bytes and sampling frequencies can be as high as 1000 Hz. In addition, each sensor node usually has multiple sensing channels, increasing the data generated by each node. Such high sampling rates usually preclude real-time data collection, as even a small number of nodes can saturate the available network bandwidth. As a result, sensing and data collection take place sequentially in most SHM applications.

In the Jindo project, each node measures acceleration in three directions at 10-50 Hz and saves it in a 2 byte format. The sensing duration was from 2 to 17 minutes. Typically, the size of the acceleration records collected at each node was 60 KB. When the size of packet payload is 100 B, the 60 kB data is divided into 600 packets. However, the sensing duration for this deployment, and
thus the size of the data generated, are not the maximum values for general SHM applications; requirement on data size can be much more severe.

2.2.2 Dense deployment of sensor nodes in large spatial regions

Civil infrastructure is typically extremely large; for example, the length of some bridges can exceed several kilometers. Because single-hop communication often cannot cover the entire structure, stable data transfer from nodes requires multi-hop communication. In addition, multi-hop communication is considered efficient and desirable; with proper scheduling, multi-hop can save power by using shorter links (Subramanian and Katz 2000). Moreover, local vibration characteristics and spatial distribution of dynamic properties are often of interest, which necessitates dense deployment. Therefore, the communication protocol needs to support large and dense multi-hop networks; design and implementation of such a protocol is generally challenging.

For bridge structures in particular, a unique characteristic is that the network topology is linear (i.e., the deployment area is long and in one dimension). Under this condition, a coarse deployment allows only a single chain-like multi-hop routing tree, leaving no alternate routes. On the other hand, dense deployments with multiple nodes in single-hop ranges allow for alternate routes as needed. For example, consider the 70 sensor nodes deployed on the Jindo Bridge; 16 were installed on the cables; with the balance installed on the deck or on the pylons (see Fig. 2). Most sensors on the cables were installed on every other cable on one of the two cable planes. Sensors were installed on the bottom side of the deck at a distance of approximately 25 m apart, corresponding to the distance between anchorage points of monitored cables. For the pylons, sensor nodes were installed only at the top of the pylons and a few meters above the deck. Although this topology is primarily linear, the dense nature of such deployment is beneficial to rapid and robust data collection.

2.2.3 Radio communication environment

The radio communication environment on the bridge can be complex due to RF reflection, refraction, absorption and other phenomena. Bridges consist of numerous components made from steel, concrete or other materials. Some bridge components may be between two WSS nodes, interrupting direct line-of-sight communication. Therefore, the communication range on a bridge will vary from place to place, and its estimation prior to on-site tests is challenging. In locations where communication range is limited, link asymmetry may prevent bidirectional communication between nodes at shorter distances than commonly seen in other applications. This problem is due to the combined effects of non-uniform antenna directionality and RF signal strength degradation due to the above-mentioned environmental factors. As a solution, multi-hop communication schemes that consider the bidirectional quality of each link are desirable.

As an example, consider the Jindo Bridge, which is comprised mainly of a steel box-girder, pylons and cables, as well as non-structural elements such as handrails, light poles and road pavement. For the long-term deployment, the gateway nodes were strategically installed on the pylons of the first Jindo Bridge, providing clear line-of-sight with most of 70 Imote2 sensor nodes. As a result, even the farthest nodes (>150 m) were within single-hop range of one of the two gateway nodes. In contrast, the campaign-type deployment of sensor nodes on the top side of the deck showed much shorter communication ranges, which is attributable to several reasons. First, sensor nodes installed on the top side of the deck do not necessarily have line-of-sight communication due to bridge deck camber. Non-structural elements on the top side of the deck, as
well as cars and pedestrians, also affect the transmission range. Finally, communication distance varies significantly depending on exactly where the nodes are installed and their antenna orientation. For example, sensor installations on the pavement, at the bottom of handrails, and on top of the handrails showed significantly different communication ranges. In general, sensor nodes elevated above the ground improves communication range (Linderman et al. 2010, Kim et al. 2010).

2.2.4 Nodes at fixed locations

For most structural health monitoring applications, sensor installation locations are predetermined based on design drawings and structural considerations. These installation locations do not necessarily correspond with locations that are desirable with respect to RF communication. If the installation locations result in short communication range, countermeasures are needed. Separation of the sensing and communication (i.e., the antenna) components of the sensor node can be a solution. For example, ground-mounted sensors can employ elevated antennas (Jang et al. 2010, Kim et al. 2010).

Moreover, sensor nodes, including their antennas, seldom move, once installed. In this sense, structural monitoring applications do not need to account for frequent changes in the communication link quality; the routing tree topology should not need to change often. However, sporadic transmission interference may occur due to vehicles, pedestrians, workers, inspectors and birds; also, nodes may occasionally fail. Multi-hop communication needs to be robust in the presence of such events.

2.2.5 Need for prompt data collection/analysis

Structural vibration monitoring applications generally require prompt data collection and analysis, though data collection does not necessarily need to be in real-time. In particular, performance evaluation after extreme events such as earthquakes and typhoons must be done as soon as possible to address safety concerns. As for monitoring campaigns where operation time is limited, data collection must be done in a timely manner. When measurements involve stopping traffic, hourly workers, and/or rental equipment (e.g., exciters), minimizing long data collection times can result in significant cost savings. Moreover, shorter data collection time leads to shorter operation time resulting in extended battery life. Also, the time required for data transfer increases WSSN operational time, as leaf nodes in many systems need to transmit measurement data to the central computer and clear the local data buffer before starting the next measurement.

In the Jindo Bridge monitoring campaigns, the data collection time was significant, because the communication middleware used in the campaigns was not optimized for fast data collection. The data collection time for the monitoring campaigns was from one to a few hours, resulting in only a few sets of measurement data per daily campaign. The data collection time should be shorter to increase the amount of data obtained.

2.2.6 High requirement on reliability

Reliability of transporting acquired sensor data is vital. Most scenarios assume measurement data is available from all the nodes without intermittent loss. For example, many damage detection algorithms require sensing data from predetermined locations, while only a few algorithms (e.g., Gao and Spencer 2008) so far have been extended to provide robustness against node failure. Unresponsive nodes may impair the damage detection capability. For campaign tests, data is expected to be gathered from all of sensing locations. As for intermittent loss of data from certain nodes, the loss degrades the signal and limits the subsequent data analysis. Packet loss compensation is therefore required (Nagayama et al. 2007).
2.3 Multi-hop communication usage patterns in SHM

This section examines how multi-hop communication is utilized in SHM applications. To explore possible communication patterns, sensor network applications are classified into two categories (i.e., centralized and distributed) and characterized.

In centralized applications, a single node typically controls the behavior of the application and is often the root of a tree-like communication pattern in the network; that is, they emulate wired data acquisition systems (see Fig. 3). The communication patterns for these applications consists of configuration data being broadcast to the leaf nodes, followed by predetermined tasks such as time synchronization, sensing and data collection. All of the associated packet transfer is between the central node and the other nodes; usually data sharing among leaf nodes is not performed. Representative communication patterns are dissemination and many-to-one data sink. While in some cases local processing such as filtering and resampling may be utilized to reduce the amount of raw data generated by the sensors, the total volume of data that needs to be transferred from a large WSSN is expected to be significant. Thus, efficiency in data collection from multiple data sources is the key performance metric and a primary design goal for the application’s data transfer protocol.

In decentralized or distributed applications (see Fig. 3), several loci of control reside within the network. These nodes may act independently, or coordinate their actions with other nodes. By exploiting the in-network computing capability of smart sensor nodes the overall volume of data transferred can be considerably reduced. The network is usually divided into local clusters, which perform much of the data processing and communication internally, without interaction with the rest of the network. The communication of such decentralized applications are usually varied and include data transfer within clusters, long-distance data transfer among cluster heads and the gateway node, and possibly information exchange between neighboring clusters. Dissemination, one-to-one data transfer, one-to-many multicast, and many-to-one data sink can all be utilized. With decentralization, the number of hops for each communication instance is expected to be small, as compared to centralized systems. However, multi-hop communication is still needed, and the combinations of originator and destination nodes is much more complex than in centralized systems; thus, requiring a flexible routing service.

Due to these application specific characteristics and communication patterns, the use of a multi-hop communication protocol that is fast, flexible and reliable is critical. Several multi-hop communication
protocols have been proposed in the past for WSSNs, each targeting certain features of specific applications. To identify suitable protocols to be considered for structural monitoring applications, multi-hop communication protocols, as well as early research that employs multi-hop communication for structural health monitoring, are reviewed in the next section.

3. Survey of multi-hop communication

Multi-hop communication is comprised of two main phases, routing and data transport. This distinction follows the Open Systems Interconnection (OSI) reference model for data communication (Table 1), which is commonly used to classify network protocols. In the OSI model, routing and data transport belong to the network and transport layers, respectively. Protocols in the network layer are responsible for logical node addressing and determining desirable paths between source and destination nodes, while those in the transport layer uses the constructed paths to deliver data between nodes and provide features such as reliability. This section discusses the characteristics of several routing and data transfer techniques relevant to WSSNs and structural health monitoring.

Several routing techniques have been proposed for wireless smart sensor networks, most commonly distinguished by when and how route information is generated and how it is updated. Routing algorithms are also often specific to the network structure for which they are developed. Important properties expected from routing algorithms include loop freedom (i.e., a guarantee that a packet’s route through the network will never contain loops) and finding the best route among several possibilities based on some routing metric.

Routing protocols for wireless ad-hoc networks, that is networks without a pre-defined topology, are usually classified as either table driven or on demand (Royer and Toh 1999). In the former, each node maintains routing information for every node in the network. Routing tables are kept up to date through the use of broadcast messages propagating changes in the network structure, and/or periodic update messages that aim to keep a consistent view of the network. Protocols within this category may differ in their policy for distributing changes in network topology and the number of routing tables required. Destination-Sequenced Distance-Vector Routing (DSDV) (Perkins and Bhagwat 1994), Clusterhead Gateway Switch Routing (CGSR) (Chiang et al. 1997), and Wireless Routing Protocol (WRP) (Murthy and Garcia-Luna-Aceves 1996) are representative examples of table-driven routing protocols. On-demand routing protocols, on the other hand, postpones route establishment until the routes are actually needed. The benefit of this approach is that nodes are not required to maintain up-to-date routing tables for all nodes in the network, whereas the main drawback is

<table>
<thead>
<tr>
<th>Layer</th>
<th>Standards and Protocols</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>HTTP, FTP, SMTP</td>
</tr>
<tr>
<td>Presentation</td>
<td>JPEG, GIF, MPEG</td>
</tr>
<tr>
<td>Session</td>
<td>AppleTalk, WinSock</td>
</tr>
<tr>
<td>Transport</td>
<td>TCP, UDP</td>
</tr>
<tr>
<td>Network</td>
<td>IP, ICMP, IPX</td>
</tr>
<tr>
<td>Link</td>
<td>Ethernet, ATM</td>
</tr>
<tr>
<td>Physical</td>
<td>RS232, T1, 802.x</td>
</tr>
</tbody>
</table>
Reliable multi-hop communication for structural health monitoring

increased latency for the first routing request. Ad-hoc On-demand Distance Vector routing (AODV) (Perkins and Royer 1999), Dynamic Source Routing (DSR) (Johnson et al. 2007), Temporally Ordered Routing Algorithm (TORA) (Park and Corson 1997), Associativity-Based Routing (ABR) (Toh 1996), and Signal Stability-based Adaptive routing (SSA) (Dube et al. 1997) are well-known examples of on-demand routing protocols. When the table-driven and on-demand approaches are compared in terms of power consumption and bandwidth, the omission of overhead related to periodic routing table updates is considered the main advantage of the latter approach. Tables 2 and 3 adopted from (Royer and Toh 1999) compare different table-driven and on-demand ad hoc routing protocols, respectively.

Routing protocols for wireless ad-hoc networks can also be categorized based on network structure as flat, hierarchical and location-based (Al-Karaki and Kamal 2004). In flat networks, all

Table 2 Comparison of the characteristics of table-driven ad hoc routing protocols

<table>
<thead>
<tr>
<th>Parameters</th>
<th>DSDV</th>
<th>CGSR</th>
<th>WRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time complexity (Initialization)</td>
<td>$O(d)$</td>
<td>$O(d)$</td>
<td>$O(h)$</td>
</tr>
<tr>
<td>Communication complexity (Initialization)</td>
<td>$O(N)$</td>
<td>$O(N)$</td>
<td>$O(N)$</td>
</tr>
<tr>
<td>Routing philosophy</td>
<td>Flat</td>
<td>Hierarchical</td>
<td>Flat</td>
</tr>
<tr>
<td>Loop-free</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes, but not instantaneous</td>
</tr>
<tr>
<td>Multi-cast capability</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Number of required tables</td>
<td>Two</td>
<td>Two</td>
<td>Four</td>
</tr>
<tr>
<td>Frequency of update transmission</td>
<td>Periodically and as needed</td>
<td>Periodically</td>
<td>Periodically and as needed</td>
</tr>
<tr>
<td>Utilizes sequence numbers</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Utilizes “hello” messages</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Routing metric</td>
<td>Shortest path</td>
<td>Shortest path</td>
<td>Shortest path</td>
</tr>
</tbody>
</table>

Abbreviations: $N$ = Number of nodes in the network, $d$ = Network diameter, $h$ = Height of routing tree

Table 3 Comparison of the characteristics of on-demand ad hoc routing protocols

<table>
<thead>
<tr>
<th>Parameters</th>
<th>AODV</th>
<th>DSR</th>
<th>TORA</th>
<th>ABR</th>
<th>SSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time complexity (Initialization)</td>
<td>$O(2d)$</td>
<td>$O(2d)$</td>
<td>$O(2d)$</td>
<td>$O(d + z)$</td>
<td>$O(d + z)$</td>
</tr>
<tr>
<td>Communication complexity (Initialization)</td>
<td>$O(2N)$</td>
<td>$O(2N)$</td>
<td>$O(2N)$</td>
<td>$O(N + y)$</td>
<td>$O(N + y)$</td>
</tr>
<tr>
<td>Routing philosophy</td>
<td>Flat</td>
<td>Flat</td>
<td>Flat</td>
<td>Flat</td>
<td>Flat</td>
</tr>
<tr>
<td>Loop-free</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Multi-cast capability</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Beaconing requirements</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Multiple route possibilities</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Route table</td>
<td>Route table</td>
<td>Route cache</td>
<td>Route table</td>
<td>Route table</td>
<td>Route table</td>
</tr>
<tr>
<td>Utilizes route cache/table expiration timers</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Routing metric</td>
<td>Shortest and freshest path</td>
<td>Shortest path</td>
<td>Shortest path</td>
<td>Associativity and shortest path and others</td>
<td>Associativity and stability</td>
</tr>
</tbody>
</table>

Abbreviations: $N$ = Number of nodes in the network, $d$ = Network diameter, $z$ = Diameter of the directed path where the REPLY packet transits, $y$ = Total number of nodes forming the directed path where the REPLY packet transits
nodes have the same role, while in hierarchical networks nodes are assigned different responsibilities based on their position in the hierarchy. In location based protocols, the knowledge of the physical location of nodes is exploited, in that data is sent to the desired region of the network, instead of being propagated throughout the entire network. This classification is less useful in the SHM arena, where applications can fall into either of the three categories or a combination thereof, making development of a versatile routing protocol challenging.

Efficient, and reliable data transfer is an important feature of data-intensive applications such as SHM. Implementations of reliable data transfer can be classified into redundant transmission and acknowledgment-based approaches. While the former can be more efficient and simpler to implement, significant data loss due to the bursty nature of packet losses, cannot be completely compensated by this statistical approach. On the other hand, the acknowledgment based approach can be rather slow, particularly for transfer of large amounts of data. Nagayama and Spencer (2007) proposed a single-hop reliable communication protocol involving only a small number of acknowledgment packets. This protocol was tailored for densely deployed sensor networks used in SHM applications, with the aim of increasing the scalability and efficiency of the WSSN. While this protocol provides fast communication, together with packet loss compensation, it is limited to single-hop networks.

Several attempts to develop a reliable multi-hop framework for structural vibration monitoring have been reported. Xu et al. (2004) introduced a WSSN system called Wisden, the Reliable Data Transport component of which uses a combination of hop-by-hop and end-to-end methods to recover from packet loss. Intensive use of overhearing, where nearby nodes receive packets intended for one of their neighbors, associated with this approach to packet loss recovery can be problematic. Radio communication consumes a noticeable amount of energy, even when nodes are in the listening state. Therefore, nodes may be put into the low-power mode to conserve energy, making overhearing intricate. Mechitov et al. (2004) designed a distributed sensing system for SHM applications that emulates the functionality of a centralized wired sensor network. The system features a self-organizing tree structure for routing and opportunistic data aggregation to tackle the problem of limited bandwidth; in this approach, the communication speed issue remains unresolved, particularly as the number of nodes increases. Kim et al. (2007) and Pakzad et al. (2008) designed and implemented a multi-hop wireless sensor network to monitor the Golden Gate Bridge. A reliable communication package was built on top of MintRoute and simple broadcast (Woo et al. 2003). The link quality metric for routing is packet loss and successful delivery events, obtained through snooping methods. Data reliability has been provided using selective negative acknowledgments (NACKs), while keeping network overhead as low as possible. The associated network cost of this method is not insignificant, however; the time required for the transfer of a data record stored on the 512 KB flash memory (e.g., 80 seconds of data for 3 channels sampled at 1000 Hz) from 64 nodes was reported to be more than 12 hours, for an effective data throughput of approximately 0.5-0.7 kB/s, which emphasizes the need for communication speed improvement in addition to maintaining reliable data transfer.

4. AODV routing protocol

Based on a careful comparison of the characteristics of the available routing algorithms against the requirements and constraints imposed by SHM applications, AODV is chosen to be the most suitable routing algorithm for multi-hop communication in SHM networks; it has favorable time and communication complexity, low overhead, and reasonable routing latency. It guarantees loop-freedom
of routes by means of a destination sequence number, which is updated whenever new information about a destination is received. Additionally, the AODV route discovery packets are disseminated only when necessary, saving bandwidth and reducing congestion (Perkins and Royer, 1999). Using this protocol, general topology maintenance is not needed, i.e., only local connectivity information is retained. Another advantage of this protocol is that route information is stored only on nodes that are involved in the routing, thus providing greater scalability. Moreover, AODV is one of the most widely studied and popular routing algorithms and is the only on-demand routing protocol for which a simplified publicly available implementation is available for TinyOS, the operating system for Imote2-based wireless sensor networks. In what follows, this algorithm is first described and then the properties of AODV relative to SHM applications are discussed.

In the AODV protocol, when a node needs to communicate with another node in the network, it searches its route table for a route to the destination. If no such route is found, a route request (RREQ) message is initiated. The RREQ message is then advertised into the network. Route reply packets (RREP) originating at the destination or intermediate nodes knowing a path to the destination establish the route in the reverse order. Once receiving the RREP messages, the source node chooses a path with the minimum number of hops. Route freshness and loop freedom are guaranteed through the use of sequence numbers.

Fig. 4 shows an example of AODV route discovery method. Here, node A is the source, and node I is the destination. The source node disseminates a RREQ message. Nodes that receive the RREQ message rebroadcast; this process is repeated until the request reaches the destination node, or a node that has a route to the destination. At this point, a route reply message is sent back to the source, notifying it that the route was found. Among the received routes, the source node chooses the one with the minimum hop count for data dissemination.

The AODV protocol is designed to find a route connecting two nodes which may be many hops apart. As explained in the previous paragraphs, RREQ packets leave the originator node and diffuse in the network searching for the destination; intermediate nodes that receive RREQ packets rebroadcast. To prevent RREQ packets from traveling across the network indefinitely, the lifetime and therefore the maximum distance a RREQ packet can travel, is limited by a Time-To-Live (TTL) value. The TTL value is a mechanism to limit the scope the RREQ travels, which in turn reduces the overall power consumption of the network. In general, TTL is set via an expanding ring search; TTL is initially set as a small number and incremented if the destination is not reached. However, the appropriate TTL value can be configured based on the network and application. While large

![Diagram of AODV route discovery](image)

Fig. 4 An example of AODV route discovery, node A is the source and I is the destination, the source chooses the route with the shortest hop count
TTL values ensure full reachability, smaller values may be appropriate in some circumstances (e.g., for communication within a cluster or only with immediate neighbors).

The reason for choosing an on-demand routing protocol over a table-driven protocol comes from the unique requirements of SHM applications, where the network structure is predefined and mostly static. Therefore, imposing the overhead of periodic route table exchange is not rational. On the other hand, because the probability of node failures due to battery failure or other hardware problems is high, finding the routes once and maintaining fixed routing tables is inadequate. With respect to WSSNs deployed on bridges, the near-linear topology can be used to reduce significantly the overhead that is caused by route request message broadcasts in the AODV routing protocol. Moreover, the dense deployment and stability of the routing structure results in long-lived paths which in turn reduces the overhead of route discovery.

The flat routing philosophy of this protocol makes it a suitable choice for routing in SHM applications with linear network topologies. Moreover, the method of route discovery in AODV is very flexible, which makes it suitable for diverse SHM applications and allows it to support new applications with different communication patterns. AODV supports a wide variety of communication patterns, including multicast transmission, which is highly desirable as the network size increases (although not available now, future implementation of AODV for TinyOS can include this feature).

As mentioned in Section 2.2, one characteristic of SHM applications is the deployments are typically large-scale and dense; providing multicast capabilities will allow efficient scaling up to large network sizes.

As a result, AODV is adopted as the routing protocol for the reliable multi-hop communication approaches presented in this paper. However, some adjustments to the AODV routing metric are required, as the hop count routing metric can lead to selection of paths with long and unreliable links. This problem will be further appraised in the next sections, and an approach proposed to address this difficulty.

5. Routing customization and data transport

Multi-hop communication schemes that do not employ coordinated transmission control usually require long data collection times due to packet congestion and collision which slow data transport (Mechitov et al. 2004, Kim et al. 2007). Such approaches are impractical for applications that need prompt information about structural performance. Two cardinal solutions to the problem of long data collection times are decentralization and increasing data transfer throughput. Correspondingly, two complementary approaches to reliable multi-hop communication are proposed in this section.

The first implementation focuses on any-to-any communication needed for decentralized SHM applications. This flexible implementation contrasts well with multi-hop communication implementations for SHM applications reported in the past, which focus on specific data flow patterns such as central data collection and dissemination, and are not easily extended for decentralized applications. A common networking infrastructure to support these diverse communication functionalities, termed herein as General Purpose Multi-hop (GPMH), is proposed and implemented.

The second implementation, on the other hand, seeks to minimize the long times associated with single-sink data collection, frequently termed many-to-one or central data collection, by increasing data transport efficiency. Among the various communication patterns found in SHM applications, single-sink data collection takes the longest time. While decentralization of operation can reduce the
need for central data collection, single-sink data collection is still employed within hierarchical groups (Nagayama and Spencer 2007, Sim and Spencer 2009); fast single-sink data collection is undoubtedly vital. By taking into account the communication patterns of centralized data gathering applications and the RF communication characteristics of WSSNs, an efficient data collection approach, termed herein as Single-sink Multi-hop (SSMH), is proposed.

5.1 Flexible general purpose multi-hop (GPMH) communication

This section describes GPMH, a flexible and adaptable approach for reliable multi-hop communication. SHM applications for large-scale WSSNs are quite complex, typically including several stages of operation, such as initialization, sensing, data processing and aggregation. Different applications, and even different parts of a single application, require different types of communication and data transfer (e.g., unicast or multicast from a single source, aggregation from multiple sources, peer-to-peer data exchange). This inherent complexity impacts significantly the design of WSSN-based monitoring systems, including multi-hop routing protocols. The Illinois SHM Project (ISHMP) Services Toolsuite (Rice and Spencer 2009), taken as the basis of this implementation, seeks to surmount the complexity problem using service-oriented architecture (SOA). The Toolsuite features a basic applications such as centralized data acquisition and decentralized data aggregation, as well as higher-level SHM applications that can perform modal analysis, system identification, and damage detection. A variety of utility services and applications for interacting with the deployed WSSN are also included. In SOA, an application is comprised of software components, called services that are linked together to form the application (Rice and Spencer 2010). As illustrated in Fig. 5, SOA allows for the application-specific logic and control structures to be decoupled from the low-level mechanics of sensing, data processing and communication. Because internal details are encapsulated into each service, one service can be replaced with another without changing other parts of the application.

GPMH is designed as a flexible reliable multi-hop routing service within the ISHMP Services Toolsuite; therefore, all applications built using the Toolsuite can enable reliable multi-hop communication simply by replacing the single-hop reliable data transfer service with the GPMH implementation. GPMH provides a common networking infrastructure, including multi-hop data transfer, which enables diverse communication functionality and avoids unnecessary code duplication, compatibility issues, and poor extensibility and maintainability. In the remainder of this section, changes made to the baseline AODV routing algorithm for implementation in GPMH are presented first, followed by a description of the associated data transfer service.

5.1.1 Modifications to the routing protocol
This section describes changes made to the baseline AODV routing protocol to meet SHM

Fig. 5 A damage detection application composed from services in the ISHMP Services Toolsuite
application requirements. Deployment of a WSSN monitoring system for full-scale civil infrastructure is a challenging task that needs to take into account several structural and environmental factors that are difficult to address prior to deployment and are not often encountered in traditional wireless networks. As such, measuring, evaluating and monitoring the performance of the network during the deployment and operation phases are critical; data collection is not the only task involved in the deployment and operation of a WSSN monitoring system. On-site measurement of radio signal strength and link quality between sensor nodes, network status and performance auditing, and periodic monitoring of node battery levels are among the tasks that must be performed alongside data collection.

Communication patterns within these tasks may have different requirements for routing than those dictated by the application scenario. For instance, while radio signal strength measurement must take place along the same routes as data collection, which would depend on whether the latter is centralized or distributed, communication patterns for the battery measurement service need not follow the same routes, as it only involves point-to-point communication between the gateway node and the sensors. This situation prevents using the same routing topology that may be eventually employed for data collection. Moreover, the topology may change frequently as additional nodes are deployed or existing ones moved to different locations. These considerations indicate that a flexible, application-independent multi-hop communication service is required under these circumstances.

The original design of the AODV routing protocol specifically considers packet exchange among mobile nodes and thus includes mechanisms to update routing information frequently. In particular, the AODV protocol uses periodic probe packets for route maintenance. However, node mobility is not commonly an issue in structural vibration monitoring. Moreover, this method of update propagation consumes significant power. For these reasons, the proposed approach omits periodic probe messages. To cope with the problem of route maintenance which is caused by exclusion of AODV’s local connectivity mechanisms, each entry of the routing tables is associated with a time-stamp that is updated whenever the route is updated or used. Route entry not used or updated for a specific period of time is deleted. The elapsed time before deleting an entry depends on the scale of the network, as well as the topology’s stability. This procedure is deployed to keep the nodes from using out-of-date routes while avoiding costly update messages.

In the proposed implementation, RREQ and RREP packets with a signal strength indicator lower than a threshold are discarded to ensure high-quality links. The primary reason behind adopting the Received Signal Strength Indication (RSSI) threshold is that its use imposes no additional overhead to the network, it is easy to obtain, and it gives a reasonable estimate of link quality. However, the threshold should be specified carefully, because the only route to some nodes may include links with low RSSI packet values. If the chosen threshold is too low, the network may suffer from a flood of unnecessary messages, while if too high, the network may become partitioned.

In SHM applications, keeping the routing delay as small as possible is important. To reduce the delay caused by the routing protocol, RREQ messages are not regenerated when route discovery is unsuccessful; thus, the request for repeated route discoveries is initiated from the higher layers. In GPMH, this task is handled by the reliable data transfer service. This method transfers the control over the delay imposed by routing to the higher level service (reliable data transfer) and simplifies the adjustment to application needs in terms of latency.

The GPMH implementation of AODV employs an alternative to the standard hop-count routing metric used for evaluating different paths. The major drawback of the hop-count routing metric is that it may lead to the selection of long links, which in turn result in an increase in the loss ratio
and power consumption, as well as a decrease in signal strength indicator for the received packets. GPMH implements a new route metric based on the link quality indicator (LQI), which is a measurement included in the header of each received packet characterizing the quality of link over which the packet was transmitted. The LQI value is calculated for each received packet by the CC2420 radio, and measures the received energy level and/or SNR (Chipcon Products 2004).

LQI is designed to be a better estimate of overall link reliability (packet reception rate), whereas RSSI is only a measure of maximum signal level, as mentioned above. However, Srinivasan and Levis (2006) have concluded, based on empirical evaluation, that an RSSI-based link quality indicator is a superior predictor of link reliability compared to LQI. There are two notable exceptions to this finding: (i) environments with asymmetric link quality and (ii) communication near the limit of radio sensitivity. These conditions are rare in many WSSN deployments; however, they are precisely the conditions encountered in SHM deployments similar to those on the Jindo Bridge (see Section 2.2). LQI is expected to have a higher correlation with link reliability when the network topology is sparse, and poor-quality links are prevalent. Moreover, preliminary testing of GPMH deployments on civil structures has provided empirical support for this observation. In GPMH, each RREQ packet carries a route metric, which is calculated on each intermediate node. The new route metric is a linear combination the hop count and the LQI value for the received packet. This routing metric is similar to the metric presented in (Moinzadeh et al. 2010), except that the link quality indicator is used herein instead of the signal strength. Other routing metrics, such as the four-bit link estimation (Fonseca et al. 2007) or a hybrid implementation may provide superior performance under certain conditions; however, a detailed evaluation is beyond the scope of this paper. The proposed routing metric provides a sufficiently reliable assessment of path quality, while not adding significant overhead to the protocol. Moreover, the simplicity of using this metric along with the built-in metric of AODV is attractive.

5.1.2 Modifications to the reliable data transfer service

In what follows, the reliable multi-hop data transfer service is briefly introduced and its important features are discussed. This data transfer service has been designed as a natural extension to the Illinois SHM Project Services Toolsuite, which employs a service-oriented architecture to manage the intrinsic complexity in large-scale WSSN applications. The GPMH communication protocol is implemented underneath the reliable communication protocol developed by Nagayama and Spencer (2007). As a result, the multi-hop data transfer functionality can be added transparently to all applications built using the Toolsuite simply by replacing the single-hop reliable data transfer service with its multi-hop counterpart.

This reliable data transfer service is implemented on top of the routing protocol in an end-to-end manner. Packets are sent to the destination node over multi-hop links without intermediate checks. If missing packets are detected, the destination node requests for the missing packets, and the originator sends them again. To minimize packet overhead, NACK packets are utilized. Here, short messages and long data records are treated separately. Moreover, based on whether the communication is unicast or multicast, a different procedure may be applied (Nagayama and Spencer 2007). For long data records, the sender breaks the data record into smaller packets and then sends them. Once all the packets are transmitted, the sender returns a message to the receiver, indicating the end of data transmission. Subsequently, the receiver responds to the sender with the packets that are missing. Only the missing packets are retransmitted. For short messages, because only one packet is sent, an acknowledgment is returned from the receiver to the sender for each
packet. This method of end-to-end reliability support alleviates the need for large buffers on intermediate nodes as packets need little or no processing on these nodes. Moreover, if packet loss for each link is expected to be negligible, the end-to-end reliability check can reduce communication related to acknowledgment packets and allow for fast and efficient data transfer. In the case of high quality intermediate links, this approach can also result in a reduction in power consumption.

Several changes to the existing single-hop reliable data transfer service were required to extend it to exploit the AODV routing protocol. First, all transmissions of this service were replaced with the modified TinyAODV send and receive interfaces. To use the reliable data transfer service coupled with the AODV multi-hop routing, delays were added between consecutive transmissions to accommodate the additional time required for multi-hop data transfers. These delays allow for the underlying routing protocol to stabilize before a new request is generated or before more data is sent. Moreover, the send and receive timeouts in this service were increased relative to the delays in the routing algorithm. Although these changes slow down the applications, they allow route discovery to be performed without interruption. The resulting service allows for reliable multi-hop transmission of data packets that is made possible through the use of the AODV routing protocol.

5.2 Efficient single-sink multi-hop (SSMH) communication

This section describes SSMH, which is a multi-hop communication protocol designed for efficient collection of large amounts of data from arrays of sensor nodes. The routing phase is prompt and congestion-free formation of the shortest-path (i.e., smallest-number-of-hop) routing-tree, which contribute to faster data collection. While searching routes to or from many nodes usually requires transmission of many packets resulting in packet congestion with a high probability of packet collisions, the proposed approach resolves these issues taking advantage of specific communication patterns involved. The data transfer phase is conducted in a link-by-link manner over the established routes. The data collection time required in this phase is reduced by employing efficient and reliable link-by-link data transport protocol and allowing multiple neighboring pairs of nodes assigned with distinct frequency channels to transfer data simultaneously.

5.2.1 Shortest path search for single-sink data collection

While the standard AODV protocol has a mechanism to choose the shortest path under any-to-any communication, the mechanism involves a large number of broadcasts. This broadcast packet traffic can be particularly heavy when many nodes initiate the route discovery process simultaneously and also when the Time-To-Live (TTL) value is large; such transmissions may cause numerous packet collisions. Also, the number of route table entries will be immense for large WSSNs wasting sensor node memory. SSMH improves the route discovery process by assuming single-sink data collection scenarios and by constructing routes in incremental steps. The details of the customized route discovery process are explained in the following paragraphs and illustrated in Fig. 6.

In this proposed customization, TTL is always set to one hop and each leaf node repeatedly performs a route search toward the sink node until a route is found. First all nodes within single-hop range from the sink identify the sink and establish single-hop routes; subsequently, all nodes within two-hop range find nodes which already have routes to the sink. The process continues hop-by-hop in this manner until all nodes set up routes.

To establish the single-hop routes, each leaf node initiates route search toward the sink node after
receiving a command packet that was disseminated over the network. The AODV routing process with TTL = 1 starts by each node broadcasting a RREQ packet. To reduce packet collision, the RREQ packet is sent after some random waiting time. The transmission is repeated multiple times to compensate for packet collisions; this repetition can practically eliminate the possibility of missing the RREQ packet due to collisions. Because the TTL value is one, only RREQ packets from nodes in a single-hop range reach the sink node. On reception of these RREQ packets, the sink node examines the Received Signal Strength Indication (RSSI) value and disregards packets with RSSI values lower than a specified threshold. Note that RSSI is employed as the link quality metric, but other metrics may be used in its place. The sink node then returns the RREP packets only to the certified nodes; the RREP packets are sent multiple times to compensate for packet collisions. When each originator of route search in single-hop range receives the corresponding RREP packet, its RSSI value is examined and single-hop route is established if the value is larger than the threshold. Created routes are clearly of the shortest path (i.e., one hop), and the quality of the links, whose RSSI values are greater than the threshold, is considered satisfactory.

After a waiting time, all the nodes except for those which have already established routes initiate the AODV route discovery process again with TTL = 1. Not only the sink node, but also the leaf nodes possessing routes to the sink (i.e., nodes in the single-hop range from the sink) are qualified to respond to the RREQ packets this time. On reception of a RREQ packet, the qualified nodes examine the RSSI value and return RREP packets. When the corresponding originator receives the RREP packet, the RSSI value check is conducted and a route is established. Because multiple nodes are qualified to return RREP messages and may reply, the originator might receive multiple RREP packets. When RREP messages with a smaller number of hops are received, the route table entry is updated. The table can also be updated when RREP with the same number of hops but a higher RSSI values is received. RSSI values of RREQ packets are included in RREP packets, and the smaller of RREQ and RREP RSSI values are compared to that on the table for update. In this manner, nodes in the two-hop range from the sink can establish routes. When this process is conducted again, nodes in the three-hop range establish routes. The process is repeated for a predetermined number of times.

One drawback of this approach comes from link asymmetry. When a RREQ originator updates its route upon reception of a better RREP message, it does not reliably inform the previously-linked node of this change. Although the established routes are stable and with the minimum number of hops, both in the forward and backward directions, nodes on the routes do not know the backward paths. If backward paths are needed (e.g., one-to-many communication), subsequent actions should
be carried out; for example, the originator can send a packet to the sink node informing all the intermediate nodes of the established route.

5.2.2 Link-by-link block data transfer using multiple RF channels

Sending multiple packets successively along multi-hop routes as in GPMH requires a clear time between packet transmissions to avoid packet collisions, which slows down multi-hop communication as compared with single-hop communication (Kim et al. 2007). To better understand why multi-hop data throughput is low and to prepare for presentation of a solution to this issue, consider the case where multiple packets are transferred through four nodes as shown in Fig. 7. Node A initiates the data transfer by transmitting the first packet “p1”. If node B forwards this packet to C and node A transmits the second packet “p2” immediately, the chance is high that node B is in the transmit mode when “p2” reaches node B. If node A waits until “p1” reaches node C to send “p2”, “p1” from node C and “p2” from node A interfere with each other at node B. Therefore, node A needs to wait until “p1” reaches node D before the next transmission. Because of possible temporary fluctuation of communication range, variations in travel time due to packet processing time variation at each node, and other reasons, this clear time between two successive packet transmissions is typically set larger than the average three-hop travel time. In Fig. 7, only one node is included in each hop range for the sake of clarity. If multiple nodes are in each hop range, these nodes may also cause RF interference and need to have appropriate clear time.

One problem with the packet collision avoidance through transmission time slot division, as described above, is that it slows down communication. Multi-hop data transfer protocols, such as MintRoute (Woo et al. 2003) and Collection Tree Protocol (Gnawali et al. 2009), utilize transmission timers, which in principle, results in a much smaller throughput than for single-hop. As a result, the transfer of large amounts of data may take an impractically long time. An alternative approach to avoid collisions is through frequency slot division (i.e., the use of multiple RF channels); in this case, long clear times are not of absolute necessity. When a neighboring node is communicating using one channel, surrounding nodes can communicate using different channels. The Imote2, as well as many other smart wireless sensor platforms, employs a 2.4 GHz IEEE.802.15.4 RF device with 16 user-selectable channels, each requiring 5 MHz of bandwidth between 2405 MHz and 2480 MHz. In contrast to 2.4 GHz IEEE 802.11, the IEEE.802.15.4 channels do not have overlapping frequency bands; simultaneous communication over all 16 channels is possible. Most previous wireless sensor networks utilized only one channel in the network. However, data intensive applications such as structural health monitoring need higher throughput; use of multiple RF channels is essential.
channels is a potential solution.

Channel switching is carefully integrated into SSMH data transfer so that the RF channel is switched only when needed. Simply having multiple groups of smart sensors with different RF channels results in multiple independent sensor groups which cannot communicate with each other; time synchronization becomes challenging and control packets cannot be easily spread over the entire network. Furthermore, splitting the entire network into multiple independent groups reduces redundancy in the network. Also, channel switching timing is important. Both the intended sender and receiver should collaborate and change their channels in concert. When the frequency is switched back, both nodes should collaborate again. If the RF channel switch notification packet is dropped, one node remains on a different RF channel and becomes unreachable. Implementation of such synchronized frequency switching is not trivial and should be employed infrequently. In the proposed data transfer protocol, sensor nodes switch the channel for block-by-block (e.g., 1MB) data transport instead of switching the channel for packet-by-packet transmission. A pair of nodes switches the RF channel, transfers blocks of data, and then switches the channel back. The data transfer then moves to the next hop. The single-hop reliable communication middleware service (Nagayama and Spencer 2007), which can transfer data quickly with packet loss compensation, is utilized for each link. Two frequency switching approaches are explained next.

5.2.2.1 Dynamic channel allocation

One approach for frequency switching is dynamic channel allocation. Prior to the link-by-link data transfer, the sender searches for an available wireless channel by changing its RF channel to a tentative channel and listening to RF packets. A TinyOS function which counts the received RF packets over the last one-second is utilized to determine channel availability. If the overheard packet number is small, the sender considers this channel as available. If the number is large, the node examines another RF channels. Once an available channel is found, the RF channel is switched back to the original channel and one packet including information about the available channel number is sent to the receiver asking whether the receiver is ready to receive a new data set via the channel. The receiver responds only if ready. If the sender does not receive a reply from the receiver, it repeats this process at a certain interval. Before the receiver responds, the available channel is also examined by the receiver in the same manner. In the receiver response packet, the channel availability is included. If the channel is not available, the sender repeats the process of searching for an available channel and then notifies the receiver again. If the channel is available, the sender reliably notifies the receiver that these two nodes should then switch to the available channels after a certain time delay. Using the new channel, the two nodes perform data transfer.

Two pairs of nodes in a given neighborhood may begin the above-mentioned channel search at the same time; as a result, they both will be in the listening mode to monitor RF activity and cannot find each other’s activity. If the two pairs begin data transfer in the same channel without knowing each other, packet collisions will frequently occur. To reduce possible occurrence of such collisions, the RF channel search is performed after a random wait time. Nevertheless, the chance of two pairs switching frequency to the same channel simultaneously cannot be eliminated. When such collisions occur, link-by-link data transfer takes much longer than usual. Therefore, a timeout for link-by-link data transfer is utilized to detect such collisions. If link-by-link data transfer times out, then the data transfer is halted, and resumed after a random wait time.
5.2.2 Static channel allocation

The second approach employs static channel allocation (see Fig. 8). Depending on the number of hops toward the sink node, nodes are divided into layers and each layer is assigned two channels in addition to the common communication channel; one corresponds to data transmit and the other corresponds to data reception. The data transmit channel of nodes in the $n$-hop layer is the same as the data reception channel of the upper-layer or $n-1$-hop layer (i.e., the layer closer to the sink) nodes. The data reception channel of the $n$-hop layer is the same as the data transmit channel of the lower-layer or $n+1$-hop layer (i.e., the layer farther from the sink) nodes (see Fig. 8). While the number of available RF channels is limited (i.e., 16 for IEEE802.15.4), the RF channels are utilized in a circular manner, providing network scalability. For example, when there are more than 16 hop layers, the 17th hop layer uses the same RF channel as the 1st hop layer. Because these two layers are physically apart from each other, the chance of interference is minimized. Once data is ready to be transferred using the routing tables, all the nodes switch from the common communication channel to their own data reception channels. When each node starts data transfer, the sender switches its RF channel to its data transmit channel and examines whether the channel is used by other nodes. If the channel is used, the node waits for a random time. Note that even seconds, instead of milliseconds, of waiting time would not slow down the total network throughput significantly when each hop data transfer time is tens of seconds or longer. If not, the node sends an inquiry packet asking whether the receiver is ready. If the receiver is not involved in communication with another node, has available buffer space, and is not overhearing packets from other communication pairs, the data transfer begins; large amounts of data are transferred for each instance. After the data transfer, the sender switches the RF channel to its data reception channel. If the receiver is not ready and does not respond, the sender waits for a random time before sending the inquiry packet again.

To eliminate bottlenecks at nodes which have many children (i.e., nodes directly under the node of interest), as compared to the other nodes in the same layer, on-demand rerouting is employed. When an upper-layer node is not able to receive data from the lower-layer because the upper-layer node is forwarding data to an upper-layer node or because the buffer is full, the lower-layer node can start searching for a new parent node by initiating the route discovering process and then send data using this new route. In this way, channels are well utilized and bottlenecks created at a node
with many children can be resolved. Because the static channel allocation approach is simpler, and simplicity usually results in fewer programming bugs and fewer sensor network hang-ups that are typically unforeseen before full-scale deployment, the second approach was employed in the SSMH implementation on the Imote2 platform. However, if a WSSN is used in environments where interference with other RF devices is severe and/or varies with time, the dynamic channel allocation approach better suits the problem.

While this approach has been explained assuming single-sink data collection applications, its extension to multi-sink applications is rather straightforward. When two or more clusters of sensor nodes have their respective destinations, nodes can start the route search process simultaneously toward their own destinations. Data transport can be performed utilizing the established routes if RF channels are appropriately assigned for each sink or if dynamically allocated. In situations where each node needs to make routes to more than one destination, the routing process is performed for each destination.

5.3 Preliminary results

This section presents preliminary results for both the GPMH and SSMH reliable multi-hop communication protocols.

The GPMH reliable multi-hop communication protocol has been evaluated on several test beds. Initial tests were carried out in an office building with 5 to 15 nodes. Subsequently, experiments with 24 nodes were performed in an open parking garage, where the distance between nodes was between 5 m and 8 m. In these experiments, the average route discovery time was approximately 50 seconds. To balance prioritization of stable, high-quality routes with the need to communicate in situations where the signal strength is adversely affected by the environment, an LQI threshold of 60 was determined empirically. The maximum observed hop count for the deployment was 3. In all of the experiments, a linear topology was employed to aid measurement and performance evaluation. For the range of experiments considered, the only change required for integration of GPMH into the various applications was to change from the peer-to-peer communication interface to the interface provided by GPMH, confirming the flexibility, and adaptability of GPMH. Moreover, these experiments played an important role in optimizing the implementation.

The efficiency of data collection employing the SSMH communication protocol was evaluated on a suspension bridge in Japan. Along the main girder of the bridge, 49 sensor nodes were installed. Two base station nodes formed route trees and collected all the vibration measurement data. When 24 nodes under one of the two base stations sent 108 kB of data from each node, the acknowledgement-based reliable data transport was completed in six minutes, which resulted in 7 kB/s or 58 kbps data collection speed. The number of hops was eight at maximum. Because laboratory experiments have determined that the maximum single hop data transport speed of the reliable communication protocol is about 10 kB/s, the multi-hop communication approach can be considered to be quite efficient. The achieved multi-hop performance provides approximately a ten-fold improvement on the throughput of the MintRoute-based data collection strategy (Kim et al. 2007).

6. Conclusions

Reliable multi-hop communication is an essential functionality of WSSNs for full-scale structural
health monitoring. Based on an analysis of application specific characteristics, routing and data transfer protocol customizations are proposed. The Ad-hoc On-demand Distance Vector (AODV) routing protocol was adopted with customizations of the routing metric and exclusion of unnecessary functionality. Additionally, two data transfer services utilizing AODV routing are proposed. The GPMH service features sufficient flexibility to accommodate a broad range of communication patterns, suitable for centralized and distributed data collection, as well as application-independent communication tasks. The SSMH service, on the other hand, focuses on efficient collection of large amounts of data at a single sink node, concurrently exploiting multiple radio channels. Both of the proposed approaches have been implemented on the Imote2 platform and applied in laboratory tests as well as test deployments on full-scale bridges.

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Rapid-to-deploy reconfigurable wireless structural monitoring systems using extended-range wireless sensors

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Abstract. Wireless structural monitoring systems consist of Networks of wireless sensors installed to record the loading environment and corresponding response of large-scale civil structures. Wireless monitoring systems are desirable because they eliminate the need for costly and labor intensive installation of coaxial wiring in a structure. However, another advantageous characteristic of wireless sensors is their installation modularity. For example, wireless sensors can be easily and rapidly removed and reinstalled in new locations on a structure if the need arises. In this study, the reconfiguration of a rapid-to-deploy wireless structural monitoring system is proposed for monitoring short- and medium-span highway bridges. Narada wireless sensor nodes using power amplified radios are adopted to achieve long communication ranges. A network of twenty Narada wireless sensors is installed on the Yeondae Bridge (Korea) to measure the global response of the bridge to controlled truck loadings. To attain acceleration measurements in a large number of locations on the bridge, the wireless monitoring system is installed three times, with each installation concentrating sensors in one localized area of the bridge. Analysis of measurement data after installation of the three monitoring system configurations leads to reliable estimation of the bridge modal properties, including mode shapes.

Keywords: structural monitoring; wireless sensors; modal analysis; smart structures.

1. Introduction

The monitoring of civil structures is an important step in improving the understanding of structural behavior under normal and extreme loads (e.g., earthquakes), as well as illuminating the degradation mechanisms that naturally occur in aging infrastructure systems. Currently, structural monitoring is reserved for special structures (e.g., long-span bridges, hospitals) located in zones of high seismic risk or where strong wind conditions prevail. Even fewer monitoring systems
have been deployed for monitoring the health of structures. Market penetration for structural monitoring remains largely limited by the cost and by the complexity of installing wired monitoring systems in large structures. Wireless sensors have been proposed to alleviate the expense and effort required to install a monitoring system. Since the seminal study of wireless structural monitoring by Straser and Kiremidjian (1998), the state-of-the-art in wireless sensing has rapidly evolved with many viable wireless sensing solutions available for reliable structural monitoring (Spencer et al. 2004, Lynch and Loh 2006). In addition, many academic groups have showcased the potential role that wireless sensors can play in future structural monitoring systems through field implementations in actual operational bridges. A non-exhaustive set of recent field deployments include wireless monitoring of the Alamosa Canyon Bridge, New Mexico (Lynch et al. 2004a), Geumdang Bridge, Korea (Lynch et al. 2006), Gi-Lu Bridge, Taiwan (Lu et al. 2006), Golden Gate Bridge, California (Pakzad et al. 2008) and Wright Bridge, New York (Whelan and Janoyan 2009).

Historically, structural monitoring systems have been viewed as static systems that, once installed in a structure, are rarely changed or modified. This perspective likely finds its origin in the fact that wired monitoring systems are challenging to install and modify. However, wireless sensors eliminate the need for wiring and are therefore easier to install than their wired counterparts. Rapid installation renders wireless monitoring systems very attractive for short-term deployments where response data from operational structures is desired over short periods of time (e.g., hours, days or weeks). For example, short-term monitoring can offer sufficient data from which a rapid condition assessment can be made of an operational bridge (Salawu and Williams 1995). Furthermore, the modularity of the wireless sensors within the monitoring system architecture facilitates relatively easy reconfiguration and modification of the monitoring system topology. Using a small number of wireless sensor nodes, a large number of sensor locations can be achieved.

In this study, a rapid-to-deploy wireless monitoring system is proposed for short-term monitoring of highway bridges. The wireless monitoring system is assembled using a low-cost, low-power wireless sensor node (termed Narada) developed for monitoring civil structures as its primary building block. The wireless sensor node features a high-resolution, multi-channel sensing interface, a powerful microcontroller core, and a wireless communication interface. To allow the wireless sensor node to achieve adequate communication ranges appropriately scaled to the dimensions of the structure, a modified version of a standard IEEE 802.15.4 wireless transceiver is fabricated for long-range wireless communications. Specifically, a power amplification circuit is coupled with the transceiver to increase the radio frequency signal by 10 dB. To highlight the utility of a reconfigurable wireless monitoring system, a network of 20 Narada wireless sensors are deployed on the Yeondae Bridge, located in Icheon, Korea. The monitoring system is installed and reconfigured twice in order to achieve three different sensor topologies in the structure. The vertical acceleration response of this 180 m steel box girder bridge is monitored during controlled truck loading for each configuration of the wireless monitoring system. With intentional overlapping of the three topologies, the mode shapes of the Yeondae Bridge are obtained during off-line analysis of the wirelessly acquired acceleration response data. The paper is structured as follows: first, the Narada wireless sensor node is introduced; second, a modified wireless transceiver for extended-range telemetry is integrated with Narada and analyzed during range testing; third, a short-term measurement campaign on the Yeondae Bridge using the proposed wireless monitoring system is presented along with measurement results; finally, the paper concludes with a detailed modal analysis of the bridge conducted off-line using wireless response data.
2. Extended-range wireless sensor for structural monitoring

The Narada wireless sensor (Fig. 1) was designed at the University of Michigan for use in smart structure applications including for monitoring and feedback control of large-scale civil structures (Swartz et al. 2005). Unlike other application areas, the use of wireless sensors in civil structures requires a low-power hardware design that allows a node to survive for long periods of time (e.g., years) on battery or energy harvesting power sources. The large spatial dimensions of civil structures require large communication ranges in the hundreds of meters. In addition, many civil structures exhibit low amplitude vibrations; high-resolution digitization is therefore necessary to ensure low voltage sensor signals remain well above the quantization error inherent to the analog-to-digital conversion process. Finally, the overall cost of the wireless sensor design should be minimized to ensure that the technology is attractive for commercial adoption. Narada has been designed using commercial off-the-shelf embedded system components to achieve a low-power, high resolution wireless sensing and actuation node capable of long-range communication. In comparison to other commercial wireless sensor nodes (e.g., Crossbow Motes, Crossbow iMote and Moteiv Telos), the Narada wireless sensor platform offers true, 16-bit analog-to-digital conversion for the digitalization of sensor data, as well as a modular radio design that supports the use of a power amplified IEEE802.15.4 radio capable of communication ranges in excess of 500 m. Another distinguishing feature of the Narada wireless sensor node that is beyond the scope of this study is the inclusion of an actuation interface for high speed feedback control of actuators.

![Fig. 1 Narada wireless sensor for structural monitoring: (a) main printed circuit board with four functional blocks specified, (b) standard CC2420 transceiver daughter board, (c) power amplified CC2420 daughter board and (d) fully assembled units for regular- and extended-range telemetry](image-url)
2.1 Narada hardware design

The hardware design of Narada encapsulates the aforementioned functionality necessary for effective operation in structural monitoring applications. In particular, the hardware design of the low-power node is decomposed into four functional blocks that support the node’s capabilities to sense, communicate, compute and actuate. (Swartz et al. 2005). The first two capabilities (i.e., sensing and communication) replicate the functionality of sensors in the traditional monitoring paradigm. However, the inclusion of computing into the wireless sensor node represents a significant departure from that paradigm since it empowers the wireless sensor node to interrogate raw sensor data individually or collectively with other wireless sensors in a network. In-network data processing (in lieu of communicating high-bandwidth raw data streams) has proven effective in enhancing the reliability of the wireless communication channel while preserving power in battery operated devices (Lynch et al. 2004b, Nagayama and Spencer 2007, Zimmerman et al. 2008, Rice et al. 2008, Kijewski-Correa and Su 2009, Jones and Pei 2009).

More recently, it has been proposed that wireless sensors leverage their computational capabilities for service as a controller in real-time feedback control systems (Swartz and Lynch 2009). To achieve this goal, the capability to command actuators has emerged in the design of some wireless sensor prototypes proposed for smart structure applications.

For data collection, Narada’s sensing interface is designed around the Texas Instruments ADS8341 analog-to-digital converter (ADC). This ADC supports high data rate collection (maximum 100 kHz) simultaneously on four independent sensing channels (Texas Instruments 2003). The ADS8341 was chosen for the Narada design for two reasons. First, it has a high 16-bit digital resolution that is suitable for ambient structural vibration measurements. Second, the ADC can be programmed to collect four channels of single-ended inputs or as 2-channels of differential inputs. While a large fraction of sensors used for structural monitoring are single-ended, some sensors recently proposed for structural monitoring (e.g., the Silicon Designs SD2012 accelerometer) offer superior performance when utilized in differential output mode (Silicon Designs 2009). After data is collected by the sensing interface, it is passed to the computational core consisting of an embedded microcontroller (Atmel ATmega128) and memory. The Atmega128 is a low-power, 8-bit microcontroller with 128 kB of flash memory (for the storage of programs), 4 kB of electrically erasable programmable read-only memory (for the storage of program constants) and 4 kB of static random access memory (for the storage of sensor data). To enlarge the amount of memory available for the storage of sensor data, an additional 128 kB of external static random access memory is included in the sensor design. The physical circuit corresponding to the computational core and sensing interface are combined on the same 4-layer printed circuit board (Fig. 1(a)). While beyond the scope of this paper, a 2-channel, 12-bit digital-to-analog converter (Texas Instruments DAC7612) is also included in the Narada circuit board to serve as an actuation interface. The Narada actuation interface has been previously utilized during wireless structural control studies (Swartz and Lynch 2009). The printed circuit board (PCB) has been carefully designed to ensure digital circuitry (e.g., microcontroller or memory) and its associated noise does not contaminate the performance (i.e., reduce the effective resolution) of the ADC. The PCB design preserves almost the full 16-bit ADC resolution with the quantization error measured to be slightly greater than one bit (i.e., ADC’s resolution is estimated to be about 15-bits which corresponds to a quantization error of 0.15 mV relative to the 0-5V input voltage range of the ADC).
The performance of the wireless structural monitoring system is directly correlated to the performance of the wireless transceivers utilized for communication in the system. While a plethora of transceivers have been previously integrated with various commercial and academic prototypes (Lynch and Loh 2006), the field appears to be converging on transceivers that comply with the IEEE 802.15.4 radio standard. This standard defines a physical (PHY) and medium access control (MAC) protocol layer for low-power short-range wireless personal area networks (WPAN) such as sensor networks (IEEE 2006). In the design of Narada, the popular Texas Instruments CC2420 IEEE 802.15.4 transceiver is selected (Texas Instruments 2008). The CC2420 operates on the 2.4 GHz band at 250 kbps using direct sequence spread spectrum (DSSS) radio frequency modulation techniques. The transceiver is obtained from the vendor on its own printed circuit board; this daughter board (Fig. 1(b)) can be easily connected to the main Narada circuit board (Fig. 1(d)).

A particularly useful feature of the CC2420 transceiver is that the output wireless signal can be easily varied from weak to strong; signal strength is set by writing to an internal hardware register on the CC2420. Allowing the user to set the wireless signal strength is a powerful feature of the CC2420. In effect, an end-user can balance communication range and power consumption of the radio. For example, eight discrete levels of radio strength can be selected ranging from 0 to -25 dB. The power consumption of the radio when using a signal strength of 0 dB (long-range) is 57.4 mW. In contrast, when configured to use a signal strength of -25 dB (short-range), the radio only consumes 28 mW. The discrete levels of radio strength and their corresponding power consumption characteristics during transmission are plotted in Fig. 2. It is difficult to prescribe a precise range to each of these output signal strengths since communication range is a function of the output power, antenna type, antenna location, as well as many other environmental parameters (Bensky 2004). However, under favorable conditions, an output power of -25 dB would offer short communication ranges (10’s of meters) while a 0 dB power level could achieve ranges in excess of 100 m.

In civil engineering applications, the size of the instrumented structure often necessitates that data be transmitted distances in the hundreds of meters. Therefore, the short communication range
offered by the standard CC2420 transceiver could require the deployment of a multi-hop wireless sensor network in which data is “hopped” from node-to-node until it reaches its intended recipient. However, the redundant data transmission in multi-hop networks consumes precious communication bandwidth thereby limiting the effective throughput of the network as a whole (Raghavendra et al. 2004). Where data throughput is critical, bandwidth may be recovered by increasing the transmission range of individual units. Increased range can be achieved by increasing the transmitted signal strength. One means of increasing signal strength is to adopt specialized antennas such as high-gain, directional antennas where the signal is concentrated in a radio frequency (RF) beam oriented in a specific direction. Another approach is to amplify the signal output.

In this study, a power-amplified CC2420 transceiver circuit (Fig. 1(c)) fabricated to fit the Narada radio interface is adopted (Grini 2006). This extended-range transceiver amplifies the CC2420 output signal by 10 dB using a power amplifier circuit between the CC2420 chip and the antenna connector. In the United States, the power amplified CC2420 operates below the Federal Communications Commission (FCC) maximum permissible power level of 1 W. To achieve the 10 dB gain in signal strength, the power-amplified circuit consumes twice the current of the standard CC2420 transceiver board when transmitting. The radio strength of the extended-range radio and its corresponding power consumption characteristics when transmitting are plotted in Fig. 2. When the extended range radio is idle, the power amplification circuit only draws 6 mW of power. The short-range and extended-range radios are modular components that can be swapped using the same underlying Narada circuit board as shown in Fig. 1(d). This design approach allows the end-user to select the CC2420 transceiver board that best meets their range requirements and energy budgets (in the case of battery operated devices).

2.3 Embedded software design

An embedded operating system has been custom written for the Narada wireless sensor node. The role of the operating system is to simplify the operation of the wireless sensor for end-users and to provide an intermediate software layer between hardware and upper software written for data interrogation. Data acquisition (DAQ) modules have been written for the embedded operating system to provide Narada with the capability of real-time continuous data streaming or buffer-burst data transfer. The DAQ package included in the embedded operating system is written to collect data from the node ADC and to wirelessly transmit the data to a desired location including to a laptop personal computer (PC) serving as a remote data repository. In this study, a centralized PC will be utilized to coordinate the activities of the wireless monitoring system and to serve as a single repository of network measurement data. A text file containing DAQ parameters is created by the user, processed by an executable server program running on the PC, and wirelessly transmitted to the network over a CC2420 development board connected to the PC serial port. This text file includes parameters such as mode of operation (continuous data streaming versus buffer-burst data transfer), identification numbers of the Narada nodes to use, Narada ADC sensor channels to use, sampling frequency (up to 10 kHz), sensing duration (dependent on sampling rate), and number of samples to buffer locally before transmitting in the buffer-burst mode of operation (up to 30,000 samples).

There are practical limitations on the total number of sensing channels that may be included in a network designated to run in the continuous data streaming mode. In effect, the wireless sensor network is limited by the available bandwidth on a specific channel of the IEEE 802.15.4 radio
Rapid-to-deploy reconfigurable wireless structural monitoring systems using extended-range wireless sensors

spectrum (2.4 GHz). Access to the shared wireless channel is controlled by a time-division multiple access (TDMA) scheme in which each sensor is queried by the server at a specified time for data locally stored in its memory bank. Once data is successfully transmitted, it can be overwritten by the node. However, this method is only reliable if the server has sufficient time to collect locally buffered measurement data before the memory bank fills to capacity. Hence, the server can determine before data collection if, for a given number of sensor channels in the monitoring system and a given sample rate, the network has enough time to collect data from each node before the local data buffer must be overwritten. If the server determines a priori that there is a risk of losing data (due to too many channels collecting data at too fast of a sampling rate), it will stop the data collection process and alert the end user. For example, the system sampling at 100 Hz will only be able to collect data from 15 sensor channels before data transmission between the wireless sensors and the PC would require more time than the time it takes to completely fill the local memory at the sensor nodes. To increase the total number of sensor channels in the monitoring system, one approach is to divide the network of Narada nodes into separate channels in the 2.4 GHz spectrum (16 are available); each channel can then be concurrently serviced by the PC using separate receivers (Swartz et al. 2009). In buffer-burst mode, the PC commands the network of wireless sensors to collect a fixed number of data points, store the data in memory (up to 60,000 data points) and stop data collection. The PC server then would query each sensor one at a time to retrieve measurement data locally stored after data collection has ceased. In this approach, there is no theoretical limit on the number of channels that can be collected at one time by the monitoring system.

Another challenge inherent to wireless sensing is time synchronization of individual nodes operating in the wireless network (Raghavendra et al. 2004). Unlike in traditional wired monitoring systems where a single ADC is used in a multiplexed fashion to sample multiple sensor channels, a wireless sensor network is composed of multiple ADCs each being timed by a local clock. Precise time synchronization of the independent clocks must take place using the communication media and will be dependent upon the propagation and processing of synchronization messages broadcast between wirelessly networked nodes. Errors in synchronization between data streams lead to corruption of the phase information contained in the data signals. This can adversely affect the accuracy of some processing algorithms commonly associated with modal analysis (Ginsberg 2001), input-output or multiple-output modeling (Lei et al. 2005), or feedback control (Lian et al. 2005). This task is made more difficult in wireless networks where signal propagation times are stochastic and direct communications between all units in the network may not be possible (Raghavendra et al. 2004). Only recently have elegant strategies for accurate time synchronization have been reported (Nagayama and Spencer 2007, Yan et al. 2009).

In the embedded operating system of Narada, time synchronization is achieved through the use of beacon signals. Prior to data collection, the Narada wireless sensors in the monitoring system are notified of a pending data collection request. Upon receipt of this notification, each node goes into standby mode waiting to receive a beacon packet from the PC. Assuming receipt of the beacon packet occurs at the same time in all of the nodes, a start time is established and the data collection process initiated. However, small synchronization errors can result from beaconing due to different signal propagation times and different processing times. The differential signal propagation times are stochastic, but are limited by the signal propagation range of the system. For example, if a node is 1 km from the PC server, the time for the beacon to travel (based on the speed of light) is as large as 3.3 μs (a rather negligible number when considering the fact that sampling frequencies in structural monitoring systems are generally less than 1 kHz). More significant is the differential processing
time. The synchronization error from differential processing can be minimized by limiting the actions of the wireless sensors prior to the start of a data collection run. In Narada, the node is placed in a wait state (composed of a “while” loop) that repeats the execution of four assembly instructions. The wait state stops when the PC server’s beacon packet is received and serviced. This practice limits the differential processing time to at most, four clock cycles on the Atmega 128 microcontroller plus any delays in processing packets in the CC2420 transceiver.

Since the time synchronization error is stochastic, it must be experimentally quantified. The synchronization error due to differential processing time has been characterized experimentally by use of multiple, collocated sensing nodes programmed to raise a digital logic line when the first data point is ready upon reception of the system start beacon. The differential processing time is then measured on a digital oscilloscope during repeated measurements. The differential processing time synchronization error on Narada is found to be a Poisson distribution with a mean of 7.4 $\mu$s, and peak observed value of 30 $\mu$s. The distribution of these errors is depicted in Fig. 3. Considering 200 Hz as a typical sampling frequency for civil engineering applications, these results indicate a maximum synchronization error of less than 1 % of a typical time step on the Narada system.

3. Performance assessment of the extended-range wireless transceiver

The performance of the extended-range IEEE 802.15.4 wireless transceiver is quantified by conducting range testing in an outdoor paved lot. Special embedded software is written for the Narada wireless sensor node where one wireless sensor transmits data packets that are then received by a PC server. The strength of the Narada radio signal is recorded using the radio signal strength indicator (RSSI) field that is appended to each packet header received by the transceiver. To understand how the performance of the radio varies as a function of range, the test is repeated with the wireless sensor placed at varying distances away from the PC server. A total of four tests are conducted using a Narada wireless sensor node placed 50 cm above the surface of the ground:
Rapid-to-deploy reconfigurable wireless structural monitoring systems using extended-range wireless sensors

i. A Narada wireless sensor node with a standard-range IEEE 802.15.5 transceiver integrated is used during range testing. An omni-directional swivel antenna (Antenova Titanis) is used as the radio’s primary antenna.

ii. A Narada wireless sensor node with an extended-range IEEE 802.15.5 transceiver integrated is used during range testing. An omni-directional swivel antenna (Antenova Titanis) is used as the radio’s primary antenna.

iii. A Narada wireless sensor node with a standard-range IEEE 802.15.5 transceiver integrated is used during range testing. A directional antenna (D-Link DWL-M60AT) is used as the radio’s primary antenna.

iv. A Narada wireless sensor node with an extended-range IEEE 802.15.5 transceiver integrated is used during range testing. A directional antenna (D-Link DWL-M60AT) is used as the radio’s primary antenna.

First, the omni-directional antenna is used with the standard- and extended-range IEEE 802.15.4 transceivers. The omni-directional antenna radiates RF energy in all directions from the Narada wireless sensor node. The test results are plotted in Fig. 4(a); the signal strength of the standard-range radio drops quickly at around 200 m with communication failures experienced. However, the extended-range radio operates at 300 m due to enhanced signal strength. Next, the directional antenna is used with Narada nodes with the standard- and extended-range radios integrated. The directional antenna concentrates the RF energy into a specific beam direction; the concentration of RF energy in a single direction should result in higher RSSI measurements along with greater communication ranges. Fig. 4(b) shows the results focusing on data above 250 m. The signal strength of the extended-range radio is roughly 10 dB greater than that of the standard-range radio. It can be concluded that the communication range of the standard-range radio is around 500 m. However, performance range of the extended-range radios is expected to be more than 600 m.

In general, the 10 dB gain achieved by the extended-range radio results in at least 100 m of additional range for the case of both antennas (omni-directional and directional). However, it should be noted that this added range does come at the cost of increase power consumption by the radio. When maximum communication range is necessary, the range tests reveal that the best antenna to use with Narada is a directional antenna. While impressive communication ranges are achieved with a

Fig. 4 Range testing of the Narada wireless sensor: (a) RSSI of the standard- and extended-range radios using an omni-directional antenna and (b) RSSI of the standard- and extended-range radios using a directional antenna
directional antenna, the wireless sensor node is only capable of communication in one direction. While acceptable in a hub-spoke network architecture, directional communication is less attractive in multi-hop mesh network architectures.

4. Validation of the reconfigurable wireless monitoring system on the Yeondae Bridge

To validate the performance of a reconfigurable wireless monitoring system designed from Narada wireless sensors, full-scale dynamic testing is conducted on an operational highway bridge. The Yeondae Bridge, located in Icheon, Korea, is selected. The monitoring system is installed and reconfigured multiple times during forced vibration testing of the bridge using a calibrated truck.

4.1 Yeondae Bridge, Korea

The Korea Expressway Corporation (KEX) has constructed a 7.7 km test road along the Jungbu Inland Highway in the vicinity of Icheon, Korea. The test road is a redundant section of the two lane southbound Jungbu Inland Highway that can be opened and closed to highway traffic. The test road was constructed to monitor the behavior of concrete and asphalt pavement systems designed using Korean design codes under normal truck loads (Lee et al. 2004). A combination of strain gages, soil pressure sensors and thermocouples are installed along the length of the test road; in total, 1897 sensors are installed within the test road. Along the length of the test road are two medium-span highway bridges (i.e., Geumdang and Yeondae Bridges) and one short-span highway bridge (i.e., Samseung Bridge). Despite the existence of the pavement monitoring system along the test road, the bridges are not instrumented with sensors. Rather, the KEX has partnered with the
Rapid-to-deploy reconfigurable wireless structural monitoring systems using extended-range wireless sensors

Smart Infrastructures Technology Center (SISTeC) to experiment with emerging structural health monitoring (SHM) technologies on the test road bridges. A large number of studies focused on the installation of sensors on the three highway bridges have been reported (Lee et al. 2004, Lynch et al. 2006, Lee et al. 2007, Koo et al. 2008).

Of the three bridges available, the Yeondae Bridge (Fig. 5) is selected for validation of the reconfigurable wireless structural monitoring system. The bridge is 180 m long and is slightly curved at one end (with a radius of curvature of 1718 m). Along the length of the bridge are three concrete piers that divide the bridge into four identical spans, each 45 m long. To accommodate vehicles driving along the curved sections of the bridge, the road has a varying cross-sectional slope from 2.75% to 4%. The bridge also has a large skew angle of 40° at both ends.

The cross section of the bridge consists of two partially-closed trapezoidal steel box girders. The boxes are 2.2 m tall with top and bottom widths of 3.1 m and 2.1 m, respectively. The concrete deck is 27 cm thick and is designed to act in composite action with the steel box girders. The design of the top flange of the steel box girder varies depending on the flexural moment imposed on the section. At the middle of each span where positive bending moment occurs, the steel box girders are open at their tops, a detail that forces the concrete deck to take the full compressive stress of the bridge section. In contrast, the steel box girders are closed on the supports in order to impose the tensile stress to the top flange of the girder rather than in the concrete deck. The Yeondae Bridge is the first example of a partially-open steel box girder bridge in Korea. Due to the unique geometric and structural design features of the Yeondae Bridge, it is anticipated that the bridge will exhibit unique modal properties. To accurately identify these modal properties, a dense instrumentation of vibration sensors will be required during monitoring of the bridge.

4.2 MEMS accelerometers and signal conditioning

To measure the vertical acceleration of the bridge, two different types of microelectromechanical system (MEMS) accelerometers are adopted for integration with the Narada wireless sensor nodes: 14 Crossbow CXL02 accelerometers and 6 PCB Piezotronics 3801D1FB3G accelerometers. Both accelerometers are capacitive-type MEMS accelerometers and are commercially fabricated using standard micromachining methods in a clean-room environment. Compared to other accelerometer types (e.g., piezoelectric or force balanced), these capacitive MEMS accelerometers are relatively low cost, costing $300 or less. The CXL02 accelerometer has an acceleration range of ±2 g, noise floor of 0.5 mg, and sensitivity of 1 V/g. The 3801D1FB3G is a ±3 g accelerometer with a 0.15 mg noise floor and 0.7 V/g sensitivity. Both accelerometers are powered by 5 V and output an analog voltage signal between 0 and 5 V (with 2.5 V corresponding to 0 g).

The low noise floors associated with both MEMS accelerometers were determined to be slightly below the quantization error inherent to the 16-bit ADC (with an effective resolution of 15-bits). However, amplification of the accelerometer outputs can drastically improve the signal-to-noise ratio of the digitized acceleration signals. In order to overcome the reduced resolution of the 16-bit ADC, the outputs of the MEMS accelerometers were amplified by a factor of 20 using a custom-designed amplification board (Lynch et al. 2006, Wang et al. 2007). The signal conditioning board also includes a band-pass filter with a pass-band of 0.014 to 25 Hz. The band-pass filter rejects high frequency electrical noise in the sensor output in addition to anti-aliasing the acceleration signals.
4.3 Deployment of the wireless monitoring system

In this study, 20 Narada wireless sensors are utilized with one single-axis accelerometer (Crossbow CXL02 or PCB 3801D1FB3G) interfaced to each node. Each accelerometer is mounted directly to the surface of the bridge deck to measure the vertical deck acceleration (see Fig. 6(b)). In order to realize a very dense sensor network along the 180 m long bridge, a reconfiguring strategy was adopted with the system modified twice after the initial deployment. Instead of installing all 20 wireless sensors across the entire length of the bridge, the system is first deployed with a dense instrumentation of sensors (7.65 m separation between each sensor) concentrated along the northern one-third of the bridge span with 10 units on each side of the bridge (Fig. 6(a)). To improve the performance of the wireless communications, each wireless sensor node was placed on top of a 56 cm tall rubber traffic cone with the accelerometer connected to each node via a short shielded wire (Fig. 6(b)).

The main advantages of wireless sensors are their mobility; in this study, this mobility is exploited to facilitate reconfiguration of the monitoring system. After dynamic testing with the first installation, the twenty wireless sensor-accelerometer pairs are relocated to the center sections of the bridge, as shown in Fig. 6(a). Since modal analysis will be conducted using response data collected, four sensor locations are kept the same between the first and second system configurations. This intentional overlap between two separate installations will allow for the bridge response to be compared between separate excitation events and to permit the stitching together of global mode shapes. After
data is collected by the second installation, the system is again reconfigured to form a third installation that records the response of the southern-most portion of the Yeondae Bridge (Fig. 6(a)). Due to the absence of cabling work, each sensor installation takes less than one hour to complete. By the end of the test, the reconfiguring strategy adopted results in a dense nodal configuration with wireless sensors installed in 50 different locations along the bridge length.

A receiver (using a directional antenna) is attached to a PC server so that the server can operate the network and collect data from individual wireless sensor nodes deployed along the deck of the bridge. The PC server consists of a laptop computer with a Chipcon CC2420 transceiver attached to its serial port. The PC server is positioned in a fixed location near the northern abutment of the bridge (Fig. 6(c)). This location commands a line-of-sight view of every wireless node on the bridge deck. Reliable communication is anticipated between the receiver and the furthest deployed Narada node (which is using a directional antenna and extended-range radio) during the 3rd installation because the maximum communication distance between them is less than the 180 m. During the 1st system installation, sensors closest to the receiver (nodes S1 through S5 and S11 through S14) utilize omni-directional antennas attached to the extended-range radio. For the other sensor locations along the bridge deck, directional antennas are attached to the Narada extended-range radio.

4.4 Forced vibration bridge testing

During the time of testing, the KEX closes the test road to regular traffic so that forced vibration testing of the Yeondae Bridge can be conducted using controlled truck loading. Forced vibration tests are conducted using a 3-axle truck (Fig. 7) with a total weight of 25 metric tons (measured at a local weigh station prior to arrival at the bridge site). Considering the fact that truck speed is a key factor in the excitation of bridges (Cantieni 1983), this study explores different truck speeds varied from 30 to 70 km/hr in increments of 10 km/hr (i.e., 30, 40, 50, 60 and 70 km/hr).

For each installation of the wireless monitoring system, the truck is driven over the bridge at each of the five truck speeds. Each time the truck is driven over the bridge, the wireless monitoring system records the vertical acceleration response of the deck at a sample rate of 100 Hz in a buffer-
burst data collection mode. Prior to the truck’s entry onto the bridge, the PC server in the wireless monitoring system time synchronizes the nodes and initiates the data collection process by broadcasting a beacon signal. A total of 90 seconds of acceleration data is collected by the wireless monitoring system during each bridge crossing by the truck. The 90 s acceleration time history record collected at each wireless sensor is stored in memory prior to communication to the PC server. With each measurement point 16-bits, the 90 s time history record occupies 18 kB of memory which is only 14% of the memory available on the Narada node. Once the data collection task is completed, the central PC server queries each wireless sensor one-by-one for measurement data.

In total, 15 separate dynamic tests are conducted during the measurement campaign on the Yeondae Bridge. Specifically, the truck is driven across the bridge at five different speeds for each configuration of the wireless monitoring system. Fig. 8 presents a typical measured response of the bridge for sensor location S1 through S10 (Fig. 6(a)) for the first sensor network installation. Fig. 8(a) corresponds to the response of the bridge resulting from the truck crossing the bridge at 30 km/hr while Fig. 8(b) corresponds to the truck crossing at 70 km/hr. The wireless monitoring system collects data for 90 seconds which is sufficient to completely capture the response of the bridge regardless of the truck speed. A 30 sec segment of the bridge response to the 70 km/hr truck at sensor locations S1 and S4 in the first system installation is presented in Fig. 9. During data collection, no data loss is encountered revealing the robustness of the wireless communications in the Narada wireless sensor network. As can be observed in the time history plots, the acceleration response for each truck crossing is time synchronized with the initiation of bridge response occurring at the same time. As expected, larger levels of acceleration are observed when the truck is driven over the bridge at higher speeds.

![Fig. 8 Acceleration response of the Yeondae Bridge measured at the first sensor installation: (a) 30 km/hr truck speed and (b) 70 km/hr truck speed, sensor number (S1 through S10) corresponds to the number presented in Fig. 6(a)](image-url)
Rapid-to-deploy reconfigurable wireless structural monitoring systems using extended-range wireless sensors

Modal analysis by frequency domain decomposition (FDD)

Modal analysis is conducted on the bridge response data to derive mode shapes. In particular, the FDD method is used in this study, because it is an output-only modal analysis method. While some information is known about the bridge loading (e.g., the weight and speed of the truck), only measurements of the bridge response are available for analysis.

5.1 Frequency domain decomposition (FDD)

FDD is an output-only version of the complex mode indication function (CMIF) method which is a sophisticated frequency domain modal identification method that is capable of accurately identifying the real and imaginary components of closely spaced modes. Output-only system identification is theoretically valid under the assumption of a broadband, white noise input. Broadband inputs excite every vibrational mode of the system with identical intensity due to their infinite frequency bandwidth and constant spectra. Therefore, system identification can still be conducted on broadband excitations despite ignorance of the specific input time history record. Since the early 1980s, the decomposition of output spectra using singular value decomposition (SVD) has been studied (Peeters and Ventura 2003). Shih et al. (1988) applied SVD to decompose system frequency response functions (FRF) to identify complex-valued modes using input-output data sets. Later, Brinker et al. (2001) reformulated their approach by using the power spectral density (PSD) functions of the system output; the approach was named frequency domain decomposition. The approach offers a robust method of extracting mode shapes of a structure when excited by a broadband excitation source.

The power relationship between the system input, \( u(t) \) and the measured output, \( y(t) \) can be expressed in the frequency domain as follows

\[
G_{yy}(j\omega) = H(j\omega)G_{uu}(j\omega)H^{H}(j\omega)
\]  

(1)

where \( G_{uu}(j\omega) \) is the power spectral density (PSD) matrix of the input, \( G_{yy}(j\omega) \) is the PSD matrix of

Fig. 9. Acceleration response of the Yeondae Bridge for the 70 km/hr truck at sensor locations S1 (top) and S4 (bottom) in the 1st installation of the monitoring system. The two vertical lines correspond to the point in time when the truck enters and exits the bridge.
the output, \( H(j \omega) \) is the FRF matrix of the structural system, and \( H^H(j \omega) \) is the complex transpose conjugate of \( H(j \omega) \). If the input, \( u(t) \) is ideal white noise, then \( G_{uu}(j \omega) \) can be considered as constant in an infinite frequency range; hence, the output PSD, \( G_{yy}(j \omega) \) directly reflects the product of FRFs, \( H(j \omega) H^H(j \omega) \), in other words, the system power characteristics. By using SVD, the output PSD matrix can be decomposed into singular vectors and singular values. It is singular vectors corresponding to large singular values (modal frequencies) that are correlated to the mode shapes of the structure.

### 5.2 Data partitioning prior to the application of FDD

Some challenges associated with the application of the FDD method are first identified prior to its use for identification of the Yeondae Bridge mode shapes. Specifically, the FDD method is based on the estimated output PSD function which is only valid for a stationary stochastic process. Unfortunately, dynamic bridge testing using a single moving truck does not represent a stationary stochastic process since the truck mass is moving thereby experiencing a non-linear, time-varying coupling with the bridge. However, the free vibration response of the bridge after the truck has left the bridge can be considered as a stationary stochastic process. Thus, in this study the free vibration response of the bridge is used exclusively during modal analysis.

The full time history response collected by the monitoring system is delineated into two portions (i.e., forced and free vibrations). Forced vibrations correspond to the portion of the acceleration time history records of when the truck is on the bridge. After the truck has exited the bridge, the bridge continues to vibrate due to its free vibration behavior. Fig. 9 shows the acceleration time history response of the Yeondae Bridge corresponding to the 70 km/hr truck excitation measured at sensor locations S1 and S4 in the first sensor network installation. In Fig. 9, two vertical lines are superimposed on the time histories to denote the arrival and exit times of the truck on the bridge. Given the location of sensor S1 (it is only 0.55 m away from the expansion joint between the bridge deck and the northern bridge approach), it can be used as a trigger sensor from which the time of the truck first entering the bridge can be identified. It should be noted that because the Yeondae Bridge is supported on elastomeric pads (which act mechanically like low-pass filters isolating vibration from the span surroundings), determination of truck arrival times based on threshold detection should be accurate. The exiting time calculated from the known bridge length and established truck speed is recognized to only be a rough approximation of the exit time of the truck. To proceed with modal analysis, the free vibration response of the bridge well after the estimated exit time of the truck is used as a stochastic stationary process for modal analysis by the FDD method. This approach to partitioning the measured bridge response is executed on the entire data set (i.e., on every data record collected during the 15 separate dynamic tests).

### 5.3 Application of the FDD method

In this study, the free vibration response of the bridge is used for extraction of the bridge modal frequencies and mode shapes. Before mode shapes can be estimated, the modal frequencies of the bridge must be identified. A peak picking approach for estimation of modal frequencies is adopted. As shown in Fig. 10, power spectral density functions obtained from the free vibration response of two collocated sensors at location S9 (1st installation) and S1 (2nd installation) are plotted. The PSD function calculated for each sensor location was improved by using a Hanning window on the time-history data prior to the use of the fast Fourier transform (FFT) algorithm. In addition, repeated
Fourier spectra calculated from time-history records with 50% time-domain overlap are averaged. This approach to improving the PSD spectra provides a good trade-off between the reduction of noise and the distinctive qualities of the modal peaks (Oppenheim and Schafer 1999). Based on the PSD plots, the first five modal frequencies of the bridge are identified at 2.25, 2.64, 3.34, 4.00 and 4.88 Hz.

Using the estimated PSD functions, the mode shapes of the Yeondae Bridge are estimated by the FDD method for each network configuration. Then, the mode shapes calculated for the three separate network installations are stitched together. Specifically, the local mode shape corresponding to one system installation is scaled (by a scalar constant) relative to the local mode shape of the next installation such that the sum of the differences between the mode shape values at the overlapping nodes is minimized. Fig. 11 depicts the first 5 modes identified (2.25, 2.64, 3.34, 4.00 and 4.88 Hz).
Of the five modes extracted, the first three modes are pure flexure modes (2.25, 2.64 and 3.34 Hz), the last mode (4.88 Hz) is a pure torsion mode, and the fourth mode (4.00 Hz) is a combined flexure and torsion mode. The first three mode shapes are flexural bending modes that also correspond to modes calculated off-line using a finite element model of the bridge (Kim et al. 2009). The fifth mode is a torsional mode that is also in strong agreement with the finite element model. This result proves the quality of the data collected and the accuracy of the off-line modal analysis.

6. Conclusions

In this study, an extended-range Narada wireless sensor is proposed for structural monitoring applications. Power amplification of the output of an IEEE 802.15.4 transceiver (i.e., Texas Instruments CC2420) led to a 10 dB gain in the radio signal strength resulting in improved wireless communications in large-scale structures such as medium-span highway bridges. Twenty extended-range Narada wireless sensors are deployed for short time periods on the Yeondae Bridge to measure the bridge acceleration response to truck loading. The mobility of the wireless sensors is leveraged to reconfigure the wireless monitoring system to attain three network configurations that capture the bridge response at 50 different measurement locations. For each of the three network configurations, a 3-axle truck weighing 25 tons is driven across the bridge at speeds ranging from 30 to 70 km/hr. Rapid installation and reconfiguration of the wireless monitoring system is proven to be feasible for short-term monitoring of operational highway bridges. The installation and reconfiguration of the monitoring system took about 1 hour to complete. The performance of the extended-range radio integrated with each Narada node proves robust with nearly 100% data delivery rates during three consecutive days of testing. In addition, time synchronization using a beacon approach proves to be accurate. Using the high fidelity acceleration data collected by the wireless monitoring system, offline modal analysis is conducted including peak picking (to identify modal frequencies) and the use of the frequency domain decomposition method (to identify mode shapes). Reasonable modal frequencies and mode shapes are attained.

This study lays the foundation for future work aimed at deploying Narada wireless sensors on highway bridges permanently. Current work is focused on a long-term field deployment study of the extended-range Narada wireless sensors on bridges in Korea (such as the Geumdang and Samseung Bridges along the Korean test road) and in the United States. While this study exclusively used accelerometers to measure structural vibrations, future efforts will concentrate on a more heterogeneous array of sensors including accelerometers, strain gages, anemometers, thermometers and linear displacement sensors intended to measure both environmental bridge conditions and bridge responses to load. In addition, the FDD analysis conducted off-line is already embedded in the computational core of the Narada wireless sensor for collective computing within the sensor network. The embedded FDD analysis, along with other modal analysis techniques (e.g., stochastic subspace methods), will be executed in-network in future field studies. Accurate mode shape estimation requires the wireless sensor network to be continuously time synchronized during long-term deployments; the issue of clock drift over long periods of operation must be corrected through repeated beacon-based synchronization (as was done in this study). However, more robust long-term strategies for clock synchronization are currently under exploration for embedment in the Narada wireless sensor platform.
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Development and deployment of large scale wireless sensor network on a long-span bridge

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Abstract. Testing and validation processes are critical tasks in developing a new hardware platform based on a new technology. This paper describes a series of experiments to evaluate the performance of a newly developed MEMS-based wireless sensor node as part of a wireless sensor network (WSN). The sensor node consists of a sensor board with four accelerometers, a thermometer and filtering and digitization units, and a MICAz mote for control, local computation and communication. The experiments include calibration and linearity tests for all sensor channels on the sensor boards, dynamic range tests to evaluate their performance when subjected to varying excitation, noise characteristic tests to quantify the noise floor of the sensor board, and temperature tests to study the behavior of the sensors under changing temperature profiles. The paper also describes a large-scale deployment of the WSN on a long-span suspension bridge, which lasted over three months and continuously collected ambient vibration and temperature data on the bridge. Statistical modal properties of a bridge tower are presented and compared with similar estimates from a previous deployment of sensors on the bridge and finite element models.

Keywords: wireless sensor network; testing and calibration; MEMS; modal analysis; bridge monitoring.

1. Introduction

Advances in micro-electro-mechanical-systems (MEMS) technology as well as wireless network systems have attracted attention to the applications of wireless sensor networks (WSNs) in different areas of engineering. One such area of interest is the implementation of WSNs for structural monitoring applications. Several research groups have developed hardware and software wireless sensor network (WSN) platforms to address different requirements of this application and/or deployed a prototype system on civil structures. Spencer et al. (2004), Spencer (2003), Ruiz-Sandoval et al. (2006), Ruiz-Sandoval et al. (2003), Lynch et al. (2003), Lu et al. (2006), Lynch et al. (2005), Aoki et al. (2003), Nagayama et al. (2004), Whelan and Janoyan (2009), Hackmann et al. (2008), Wu et al. (2009), Cho et al. (2008) and Rice and Spencer (2008) are a few examples of such studies. A critical task in developing a new hardware platform which is based on advanced technology is the testing and validation processes. Only after the primary performance of the new systems have been validated can their advantages in terms of low-cost, ease of installation and maintenance, and superior computational capabilities be utilized.

Pakzad et al. (2008) describes an integrated platform for structural monitoring applications, which

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consists of a sensor board with four channels of accelerometers and a thermometer. The sensor board is equipped with dedicated filtering and digitization chips. This platform accepts MICAz motes for control and communication and runs a control software based on TinyOS operating system (Hill et al. 2003). Building up on that work, this paper presents testing and validation processes for the hardware through laboratory and field experiments. The objective of this paper is to present several testing protocols that can be used to evaluate the performance of the hardware for various circumstances. Several laboratory tests are described which examine the behavior of the sensor board under static and dynamic excitations and quantify their characteristic noise levels. Calibration parameters for each sensor are estimated and linearity of their response is evaluated. The behavior of the sensor board under varying temperature profiles is tested and response histograms are presented. The integrated system is deployed on a long-span bridge and the results of statistical modal identification of a tower of the bridge are presented and compared with similar estimates from a previous deployment of sensors on the bridge and finite elements models.

The organization of the remainder of the paper is in three main parts. The hardware platform and its different components are described in section 2. Then the laboratory testing and calibration processes are presented in section 3. Sections 4 and 5 describe the field deployment of the WSN on Golden Gate Bridge as a testbed and present the analysis results.

2. Hardware platform

The wireless sensor network consists of a set of connected sensor nodes. Each node has three main hardware components: sensors, filters and micro-controller, and radio for wireless communication. The sensor board, which has the sensing, filtering and analog-to-digital converters, is shown in Fig. 1. These hardware components are discussed in this section in more details.

2.1 Sensors

The main sensors on the node are MEMS accelerometers. For the measurement of low-level and high-level accelerations, two commercially available sensor units are used in each of two directions.
Development and deployment of large scale wireless sensor network on a long-span bridge

The use of two sensor types is a cost-effective solution and allows examination of performance-price tradeoffs. The high-level sensor is Analog Device’s ADXL 202 shown in Fig. 2(a), a widely used device that provides ±2.0 g range with a sensitivity of 1 mg at 25 Hz (Analog Devices 1999). It is a low-cost (~$10 in 2005), low-power complete two-axis accelerometer, which can measure both dynamic acceleration (vibration) and static acceleration (gravity). Its dimensions are 5 mm × 5 mm × 2 mm. Its nominal resolution is 200 µg per root-square Hz, allowing signals below 2 mg (at 60 Hz bandwidth) to be resolved. Accelerometer noise has the characteristic of white Gaussian noise that contributes equally at all frequencies. This accelerometer provides the required range of strong motions for the node.

Fig. 2(b) shows a Silicon Designs 1221, which provides acceptable sensitivity for low-level ambient structural vibrations at a relatively low cost (Silicon Designs 2007). This single-axis sensor also responds to both static and dynamic vibrations, provides the sensitivity required for ambient vibrations, and has a nominal noise level of 2 µg per root-square Hz. The range of Silicon Designs device is reduced to ±0.150 g so by using 16-bit A/D converters maximum nominal resolution of 4.6 µg is achieved. Tests show that the noise floor of the accelerometer itself is controlling and the device is sensitive to within 10 µg (see the following section for more details).

The other sensor on the board is a thermometer to provide accurate temperature data at each node. This is an important piece of information since tests showed that the sensors are sensitive to temperature changes and the temperature information can be used to calibrate the sensors.

2.2 Filtering and analog/digital conversion

Each channel from the MEMS accelerometers provides an analog voltage that is fed to a single-pole (-6 db) anti-aliasing low-pass filter with a cutoff frequency of 25 Hz. The filter was set for a long-span bridge application because even very high vibration modes have frequencies well below the cutoff frequency. The filtered analog signal is fed to 16-bit analog-to-digital converter (ADC) for each of the four channels. Sampling is done at a high frequency (1 kHz), but the digitized signal is downsampled by averaging, which acts as a digital filter and reduces the Gaussian noise level by a factor of \( \sqrt{n} \), when every n samples are averaged. Combination of the 25 Hz analog anti-aliasing filter, high-frequency sampling at 1000 Hz, and downsampling, provides a simple and power efficient approach for high-resolution acceleration measurement.
2.3 Control and communication unit

The mote with a micro-controller provides local processing and storage capability and a low-power radio communication for a node. The MICAz mote was selected because it has a good tradeoff between processing and communication capability, and power requirements (Crossbow Technology, 2007). The MICAz, pictured in Fig. 3, has 512 kB flash memory, which can store up to 250,000 two-byte data samples, and a 2.4 GHz radio-frequency (RF) Chipcon CC2420 transceiver with a hardware interface that can support commercially available bi-directional antennas. The ability of the mote to connect with a bi-directional antenna was an important factor because the long-span bridge application required a linear network topology and a standard omni-directional antenna would have wasted a significant amount of radio power. Based on the power usage testing of the node (Pakzad et al. 2008), it was decided to use four 6 V lantern batteries to provide 12 V and 15 Ah in the deployment.

3. Testing and validation

Micro-electro-mechanical-system (MEMS) devices are a relatively new category of integrated electronic chips and therefore do not have a long track record of performance for various applications. This makes the process of testing and validation of the hardware and control software critical, because one of the tasks for any research project that uses these devices is to evaluate and validate their performance. Only after establishing such performance measures, can the advantages of MEMS devices in terms of small size, low cost, ease of installation and maintenance, and eventually scalability be considered. In this section the testing and calibration of the sensor network for structural monitoring is presented. Four major categories of tests were performed on the accelerometer sensors: calibration and linearity tests, static tests, shaking table tests, and temperature sensitivity tests. The calibration tests evaluated the linearity of the response of each sensor to acceleration input. The calibration parameters were estimated for use in further testing and comparison with other devices. The static tests evaluated the performance of the sensors under ambient conditions to establish the noise characteristics of the accelerometers. The shaking table tests were performed to analyze the dynamic range of the sensors and test the response characteristics in the frequency range of interest. The
temperature tests evaluated the sensitivity of the accelerometer sensors to temperature change. Each set of tests and results are presented in the following sections.

### 3.1 Calibration and linearity tests

The sensor boards were manufactured in two categories: *horizontal boards*, and *vertical boards*. The horizontal boards are designed for the bridge span to measure acceleration in transverse and vertical directions, so the range of the low-level Silicon Designs 1221 sensor in vertical direction is adjusted to gravity to include 850 mg to 1150 mg interval. The vertical boards, designed to measure accelerations in transverse and longitudinal directions, do not need the adjustment for the gravity and can be used on the bridge tower. Overall, seventy-eight horizontal boards and twenty vertical boards were manufactured.

The accelerometer sensors were calibrated so the digital output of the analog/digital converter (ADC) can be translated into an acceleration value. Calibration was performed by subjecting the sensor to known static accelerations and determining the digital output for that input. The calibration process is performed using the acceleration due to gravity by tilting the sensor between a position parallel to the ground that produces 1.0 g, and vertical position, which corresponds to zero acceleration. At each stop the ADC readings are recorded and compared with the corresponding acceleration and the linear shift and scale factors are estimated. Several stops between vertical and horizontal positions are used to examine the linearity of the accelerometer response. This method has the advantage of simplicity and ease of use, and does not require complicated equipment. It is, however, limited to ±1.0 g range, so it is required to assume that the response remains linear for larger accelerations. Another implicit assumption is made that the acceleration readings are independent of frequency of the input signal and the DC calibration is valid for dynamically applied excitations.

For field deployment, the calibration parameters for every sensor on each board, i.e., shift and scale parameters, were individually determined with tilt tests. A Yuasa 220 single axis rotary tilt table with a UDNC-100 programmable controller was used to tilt the sensor boards, as shown in Fig. 4. The rotary table has a resolution of 0.001 degrees, with an optional horizontal or vertical setting position. The programmable controller was set up to rotate the board under test to a station with a specific angle and collect 1500 samples from each of the four accelerometer channels, before rotating the board further to the next station and repeating this process. The thirteen predefined stations and the corresponding angles and accelerations are listed in Table 1. The horizontal sensors
were subjected to the full range of $-1.0 \text{ g}$ to $+1.0 \text{ g}$ with the rotation of one-half revolution about the horizontal axis.

The ADXL 202 sensor measures the whole interval since its operational range is $\pm 2.0 \text{ g}$. The Silicon Designs 1221 sensor saturates at Station 1, and remains so until Stations 4 or 5, where its operational range of approximately $\pm 150 \text{ mg}$ is reached. This channel saturates again at Stations 9 or 10 where the applied acceleration exceeds its range. In the vertical direction the corresponding acceleration at Station 1 is zero, which is in range for the ADXL 202 but out of range for the Silicon Designs 1221. At Stations 2 through 12 the acceleration goes from $866 \text{ mg}$ to $1.0 \text{ g}$ and again back to $866 \text{ mg}$, which is measured by both vertical sensors. The Silicon Designs 1221 sensor saturates at Station 13. Fig. 5 shows the rotation angle $\theta$ with respect to the horizontal direction. The acceleration generated in vertical and horizontal sensors when the board is tilted by an angle $\theta$ is

\[
\begin{align*}
Acc_{\text{Hor}} &= \sin(\theta) \cdot g \\
Acc_{\text{Ver}} &= (1 - \cos(\theta)) \cdot g
\end{align*}
\]

![Fig. 5 Schematic tilt of sensor board by an angle $\theta$](image)
Fig. 6 shows typical calibration results for one of the horizontal boards. The figure also shows the linearity and range of the sensors under test. The linearly fit line extends from zero count to the full count (65535) to extrapolate the actual range of the sensor. This line varies slightly from sensor to sensor, and from board to board depending on manufacturing and circuitry differences.

The data confirm that all four accelerometer channels on all sensor boards have a linear response to tilt, and hence shift and scale factors would be sufficient to calibrate the digital outputs.

3.2 Static noise characteristics tests

Every sensor has a characteristic noise level which represents sensor circuitry’s noise floor under no external excitation. The purpose of static noise tests is to estimate this noise floor and compare the
performance of the sensors with other devices with known noise characteristic in a quiet environment.

The static tests consist of two experiments that were conducted at Berkeley Seismological Laboratory facilities. The first test was performed in a laboratory in McCone Hall, and the other in a vault in Tilden Hill, near UC-Berkeley campus. The test in Berkeley Seismological Laboratory was performed in the second floor of McCone Hall, under ambient vibrations in an active environment of an academic building. The prototype sensor board was attached to the floor of the building and acceleration data at the rate of 580 Hz was collected for 1600 seconds. This test was then repeated in a seismic vault in Tilden Hill near Lawrence Berkeley Laboratories (LBL Vault), which is located inside a cave on solid rock, and houses Berkeley Seismological Laboratory’s low-noise seismometers. A BKS FBA-23 reference accelerometer, with the root mean square (RMS) noise level of 0.2 \( \mu g \) in the [0 25] Hz interval, was used as the reference sensor to compare the recorded vibrations and estimate the noise floors (results not shown here). Fig. 7(b) shows the prototype sensor board, weighted down by a heavy piece of lead inside the LBL Vault during the test.

The signals from the static noise tests in both time and frequency domains are presented in Fig. 7(a). The time histories are plotted for 1600 sec, and the power spectral densities are limited to 50 Hz. Both sets of plots confirm that the signal from McCone Lab is noisier than the one from LBL Vault. The sensor board experienced a noticeable temperature change during the LBL Vault

![Fig. 7 (a) Time and Frequency plots for static test at McCone Lab and LBL Vault, (b) sensor board in LBL Vault, (c) zoom plot of the noise power spectral density of Silicon Designs 1221 sensor at LBL Vault and McCone Lab and (d) zoom plot of the very low noise power spectral density](image-url)
Development and deployment of large scale wireless sensor network on a long-span bridge

533

test, which is the likely source of the small bump at the beginning of the time history plot and the slow drift afterwards. Otherwise, the signal remains between ±100 μg of the de-trended level. The signal from the McCon Lab varies in an interval of ±2 mg, with a distinct frequency that can be observed in plots of both time and frequency domains. The likely source of the 8 Hz peak in the power spectral density (PSD) at McCon Lab is that this is a transverse vibration mode of the building, which has a very stiff reinforced concrete shear walls. A zoom plot of the power spectral densities of both signals is shown in Fig. 7(c). This graph shows that the low-frequency noise level of the sensor is at -40 dB, so for frequencies over 0.1 Hz, the root mean square acceleration noise per root-Hz is calculated as follows

\[ e_{f>0.1Hz} = \sqrt{10^{-4}} = 10^{-2} \text{mg/}\sqrt{\text{Hz}} = 10 \text{ μg/}\sqrt{\text{Hz}} \]

There is, however, a significant increase in the noise level for frequencies lower than 0.1 Hz. Assuming -20 dB noise power at DC and -37 dB at 0.1 Hz (see Fig. 7(d)), the equivalent RMS noise level per root-Hz in the [0 0.1] Hz is estimated by

\[ e_{f<0.1Hz} = \sqrt{\frac{10^{-2} + 2 \cdot 10^{-4}}{2}} = 0.071 \text{mg/}\sqrt{\text{Hz}} = 71 \text{ μg/}\sqrt{\text{Hz}} \]

The relatively flat part of the PSD for the tests at McCon Lab and LBL Vault in Fig. 7 is due to the characteristic noise of the accelerometer and amplifier, which shows that the self-noise of the Silicon Designs 1221 sensor is higher than the background low frequency noise at both test locations.

The digitization sensitivity of the Silicon Designs 1221 sensors after limiting the range to ±150 mg and using a 16-bit ADC is 300 mg/2^{16-1}=4.6 μg, which is less than the characteristic self-noise of the sensors. These static tests confirm that the noise floor of the low-level high-sensitivity Silicon Designs 1221 accelerometers are well within the target noise level of less than 100 μg for ambient vibration monitoring of a long-span bridge.

3.3 Dynamic range shaking table tests

The static tests of the prototype sensor boards provided valuable information about the noise characteristics of the sensors, but they do not say much about the response accuracy or range under dynamic excitation. The purpose of the shaking table tests, conducted during the development of the prototype boards, was to confirm that the sensors have predictable response when subjected to dynamic motion. To this end, a mass-spring low-noise short-period vertical shaking table constructed from a Johnson-Matheson Model 6840 was used to subject the sensors in the vertical direction to harmonic vibrations with varying amplitudes. Fig. 8(a) shows the set up of the tests. A reference Wilcoxon 731-4A low-noise piezoelectric accelerometer was also placed on the shaking table. A harmonic function generator was used to dynamically drive the table at frequencies 0.5, 1, 2, 4 and 5 Hz, each for approximately 30 sec. Both high-level ADXL 202 and low-level Silicon Designs 1221 sensors in vertical direction were used to collect data during the tests.

Fig. 8(b) shows the time histories of the recorded signals for the prototype sensor boards as well as the reference accelerometer. Power spectral densities using Welch method for the signals from three sensors are plotted in Fig. 8(c). Data from low-level Silicon Designs 1221 in both time and frequency domains are very similar to that for the reference low-noise sensor. The ADXL 202 sensor has a higher noise floor; it is especially evident that in the low-frequency area of the plot the
534

Shamim N. Pakzad

noise floor of the ADXL 202 is about 20 dB higher than Silicon Designs 1221. All sensors in both experiments show a higher DC noise level that particularly affects [0 0.1] Hz interval, undermining the advantage of using Silicon Designs 1221 in the very-low-frequency range. The similar time series of the dynamic tests and their corresponding power spectral densities demonstrate that the MEMS accelerometers accurately measure dynamic accelerations in the frequency range of interest.

3.4 Temperature sensitivity tests

MEMS accelerometers are temperature sensitive devices because the piezoelectric and flexibility properties of the silicon oscillators vary with temperature. The variation in the recorded acceleration during the static test on the LBL Vault, shown in Fig. 7(a), is an example of this temperature sensitivity. To understand this phenomenon a series of temperature tests were performed on the prototype sensor boards using an oven with controlled heating and cooling devices. Fig. 9(a) shows the temperature and acceleration recording of one typical test. The temperature time history plot represents the temperature profile of the test, which starts at room temperature. After an initial period of soaking, the oven cools at the rate of one degree per minute for five minutes, followed by a five-minute period of soaking until it reaches five degrees. After soaking at this temperature for five minutes, the warming period begins, again at a rate of one degree per minute for five minutes followed by soaking for five minutes, up to forty-five degrees, and then cooling again to twenty-five degrees. The second part of the profile consists of continuous warming/cooling, followed by longer soaking periods. The middle plot in Fig. 9(a) shows the acceleration response to this temperature change. The two time histories visually match, which can be observed in the bottom plot of Fig. 9(a) as a relatively straight line fits the two parameters. To examine the temperature
sensitivity in more detail, Figs. 9(b) and 9(c) present two-dimensional histograms of the relationship between acceleration and temperature. In these figures, the concentration of points in any bin out of approximately 20,000 bins in each plot is logarithmically represented by the color codes.

The temperature tests demonstrate that the acceleration response generally varies linearly with temperature. For the Silicon Designs 1221 accelerometers on a typical sensor board (Board 1, Fig. 9(b)), this variation is $8 \text{mg}/45^\circ\text{C} = 0.18 \text{mg/}^\circ\text{C}$. For ADXL 202 sensors on boards 1 in Fig. 9(c) the response is more non-linear and there is hysteresis behavior in the temperature response. Although for the channel in the horizontal direction the response variation is fairly small (about 8 mg), the channel in the vertical direction shows 25 mg response variation for the 45 degree temperature change and the difference between the hysteresis loops (loop diameter) is as large as 5 mg.

The hysteresis behavior of the sensors is not limited to ADXL 202 sensors; the response of Silicon Designs 1221 sensors on other sensor boards, subjected to the same temperature profile showed similar hysteresis loops. The hysteresis behavior of the response of some sensors to the temperature change is not fully understood. The oven test was repeated several times with different sensor boards, and similar results were observed. Further study of this phenomenon is left to future investigation. One possible explanation for this hysteresis behavior is the fact that the electronic circuitry inside the sensors generates small amount of heat and thus experience heating/cooling cycles independently of

Fig. 9 Acceleration versus temperature in oven test for low-level vertical Silicon Designs 1221 sensor on prototype board: (a) time series, (b) two-dimensional histograms for Silicon Designs sensors and (c) two-dimensional histograms for ADXL sensors
the outside temperature. This cyclic heating pattern adds to the outside temperature change and affects the acceleration measurement.

4. Large-scale deployment on Golden Gate Bridge

Fig. 10 shows Golden Gate Bridge at the entrance of the San Francisco Bay, which has a 1280 m (4200 ft) long main-span and 343 m (1125 ft) side-spans. Two stiffening trusses support an orthotropic roadway deck and horizontal planes of wind bracing system at the bottom plane of the truss chords. The legs of the towers, 210 m (745 ft) above the water level, have cellular box sections, connected by horizontal struts at seven elevations (Strauss 1937, Stahl et al. 2007). The wireless sensor network that was designed and developed in this paper was deployed on the bridge to measure and record ambient accelerations. The sensor network consisted of 64 nodes on the main-span and the south tower of the bridge, as shown in Figs. 10 to 12. The network was designed to be scalable in terms of the number of the nodes, complexity of the network topology, data quality and quantity by addressing integrated hardware and software systems such as sensitivity and range of (MEMS) sensors, communication bandwidth of the low-power radio, reliability of command dissemination and data transfer, management of large volume of data and high-frequency sampling (Pakzad et al. 2008). The nodes on the main-span measure acceleration in vertical and transverse directions (Pakzad and Fenves 2009). On the tower, the nodes measure acceleration in transverse and longitudinal directions.

The instrumentation plan for the wireless sensor network for the bridge is shown in Fig. 10. The nodes on the main-span were located based on the range of the radio transmission distance at 30.5 m (100 ft) spacing, but a 15.25 m (50 ft) spacing was used where an obstruction hindered radio communication. Each main-span node was attached to the top flange of the floor girder directly inside of the cable. The eight nodes on the south tower were placed at the ends of four struts above

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Fig. 10 Instrumentation plan for 56 accelerometer sensor nodes on the main-span of Golden Gate Bridge
Development and deployment of large scale wireless sensor network on a long-span bridge

Fig. 11 Views of the main-span and south tower of Golden Gate Bridge as well as a node with its battery pack and bi-directional antenna installed on the main-span.

Fig. 12 Elevations of the south tower of Golden Gate Bridge, and temporary installation of a wireless sensor node on the tower.
the roadway. Fig. 12 shows the elevation of the south tower and maps the location of the nodes. It also shows the temporary installation of a node on the tower with the antenna and battery pack. The tower nodes have a clear line of sight between them and hence have greater radio range than the main-span nodes. The node on the west side of the strut above the superstructure collects data from all the nodes on the tower and transmits them to the network on the main-span. Fifty-three (53) nodes were installed beginning on July 10, 2006, on the west side of the main-span. On September 15, 2006, the batteries were replaced for the nodes on the main-span and three extra nodes were added on the east side. The east side nodes were located at the two quarter-spans and the mid-span of the bridge and had radio communication with the west side nodes under the roadway deck. There were a total of 174 data collection runs of the network during the deployment which lasted until October 14, 2006, including testing and debugging, so all of the collected data sets do not contain data from all of the nodes.

The sampling rate for all runs was 1 kHz, but since the significant vibration frequencies of the bridge are much lower, the data were averaged on the node and downsampled to 50 to 200 Hz prior to transmission. The averaging is very effective in reducing the noise level and improving the accuracy of the estimated parameters. In some of the runs all five channels on a node (two high-level motion sensors, two low-level motion sensors and the temperature sensor) were sampled, but in other runs the channels were limited to the low-level accelerometers to reduce the volume of data. The 512 kB flash memory of each node can buffer 250,000 samples of data, which may be allocated to any combination of the five sensor channels on the node (four accelerometer channels and a temperature sensor). Each run started with a pause to synchronize the network and disseminate a command to start sampling at a future time. After the scheduled sampling took place, there was a pause to establish the network routing. The recorded data were then transferred from each node to the base station using the reliable data communication and pipelining. Each run generated up to 500 kB data per node, which for the network of 60 nodes produced 30 MB data for 15 million samples. Approximately 1.3 GB data was collected during the deployment of the wireless sensor network on Golden Gate Bridge.

5. Statistical modal identification for the south tower

The ambient vibration data from the main-span of Golden Gate Bridge described in the previous section was examined and the result was presented in Pakzad and Fenves (2009). In this section the results of a statistical analysis of the identified vibration modes of the south tower is presented. Although the bridge including the south tower has been instrumented in the past, none of the earlier studies have provided data collected over an extended period of time to allow a statistical analysis of the modal properties. The contribution of this section is to demonstrate that the dense temporal sensing possible with WSNs, provides a high resolution and confidence in the identified vibration modes. The advantage of temporal density of the data is examined by estimating statistical properties for the identified vibration modes. The distribution of the identified mode shapes is examined by their confidence intervals.

Auto-Regressive with Moving Average (ARMA) method is used to identify the modal properties of the tower. For more information about the method as well as the choices for parameters refer to Pakzad and Fenves (2009), Pandit (1991), De Roeck et al. (1995), Andersen (1997), Heylen et al. (1995), and Pappa et al. (1993). For the mode shapes, the statistics are also presented by the mean
value of the parameters and their confidence intervals (CI). A 95% CI for a point-estimated parameter can be interpreted as an interval that is believed, with 95% confidence, to include the true value of the parameter. In other words, if the same procedures are repeated (sampling from the population, estimating the parameter and finding CIs), 95% of the times the estimated CIs are expected to include the true value of the parameter.

The statistical analysis allows inference about the certainty of the estimation of modal vibration properties. The narrower the confidence intervals are, the less uncertainty the estimated values have. The approach can also be used as a comparison basis for other estimations of the same modal parameters. A new estimate that lies inside the CI is consistent with the hypothesis that no change has occurred. If it falls outside the interval, the inconsistency can be explained by a change in the underlying parameter.

The results of system identification from all 174 runs are used to estimate statistical properties of vibration frequencies, damping ratios and mode shapes for the longitudinal, torsional and transverse modes of the tower.

The identified mode shapes, presented in Figs. 13-15 are generally consistent with the dynamic properties of the bridge tower. Note that in all cases since no sensors were installed on the tower below the roadway level, only the behavior of the upper part of the tower is included. The modal displacements are set to zero at the roadway level and the mode shapes are plotted relative to that. In the longitudinal direction the first mode frequency is 0.583 Hz, and the mode shape has no modal nodes (Fig. 13). The second, third and fourth frequencies are 1.805 Hz, 3.345 Hz and 4.733 Hz and the mode shapes have one, two and three modal nodes respectively. The damping ratios for these four modes are less than 0.7%. The first three torsional frequencies are 0.926 Hz, 2.239 Hz and 4.262 Hz, with damping ratios up to 1.5%, and zero, one and two modal nodes respectively. In the transverse direction the first mode frequency is 0.239 Hz, very close to the first transverse frequency of the main span. The estimated modal ordinates of this mode are very close to unity,

![Figure 13](image-url)
which suggests that this mode is in fact the first transverse mode of the entire bridge. The second mode at 0.425 Hz frequency has a linear shape consistent with the first mode of a tower structure. The third and fourth modes at 1.397 Hz and 2.482 Hz have one and two modal nodes respectively.

The figures show the 95% confidence intervals for the mode shapes. Also included, are the results from an earlier deployments of accelerometers (Abdel-Ghaffar and Scanlan 1985) and finite element
models of the bridge (Abdel-Ghaffar et al. 1985). Note that in both of these cases the mode shapes are evaluated at all seven struts of the tower, from strut 1 at the top of the tower to strut 7 at the water level. The results in nearly all cases generally matches the CIs, with the cases where the modal ordinates at the roadway are closer to zero being more accurate than the others.

6. Conclusions

Development and large scale deployment of a MEMS-based wireless sensor network on a long span bridge was described. The hardware of the sensor nodes consists of a sensing unit of high- and low-level accelerometers and thermometers, control and filtering unit for on-board analog and digital data processing, and radio chips for wireless communication. Extensive laboratory testing was performed to validate the hardware system and evaluate its performance under different excitations and environmental circumstances. Each sensor board was individually calibrated using a tilt mechanism and the linearity of the response of each sensing channel was confirmed. Several prototype tests were performed to characterize the static and dynamic noise levels of the sensors. Low-level Silicon Designs has a RMS noise level of $71 \mu g/\sqrt{Hz}$ in the very low frequency range (below 0.1 Hz) which linearly reduces to $10 \mu g/\sqrt{Hz}$ for larger frequencies. The accelerometers performed well in shaking table dynamic tests with sweeping frequencies and matched the response of a reference sensor. All of the tested accelerometers showed some hysteresis response to changing temperature. Although the exact source of this behavior is not fully understood, but the micro heating of the accelerometer as a result of its operation is a contributing factor. Additional testing is required to investigate this phenomenon and address it in the future sensor design.

A large-scale wireless sensor network, consisting of 64 sensor nodes was deployed on Golden Gate Bridge for a period of more than three months and 174 sets of data were collected. The data consisted of a combination of ambient accelerations from low-level and high-level accelerometers and temperature. The statistical modal analysis of the vibration data for the south tower is presented in this paper. Longitudinal, transverse and torsional modal properties of the tower and their statistics are estimated. The mode shapes and their 95% confidence intervals are presented and compared with the estimated modes using finite element models as well as an earlier deployment of sensors on the bridge. The results in most cases match, in that the confidence intervals include the point estimates of the previous methods. It is also observed that the confidence intervals are very small, which indicates high quality and consistency of the data.

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Non-invasive acceleration-based methodology for damage detection and assessment of water distribution system

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Abstract. This paper presents the results of a pilot study and verification of a concept of a novel methodology for damage detection and assessment of water distribution system. The unique feature of the proposed noninvasive methodology is the use of accelerometers installed on the pipe surface, instead of pressure sensors that are traditionally installed invasively. Experimental observations show that a sharp change in pressure is always accompanied by a sharp change of pipe surface acceleration at the corresponding locations along the pipe length. Therefore, water pressure-monitoring can be transformed into acceleration-monitoring of the pipe surface. The latter is a significantly more economical alternative due to the use of less expensive sensors such as MEMS (Micro-Electro-Mechanical Systems) or other acceleration sensors. In this scenario, monitoring is made for Maximum Pipe Acceleration Gradient (MPAG) rather than Maximum Water Head Gradient (MWHG).

This paper presents the results of a small-scale laboratory experiment that serves as the proof of concept of the proposed technology. The ultimate goal of this study is to improve upon the existing SCADA (Supervisory Control And Data Acquisition) by integrating the proposed non-invasive monitoring techniques to ultimately develop the next generation SCADA system for water distribution systems.

Keywords: water pipe monitoring; MEMS sensors; ruptures; wireless sensor network.

1. Introduction

Urban water distribution systems, particularly underground pipeline networks, can be damaged due to earthquake, pipe corrosion, severely cold weather, heavy traffic loads on the ground surface, and many other man-made or natural hazards. In all these situations, the damage can be disastrous: interruption of potable water supply will create major human health problems, let alone all kind of inconveniences; pipe damage may result in reduction in the water head diminishing post-earthquake firefighting capability; water leakage at high pressure may threaten the safety of nearby buildings due to scouring of their foundations; flooding could create major traffic congestion if a pipe ruptures under a busy street. Yet, the current technology is not capable of accurately identifying the location and extent of the damage easily and quickly, even after a major rupture (including severe damage) event. This paper demonstrates the use of a sensor network for identifying the location and extent of

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pipe rupture in real-time so that emergency response measures can be rapidly implemented to minimize disaster consequences.

This paper focuses on the identification of pipe rupture arising from several sources other than earthquake ground motion. These sources include corrosion and aging, excessive surface traffic loading, soil failure, etc. For identifying earthquake induced pipe ruptures, sophisticated analytical models considering the interaction between soil and pipe networks are needed, and they are currently being developed on the basis of more elaborate laboratory and field tests. However, the information obtained from the present pilot study is providing a valuable knowledge-base for the future study. For this reason, the present paper develops and demonstrates an advanced sensor network for real-time monitoring and condition assessment of utility water distribution systems such as the Los Angeles water network, which recently suffered from a large number of non-seismic episodes of pipe ruptures.

The sensor network developed in this paper consists of a platform of multiple real-time wireless and energy-efficient sensors and sensor nodes. Each node transmits wirelessly the data sampled by Micro-Electro-Mechanical Systems (MEMS) and other emerging sensors. Collectively, these sensors have been assembled into two different sized packages: the full-sized version called PipeTECT (Shinozuka et al. 2010) and the miniature version called Eco (Park and Chou 2006). Both have been designed, assembled and tested in the laboratory as well as in the field at UC Irvine and are particularly being tailored for civil engineering applications. The current-generation PipeTECT and Eco are equipped with triaxial MEMS accelerometers. The accuracy of these devices has been verified against traditional high-precision piezoelectric accelerometers in the field and by shake-table tests. Indeed, these tests have validated the ability of the sensor to make the low-frequency observations necessary for monitoring and remotely visualizing (by wireless communications) large-size civil engineering structures in real-time. The substantial cost-effectiveness, robustness, durability, small size and light weight of PipeTECT and Eco sensors make it possible to densely configure observational networks for many types of civil infrastructure systems such as bridges, buildings and pipeline networks.

This study concentrates on the application of sensing technology to pressurized water distribution systems and we develop methods for rapidly detecting and locating the source of anomalies in the water system. Such anomalies can be caused by one of many events such as pipe rupture and pump failure. To develop a novel means of identifying the location and extent of pipe rupture, we take advantage of two major hydraulic behaviors. First, the temporal pressure change is larger at a location closer to the source of transient and decays within distance in both pipe directions, as the numerical simulation using transient hydrodynamic analysis software shows. Therefore, if we install populated pressure sensors throughout the water network, say at each network joint, and continuously monitor the pressure there, the rupture location(s) can be identified in the pipe segment between the two adjacent joints where the local maximum water head gradient (MWHG) are observed simultaneously. However, additional study is needed to confirm a reliable correlation between the extent of the rupture and maximum MWHG values. Second, experimental results show that a sharp change in the water pressure is always accompanied by a sharp change in the acceleration on the pipe surface at the corresponding location along the pipe. This makes it possible to replace the entire process of water pressure monitoring with acceleration monitoring on pipe surface. The latter is significantly less costly compared with the former, because MEMS acceleration sensors for noninvasive sensing are generally much less expensive than pressure gauges for pressure monitoring in an invasive mode.

Thus, monitoring is made not for MWHG but for MPAG (maximum pipe acceleration gradient). As a first step, using a small-scale pipe network, this paper shows the result of a laboratory experiment
that serves as the proof of concept of this new technology, which represents a prototype of the next generation of SCADA (Supervisory Control And Data Acquisition) for water distribution systems.

2. Invasive damage detection using hydraulic transient

2.1 Related studies

Representative previous studies performed for detection of physical damage in water pipes were reviewed. None of them uses pipe acceleration for identifying location and/or extent of pipe rupture.

Liou and Tian (1995) detects pipeline ruptures based on the acquisition and transient analysis of real-time data.

Gao et al. (2005) uses correlation techniques for leak detection and location identification by analyzing the acoustic wave associated with leakage. These techniques are satisfactory for metal pipes, but they are unreliable for nonmetallic pipes in which the acoustic signals attenuates very rapidly.

Ferrante and Brunone (2003) applies several signal processing techniques to the pressure signal in the frequency domain, such as harmonic and wavelet analysis. Such techniques are used to enhance the disparity of the defective signal compared to the benchmark or non-defective signal. Also, wavelet techniques are efficient in detecting any singularity associated with the noise from the discharge.

Wang et al. (2002) detects damage in the pipelines by measuring damping of the transient events based on the fact that the different frequency components are damped differently in the presence of a rupture.

Liggett and Chen (1994) calibrates and determines rupture or unauthorized use in the pipeline systems based on inverse transient analysis in the pipe networks. These techniques solve the inverse problem from the measured pressure head data to detect the extent of rupture but involve extensive computational effort after the relevant data are collected. However, no single method can always meet operational needs from an accuracy and cost point of view (Furness and Reet 1998).

Hunaidi and Chu (1999) characterizes the frequency content of sound/vibration signals from leakage in plastic pipes as a function of leak type, flow rate and pipe pressure. In this study, acceleration of the top surface of the fire hydrant instead of the pipe surface acceleration is used to identify leak characteristics.

2.2 Hydraulic Transients

A hydraulic transient represents a temporary, often violent, change in flow pressure, and other hydraulic conditions in a water distribution system from an original (first) steady state to a final (second) steady state the system achieves after the effect of the disturbance that caused such a transient is absorbed into the second state. The disturbance includes such events as a valve closure or opening, a pump stopping or restarting, and pipe damage or rupture leading to substantial water leakage. The transient can produce a significant change in the water head and pipe pressure. It is envisioned that the sudden change of such pressure will generate a measurable pressure wave and can be used for detection and localization of pipe damage. If the magnitude of this transient pressure is beyond the resistant capacity of system components, then it can induce a significant damage on the pipes, possibly resulting in equally significant system failures. Therefore, it is important to simulate the transient behavior of the water system under various adverse scenarios in order to understand the
magnitude of these effects.

In this study, the industry-grade computer code HAMMER (HAESTAD Press 2003) is employed to generate time histories of key hydraulic parameters (primarily water head and flow rate). Fig. 1 shows an example hydraulic system for which analysis is carried as in HAMMER User’s Guide. This water system consists of two reservoirs, one pump, one valve, 38 nodes and 54 pipe links. In the following, we first consider a case in which a pipe rupture occurs at the midpoint of Pipe P111. In this case, a new node is created at the rupture location in this link (two thick circles in Fig. 1), and the numerical analysis continues. The time histories of the computed water head at Joints J9 and J11 are plotted respectively in Figs. 2(a) and (b). Secondly, we consider a sudden stop of the pump station (node PMP1) due, for example, to seismically induced power blackout. The corresponding water head transient behavior is quite dramatically time variant, as shown in Figs. 2(c) and (d), computed respectively at Joints J13 and J20. The water head transient behaviors under other pipedamage scenarios with appropriate physical parameters of nodes and pipes are shown in Shinozuka and Dong (2005).

3. Proposed method of rupture detection

3.1 Noninvasive method using acceleration gradient

A method of rupture detection and localization, including the identification of malfunctioning equipment (typically pumps) is described here based on the comparison of the hydraulic parameters...
Non-invasive acceleration-based methodology for damage detection and assessment of water distribution system

Before and after each damage event. For the primary purpose of a rapid detection and localization, it is most effective to catch the sign of abrupt change at the outset of the event. Fortunately, for a sudden change such as a pipe rupture and pump stoppage, the response of the network is rapid particularly in the neighborhood of the source. This suggests that some measurable signature that indicates the rapidity of this change can be used for the purpose of such an identification. One convenient quantity that serves this purpose is the water head gradient as defined below.

\[
D = \frac{H_2 - H_1}{t_2 - t_1}
\]  

Here, \(H_1\) and \(H_2\) are the water head at a joint of interest at time \(t_1\) and \(t_2\), respectively. In this study, \(t_2 - t_1 = 0.2\) (seconds) is used for computation.

During the normal steady state operation, \(D\) is usually negligibly small. In this paper, the water head gradient measured at the joints are integrated into a GIS platform for real-time visualization and for other advantages. Fig. 1 shows the distribution of water head gradient \(D\) in a contour plot in the extended network space for the convenience of visualization. The contour plot indicates that the damage location can be identified to be in Pipe P111 between nodes J9 and J11 where the water head gradients are locally at their maxima.

Fig. 2 Nodal water head time histories under damage events
3.2 The novelty of the method

In this section, we introduce a novel rupture detection method based on a wireless MEMS-sensor network that monitors the pipe surface acceleration typically at each network joint in a non-invasive fashion and computes in real-time a measure of acceleration-change. To be more specific, MEMS sensors are installed at all the joints in the pipe network so that at least two end joints of every link of the network are monitored. When a rupture occurs in the network, the sudden disturbance in the water flow and pressure induces corresponding sudden change in the acceleration of pipe vibration. This change in the pipe acceleration is measured, and on the basis of these acceleration data, the location of the pipe rupture can be found in the pipe segment between the two end joints where the acceleration gradient values form local maxima. This is consistent with the result of an analytical simulation as shown in Fig. 1 demonstrating that the rupture is found between two end joints where the water head gradient form local maxima. This procedure, utilizing the non-invasive pipe surface acceleration measurement, facilitates a simple and cost-effective identification of ruptured pipe segment. Fig. 3 shows a comparison between the proposed non-invasive local maximum pipe acceleration gradient (MPAG) method (right column) and the invasive local maximum water head gradient (MWHG) method (left column). We note that the development of the exact correlation between the water pressure and the corresponding acceleration on the pipe surface needs further analytical study assisted by calibration on the basis of small scale model tests, and the field tests using actual water systems. For the field test, we plan to take advantage of scheduled events by the system owner/operator including valve opening and closing, switching on and off the pumps, and water discharge. We intend to make best out of these field experiments to calibrate in developing analytical models for the water pressure-pipe acceleration correlation.

3.3 The correlation between water pressure and acceleration

Pressure variations and flow-induced pipe vibrations are two strongly correlated quantities. The internal pressure $p$ of a pipe can be expressed as $p = p_o + dp$, where $p_o$ is the nominal pressure and $dp$ is the pressure variations. Since the nominal pressure $p_o$ does not contribute to the flow-induced pipe vibrations, only the pressure fluctuations $dp$ will be considered. The pressure $dp$ is balanced by the elastic stresses, $p_{el}$, and the inertia stresses, $p_{in}$, in the pipe wall, i.e., $dp = p_{el} + p_{in}$. Assuming $F_{el}$ is the unidirectional force developed against the pipe wall, then

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**Fig. 3 Damage identification methodology**
Non-invasive acceleration-based methodology for damage detection and assessment of water distribution system

\[ F_{el} = \frac{p_{el}Dl}{2tl} = \frac{p_{el}D}{2t} \]  

(2)

where \( A \) is the cross sectional area, \( D \) is the pipe diameter, \( l \) is arbitrary length of the pipe, and \( t \) is the pipe wall thickness. Hook’s law declares

\[ F_{el} = \frac{AE}{E} = \frac{E \pi \delta_D}{\pi D} = \frac{E \delta_D}{D} \]  

(3)

where, \( E \) is pipe’s elastic modulus, \( \varepsilon \) is strain, \( \delta_D \) is pipe’s diameter deformation. From Eqs. (2) and (3)

\[ p_{el} = \frac{2tE\delta_D}{D^2} = \frac{4tE\delta_D}{D^2} \]  

(4)

where \( \delta \) is the displacement of the pipe wall.

\[ F_{in} = ma = (\pi tlD\rho)a \]  

(5)

where \( m \) is the mass, \( a \) is the acceleration, and \( \rho \) is the mass density of the pipe. From Eqs. (4) and (5), the pressure fluctuations \( dp \) can be expressed as

\[ dp = p_{el} + p_{in} = \frac{4tE\delta_D}{D^2} + t\rho a \]  

(6)

and thus the correlation between pressure variations and pipe wall acceleration becomes readily available. Further assuming:

\[ \delta = \delta_0 \sin(\omega t) \]  

(7)

Eq. (6) can be rewritten

\[ dp = \left(\rho - \frac{4E}{D^2\omega^2}\right)ta \]  

(8)

and the correlation is even more apparent. Another simple approach is to simulate the piping system as one dimensional beam model. Evans et al. (2004) took this approach and derived Eq. (9)

\[ dp = \frac{A\gamma a}{g} \]  

(9)

where \( g \) is gravitational acceleration, \( A \) is cross sectional area of the beam and \( \gamma \) is specific weight of the beam. Eq. (9) again indicates that the acceleration of the pipe is proportional to the pressure fluctuations in the fluid. As seen from the above equations, analytical calculations, which are based on different simplifying assumptions and theoretical models, can be derived and can serve as a first basis in describing pipe vibrations due to pressure fluctuations in a pipeline system. However, in its full detail, this phenomenon is very complex and requires use of experimental and more sophisticated analytical/numerical investigation.

In this background, we emphasize the use of acceleration data measured on the pipe surface as a measure of pipeline health. This study relies on the hypothesis that rupture of considerable size in the system causes sudden expulsion of water, resulting in abrupt change in force on the pipe internal wall to enhance the vibration of the system. Thus, a ruptured segment of the integrated system is
expected to show a distinctly different transient response compared to the response associated with other common ambient forces.

4. Wireless sensing platform

4.1 Existing systems

Wireless platforms can be roughly classified into three types: real-time monitoring, data logging and event-detection. The first is required to send the measured data immediately after the event, while the second aims to collect data for later analysis, and the third can be either. The proposed sensor technology provides a platform with near-real-time monitoring system for wireless data acquisition, transmission, processing, analysis and decision making. The challenges to designing a real-time monitoring system are fast communication links, fair and efficient media access control (MAC) protocols, and low-latency routing protocols.

Several wireless sensor platforms such as Imote, Mica2, and Tmote can all be used, assuming they are interfaced with the right sensor modules. Sensor modules vary depending on the application and technique. For instance, medium to large-sized leakage detection may use time-synchronized pressure and velocity (flow) data (Stoianov et al. 2003); sewer line monitoring may require hydraulic and water quality sensors as well as combined sewer outows (CSO) (Stoianov et al. 2006); pipe failure detection may use acoustic/vibration sensors, velocity (flow) sensors, and pressure sensors for measuring transient (Stoianov et al. 2007). Pipe leakage may use barometric pressure sensors (Bakar et al. 2007) or acoustic sensors (Jin and Eydgahi 2008). However, the choice of the platform depends on many factors, including power and latency constraints, data rate, and local processing demand.

For real deployments, our PipeTECT system uses wired connection from sensor modules underground to the long-range radio above ground. For the purpose of our proof of concept in this paper, however, we chose the ultra-compact wireless sensor platform called Eco, as described next.

4.2 Eco wireless sensor platform

The Eco platform is composed of one base station serving up to 50 Eco nodes to support the proposed real-time monitoring damage localization methodology (Chen and Chou 2008). The components of the Eco platform are shown in Table 1.

4.2.1 Eco

The Eco node is ultra-compact, low power, low cost, and suitable for dense deployment with a short wireless range (Chou 2010). With the dimension of 13×11×7 mm³ including 40 mAh Li-polymer battery, Eco is one of the world’s smallest wireless sensor nodes to date, as shown in Fig. 5. It is equipped with a triaxial accelerometer, a chip antenna, a temperature sensor, an infrared sensor and a flex-PCB expansion port. It consumes less than 60 mW maximum. The Eco node consists of ve subsystems: MCU, radio, sensors, power and expansion port. The MCU (microcontroller unit) on the Eco node is the nRF24E1, which has an integrated 2.4 GHz RF transceiver with a data rate of up to 1 Mbps. The communication distance is up to 10 m. These features enable it to acquire data on a real-time basis. The triaxial acceleration sensor (Hitachi-Metals H34C) has a ±3 g range and temperature from 0-75 °C. In addition, we can not only update the firmware of Eco remotely but also program many
Thanks to its ultra-compact size and low power consumption, Eco nodes can be applied to many kinds of scenarios, including medical diagnosis, environmental and structural-health monitoring, and new human-computer interface. We take advantage of their characteristics and deploy multiple Eco nodes at the joints of a water distribution network to find the damage location for several reasons. First, it is small and self-contained, making it easy and minimally intrusive to deploy. Since we have built a large number of these units for another project, they are ready to use and our unit cost is low. Second, it has a high data rate of 1 Mbps, to be upgraded to 2 Mbps in the next version.

Table 1 The specification of eco and base station

<table>
<thead>
<tr>
<th></th>
<th>Eco (Park and Chou 2006)</th>
<th>Base station (Chen and Chou 2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (mm³)</td>
<td>13×11×8</td>
<td>76.2×114.3×31.7</td>
</tr>
<tr>
<td>Sensor</td>
<td>Triaxial accelerometer ±3 g (H34C)</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>temperature sensor, infrared sensor</td>
<td></td>
</tr>
<tr>
<td>Power consumption</td>
<td>60 mW</td>
<td>900 mW</td>
</tr>
<tr>
<td>Max. air data rate</td>
<td>1 Mbps</td>
<td>2 Mbps</td>
</tr>
<tr>
<td>Power supply</td>
<td>40 mAh Li-Polymer (3.7 V) batt.</td>
<td>DC 500 mA (3.3 V)</td>
</tr>
<tr>
<td>Wired interface</td>
<td>Serial, SPI</td>
<td>10/100 base/T Ethernet</td>
</tr>
<tr>
<td>Wireless interface</td>
<td>2.4 GHz shockburst</td>
<td>2.4 GHz enhanced shockburst</td>
</tr>
<tr>
<td>Radio range (m)</td>
<td>10–20</td>
<td>10–20</td>
</tr>
<tr>
<td>Cost</td>
<td>US$30 (@Qty 1000)</td>
<td>US$100 (@Qty 1)</td>
</tr>
</tbody>
</table>

Fig. 4 Photos of base station

(a) 2.4 GHz RF module       (b) Microcontroller board

Fig. 5 Photos of the Eco wireless sensor node

(a) On the finger          (b) Eco size          (c) Top/Botom view

separate nodes at once (Chen 2008).
This is in contrast to 19.2 kbps to 250 kbps for the most popular motes. Although more local processing can dramatically reduce the bandwidth demand, high-speed radio occupies the frequency band for a shorter amount of time to transmit the same amount of data. This means it will be more scalable to a large number of nodes with less contention among nodes. As with any wireless protocol, packet loss is inevitable and varies under different conditions. We observed a packet loss rate of under 5%.

4.2.2 Ethernet base station

The Ethernet Base Station is the unit that enables communication between the computer and Eco nodes. The base station connects to the host PC via 10/100 Mbps wired Ethernet interface. Fig. 4 shows the picture of the base station hardware. It consists of two modules: microcontroller board and 2.4 GHz RF module. The microcontroller board has a 10/100 Mbps Ethernet port, RS-232 port, 40 general-purpose I/O pins, and SPI for the connection to 2.4 GHz RF module. One base station can aggregate data from up to 50 Eco nodes using a low-complexity, high throughput multiple-access wireless protocol based on the concept of pulling (Yoo et al. 2009). A base station may pull autonomously or may be transparent to the host by passing commands and data through. Depending on commands, sensor nodes can send multiple replies for a single command. The pulling commands also effectively serve as a centralized time synchronization mechanism on the Eco nodes with a ±1 ms accuracy.

4.3 Calibration test

To evaluate the performance of Eco, we conduct a lab experiment employing a shake table. Specifically, this experiment has been carried out at the low frequency of the shake table (1 Hz) to show the possibility of applying to structural-health monitoring. Eco and a traditional high-precision piezoelectric accelerometer, model #AS-3257 from Tokyo Sokusin, were both installed on the shake table to measure the vibration. Fig. 6 shows the time-histories and the FFT (Fast Fourier Transfer) results from Eco and the AS-3257 were nearly identical to each other. The FFT was carried out using standard Cooley-Tukey Fast Fourier Transform algorithm (Cooley and Tukey 1965). Herein,
we carried out the FFT using standard Matlab 7 command. The number of FFT data points was 1024. The sampling frequency was 125 samples/sec. The leakage will be handled by a smoothing technique using standard spectral window function such as Hann window.

5. Preliminary experiments

5.1 Experimental setup

To validate the concept for noninvasive acceleration-based damage detection and assessment method of water distribution system using a wireless MEMS sensor network, a miniature water distribution system was constructed with 40 PVC pipes of 1.5-inch (3.8 cm) diameter with two valves labeled A and B. Fig. 7(a) shows the photo of this small-scale model, while Fig. 7(b) shows the overall size of this model to be about $600 \times 600$ cm$^2$, where valves A and B are used to control water pressure inside the water distribution system and to emulate a rupture, respectively. Valve A can be adjusted manually to three states: closing, half-opening and complete opening, where closing means high pressure and no water flow; half-opening means medium pressure with water flowing in the pipe network; and complete opening means low pressure with water flowing. The half-opening case is similar to real water distribution system with ambient noise. Initially, both valves are closed to allow the pressure to build up gradually, and then valve A is opened by half. This procedure can
Fig. 8 Acceleration data measured by Eco nodes
provide not only a semi-steady-state water pressure inside the pipe network but also an ambient noise due to water flowing inside the pipe. Recording of the data begins after the water distribution system has been injected water and reached steady state, and recording stops a few seconds after valve B has been abruptly forced open completely to simulate a pipe rupture.

Eco nodes are installed at 17 joint points on the water distribution system to collect vibration data in real-time, as shown in Fig. 7(b). The data is wirelessly transmitted continuously to a host computer via a base station in near real-time, with about 1 second of lag.

5.2 Results and analysis

Fig. 8 shows the measured data of rapidly changed acceleration using an Eco-based MEMS sensor network. Each Eco node is equipped with a triaxial accelerometer, and 17 nodes with three channels each successfully transmitted acceleration at 125 samples per second in real time to a laptop computer. A sequence of Z-direction acceleration records is plotted in Fig. 8.

We plot representative acceleration data from eight of the 17 joints, and they are labeled 1, 3, 7, 8, 11, 13, 15 and 16. These plots show that the effect of simulated rupture measured in terms of the magnitude (intensity) of acceleration depends on the distance between the rupture location and the sensor locations. For example, Figs. 8(a) and (b) show two representative acceleration data measured on the segment of rupture; (c) and (d) show those measured one segment away from the rupture point; (e) and (f) are those two segment away; and (g) and (h) are those one and two diagonals away, respectively. The sharp change of acceleration in each chart corresponds to the event of opening valve B.

Upon closer examination of Fig. 8, we find that the amplitude of each peak is different. The accelerations at joints 3 and 7 on the rupture segment are 2 g and 1.9 g, respectively. At one segment away (joints 8 and 13), they are 1.27 g and 0.73 g, and at two segments away (joints 1 and 16), they are 0.47 g and 0.72 g. This reveals that the acceleration change (which is almost equal to the acceleration itself because the ambient acceleration is negligibly small) is (locally) largest at the two ends of the ruptured segment. The magnitude of the acceleration change decreases as one moves away from the rupture point in distance as shown in Fig. 7(a). Using these experimental results, we can plot a

![Contour Map for Measured Acceleration](image1)

![Visualization of measure acceleration data](image2)

Fig. 9 Simulation results for a miniature water distribution system
contour map for the convenience of visualization as shown in Fig. 9, which corresponds to the contour map in Fig. 1. The simulated damage in this case is located in the innermost and smallest polygon. These experimental results confirm that the proposed method is promising in that the change in the pipe surface acceleration can be used as metric to develop the contour map from which the location and extent of pipe damage can be identified.

6. Conclusions

We propose a novel water-pipe damage detection method based on time-correlated acceleration data collected using a wireless MEMS-sensor network from different joints of a water distribution system. Each sensor measures the acceleration change on the pipe surface non-invasively to determine rupture events and to locate the point of rupture. The results of the preliminary experiment validate the concept of measurement of pipe acceleration for damage detection. To enhance the accuracy of detecting damage location in a larger-scale water distribution system, many improvements are needed. For time synchronization, a distributed scheme using WWVB (atomic time broadcast) and GPS are being evaluated. The centralized wireless communication protocol will also be replaced with a more distributed scheme and relaying capability to handle the much longer expected range. We are also evaluating better algorithms for data analysis, including the possible use of frequency-domain analysis. Further study is needed to correctly analyze the situations in sharp bends and T-joints and to understand the pipe vibration under the ambient and transient hydraulic conditions. We plan to install a new platform with greatly enhanced wireless communication capabilities on a subset of a regional water supply network such as the City of Westminster and the Irvine Ranch Water District, where their existing SCADA measurements can be used for possible comparison.

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References


Experimental validation of a multi-level damage localization technique with distributed computation

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Abstract. This study proposes a multi-level damage localization strategy to achieve an effective damage detection system for civil infrastructure systems based on wireless sensors. The proposed system is designed for use of distributed computation in a wireless sensor network (WSN). Modal identification is achieved using the frequency-domain decomposition (FDD) method and the peak-picking technique. The ASH (angle-between-string-and-horizon) and AS (axial strain) flexibility-based methods are employed for identifying and localizing damage. Fundamentally, the multi-level damage localization strategy does not activate all of the sensor nodes in the network at once. Instead, relatively few sensors are used to perform coarse-grained damage localization; if damage is detected, only those sensors in the potentially damaged regions are incrementally added to the network to perform finer-grained damage localization. In this way, many nodes are able to remain asleep for part or all of the multi-level interrogations, and thus the total energy cost is reduced considerably. In addition, a novel distributed computing strategy is also proposed to reduce the energy consumed in a sensor node, which distributes modal identification and damage detection tasks across a WSN and only allows small amount of useful intermediate results to be transmitted wirelessly. Computations are first performed on each leaf node independently, and the aggregated information is transmitted to one cluster head in each cluster. A second stage of computations are performed on each cluster head, and the identified operational deflection shapes and natural frequencies are transmitted to the base station of the WSN. The damage indicators are extracted at the base station. The proposed strategy yields a WSN-based SHM system which can effectively and automatically identify and localize damage, and is efficient in energy usage. The proposed strategy is validated using two illustrative numerical simulations and experimental validation is performed using a cantilevered beam.

Keywords: wireless sensor network; damage localization; damage detection; structural health monitoring.

1. Introduction

According to a recent report from the American Society for Civil Engineers, “more than 26%, or one in four, of the nation’s bridges are either structurally deficient or functionally obsolete” (ASCE 2009). Actually, a large percentage of the bridges in use in the United States have been used for several decades, often beyond their intended service lifetime, and their condition should be assessed and monitored during future usage. The collapse of the I-35W highway bridge over the

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Mississippi River in Minneapolis (Minnesota, US, August 2007) further underscores the need for reliable and robust structural health monitoring (SHM). With low installation and maintenance expenses, structural health monitoring and damage detection based on wireless sensor networks (WSNs) has attracted much attention. Using a WSN, a dense deployment of measurement points in a structure is possible, which facilitates accurate and fault tolerant damage detection techniques (Nagayama and Spencer 2007).

Although the SHM systems based on WSNs have shown considerable promise (Horton et al. 2002, Lynch et al. 2002, Spencer 2003, Yu et al. 2009, Yu and Ou 2009) for civil infrastructure applications, they present some new technical challenges for real-world applications, such as, energy supply constraints, time synchronization errors (TSEs), limited wireless communication bandwidth, and unreliable wireless communication (Wang et al. 2007a). In particular, the limited energy available in each sensor node presents challenges for long-term operation of SHM systems. Schemes for conserving energy to prolong the lifetime of a WSN can be classified into three categories.

i) Energy harvesting technologies: the concept of energy harvesting was introduced to WSNs to recharge batteries from solar or vibrational energy (Hill 2003, Feng et al. 2002). ii) Power management techniques: certain protocols may be used to minimize the energy consumption of a node while it is awake. For example, duty cycling protocols like BoX-MAC (Moss and Levis 2008) and SCP (Ye et al. 2006) topology control protocols such as ART (Hackmann et al. 2008). Alternatively, wireless sensors may be designed to consume very little power in the sleep state, so much so that the energy used to make the sensor active for any reason can be orders of magnitude greater than making the sensor remain asleep (Polastre et al. 2005). Therefore, an alternative is to make unused sensors enter a low power sleep mode, and wake up periodically or by event-triggered signals (Galbreath et al. 2003). iii) Power efficiency by reducing the amount of wireless communication: because wireless communication often consumes the greatest amount of energy among all components in an awakened node, algorithms which require transmission of long time-history records to the central server should be avoided. Power efficiency can be achieved by pre-processing the raw data at each sensor node prior to transmission and then just transmitting small amount of useful results wirelessly.

Because current power harvesting techniques that provide a low-cost, portable solution for WSNs are still under development (Wang et al. 2007a), research in power efficiency through distributed computing has received considerable attention. Lynch et al. (2004) embedded an algorithm into each wireless sensor to locally process measured raw data to identify AR or ARX coefficients using collected responses, and took the residual error of the AR or ARX model as a damage sensitive feature. The damage detection algorithm, statistical pattern recognition, was employed to perform a statistical analysis on extracted damage features to identify damage. Only the AR or ARX model coefficients were wirelessly transmitted, and therefore, the energy consumed for transmission was considerably reduced. This type of distributed computing strategy for damage detection has also been employed by Chintalapudi et al. (2005), although the damage detection algorithm used here was based on detecting frequency shifts caused by damage. However, both methods were only used to identify the existence of damage. To localize damage, Castaneda et al. (2008) and Hackmann et al. (2008) employed the DLAC method (Messina et al. 1996) which is based on a correlation analysis between identified natural frequencies from measured data and analytical ones in each simulated damage pattern. Herein, an FFT algorithm and a curve fitting technique for the power spectral density (PSD) of the response were embedded in the microprocessors of wireless sensors for locating resonant frequencies. Only a small number of curve fit parameters were transmitted wirelessly to the base station for further
identifying natural frequencies and performing the DLAC method. However, the DLAC method has some limitations because it is not applicable to multiple damage scenarios or structures with symmetries. Some other research based on decentralized the damage detection procedures across a WSN can be referred to (Jeong et al. 2009, Wang et al. 2007b).

In this study a WSN-based SHM system is developed based on the integrated constraints associated with both accurate damage detection and energy consumption. We implement a modal identification method and flexibility-based damage detection methods using the wireless sensor network. A combination of the last two energy-conserving techniques is used to extend the lifetime of this SHM system. A multi-level damage localization strategy is proposed and experimentally validated. The sensor nodes are activated in the network in stages to improve the efficiency of the network. Relatively few sensors are used to perform coarse-grained damage localization. If damage is detected, only those sensors in potentially damaged regions are incrementally added to the network to perform finer-grained damage localization. Two damage localization methods which are suitable for multi-level damage localization are discussed, which are the ASH (angle-between-string-and-horizon) or AS (axial strain) flexibility-based damage detection methods (Yan et al. 2008, 2009). These methods involve both information on mode shapes and natural frequencies and thus can localize multiple damage sites in structures.

The proposed approach is designed to use a distributed computing strategy and uses a multi-level damage detection method. Computations associated with modal identification and damage detection steps are executed across multiple sensor nodes to distribute the computing across the WSN. In this way, the raw data is processed at each sensor node, and minimal amounts of useful intermediate results are transmitted wirelessly. The distributed computing strategy with the same modal identification method was also used in (Zimmerman et al. 2008). However, the communication cost and computation cost of the system described in this paper is reduced compared to that in (Zimmerman et al. 2008). Rather than transmitting the peaks in the PSD of the response at each sensor node to the next sensor node, having the FDD procedures executed at the next sensor node(s) to obtain partial two-node mode shapes that must be stitched together, we transmit the peaks in the PSD of the response at each sensor node to a common node directly. With less communication involved, it is reasonable to assume that less energy is consumed than in (Zimmerman et al. 2008). Additionally there may be advantages in terms of the accuracy of the identified mode shapes. Herein an approach is proposed to implement a two-stage damage detection strategy and numerically demonstrated using a cantilever beam and a truss. Then, experimental validation is performed using a WSN and a cantilever beam.

2. Background

2.1 Modal identification using FDD

When monitoring in service civil engineering structures, the primary sources of external excitations are ambient vibrations such as those caused by wind or traffic loads. Because ambient excitation sources are often unmeasurable, only the resulting structural responses, the system outputs, can be reliably used for modal identification and damage detection. One effective method for output-only modal identification is the Frequency Domain Decomposition (FDD) method (Brinker et al. 2008). The FDD method is employed here for its speed and suitability for distributed computation in a WSN.

In the FDD method, the cross spectral density (CSD) function matrix relating responses at each discrete frequency is first estimated. To minimize the impact of measurement noise, the averaged CSD
matrix is obtained by performing an averaging operation on the CSD matrices estimated from multiple frames of data. Then a singular value decomposition (SVD) is performed on the averaged CSD matrix at each discrete frequency. The maximum singular value in each singular value matrix is collected to form a vector. From the peaks of this vector, structural natural frequencies are identified. The first column of the left singular decomposition matrix corresponding to a particular natural frequency is an estimate of the corresponding mode shape. In the implementation discussed herein, because only output information is used for identification the identified results from the FDD method are actually operational deflection shapes (OPS).

2.2 Flexibility-based damage detection

Techniques for damage detection based on structural flexibility have been gaining attention. A good estimate of the flexibility matrix can be obtained with easily identified low-frequency modes, making them attractive for civil engineering applications. Also, the flexibility matrix corresponding to the sensor coordinates can be extracted directly from the matrices of system realization. For these reasons, and due to their success in prior studies (Pandey and Biswas 1995, Bernal and Gunes 2004, Gao and Spencer 2002), flexibility-based methods are employed in this study.

Based on the assumption that the presence of damage in structures reduces structural stiffness, and thus increases structural flexibility, the change in structural flexibility between the pre- and post-damaged states can be used to detect damage, which is the fundamental basis of the classical flexibility difference method (Pandey and Biswas 1995). Because the damage detection results using classical flexibilities are embodied as nodal or DOF’s (degree of freedom) characterization, the classical flexibility difference method cannot directly localize damage to exact elements. Consequently, the ASH flexibility-based method (Yan et al. 2008) was proposed for localizing damage in beam-like structures. This method determines the change in Angles-between-String-and-Horizon (ASHs) of beam elements caused by damage, and thus it can localize damage to exact elements. The ASH flexibility matrix can be constructed as

\[
F_\theta = \sum_{r=1}^{n} \frac{1}{\omega_r^2} R_r R_r^T
\]

where \(\omega_r\) is the \(r\)th circular modal frequency; \(n\) is the number of modes used; \(R_r\) is called the \(r\)th ASH mode shape, which can be expressed in terms of the \(r\)th translational mode shape as

\[
R_r = \left[ \frac{1}{l_1} \phi_{1,r} \quad \frac{1}{l_2} (\phi_{2,r} - \phi_{1,r}) \quad \cdots \quad \frac{1}{l_i} (\phi_{i,r} - \phi_{i-1,r}) \quad \cdots \quad \frac{1}{l_n} (\phi_{n,r} - \phi_{n-1,r}) \right]^T
\]

where \(\phi_{i,r}\) denotes the \(i\)th component of the \(r\)th mode shape, and \(l_i\) denotes the length of the \(i\)th beam element. The components in the \(r\)th column of this flexibility matrix represent the ASHs of all beam elements of the structure resulting from a unit moment applied at two nodes of element \(r\), with no force or moment on the other elements. Thus, the components in the ASH flexibility are associated with beam-elements of the beam's finite element model rather than nodes.

The maximum absolute values of the components in each column or the diagonals in the difference of ASH flexibility matrices between the pre- and post-damaged structures are extracted as damage indicators. By observing a “step and jump” in the plot of damage indicators versus element numbers, the damage locations are determined.
To perform damage localization at the member-level in truss or frame structures, the Axial Strain (AS) flexibility-based method was proposed (Yan et al. 2009). The physical meaning of the AS flexibility is as follows: the components of the $r$th column of this flexibility matrix represent the axial strains of all elements or members resulting from a pair of axial forces with equal amplitudes, which are equal to the reciprocals of the length of the $r$th member, but acting in opposite directions at two nodes of the $r$th member. The basic idea is that if members in a structure are dominated by axial forces, as in truss structures, the axial strain will be a better index than deflection for damage detection.

The AS flexibility matrix is best explained through an example. For the truss in Fig. 1, the AS flexibility matrix is assembled as

\[
\text{ASF} = \sum_{r=1}^{n} \frac{1}{\omega_r^2} S_r S_r^T
\]

where

\[
S_r = \begin{bmatrix}
    c_1 \frac{(\varphi_{2a-1,r} - \varphi_{2b-1,r})}{l_1} + s_1 \frac{(\varphi_{2a,r} - \varphi_{2b,r})}{l_1} \\
    \vdots \\
    c_j \frac{(\varphi_{2a-1,r} - \varphi_{2p-1,r})}{l_j} + s_j \frac{(\varphi_{2a,r} - \varphi_{2p,r})}{l_j} \\
    \vdots \\
    c_n \frac{(\varphi_{2a-1,r} - \varphi_{2p-1,r})}{l_n} + s_n \frac{(\varphi_{2a,r} - \varphi_{2p,r})}{l_n}
\end{bmatrix}
\]

$S_r$ is called the $r$th axial strain mode shape and its $j$th component $c_j \frac{(\varphi_{2a-1,r} - \varphi_{2p-1,r})}{l_j} + s_j \frac{(\varphi_{2a,r} - \varphi_{2p,r})}{l_j}$ is associated with the $j$th member of the structure. $l_j$ and $\varphi_{2p,j}$ denote the length of the $j$th member and the $2p$ component of the $r$th mode shape, respectively, and $c_j$ and $s_j$ denote the cosine and sine of the angle between the $j$th member and the $x$-axis in the global coordinate system.

The percent change in diagonal elements of the AS flexibility matrices before and after damage is taken as the damage indicators for each element. The elements associated with large values of damage indicators are identified as damaged.

In the original definition of the ASH or AS flexibility-based method, the mode shapes are required to be mass-normalized (Yan et al. 2008, 2009). However, the unit-length normalization of mode shape vectors is also working for their application. It is equivalent that the mass matrix is assumed to be an identity matrix. If the mass of a structure is really distributed uniformly along the structure, the
obtained flexibility is actually proportional to the real flexibility, and the proportional coefficient is an element in the mass matrix. In addition, considering that the identified mode shapes by the FDD method are operational deflection shapes (ODS), the ASH or AS flexibility constructed from the ODSs and/or non-normalized modes are actually pseudo-ASH or AS flexibility. In the sequel, "pseudo" is omitted.

3. Distributed computation strategy

In this section, the FDD method is modified to reduce computational efforts, and the way in which the modified FDD method and flexibility-based damage detection methods are distributed throughout a WSN is discussed to reduce the wireless communication amount to make effective use of energy in each sensor node.

A variation on the traditional FDD method is proposed here. Rather than performing a SVD on each of the CSD matrices at all discrete frequencies, a method with minimal computational efforts, peak-picking, is applied first to identify the natural frequencies. Then, noting that only the left singular decomposition matrices associated with the identified natural frequencies are used for obtaining mode shapes, we perform a SVD on each of the CSD matrices associated with those natural frequencies. And accordingly, we will just construct the CSD matrices associated with natural frequencies. In this way, the computational cost of identifying modal parameters is reduced considerably.

To construct the CSD matrices associated with natural frequencies under a WSN, we need to calculate the value of the CSD at each natural frequency for every pair of responses. Because the FFT of each response is obtained independently at each leaf node when using a distributed approach, we must relate the spectral responses at each leaf node. In addition, note that an averaged CSD matrix at a particular discrete frequency is only related to the CSD matrices associated with this discrete frequency obtained from different frames of data. Therefore, only the spectral responses associated with the natural frequencies (instead of the time-history responses) must be transmitted to a common sensor node (a cluster head here) in the WSN. Thus, the amount of wireless communication is reduced considerably.

FDD is combined with peak-picking herein to identify the modal parameters. First, on the microprocessor of each leaf node, a fast Fourier transform (FFT) is performed on a frame of data collected at each sensor node as

$$X_i(\omega) = F[x_i(t)]$$  \hfill (5)

where $F[\cdot]$ represents the FFT operation. $X_i(\omega)$ is the FFT coefficient of the response $x_i(t)$ at the $i$th node. Second, the auto-spectrum of each response is calculated as

$$P_i(\omega) = X_i(\omega)X_i^*(\omega)$$  \hfill (6)

where $P(\omega)$ denotes the power spectral density (PSD) function at the $i$th discrete frequency of $x(t)$. To improve the results, several frames of data are captured and an averaged PSD is calculated. Then, the peaks of the averaged PSD of $x_i(t)$ are identified for determining the natural frequencies using that the assumption that the external excitations considered here are broadband ambient vibrations. For automated identification, one would provide appropriate frequency values to bound the searching range for each of the peaks. Here we use $\omega_p$ to represent the discrete frequencies associated with the identified
p-th peak. This step is also performed independently at each leaf node. However, not all peaks are necessarily related to natural frequencies of the system. A discussion of some practical issues associated with this step is provided in the sequel.

From each leaf node, only the resulting discrete frequencies $\omega_p$ and the FFT coefficients $X_i(\omega_p)$ corresponding to the peaks (from an FFT of each frame of data) are transmitted to a cluster head. Obviously, this significantly reduces the amount of data to be transmitted compared with transmitting the entire time history.

The remaining steps involved in modal identification are performed at the cluster head. After the cluster head receives a set of intermediate results obtained from one frame of data from each leaf node, the CSD between each response and a reference response (the response at the cluster head is taken as the reference response here) is calculated to determine if each discrete frequency $\omega_p$ is a structural frequency. To judge this, the phase of the CSD is examined. For a discrete frequency $\omega_p$, if the phase of the corresponding CSD at $\omega = \omega_p$ is close to 0 or $\pi$, the discrete frequency $\omega_p$ is a natural frequency of the structure (designated $\omega_n$). Using this criterion, the natural frequencies can be identified with the intermediate results.

Then, for this frame of data, the CSD matrix corresponding to each natural frequency is estimated from the FFT coefficients associated with the identified natural frequencies $\omega_n$ (instead of $\omega_p$). It is worth noting that, when calculating each CSD matrix, the FFT coefficients must originate from the same frame of response data for all DOFs. The estimated CSD matrix corresponding to the $k$th natural frequency $\omega_n^k$ is expressed as

$$G(\omega_n^k) = \begin{bmatrix}
X_i(\omega_n^k)X_i^*(\omega_n^k) & \cdots & X_i(\omega_n^k)X_i^*(\omega_n^k^4) & \cdots & X_i(\omega_n^k)X_i^*(\omega_n^k^7)
\vdots & \ddots & \vdots & \ddots & \vdots \\
X_i^*(\omega_n^k)X_i(\omega_n^k) & \cdots & X_i^*(\omega_n^k)X_i(\omega_n^k^4) & \cdots & X_i^*(\omega_n^k)X_i(\omega_n^k^7)
\vdots & \ddots & \vdots & \ddots & \vdots \\
X_i^*(\omega_n^k)X_i(\omega_n^k^4) & \cdots & X_i^*(\omega_n^k^4)X_i(\omega_n^k^4) & \cdots & X_i^*(\omega_n^k^4)X_i(\omega_n^k^7)
\end{bmatrix}$$

(7)

After the intermediate results obtained from various frames of data are transmitted to the cluster head, the average value of identified natural frequencies from all leaf nodes and from all various frames of data is calculated to obtain the final identified natural frequency for each mode. The averaged CSD matrix associated with each natural frequency (designated $\overline{G}(\omega_n^k)$) is obtained by performing an average on $G(\omega_n^k)$ estimated from various frames of data. Next, a SVD is performed on each of the averaged CSD matrices corresponding to each natural frequency to identify the associated mode shapes

$$U\Sigma V^T = SVD(\overline{G}(\omega_n^k))$$

(8)

where $\Sigma$, $U$ and $V$ denote the singular value matrix, the left singular decomposition matrix and the right singular decomposition matrix.

The first column of $U$ is an estimate of the $k$th mode shape (actually, ODS) and is designated $U_1$. By dividing all of the components of $U_1$ by the component of $U_1$ chosen as a reference, the normalized ODS is obtained with one component having a value of one. Its components are, in general, complex values. The phase associated with each complex value represents the phase difference between that response location and the reference sensor location in the $k$th mode. To obtain the real-valued components of the ODS, which are typically used for damage detection, the magnitude of each component
of the normalized \( \mathbf{U}_1 \) is calculated. The corresponding sign for each component is determined by its respective phase. The phases of the components in the normalized ODS are ideally equal to 0 or \( \pi \) for proportionally damped systems with no measurement error. In practice, due to measurement and numerical errors, the phases are not exactly 0 or \( \pi \). The signs of the components are determined as follows (as in the original FDD method): if the phase is in the range of \( \left[ \frac{\pi}{2}, \frac{3\pi}{2} \right] \), the corresponding sign is positive; otherwise, if the phase is in the range of \( \left[ \frac{3\pi}{2}, \frac{5\pi}{2} \right] \), the corresponding sign is negative.

Once natural frequencies and ODSs are obtained at the cluster head, they are transmitted to the gateway mote of the PC base station. The amount of data to be transferred here is also small compared to transmitting the entire time history. All the procedures of damage detection are performed at the gateway mote. First, the identified natural frequencies and ODSs are applied to construct a flexibility matrix. Then, damage indicators are extracted from the difference between the flexibility matrix in the current state and the flexibility matrix constructed from the baseline data stored in the gateway mote (details will be provided in Section 4), and are transmitted to the PC base station through a USB cable.

The distribution of the modified FDD method and damage detection methods across the WSN and the data flow between stages are shown in the flowchart in Fig. 2. Herein, it is assumed that the number of modes to be identified is \( F \), and each data frame has \( D \) sampling points, and the number of points in the FFT is \( D \). The amount of data transmitted from each leaf node to the cluster head is \( 2F \) floating, and the amount of data transmitted from the cluster head to the gateway mote is \( (n+1)F \) floating. Both are much smaller than \( D \).

In summary, in this modified FDD method, the SVD is performed on only a few matrices (the number is equal to the number of the identified natural frequencies), therefore the computing efforts at the cluster head are reduced significantly as compared with the original FDD method without sacrificing accuracy in the identified ODSs. In addition, using the distributed computation strategy, only small
amount of data is transmitted wirelessly, which subsequently alleviates the issues related to the limited power supply in WSNs.

4. Multi-level damage localization implementation

As described in Section 2, the distributed computation of modal identification and damage detection is able to reduce the energy consumption of a sensor node while it is awake. However, allowing many of the sensors to remain asleep required much less energy than that used to keep them active (Polastre et al. 2005). To take advantage of this feature, we propose a multi-level damage localization strategy to further reduce the total energy consumption in a WSN by activating relatively few sensors and allowing unused sensors to be in a sleep mode. Thus, although a large number of wireless sensors are installed in a structure, only some of them are activated at the first level and the information measured from them is used to localize damage to larger regions. Once this is done, more sensors in the damaged regions are then activated to generate a new network to perform finer-grained damage localization. The ASH flexibility-based method is identified for level-1 damage localization. This approach can locate a damage site between two measurement sensors when measured DOFs are not complete (Castaneda et al. 2008). For level-2 damage localization, different methods may be used for different types of structures.

For beam structures, the procedures to perform multi-level damage localization are as follows. When the wireless sensor network is first turned on, a baseline modal identification is performed. All sensor nodes are activated here. First, they are synchronized and acquire structural responses. Then, the acquired data is resampled to make all the responses have the same sampling frequency, perform FFT on the resampled response, pick peaks in the PSD of responses and transmit some intermediate results to a cluster head. Next, the natural frequencies and ODSs are identified at the cluster head and are transmitted to the gateway mote connected to the base station. Finally, the baseline data are stored in the gateway mote as constant parameters for a particular structure.

After the baseline modal identification is performed, the level-1 damage localization begins operating with only a few sensors activated. The data acquisition and modal identification above are repeated on these activated sensors. Then, an ASH flexibility matrix for the current state is constructed using the identified natural frequencies and ODSs. Meanwhile, a baseline flexibility matrix is constructed using natural frequencies and the associated ODS components with sensors activated, which are already stored in the gateway mote of the base station. By extracting the damage indicators from the flexibility difference matrix between the current state and the baseline, the gateway mote can determine automatically if the structure is damaged. If no damage is detected, the search ends and all the sensor nodes return to sleep until the next damage detection period comes. If damage is detected, the gateway mote will provide the information on damaged regions which are used for instructions of activating more sensors, and the level-2 damage localization will be automatically initiated.

For the level-2 damage localization, more sensors in potentially damaged regions are awakened and added to the network. The data acquisition and modal identification above are repeated on the new network. The ASH flexibility-based method is performed with an increase in the spatial resolution of sensors near the damage. Therefore, the second round can subsequently localize damage to a smaller region than the first round. This network may repeat this drill-down procedure to achieve even finer-grained results until the desired resolution is reached. The multi-level damage localization strategy with distributed computation is illustrated using an example in Fig. 3.

Let us take a bridge as an example to illustrate this proposed strategy, as shown in Fig. 3. Assume
that we deploy five wireless sensors on each segment of the bridge. At the first stage, we just activate one sensor in each segment. These sensors form one network. One sensor (with red background) is used as a manager, called as a cluster head, and the others are their subordinates, called as leaf nodes. At each leaf node, after sensing the response, the sensor does not transmit the acquired data to the cluster head or base station directly, but rather process the response onboard each sensor node and only some useful intermediate results are transmitted wirelessly to the cluster head. Using the current WSN, damage can be localized between Li3 and Lj3. To further localize damage, the leaf nodes between Li3 and Lj3 are activated and added to the network to form a new network. Performing the same procedures as above, the damage will be localized to a smaller region, between Li5 and Lj1.

For truss structures, the procedures for performing multi-level damage localization are similar to those used for beam structures. The only difference lies in that: 1) the ASH flexibility-based method is used to perform bay-level damage localization (level-1), by considering a truss as a beam, and 2) the AS flexibility-based method is used to perform member-level damage localization (level-2). Using this approach, many nodes in the WSN remain asleep for part or all of the implementation, reducing the total energy usage significantly.

5. Illustrative examples

5.1 Cantilever beam

To demonstrate the performance of the proposed strategy numerically, a cantilever beam is first considered. This beam is assumed to be made of aluminum with dimensions 2080 mm×20 mm×20 mm. Young’s modulus, the mass density and Poisson’s ratio of the material are 70 Gpa, 2700 kg/m³ and 0.3, respectively. The beam is modeled using 26 beam elements, each of 80 mm long, with 27 nodes, as shown in Fig. 4 (n = 26 here). The first four analytical natural frequencies of this beam are shown in Table 1.
Experimental validation of a multi-level damage localization technique with distributed computation

Proportional viscous damping is included with a damping ratio of 1% in each mode of the structure. Independent band-limited white noise processes are applied vertically at all nodes to simulate ambient vibration. Acceleration responses in the vertical direction are obtained in the simulation, and measurement noise is simulated by adding independent, zero-mean white noise processes with an RMS of 5% of the responses to these values. The responses are recorded at 1152 Hz.

Damage is simulated in this example as a reduction in the stiffness of some elements in the model, by assuming a 50% reduction in the cross-sectional area in elements 4 and 22. The first four natural frequencies identified in the damaged case are shown in Table 1. We use a 50% reduction in the area because this is representative of our experimental test and the testing restrictions therein (as shall be shown in Section 6). Actually, in simulation this method has been successful in localizing damage with only a 10% reduction (Yan et al. 2008).

For purposes of this example, assume that one wireless sensor is placed at each node of the model. First, for level-1 implementation, we uniformly activate a smaller number of wireless sensors to locate potentially damaged regions. Assume that seven sensors (at nodes 3, 7, 11, 15, 19, 23 and 26) are activated and only vertical responses associated with these nodes are acquired. The computing-distributed FDD method is used to identify modal parameters. The first four identified modes are used to construct the ASH flexibility matrices before and after damage. The damage indicators are plotted in Fig. 5. From the “step and jump” distribution of damage indicators, it is clear that damage occurs near nodes 3 and 23.

To further localize the damage, those sensors in the two damaged regions are activated and added to the network for a level-2 implementation. The data measured in this configuration are the responses at nodes 1 through 6, 10, 14 and 18 through 26 (17 responses in total). Fig. 6 presents damage indicators based on the ASH flexibility when more sensors are activated. The damage indicators associated with

<table>
<thead>
<tr>
<th>Natural frequencies of cantilever beam before and after damage (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical</td>
</tr>
<tr>
<td>Intact</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

Fig. 5 Level-1 damage localization results for cantilever beam using ASH flexibility-based method with seven measurement points.
elements 4 and 22 exhibit as jumps between two steps. It suggests that we successfully localize the damage to elements 4 and 22 in level-2. The damage location results using all nodal responses are shown for comparison in Fig. 7. Clearly, using the proposed strategy, damage localization results with enough accuracy are obtained with relatively few sensors.

5.2 Planar truss

In a second example we consider a 14-bay planar truss structure simply supported at the ends (see Fig. 8). The cross-sectional area of each member is $1.122 \times 10^{-4}$ m$^2$. Young’s modulus, the mass density and Poisson’s ratio of the material are $2 \times 10^{11}$ Pa, 7850 kg/m$^3$ and 0.3, respectively. The finite element model (FEM) has 28 nodes and 53 members. The numbering of elements and nodes of the FEM is
shown in Fig. 8. Lumped masses of 0.5 kg are included at the 1st and 28th nodes, and 10 kg are included on all other nodes. The first four analytical natural frequencies are listed in Table 2.

Simulation of the modal experiment is similar to that of the prior numerical example. Independent band-limited white noise processes are applied in the horizontal direction and the vertical direction at all nodes to excite the structure. The simulated sampling frequency is 560 Hz. Measurement noise is also added to the response at each node.

Damage is simulated as a 50% reduction in the cross-sectional areas of the following members: members 16, 43 and 29 in the 4th bay, and members 9, 22, 49 and 35 in the 10th bay.

In the multi-level approach on the truss, we try to first localize damage to the bays. For this step, the truss is viewed as a beam with 14 elements. Only the vertical responses of nodes along the lower chords are used to identify the modal parameters. The identified natural frequencies are listed in Table 2. The ASH flexibility-based method is employed to perform the bay-level (level-1) damage localization. The first two modes are used to assemble the ASH flexibility. The extracted damage indicators are presented in Fig. 9. The damage indicators corresponding to bays 4 and 10 exhibit as jumps between steps, which suggests that damage occurs near the 4th and 10th bays.

To further localize damage to exact members, assume that the sensors around the 4th and the 10th bays are activated (at nodes 4 through 11, and at nodes 16 through 23). The AS flexibility-based method is used and the responses measured by the recently activated sensors are used for the computing-distributed FDD method to identify modal parameters. The first two modes are used to construct the AS flexibility matrices before and after damage. The extracted damage indicators are plotted in Fig. 10. The maxima among the damage indicators suggest that the AS flexibility-based method successfully identifies all the damaged members (members 9, 16, 22, 29, 35, 43 and 49).

<table>
<thead>
<tr>
<th>Analytical</th>
<th>Identified</th>
<th>Percentage change of identified results (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intact</td>
<td>Damaged</td>
</tr>
<tr>
<td>1</td>
<td>8.57</td>
<td>7.95</td>
</tr>
<tr>
<td>2</td>
<td>29.00</td>
<td>26.68</td>
</tr>
<tr>
<td>3</td>
<td>42.74</td>
<td>40.44</td>
</tr>
<tr>
<td>4</td>
<td>57.92</td>
<td>54.46</td>
</tr>
</tbody>
</table>

Fig. 9 Level-1 damage localization results for truss using ASH flexibility-based method
6. Experimental validation

To experimentally validate the proposed approach, we deploy a network of Imote2 (Crossbow Technology) wireless sensor platforms and associated sensor boards. The modified FDD method and the two flexibility-based damage detection methods are implemented on top of the TinyOS 1.1 operating system (http://www.tinyos.net) using the nesC programming language. Our implementation leverages several existing SHM middleware services developed at UIUC (http://shm.cs.uiuc.edu/), namely, their enhanced sensor driver, a reliable data transmission network layer, and an implementation of the FTSP time synchronization protocol (Maróti et al. 2004) used for time-synchronizing the responses measured from different sensors. Procedures executed in the proposed system at the leaf nodes, cluster heads and the gateway mote of the base station are listed in the respective blocks in Fig. 3.

![Fig. 10 Level-2 damage localization results for truss using AS flexibility-based method](image)

Fig. 10 Level-2 damage localization results for truss using AS flexibility-based method

![Fig. 11 The cantilever beam and sensor placements in the experiment tests](image)

Fig. 11 The cantilever beam and sensor placements in the experiment tests
Experimental validation tests are conducted using a steel cantilever beam at the Structural Control and Earthquake Engineering Lab at Washington University. The beam is 108 in long, 3 in wide and 0.25 in thick, as shown in Fig. 11. The sensor numbers are shown in the circles in each figure. The beam is fixed to the shake table in a vertical position. Damage in the beam is simulated by adding a pair of thin, symmetric steel plates in element 4. These plates are 9 in long, 3.625 in wide and 0.0625 in thick.

In these tests, the SHM system includes a PC base station, eight Intel Imote2 motes (IPR2400) with sensor boards (ITS400C), and a “gateway” Imote2 board tethered to the base station with a PC interface board (IIB2400). Each Imote2 board is equipped with 256 KB of integrated SRAM and 32 MB of external SDRAM, an XScale CPU capable of running at speeds up to 614 MHz, an 802.15.4-compliant radio (CC2420) and a 2.4 Hz antenna (Crossbow Technology). Sensors are deployed along the beam, as shown in Fig. 11. In this experiment, all sensors are within a single hop from the base station. All modal identification and damage detection procedures are automated on the sensors. The damage indicators are extracted at the gateway mote connected to the base station.

The beam is excited along the weak axis of bending using an impact. The acceleration response in this direction is collected at each node. For data collection, the sampling frequency of acceleration response is 280 Hz, the length of record is 7168 points, and the number of points in the FFT is 2048.

First, we run the developed WSN-based SHM system on the intact beam to obtain baseline modal parameters. These values are saved on the gateway mote connected to the base station. For purposes of code validation, a file is generated containing the obtained baseline data, the identified natural frequencies (as shown in Table 3) and ODSs (as shown in Fig. 12).

Then, we deploy the WSN-based SHM system on the damaged beam. The gateway mote extracts the damage indicators automatically, and identifies if the beam is damaged and when to initiate the level-2 damage localization. For level-1 damage localization, only six sensor nodes (nodes 1, 2, 5 through 8) are activated. The extracted damage indicators at the gateway mote are plotted in Fig. 13(a). The damage indicator associated with element 3 exhibits a peak, which means the damage is localized to element 3 (corresponding to the current network architecture). Then, the system automatically

<table>
<thead>
<tr>
<th>Order</th>
<th>Intact (Hz)</th>
<th>Damaged (Hz)</th>
<th>Percentage change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5469</td>
<td>0.5469</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>3.9648</td>
<td>3.9648</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>11.1434</td>
<td>11.2109</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Table 3 Identified natural frequencies of the cantilever beam before and after damage

Fig. 12 Identified ODSs of the intact beam
activates two more sensors within element 3 and performs level-2 detection. The damage indicators extracted by the system are plotted in Fig. 13(b). From the peak among the damage indicators, we can localize damage to a smaller region (element 4 in the new network architecture) which is consistent with the position of the two steel plates.

7. Conclusions

A multi-level damage localization strategy suitable for implementation on a WSN using a distributed computation is proposed in this paper. A variation of the FDD method is employed for modal identification, and the damage detection step is based on a computed flexibility matrix. The implementation is designed to consume minimal energy. Using the distributed computation strategy, the acquired responses are processed at the sensor nodes and only a small amount of intermediate results are transmitted, reducing the energy consumed on each leaf node. Furthermore, using the proposed multi-level damage localization strategy, most of the nodes are able to remain asleep for part or all of the interrogations, reducing the total energy consumed. Numerical simulations and experimental tests were successfully conducted to validate the effectiveness of the proposed strategy.

Acknowledgments

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Experimental validation of a multi-level damage localization technique with distributed computation

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Wireless operational modal analysis of a multi-span prestressed concrete bridge for structural identification

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Abstract. Low-power radio frequency (RF) chip transceiver technology and the associated structural health monitoring platforms have matured recently to enable high-rate, lossless transmission of measurement data across large-scale sensor networks. The intrinsic value of these advanced capabilities is the allowance for high-quality, rapid operational modal analysis of in-service structures using distributed accelerometers to experimentally characterize the dynamic response. From the analysis afforded through these dynamic data sets, structural identification techniques can then be utilized to develop a well calibrated finite element (FE) model of the structure for baseline development, extended analytical structural evaluation, and load response assessment. This paper presents a case study in which operational modal analysis is performed on a three-span prestressed reinforced concrete bridge using a wireless sensor network. The low-power wireless platform deployed supported a high-rate, lossless transmission protocol enabling real-time remote acquisition of the vibration response as recorded by twenty-nine accelerometers at a 256 Sps sampling rate. Several instrumentation layouts were utilized to assess the global multi-span response using a stationary sensor array as well as the spatially refined response of a single span using roving sensors and reference-based techniques. Subsequent structural identification using FE modeling and iterative updating through comparison with the experimental analysis is then documented to demonstrate the inherent value in dynamic response measurement across structural systems using high-rate wireless sensor networks.

Keywords: structural health monitoring; ambient vibration testing; structural identification; bridge dynamics; wireless sensor networks.

1. Introduction

Analytical models of civil constructions are heavily utilized throughout the design and construction stages to safely predict allowable load capacities and service deflections. Furthermore, these computer-based mathematical representations are being extended to structural assessment, retrofit evaluation, and damage detection strategies as rehabilitation and life-cycle management have increasingly been pushed to the forefront of concern in civil engineering. While the governing
dynamics of mechanical systems are well known and increasingly well predicted through advanced computing resources, the structural dynamics of large civil constructions, such as highway bridges, are complex and often poorly reconstructed with analytical models due to uncertainties in boundary conditions and idealization of mechanical aspects. The use of in-service experimental measurements to calibrate an analytical model based on indicators of the actual response can significantly improve the accuracy and validity of the conclusions derived from analysis of such models.

One of the fundamental benefits of ambient vibration testing of highway bridges is the ability to validate or dynamically calibrate analytical models of structural systems to optimize correlation with the measured response to develop a model that is more representative of the actual in-place, as-built condition. This process is known as structural identification and generally consists of developing a preliminary finite element model with reasonable detailing of the primary structural elements and then iteratively modifying model parameters to optimally minimize the difference between the predicted and measured modal parameters of a set of modes (Aktan et al. 1998, Morassi and Tonon 2008).

Acquiring the dynamic response measurements required for structural identification has been expedited through the development of low-power radio frequency (RF) instrumentation systems. High-rate wireless sensor networks (WSN) incorporating accelerometers offer the advantage of replacing costly, unwieldy cable-based systems to permit rapid in-service dynamic assessment of large structures and bridges. Small-form embedded systems with RF communication capabilities produce easily manageable instrumentation that can be quickly placed and repositioned to perform high-density reference-based operational modal analysis (OMA) in a very short time window. Until recently, data rate limitations and packet loss resulting from inefficient network transmission protocols limited the applicability of WSN for ambient vibration monitoring of structures. However, these early deficiencies have been overcome through leveraging advanced computing peripherals and efficient, robust network transmission protocols to achieve the high data rates and lossless reception required for OMA (Whelan and Janoyan 2009).

2. Experimental test details

2.1 Nine Wells Rail Bridge

The Nine Wells Rail Bridge on Addenbrooke’s Access Road is a newly constructed bridge carrying the access road to Addenbrooke’s Hospital in Cambridge, United Kingdom over an existing railway. The bridge consists of two travel lanes for traffic as well as a 4.2 m wide foot/cycle way along the entire length of the northernmost edge. There are three spans west-to-east of lengths 27.2 m, 28.3 m and 32.2 m referenced from centerline-to-centerline of the bearings (Fig. 1). Geometrically, the two westernmost spans are on a 1:20 slope, while the easternmost span is horizontal; all spans have a nominal nine degree skew. Each span consists of twelve precast 1700 mm deep prestressed concrete beams which support a 250 mm insitu reinforced concrete slab with an additional 125 mm layer of asphalt surfacing. The precast beams contain 27 standard prestressing strands of 15.2 mm diameter with a characteristic breaking load of 232 kN that were pretensioned to 70%, or 162.4 kN. All beams are supported by laminated rubber elastomeric bearings at the abutments and bedding mortar at the piers. A 1550 mm high by 400 mm wide precast reinforced concrete parapet lines each edge of the entire length of the bridge.
2.2 Instrumentation and test details

A wireless sensor network was utilized to rapidly instrument the structure and remotely acquire high-rate, lossless data in real-time. The wireless sensing platform was developed by the authors at Clarkson University; the design and proprietary network protocol has been previously documented (Whelan and Janoyan 2009) and the system has been deployed on three field bridges in previous ambient vibration studies (Whelan et al. 2009a, 2009b). Wireless communication is facilitated by a proprietary network protocol implemented on a low-power RF chip transceiver employing direct sequence spread spectrum modulation over a 2.4 GHz carrier frequency. In this study, twenty channels sampled at a rate of 256 Sps per channel are supported within a single-hop, star topology network with further channel count expansion to the thirty total channels afforded through frequency division multiple access using an interrupt synchronized concurrent network.

2.2.1 Sensors and signal conditioning

ST Microelectronics LIS2L02AL low-noise capacitance-based accelerometers were distributed across the deck surface to record the ambient vibration response due to traffic loading. While this integrated circuit sensor is a dual-axis design, only the vertical acceleration was recorded to achieve the higher real-time sampling rates maintained over the low-power wireless network. The accelerometer has a ±2 g full-scale range, 30 μg/√Hz noise density, and nominal 2.55 mW power consumption. Hardware signal conditioning was provided in the form of programmable gain amplification set to 128V/V, a 5-th order Butterworth design analog low-pass filter with a 100 Hz pass-band (-3dB), and automatic gravitational
offset nulling through the use of a low-noise programmable voltage reference. At the 1024 Sps sampling rate employed, the 5-th order analog low-pass filter provides nearly 80dB of alias frequency rejection.

The conditioned sensor output was sampled at each node by a 12-bit analog-to-digital converter (ADC) at a rate of 1024 Sps then subsequently reconditioned in real-time within the embedded software application using digital signal processing (DSP) through a 16-bitx16-bit hardware multiplier. In this deployment, a complementary 56-th order digital low-pass filter was implemented in the DSP routine to enhance alias signal rejection prior to down-sampling the measurement to an effective rate of 256 Sps. The composite filter results in a DC-97.5 Hz measurement bandwidth (-3dB) with a minimum 74 dB rejection of alias frequencies and increases the effective number of bits of the analog-to-digital conversion by one through the oversampling ratio of four. Given the effective low-pass filter developed from the analog and digital signal conditioning described in this section and the 30 $\mu$g/$\sqrt{\text{Hz}}$ noise density of the accelerometer, the root-mean square noise of the accelerometer is approximately 296 $\mu$g over the 97.5 Hz measurement bandwidth. The sensitivity of the accelerometer, signal amplification, and resolution of the converter correspond to an ADC conversion resolution of approximately 8 $\mu$g/bit.

2.2.2 Sensor placement

The ambient vibration testing encompassed two instrumentation configurations targeted at balancing the sensor count available with modal reconstruction density and spatial aliasing considerations. The first sensor layout (Fig. 2(a)) consisted of the placement of thirty vertical accelerometers over the

![Fig. 2 Instrumentation configurations: (a) stationary vibration sensors for full-span monitoring over exterior beams, (b) reference-based dense vibration monitoring across easternmost span over all beams and (c) accelerometer and wireless sensor nodes installed on deck surfacing](image)
entire span on the deck surfacing alongside the parapets and directly over the exterior beams. Uniform spacing was employed across each span with five sensors allocated per side of the individual spans. Malfunction of the wireless sensor node at location six due to an unknown electrical short caused by a mechanical standoff necessitated removal of this location from the measurement grid; otherwise, there was no issue with any other component of the system hardware. Two construction vehicles were available at the time to provide traffic excitation through repeated, though uncoordinated, passes over the bridge span. Sampling durations of three minutes were specified to capture a large count of vehicle passes and permit high-resolution of the spectral content in the frequency domain. Typical peak acceleration recorded across the sensor array was on the order of 10 mg with most locations witnessing peak accelerations around 6-8 mg.

The first instrumentation configuration provides for the most longitudinally spatially-dense modal reconstruction across the full span, but limits modal reconstruction to the pure bending and first-order torsional mode shapes. To extend the study to higher-order torsional modes, a series of three reference-based ambient vibration tests were performed using a high density layout on the easternmost span (Fig. 2(b)). Sensor location nine in this layout was designated as a fixed reference sensor, while the remaining 29 roving vibration sensors were used to measure the dynamic response at the remaining locations. To cover all 72 locations required recording a total of three reference-based time histories over the network. Due to the use of a highly mobile, wireless platform, the reference-based testing was completed in less than 40 minutes so any temperature variation or time-dependent variation can be assumed to be negligible. During this test program, only a single, smaller truck was available to provide traffic excitation, which resulted in significantly less excitation of the structure as evidenced by the peak accelerations which rarely exceeded 4 mg across the measurement grid.

Given the nature of the loading, the system input was not measurable and the weight of the truck was not determined in the study. Traffic speed was variable and can only be coarsely estimated as typical for local traffic (25 km/hr). Truck passes were not scheduled and their time history is not particularly consequential to the analysis, as with immeasurable system inputs only output-only system identification could be applied. The use of a fixed reference sensor permits the normalization and phase correlation of the three separate test configurations without any knowledge of the truck excitation or periodicity.

3. Operational modal analysis

Given the sufficient levels of excitation during the first configuration testing, operational modal analysis was performed using the frequency domain decomposition, or peak-picking method (Fig. 3). Eigenfrequencies were selected from the peaks in the average normalized power spectral densities calculated over each span individually. The process of mode shape reconstruction was iterative in that the modes for which significant inter-span interaction is present were extracted following the finite element analysis confirming their presence. Positive identification of such modes prior to confirmation through analytical modeling is particularly difficult within output-only system identification as one usually looks for fundamental bending modes and so interaction patterns can sometimes arise spuriously as a combination of closely spaced modes rather than distinct modes.

The first twelve mode shapes identified for the full span are limited to the primary bending and first-order torsional modes due to the spatial limitations of the sensor array. Additional eigenfrequencies were evident in the spectrum, but resulted in spatially aliased mode shapes that could not be used
with confidence in the FE model updating process. To verify the validity of the identified modes in the presence of this aliasing concern and to extend the experimental series of mode shapes for improved model updating, the second sensor configuration (Fig. 2(b)) was utilized to investigate the easternmost span with dense spatial reconstruction.

Data-driven stochastic subspace identification (SSI) was leveraged as a robust output-only system identification methodology for analyzing vibration measurements with low signal-to-noise ratio due to the presence of white process and measurement noise (Peeters 2000). Since a reference-based approach was utilized with three instrumentation configurations sharing a common reference sensor, the analysis had to mesh the results from the individual tests to coordinate the development of span-wide mode shapes without the ease of frequency-based pole selection and enforcement. In this study, the system matrices were estimated for each data set individually and the mode shapes and eigenfrequency estimates were calculated for several model orders to develop a database of possible structural poles as witnessed by each configuration. Given the bandwidth of interest as identified in the prior operational modal analysis, the time series data was first low-pass filtered and decimated to an effective rate of 64 Sps to ease the computational burden and reduce model order to the desired bandwidth. Modal vectors were scaled and oriented for each data set with reference to the

![Mode 1: 4.53 Hz](image1)  ![Mode 2: 5.44 Hz](image2)
![Mode 3: 5.84 Hz](image3)  ![Mode 4: 6.63 Hz](image4)
![Mode 5: 7.56 Hz](image5)  ![Mode 6: 7.97 Hz](image6)
![Mode 7: 14.25 Hz](image7)  ![Mode 8: 14.44 Hz](image8)
![Mode 9: 14.66 Hz](image9)  ![Mode 10: 14.88 Hz](image10)
![Mode 11: 18.75 Hz](image11)  ![Mode 12: 19.81 Hz](image12)

Fig. 3 Mode shapes reconstructed from first instrumentation configuration (Fig. 2(a)) with associated experimental eigenfrequency estimates. Note: Mode shape patterns limited to pure bending and first-order torsional modes due to transverse density of sensor array. Abutment and pier supports assumed to be zero displacement.
stationary sensor to maintain continuity. Since the eigenfrequencies would rarely match exactly across the three state-space models, the mode shapes were then constructed using nearest neighbor eigenfrequencies within reasonable variance (0.05 Hz). This approach was able to reconstruct the first-order bending and torsional patterns up to the fourth order torsional mode as well as the second-order bending mode and its second-order torsional compliment (Fig. 4).

4. Structural identification

A quasi-three-dimensional finite element (FE) model was developed within the ALGOR software framework to model the Nine Wells Rail Bridge using the construction drawings to obtain element geometries and derive cross-sectional properties. The deck was modeled using Veubeke isotropic
four node plate elements with sixteen degrees of freedom (MacNeal 1994). The mesh adopted had nodes along the exterior edges of the spans as well as directly over the beams to enforce continuity in the model. Each span consists of a mesh consisting of 42 elements in the longitudinal direction by 24 elements in the transverse direction, for a total of 1008 plate elements per span (Fig. 5). The division of the deck plates into 42 elements in the longitudinal direction was chosen so as to create nodes that coincide with both of the instrumentation layouts from the experimental testing. The built-in materials library was used to specify the deck as medium strength concrete with a mass density of 2405 kg/m$^3$, 20.7 GPa modulus of elasticity, and Poisson’s ratio of 0.15. A plate thickness of 250 mm was assigned, which corresponds to the minimum design depth of the reinforced concrete slab.

The superstructure beams were modeled using 2D beam elements with cross-sectional properties calculated from the precast concrete beam detail drawings. The following cross-sectional properties were employed for each beam element: 0.603 m$^2$ area, 0.0331 m$^4$ torsional resistance, 0.165 m$^4$ moment of inertia about transverse axis through the neutral axis, 0.0131 m$^4$ moment of inertia about the vertical axis through the neutral axis, and a cross-sectional neutral axis location of 680.5 mm above the bottom edge and centrally located along the transverse direction of the cross-section used for section modulus calculations. The beams were divided into 42 elements along each span consistent with the deck mesh and the material properties were assigned as medium strength concrete. A beam offset was enforced to geometrically locate the cross-sectional neutral axis of the beams below the mid-plane of the deck plate elements consistent with the structural design.

Concerning the prestressing effects on the structural dynamics, there is recent research indicating that prestressing has little or no effect on the natural frequencies of prestressed elements (Hamed and Frostig 2006), and other researchers have adequately performed structural identification of prestressed concrete bridges while neglecting the prestress force (Morassi and Tonon 2008). Consequently, the prestress force has not been accounted for in the FE model adopted for the Nine Wells Rail Bridge. However, it should be noted that the prestressing ensures a fully non-cracked beam section so the effective cross-section can safely be assumed as the entire cross-section.

The precast reinforced concrete parapets were modeled as offset beam elements positioned over the exterior nodes of the deck. Given the sloped cross-sectional shape of the parapets, it was assumed that the average width is 300 mm to produce the following properties: 0.465 m$^2$ area, 0.0966 m$^4$ torsional resistance, 0.0931 m$^4$ moment of inertia about the transverse axis through the neutral axis, and 0.00349 m$^4$ moment of inertia about the vertical axis through the neutral axis. Consistent with the deck plates, the parapets were divided into 42 elements along each span. The deck surfacing and foot/cycle ways add additional distributed mass across the deck surface without providing significant stiffness contribution. Over the main carriageway, the 125 mm depth of surfacing was converted to an average lumped mass of 100 kg per surface area carried by the nodes. For the foot/cycle way and the curb on the south edge of the spans, this lumped mass was increased to 150 kg per node as a means of accounting for the additional mass associated with the increased depth over the verge. The mass moment of inertia for the foot/cycle way and curb is neglected since it is nominal due to the thin cross-section and respective moment arm associated with the surfacing.

The solid pier between the central and eastern spans was modeled using the same class of plate elements as the deck with the thickness increased to 2 m to reflect the pier thickness. The column supported pier between the western and central spans was modeled using beam elements to represent the columns and plate elements for the portion supporting the beams. The abutments were assumed to be sufficiently inflexible so as to be able to neglect modeling them in favor of enforcing boundary conditions at the beam connections. For the baseline FE model, fixed translational and
rotational displacement boundary conditions were enforced at the lower nodes of the columns and eastern pier. At the beam-to-abutment connections, a pinned connection was provided with the translational displacement fixed, but the rotational displacement unconstrained as a means of accounting for the allowance afforded by the laminated rubber bearings, closed cell foam, and expansion fill. While these boundary conditions are idealizations of the actual conditions, they serve as a reasonably logical starting point for the FE model from which model updating can be used to optimize the restraints to better reflect the measured in-service response.

### 4.1 Preliminary model comparison

Natural Frequency (Modal) with Load Stiffening analysis was carried out using the ALGOR v23.1 finite element analysis software package. The mode shapes corresponding to the well recognized longitudinal bending and mixed torsional bending modes are presented through the second order bending modes of each span (Fig. 6). Table 1 presents a comparison between the estimated natural frequencies of the low-order mode shapes as determined analytically through the FE preliminary model and experimentally through operational modal analysis. The eigenfrequency index of correlation, $\Delta$, is taken simply to be the percentage difference between the predicted and measured values by

$$\Delta_i = \frac{\lambda_{OMA_i} - \lambda_{FE_i}}{\lambda_{FE_i}} \cdot 100\%$$

where $\lambda_{OMA}$ and $\lambda_{FE}$ are the eigenfrequencies estimated through operational modal analysis and finite element analysis, respectively.

Eigenvalue estimates are considered in this case to be the appropriate criterion for model updating due to the very low signal-to-noise ratios that preclude high levels of confidence in the absolute accuracy of the modal vectors. However, as a useful measure of the performance of the prediction

![Fig. 6 FEA mode shapes and eigenfrequencies developed from preliminary model corresponding to modes identified in full-span OMA](image-url)
model, the modal assurance criterion (MAC) was applied to gauge the correlation between the measured and estimated modal vectors from the analytical model. The MAC is a scalar indicator with a long history in vibration-based structural identification and damage detection (Allemang 2003). The MAC value of interest to this study is applied to the measured and predicted modes of the same order and can be calculated for each mode shape through

\[ MAC_i = \frac{(\phi_{OM,i}^T \phi_{FE,i})^2}{(\phi_{FE,i}^T \phi_{FE,i})(\phi_{OM,i}^T \phi_{OM,i})} \]  

(2)

where \( \phi_{OM,i} \) and \( \phi_{FE,i} \) are the modal vectors for the i-th mode as determined through the operational modal analysis and finite element analysis, respectively. The modal vector for the FEA results was reduced to the nodes coinciding with sensor locations. The index was limited to modes with sufficient spatial measurement density for absolute confidence in identification and was performed separately for the full-span and reference-based test configurations.

In this case study, the finite element model displays surprisingly good correlation with the measured response as the natural frequencies are generally within a few percent of the measured values and the mode shapes themselves visually compare quite favorably. Quantitative correlation through the MAC value index reveals relatively favorable correlation for most modes, though the values are lower than typically desired for a final analytical model. However, the general consistency with the experimental data might warrant consideration of the preliminary model as sufficient for use as an analytical and evaluation tool. In this study, it is taken as an ideal starting point for model updating using additional measures of correlation, specifically an extension to higher-order mode shapes as permitted through the supplemental reference-based deployment.

Utilizing the reference-based dense deployment of accelerometers on the easternmost span provides an extended subset of mode shapes for comparison with the FE model prediction (Fig. 7). From these modes, it is apparent that the FE model underestimates the torsional restraint in the

<table>
<thead>
<tr>
<th>OMA mode order</th>
<th>OMA freq (Hz)</th>
<th>FEA mode order</th>
<th>FEA freq (Hz)</th>
<th>( \Delta ) (%)</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.53</td>
<td>1</td>
<td>4.61</td>
<td>1.8</td>
<td>0.821 / 0.944*</td>
</tr>
<tr>
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<td>5.44</td>
<td>2</td>
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<td>0.7</td>
<td>0.934 / 0.868*</td>
</tr>
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<td>3</td>
<td>5.76</td>
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<td>6.58</td>
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</tr>
<tr>
<td>6</td>
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<td>7</td>
<td>7.60</td>
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<td>17</td>
<td>13.67</td>
<td>-4.1</td>
<td>--</td>
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<td>8</td>
<td>14.44</td>
<td>18</td>
<td>13.90</td>
<td>-3.7</td>
<td>--</td>
</tr>
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<td>9</td>
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<tr>
<td>10</td>
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<td>14.50</td>
<td>-2.6</td>
<td>0.821*</td>
</tr>
<tr>
<td>11</td>
<td>18.75</td>
<td>23</td>
<td>16.53</td>
<td>-11.8</td>
<td>--</td>
</tr>
<tr>
<td>12</td>
<td>19.81</td>
<td>26</td>
<td>18.05</td>
<td>-8.9</td>
<td>--</td>
</tr>
</tbody>
</table>

Note: MAC values calculated from full-span instrumentation configuration, except for * values, which are calculated from the dense eastern span layout.

---

\[ MAC_i = \frac{(\phi_{OM,i}^T \phi_{FE,i})^2}{(\phi_{FE,i}^T \phi_{FE,i})(\phi_{OM,i}^T \phi_{OM,i})} \]  

Table 1 Comparison between baseline analytical (FEA) and experimental (OMA) mode shapes

<table>
<thead>
<tr>
<th>OMA mode order</th>
<th>OMA freq (Hz)</th>
<th>FEA mode order</th>
<th>FEA freq (Hz)</th>
<th>( \Delta ) (%)</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.53</td>
<td>1</td>
<td>4.61</td>
<td>1.8</td>
<td>0.821 / 0.944*</td>
</tr>
<tr>
<td>2</td>
<td>5.44</td>
<td>2</td>
<td>5.48</td>
<td>0.7</td>
<td>0.934 / 0.868*</td>
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<tr>
<td>3</td>
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<td>3</td>
<td>5.76</td>
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<td>0.751</td>
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<tr>
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<td>5</td>
<td>6.58</td>
<td>-0.8</td>
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<tr>
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<tr>
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<td>13.67</td>
<td>-4.1</td>
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</tr>
<tr>
<td>8</td>
<td>14.44</td>
<td>18</td>
<td>13.90</td>
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<tr>
<td>9</td>
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<tr>
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<td>14.88</td>
<td>20</td>
<td>14.50</td>
<td>-2.6</td>
<td>0.821*</td>
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<tr>
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<td>18.75</td>
<td>23</td>
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<td>-11.8</td>
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</tr>
<tr>
<td>12</td>
<td>19.81</td>
<td>26</td>
<td>18.05</td>
<td>-8.9</td>
<td>--</td>
</tr>
</tbody>
</table>
Wireless operational modal analysis of a multi-span prestressed concrete bridge for structural identification

bridge spans thereby producing artificially low estimates of the eigenfrequencies for the higher-order torsional modes (Table 2). The value of the supplemental spatially dense deployment is therefore extolled through the fact that this strong discrepancy would otherwise be hidden in the structural identification and the preliminary model would be assumed to be well correlated. The identification of this strong inconsistency between the predicted and measured response was only afforded through the reference-based deployment as enabled through the highly mobile and expedient to use wireless sensor network. Since the preliminary FE model already reconstructs the first-order bending and torsion modes for each span with strong correlation to the experimental results, the subsequent model updating will need to stiffen the response over the higher-order torsional modes without significantly affecting the eigenfrequencies of the already well-tuned modes.

4.2 Model updating

Model updating is the iterative process whereby the parameters associated with the boundary conditions and material properties are adjusted to best fit the numerical model to the experimental response measurements. There is no definitive process for undertaking this model tuning, particularly for ambient vibration data, and there is a great degree of subjectivity and reliance on engineering judgment and experience to select the appropriate parameters to adjust to improve the correlation between the model and the measured response. Most structural identification techniques employ some iterative process to optimize the difference between analytical and experimental estimates of the modal parameters and/or indices derived from the modal parameters (Jaishi and Ren 2005,

Note: MAC values calculated from the reference-based testing limited to the easternmost span

Table 2 FEA comparison of higher-order torsional modes reconstructed through OMA of reference-based testing on easternmost span of structure

<table>
<thead>
<tr>
<th>Eastern span mode</th>
<th>FEA freq (Hz)</th>
<th>OMA freq (Hz)</th>
<th>Δ (%)</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First-order bending pattern</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd Torsion</td>
<td>6.48</td>
<td>8.02</td>
<td>-19.2</td>
<td>0.885</td>
</tr>
<tr>
<td>3rd Torsion</td>
<td>8.25</td>
<td>12.50</td>
<td>-34</td>
<td>0.774</td>
</tr>
<tr>
<td>4th Torsion</td>
<td>11.63</td>
<td>19.61</td>
<td>-40.7</td>
<td>0.705</td>
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<tr>
<td><strong>Second-order bending pattern</strong></td>
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<td></td>
<td></td>
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<tr>
<td>2nd Torsion</td>
<td>18.17</td>
<td>17.59</td>
<td>3.3</td>
<td>0.742</td>
</tr>
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</table>

Note: MAC values calculated from the reference-based testing limited to the easternmost span
Morassi and Tonon 2008). As a general disclaimer, it should be noted that the solution to this optimization problem is non-unique and therefore does not guarantee that the end parameters and properties translate with certainty to the real-world conditions. Sensitivity analysis was conducted to determine the effect of the boundary conditions as well as the elastic modulus of the reinforced concrete deck on increasing the eigenfrequency separation between the lower-order and higher-order torsional modes to better reconstruct the measured response. However, these approaches were found to be unsatisfactory in that in each case they generally produced uniform or insufficiently small frequency shifts rather than producing the increase in eigenfrequency required for the higher-order torsional modes. To obtain the desired separation, it was found that the deck thickness had to be increased to produce the necessary increase in stiffness to resist the torsional response.

The deck thickness in the roadway was increased to 375 mm, which corresponds to the required 250 mm design thickness of the reinforced concrete deck and the 125 mm minimum surfacing layer. For the plate elements where the curb and footway exist, a total deck thickness of 500 mm was specified to account for the additional surfacing consistent with the curb height. The nodes of the deck plates were proportionally displaced as well to correctly position the mid-plane of the deck for proper geometry and correct beam offsets. It should be noted that, in this case of model updating, the authors are not modifying the geometric design of the span, but rather accounting for the stiffness contribution of the asphalt surfacing layer in the model rather than simplifying it to the associated dead-load.

The revision in modeling the surfacing as integral to the deck produced the necessary increase in the eigenfrequencies of the torsional modes in the easternmost span to reconstruct the measured response within eleven percent. In the updated model, the boundary conditions at the abutments remain pinned, though rotational restraint was also fixed about the longitudinal and vertical axes and rotational springs were added to restrain motion about the transverse axis. Eigenvalue sensitivity analysis produced optimal spring constants of 2e7 N·m/rad at the eastern abutment and 1.5e9 N·m/rad at the westernmost abutment. The optimization routine focused on minimizing the percent difference in eigenfrequency estimate for the primary and first-order torsional modes of the outer spans, which are most affected by these rotational springs. It should be noted that the design details are consistent for the two abutments and would suggest consistent rotational spring constants. The authors can only speculate that the geometric differences associated with the deck slope, skew, and span length contribute to the discrepancy in applied spring constant required to enforce continuity between the experimental and analytical results.

For nearly all of the mode shapes included in the updating process, the revised model produced better correlation with the measured eigenfrequencies and for those in which the correlation is worse, the degree of change is nominal (Table 3). Correlation between the modal vectors, as indexed by the MAC values, was also found to improve for most mode shapes. In particular, the primary and first-order torsional modes of the outer spans witnessed substantial improvement in MAC correlation through the model updating. When the predicted mode shapes are compared to those measured (Fig. 8), it becomes evident that the improvement in modal vector correlation arises largely from improved estimation of the coupled response across the spans in the optimized model. The experimental measurements clearly identify coupled motion between the spans, i.e., the central span experiences measurable deflection within the primary mode of the easternmost span. In contrast, the preliminary FEA results were sharply characterized by a general isolation of the displacement response within the spans experiencing typical modal patterns. This phenomenon further supports the decision to
increase the deck thickness in the model as such a span-isolated response in the preliminary FEA model would suggest that the relative stiffness of the deck to the piers was disproportionately low. Following model updating with the revised modeling of the deck surfacing and optimized boundary conditions, the prediction model more accurately predicts the coupled response across the spans.

<table>
<thead>
<tr>
<th>Mode shape</th>
<th>OMA freq (Hz)</th>
<th>FEA 2 Freq (Hz)</th>
<th>Δ (%)</th>
<th>MAC config #1</th>
<th>MAC config #2</th>
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</thead>
<tbody>
<tr>
<td>East P</td>
<td>4.53</td>
<td>4.53</td>
<td>0</td>
<td>0.962</td>
<td>0.974</td>
</tr>
<tr>
<td>East T1</td>
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<td>5.44</td>
<td>0</td>
<td>0.992</td>
<td>0.894</td>
</tr>
<tr>
<td>West P</td>
<td>5.84</td>
<td>5.72</td>
<td>-1.9</td>
<td>0.885</td>
<td>--</td>
</tr>
<tr>
<td>West T1</td>
<td>6.63</td>
<td>6.75</td>
<td>1.8</td>
<td>0.922</td>
<td>--</td>
</tr>
<tr>
<td>Center P</td>
<td>7.56</td>
<td>7.51</td>
<td>-0.7</td>
<td>0.802</td>
<td>--</td>
</tr>
<tr>
<td>Center T1</td>
<td>7.97</td>
<td>8.28</td>
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<td>0.812</td>
<td>--</td>
</tr>
<tr>
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<td>7.17</td>
<td>-10.6</td>
<td>--</td>
<td>0.927</td>
</tr>
<tr>
<td>East T3</td>
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<td>0.762</td>
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<tr>
<td>East 2T</td>
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</tr>
<tr>
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<tr>
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<td>19.36</td>
<td>-1.3</td>
<td>--</td>
<td>0.579</td>
</tr>
</tbody>
</table>

Note: P–Primary longitudinal bending mode; aTb–bth torsional bending pattern of ath longitudinal bending order
While at this stage the model appears to be a reliable reconstruction of the as-built construction, one of the caveats in iterative model updating is that the optimization is inherently biased toward the modes selected for inclusion in the updating process. In this study, the primary and first-order torsional modes of each span were selected due to spatial aliasing concerns in the full-span deployment and the modal parameter set was supplemented with higher-order torsional modes specific to the eastern-span as permitted through the dense reference-based testing. In total, ten mode shapes are included in the model updating, which compares favorably with similar structural identification studies (Morassi and Tonon 2008, Jaishi and Ren 2005) and is generally considered a substantial set. This particular set encompasses a significant portion of the lowest frequency modes exhibited by the structure. The higher-order modes excluded due to spatial resolution restrictions imposed by the measurement grid are generally associated with larger eigenfrequencies than those included in the updating process. Since the modal flexibility matrix is inversely proportional to the natural frequencies of the mode shape contributions (Toksoy and Aktan 1994), it follows that the excluded higher-order modes will have significantly less effect on the overall structural response and therefore correlation is less critical for these modes. This has been further evidenced by the work of Catbas et al. (2006), in which the modal flexibility matrix and analytical deflection of girders as computed from the modal flexibility matrix was found to converge after inclusion of a finite number of modes. The authors in that study found that ten modes were sufficient for convergence using measurements from a three-span reinforced concrete deck on steel stringer bridge. Since at least an equal number of modes were found to correlate well with the experimental results in the present study, the analytical model obtained through system identification is deemed sufficiently optimal and can reasonably be extended to static analyses, such as to estimate the deflection arising from prescribed loading scenarios.

5. Conclusions

High-rate, real-time wireless sensor networks facilitate rapid instrumentation of highway bridges for large-scale, dense operational modal analysis to estimate the in-service modal parameters. Such experimental estimates are particularly beneficial for validation and dynamic tuning of simplified analytical models through structural identification to derive a reliable and accurate representation of the structure with consideration of the as-built conditions. The end result is an analytical tool potentially suited for updating structural response predictions.

This study utilized a thirty channel wireless sensor network with low-cost MEMS accelerometers to expediently obtain traffic vibration response measurements over a 128 Hz signal bandwidth (256 Sps sampling rate). Testing was performed with multiple instrumentation layouts for a spatially clear representation of sixteen mode shapes, of which ten were utilized in structural identification. A quasi-three-dimensional finite element model of the bridge was constructed using plate and beam elements and then model updating was performed to calibrate the model to the measured response. Strong correlation of the general pattern characteristics and mode shape orders was evident between the experimental and analytical models with exceptional correlation in natural frequency estimates as obtained through optimization of a selection of ten fundamental modes. A primary strength of rapidly deployable and highly mobile wireless accelerometers within ambient vibration monitoring is the ease and expedience within which dense reference-based operational modal analysis can be performed. As evidenced in this study, this permits for improved structural identification by permitting an extended set of mode shapes for correlation during model updating.
From the structural identification carried out in this study, there are two primary conclusions that may be drawn from the model updating process regarding what is deemed to be the most appropriate representation of the structural elements. Foremost, the deck surfacing, curbs and cycle-ways should be modeled as structural elements with stiffness as well as mass contribution. In some studies, asphalt wear surfaces are neglected or accounted for solely as dead load. This may be an advisably conservative approach for design purposes but was found to produce artificially low estimates of the eigenfrequencies associated with higher-order torsional mode shapes. Second, the strong correlation between the developed model and the experimentally measured bridge response indicates that structural identification can be successfully accomplished for prestressed reinforced concrete designs without accounting for the prestress force. This may either suggest that the effect can be lumped into the translational boundary condition or serve as evidence in support of Hamed and Frostig (2006) who concluded negligible effect of prestress force on modal parameters.

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Wireless sensor networks for permanent health monitoring of historic buildings

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Abstract. This paper describes the application of a wireless sensor network to a 31 meter-tall medieval tower located in the city of Trento, Italy. The effort is motivated by preservation of the integrity of a set of frescoes decorating the room on the second floor, representing one of most important International Gothic artworks in Europe. The specific application demanded development of customized hardware and software. The wireless module selected as the core platform allows reliable wireless communication at low cost with a long service life. Sensors include accelerometers, deformation gauges, and thermometers. A multi-hop data collection protocol was applied in the software to improve the system's flexibility and scalability. The system has been operating since September 2008, and in recent months the data loss ratio was estimated as less than 0.01%. The data acquired so far are in agreement with the prediction resulting a priori from the 3-dimensional FEM. Based on these data a Bayesian updating procedure is employed to real-time estimate the probability of abnormal condition states. This first period of operation demonstrated the stability and reliability of the system, and its ability to recognize any possible occurrence of abnormal conditions that could jeopardize the integrity of the frescos.

Keywords: wireless sensor network; fiber optic sensors; structural health monitoring; Bayesian analysis; historic construction.

1. Introduction

As suggested by Farrar and Worden (2007), structural health monitoring refers to technologies used to assess the integrity of structures, to detect damage early and before reaching the limit state, and to periodically or continuously provide information to help reach efficient and cost effective maintenance decisions. In general, this concept applies to aerospace, mechanical and civil engineering structures. It is likewise clear that there are major differences between monitoring an historic structure and an aircraft or a bridge. Many historic buildings, well beyond their original design life span, are still preserved and used because of their historical status, artistic value or structural importance. With the accumulation of degradation and deterioration, an assessment of the structural

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integrity and safety becomes increasingly important, and an automated and effective damage diagnostic system is very useful. Examples of monitoring of historic structures can be found in the literature, while more and more conferences on historic buildings dedicate special sessions to this topic (D’Ayala and Fodde 2008, Modena et al. 2004).

A monitoring system includes a certain number of distributed sensors which are responsible for collecting measurements from different positions, and a central data acquisition system that is responsible for storing all the data from different sensors for further processing and analysis. Today, most sensor systems are cable-based and employ hub-spoke connection, with tens or even hundreds of remote sensors wired directly to a centralized data acquisition hub.

The potential advantages of wireless sensor technologies and wireless sensor networks (WSN) over conventional cabled monitoring systems have been repeatedly remarked in the literature (Lynch et al. 2002a, Spencer et al. 2003, Kijewski-Correa et al. 2005, Lynch and Loh 2006): low installation cost, highly scalable features, remote tasking ability and low-level invasion of host structures. In modern structures, wireless sensors are usually motivated by economics: Lynch and Loh (2006) have noted that the high installation and maintenance cost of cable-based sensors, is a significant impediment to their use for structural monitoring. Conversely, ease of deployment, absence of cables and limited visual impact of the system are a key asset in monitoring heritage buildings, especially in buildings containing works of art. WSNs can meet these needs, of reduced invasiveness, even with large numbers of sensors, also offering flexible sensor system configurations.

A wireless sensor (usually called sensor node in a WSN) is an updated version of the traditional sensor, operating as an autonomous data acquisition node with wireless communication (Lynch and Loh 2006). Moreover, wireless sensors can play a greater role in processing monitored data by moving the intelligence closer to the measurement point (Lewis 2004), which turns the pure data acquiring sensors into intelligent nodes and makes the wireless sensor network more powerful and energy efficient.

Many products are now commercially available for integration in WSNs for structural health monitoring. A number of authors (see for instance Xu et al. 2004, Kijewski-Correa et al. 2005), have noted that initial WSN attempts were wireless data acquisition systems emulating the hub-spoke architecture in a traditional monitoring system, replacing cables from sensors to hub with wireless communication. In other cases, the original cabled data transmission from field to server was replaced by various wireless communication technologies. Pines and Lovell (1998) proposed a conceptual framework for a remote wireless health monitoring system for large civil structures using spread spectrum wireless modems, with a range of 3 to 5 miles and data rates greater than 28.8 kbps. In the system all the data, collected by a ruggedized data acquisition system near the structures, could be downloaded via the wireless modems. Arms et al. (2008) also reported some early applications of remote monitoring technologies using the mobile phone network from the structure to the base station. However, in the local network, the sensors are wired to the local data acquisition system.

All these applications differ from intelligent WSN with local computational capabilities, therefore they are merely an exercise in the use of wireless communication for structural health monitoring. Moreover, replacing cables from site to server in a traditional system with wireless does not create a WSN, and the critical issues due to long cables from sensors to hub are still not removed. Also, with the increasing number of wireless nodes in a network, the simple hub-spoke model will suffer problems due to low bandwidth and limited power supply; in a wireless sensor network the scarcest resource is power.

Limited power is still an obstacle, limiting network lifetime and preventing widespread use of
WSN for permanent building monitoring. This is especially true in the case of historic buildings, where the typical problems (subsidence, cracks, tilting, etc.) normally require years or even decades of observation of the structure behavior.

One of the most energy consuming operations in a WSN is data transmission (Lewis 2004). Therefore, the traditional hub-spoke architecture with only single hop strategy in each transmission path is apparently not energy efficient for monitoring applications. To overcome this, computation power is deployed at the sensor node to process the raw data, minimizing data transmission over the network. Moreover, since the power demand in wireless transmission increases with the square of the distance between source and receiver (Lewis 2004), multi-hop short data transmission requires less energy than a single long hop, for the same overall transmission distance, and this can extend the service life and flexibility of the network.

To deploy computation power at a sensor node and hence allow a distributed architecture in structural health monitoring, a number of engineering analysis procedures have been enabled at the nodes. This requires use of an appropriately selected core module. In development of wireless sensing units, Lynch et al. (2002b) paid much attention to selecting adequate core hardware, responsible not only for data collection from on-board sensing transducers, but also used for data cleansing and processing. In their paper an accelerometer wireless sensor node was designed and tested using an enhanced Atmel RISC microcontroller, available on the market, to accommodate the local data processing algorithm. Sazonov et al. (2004) also presented an intelligent sensor node for continuous structural health monitoring, where an ultra-low power microcontroller (MSP430F1611 from Texas Instruments) was adopted for local computing. On the other hand, special attention was paid to integrating the structural health monitoring algorithm, with data compression, system identification and damage detection, into the wireless sensor network. Caffrey et al. (2004) developed a Wisden system based on a Mica2 “mote” for structural health monitoring applications, with a damage detection algorithm. In this scheme a simple network architecture was adopted with a single central base station responsible for storing and processing all the measurements. Differing from this centralized processing scheme, Clayton et al. (2006) proposed a decentralized data processing network architecture to exploit the local computational abilities on each node. At each sensor, the data will be first locally processed by implementing a damage localization algorithm to reduce the burden of data transmission. For more information on this aspect, see the summary review by Lynch and Loh (2006).

In response to the limited power in a network, a multi hop wireless network (Caffrey et al. 2004, Kurata et al. 2005) is a good way to avoid long distance data transmission. To improve damage detection reliability and overall effectiveness of the sensor network, Kijewski-Correa et al. (2005) designed a multi-scale wireless sensor network fusing the data from distributed and heterogeneous sensor nodes for a more robust and effective approach to decentralized damage detection.

However, most off-the-shelf wireless platforms or hardware devices are not produced specifically for civil engineering applications, even less for the specific needs of the architectural heritage. Unnecessary integration of components in a wireless node increases the cost and power consumption, hardly satisfying the requirements of structural health monitoring. The relatively high cost and limited life of the sensor nodes are major obstacles to the use of wireless sensor technology in real projects, especially for long term applications (Straser and Kiremidjian 1998, Bennett et al. 1999, Kim et al. 2007).

This paper introduces the development of a dedicated WSN and its application to an historic building, the medieval Torre Aquila in the City of Trento, Italy. A brief description of the monument is
given in the next Section, along with the reasons for installation of a permanent system and for the choice of WSN as a technology. In Section 3, we introduce the customized hardware and dedicated software developed for our specific requirements, and present the installation of the whole wireless sensor system. The system has been operating since September 2008. In Section 4, a summary of the data acquired to date is presented, and the long term reliability and stability of the system is discussed; in the same section, we also explain with some examples how the raw data are processed in order to provide the owner with information on the state of stability of tower. Finally, some concluding remarks are given at the end of paper.

2. Description of Torre Aquila

The Aquila Tower, a part of Buonconsiglio Castle, is a 31 m tall medieval tower located in the city of Trento. As reported in Castelnuovo (1987), the original construction probably dates back to the 13th century: at that time it was a simple defence tower, part of the city wall, above the city gate that was intended for the guard. At the end of the 14th century, the tower was radically modified by prince-bishop George of Liechtenstein, who intended to create a private apartment for his personal use. At the time, the tower was extended, elevated, finely decorated, and directly connected to the bishop's residence, the nearby Buonconsiglio Castle; what we see today is the result of this alteration (Fig. 1). The building is rectangular in plan, 7.8 m by 9.0 m, and features five floors, including the ground level, a passage covered by a barrel vault.

Although the tower appears to be nearly symmetrical in shape, we expect it to show strongly asymmetrical mechanical behaviour for two reasons; first, the connection to the city wall and adjacent buildings is asymmetric; second, the building clearly exhibits signs of the two independent construction phases. Even today, the ancient defence tower can be recognized to the east of the gate (Fig. 2): the plan is C-shaped, 7.8 m by 4.5 m, and the height is 25.6 m. Endoscopic tests showed that the two parts of the masonry body exhibit completely different stratigraphic and mechanical

![Fig. 1 (a) Plan view and cross sections of Torre Aquila and (b) overview of the tower](image-url)
properties (Zonta et al. 2008). In detail, the lower level walls are 40 cm thick, made of stone blocks and with an incoherent wall filling. At the upper levels, the older portion of masonry is thick stone blocks, while the more recent part is brick and stone blocks of different sizes. However, based on the past investigation, we are still cannot confirm whether the two bodies of masonry are structurally connected or not through the joint.

Today the castle is open as a historical museum, and the Aquila Tower attracts thousands of visitors every year due to a cycle of frescos, called “the Cycle of the Months”, on the second floor (Fig. 3). This consists of a total of 11 decorated panels describing courtly scenes and typical

Fig. 2 Structural joint in the wall of the tower

Fig. 3 Fresco of Cycle of the Months: June. Torre Aquila, Castello del Buonconsiglio, Trento, 3.05×2.04 m (Courtesy of the Castello del Buonconsiglio Monumenti e collezioni provinciali. Copyright reserved)
working conditions in different months of the year in ancient times (one month is missing due to the existence of a winding stair connecting the first floor and the third). These frescos are recognized as a unique example of non-religious medieval painting in Europe.

The main source of concern for the local conservation board is the preservation of this artwork, in view of possible future tunneling under the Buonconsiglio Castle area. The Castle is located at the edge of the historic center of Trento and in the past the Aquila Gate was the main entrance to the city from the east. With the expansion of the city in the second half of the 19th century, most of the eastern city wall was demolished and the entrance to the city was moved a few hundred meters south of the original gate. Today this solution is inadequate for the amount of traffic. The solution to this problem, pursued by the Municipality of Trento, is to bypass the Buonconsiglio Castle with a road tunnel. The tunnel has been long delayed not only for its high cost, but also due to the concerns of the Conservancy over the safety of the Cycle of the Months. Tunneling could cause unwanted subsidence of the Castle foundations, and also vibration which is critical to fresco preservation.

It is not clear when or even if tunneling will start: as a precaution, the castle owner accepted the idea of installing a permanent monitoring system, to warn of potential risk to the frescos, whatever the source. In terms of sensors, this system would include accelerometers and deformation gauges, with a number of environmental sensors to compensate for temperature effects; system operation also needs appropriate algorithms to process the acquired data and make them available to the user in real-time.

When starting system design, there was discussion whether to use a WSN rather than a traditional cabled based system. The many pros of WSN, and specifically the very low impact of the installation, all favoured this solution. On the other hand, at the time WSN technology was justly judged not mature enough for long-term monitoring: this route implies use of an experimental system needing much development and possibly downtime for debugging and adjustment of software and hardware. Accepting the possibility of downtime during the first year of system operation, the owner eventually agreed to the WSN-based solution. The technical details of the system later deployed in the tower are described in the next Section.

3. Design and installation of the wireless monitoring system

3.1 Sensor network requirements

We can summarize as follows the challenges met in designing the sensor network for permanent monitoring of this historic tower:

1. There are five floors, and many spatially distributed sensors are needed on the different levels to fully understand the conditions of the tower. With a single sink on the top floor, it is difficult and expensive to link each node directly to the sink. Therefore, a multi-hop WSN is needed for reliable and energy efficient wireless communication. In addition, there are various possible ways for a source node to reach the destination for data transmission, so an effective topology algorithm is needed to realize a flexible and optimum wireless communication route network.

2. The whole system is a multi-scale WSN including different types of spatially distributed sensors (deformation sensor, environmental nodes and accelerometers), whose setups and operations are quite different. The deformation sensors are deployed to monitor the static
deformation of the tower, and can work at a low sampling rate. The same holds true for the environmental nodes. However, in order to gain dynamic properties of the tower, accelerometer nodes have to work at a much higher sampling frequency. This will result in a large amount of data, which needs an efficient local processing scheme to reduce data transmission, as well as an intelligent network algorithm to achieve maximum usage of the limited bandwidth source in the network.

3) In a long term monitoring system, the life span of each node will be critical. Frequent change of batteries is not admissible, not only due to difficulty or danger of reaching the installation positions, but also to limit invasiveness and reduce maintenance costs. Effective use of limited power in a network needs dedicated hardware design, and an intelligent and efficient network algorithm using power only as necessary is also of prime importance.

4) For acceleration data, sampling synchronization is a critical issue for the vibration nodes, to allow correlation analysis between information from different nodes. This is difficult, due to the time drift between nodes, and after analysis, we selected 10% of a sampling interval (0.5 ms) as the largest time drift.

5) In a historical tower, access to adjust the sensor network each time is not admissible. In special cases, such as in the presence of many tourists, a particular network configuration adjustment could be necessary. Therefore, a remote tasking capability is indicated to enable remote control of system configuration.

As remarked in the introduction, most off-the-shelf wireless platforms or hardware do not offer the performance fulfilling the above requirements. To make up for this gap, a low cost and long lifespan wireless sensor network with customized hardware design, integrated with highly reusable and easily extensible software services has been developed, specifically for long term structural health monitoring.

3.2 Hardware

In the wireless unit, we selected 3MATE! WSN module (Fig. 4(a)), developed by TRETEC (www.3tec.it), as the core platform to provide the computational core and wireless communication functions. The 3MATE! is a TMote-like (Polastre et al. 2005) device, which is an ultra low power wireless sensor module. At the core of this mote, the Texas Instrument 16-bit MSP430F1611 microcontroller, at the peak of their product classes, is chosen for its on-chip hardware peripheral. The module has an 802.15.4-compliant radio chip and an internal microstrip antenna. The integrated radio is capable of data rates of 250 kbps and can communicate up to 50 m indoors and 125 m outdoors, with the onboard inverted-F microstrip antenna. The power supply voltage can range from 2.1 V to 3.6 V with a power consumption of a few milliwatts in active mode and microwatts in standby mode, permitting the use of two 1.5 V batteries in the normal AA, C or D sizes for up to one year of lifetime. The vibration sensor modules also had an additional 32 kByte FRAM chip to allow for energy-efficient temporary storage of vibration readings. Unlike traditional flash technology, FRAM provides faster read/write operations and a much higher number of read/write cycles with lower power consumption. The only disadvantage is its relatively lower storage densities than Flash devices and its limited storage capacity. In our design, a central sink was adopted to collect and store all the measurements from different nodes. Once the sampling process and data transmission in a session finish, the FRAM could be released for use in the next session.

The 3MATE! node with an additional FRAM chip is power efficient, with a demand below 3 μA
in sleep mode. During sampling mode, the current needed is below 3 mA, and up to 20 mA during transmission. Power consumption can be further limited by selecting only enough transmitting. The communication protocol implemented in the firmware allows a very low duty cycle of the communication task with very low impact on the overall power efficiency. Except for the two special deformation nodes described in Section 3.5, all nodes were designed to work for around one year with two pairs of D or C batteries. In the specific case of Torre Aquila, changing batteries every year is perfectly acceptable, as this operation has very low impact on the routine maintenance normally carried out in the Castle. Each node costs about 80 euro.

### 3.3 Environmental nodes

In its simplest configuration, the basic 3MATE! module has an extension board for environmental monitoring, with simple analog temperature, relative humidity and light sensors (Fig. 4(b)). In the specific application the only parameter required was temperature. The sensor measurement range is -40 °C to 125 °C with an accuracy of 0.5 °C.

### 3.4 Acceleration nodes

The accelerometer is based on a Freescale compact tri-axial sensor, using Micro Electro Mechanical Systems (MEMS) technology. Even if most recent MEMS accelerometers are widely available in digital read technology, an analog version was selected with an output voltage of
800 mV/g in 1.5 g range mode. Power consumption is approximately 1 mW, at supply voltage 2.2–3.5 V, and reduces to few microwatts in standby-mode. Unlike digital, the analog output allows the signal to be coupled with an analog front-end for further signal amplification and filtering with a resulting resolution of 0.1 mg. A/D conversion is performed by the A/D converter already integrated in the standard the 3MATE! module. Most commercial mote-based acceleration nodes fit the sensor on the wireless board or on an extension directly attached to the wireless unit. This solution is sometime preferred because it allows very simple and compact packaging. However, in this case the accelerometer response is affected by the mechanical impedance of the board/packaging system, a condition not normally acceptable in vibration monitoring of civil structures. To overcome this problem, in our design the accelerometer is mounted on an independent rigid support, anchored using glue or expansion bolts to the surface to be monitored. The accelerometer is connected to the main board with a short cable, allowing for maximum flexibility during sensor placement (Fig. 4(c)). Before installation, all the vibration nodes were calibrated on a small shaking table excited by harmonic pattern at different frequencies. During the test, the wireless accelerometer is mounted back to back with a pre-calibrated single axis standard reference accelerometer (Fig. 5(a)), which in the specific case is a piezoelectric PCB transducer, model 393B12. For each node and axis, comparison between the reference and actual signals allows calculation of the linear compensation coefficient that renders the two amplitudes identical (Fig. 5(b)); the calibration constant calculated is then recorded and later used for online compensation.

### 3.5 Deformation nodes

Here, as in any permanent monitoring system, the long term stability and reliability should be addressed with special attention not only for wireless communication but also for sensor devices. Due to their long-term stability, durability and immunity to most environmental attacks, Fiber Optic Sensors (FOS) have in the last decade attracted much attention in health monitoring of civil structures. For the reader who is not familiar with the topic, good overviews are in the textbooks by Measures (2001) and by Glišić and Inaudi (2007); but see also as sample applications Lee (2003), Sohn et al. (2003), Inaudi (2005), Bastianini et al. (2006), Inaudi and Glišić (2008). However, the generally high cost of the interrogation unit, of the order of tens of thousand of euros, is possibly

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Fig. 5 (a) Calibration test setup and (b) sample result for vibration nodes
the largest obstacle to wide application of FOS in real cases (Casas and Cruz 2003). In a large scale deployment, this cost can be justified by the high number of channels that can be interrogated at the same time by a single unit, taking advantage of the multiplexing capabilities of optical technology.

However, in practice, multiplexing implies physically wiring the remote optical sensors to a central unit, where the optical signal is demodulated and converted to digital. We can easily understand that such a multiplexed scheme is per se against the WSN paradigm, where the analog to digital conversion occurs locally in order to transmit the signal wirelessly. Thus, when we attempt to integrate an optical sensor into a wireless network, in principle the only logical scheme is to integrate one interrogation unit for each optical wireless node. From the economic point of view, this scheme is not sustainable, given the high cost of commercial interrogation units.

To overcome this problem, we developed for this application a low cost FOS technology for use with a single-channel interrogation unit. The sensing principle is to measure the optical path unbalance between a measurement fiber, fixed to the structure and a reference fiber, kept loose, by detecting the time-of-flight delay of a laser pulse split into the two optical circuits.

The optical components of the sensors are inexpensive bare fibers, and to further reduce costs, we employ off-the-shelf components in the interrogation unit: a nanosecond laser pulser, a photo-diode and a Pulse Width Modulation electronic circuit. Fig. 6 illustrates schematically the working principle of the system. A function generator drives the laser diode to emit a sequence of optical pulses (more specifically, the interrogation unit used for this application generates 1 ns pulses at 30 kHz). The resulting optical signal is split at the first coupler into the measurement and reference fibers, and then recombined at the second coupler. Because of the difference in length of the two optical paths, once recombined the pulse sequence is duplicated with a time delay proportional to the path imbalance. In the interrogation unit, the optical pulse sequence is transduced back to electric at the photo diode, and used to drive a flip-flop, which in turn controls the output voltage of the interrogation unit. Any elongation of the measurement fiber results in a change in the time-of-flight delay of the optical pulse and therefore in a change in the output voltage at the interrogation unit, which is theoretically expected to be linearly proportional. The reader is referred to Pozzi et al. (2008) for a more detailed description of the opto-thermo-mechanical relationships which link elongation to optical path imbalance.

The system was developed in a number of prototypes and tested in the laboratory to validate its

![Fig. 6 Layout of the time-of-flight fiber-optic sensor system](image-url)
Wireless sensor networks for permanent health monitoring of historic buildings

performance. More specifically, two optical arrangements were produced for this application: the first is a 100 m long optical fiber coil, designed for a measurement base of about half a meter, the second is a 15 meter gauge-length sensor. Both FOS were interfaced with the standard 3MATE! unit to provide wireless communication (Fig. 4(d)). In order to quantify the linear coefficients between deformation and electrical signal, both FOS were calibrated in the laboratory before installation (Wu 2009), and the calibration results are fitted for the coil sensor and for the 15 m long FOS respectively (Fig. 7). The test results show that system response is almost linear with precision of the order of 20-60 με. The nonlinear response observed for the coil sensor at low elongation levels is due to uneven pretensioning level of the fiber wraps, some of which are in a loose state. For higher elongations, when all the loops are appropriately pretensioned, the system exhibits good linear response.

3.6 Layout of the system

The WSN installed in the tower consists of 16 nodes, distributed on all the floors as shown in Fig. 8(a), plus one base station on the third floor, which is the gateway between the local network and Internet. The number and type of sensors in consistent with the specific requirements stated in Section 3.1. To record the vibration induced in the building, three acceleration nodes, #144, #145 and #146, were deployed, compliant with DIN 4150-3 standard (DIN 1999): specifically, one is located on the ground floor, while the other two are installed on the top floor to record the acceleration response of the tower (Fig. 8(b)).

Due to the asymmetric structural response of the building and the existence of the joint, an optical elongation sensor (node #154) was deployed along the southern wall to monitor possible joint opening on the 1st floor (Fig. 8(d)): the model adopted is the 100 m-long optical coil described in Section 3.5, pretensioned on two support wheels, anchored to the wall using expansion bolts. In order to detect elongation of the tower resulting from possible non-uniform subsidence, another 15 m-long FOS was installed along the south-west wall corner, from level +11.7 m to level +26.8 m. Details of the top and bottom anchorages of the sensor are shown in Figs. 8(e) and (f) respectively. An extension of the optical fiber enters the tower through the roof and connects to the deformation node #153, located on the top floor.

Apart from the above sensors, 11 additional nodes (Fig. 8(c)) are distributed on the floors to monitor temperature; the number of environmental nodes is redundant, because some of them serve as bridge nodes in the communication network.
As explained in Section 3.7, the system allows remote tasking of the data acquisition parameters. Table 1 summarizes the parameters currently applied: in detail FOS and environmental nodes are interrogated every minute, while acceleration is recorded in a series of sessions with a sampling frequency of 200 Hz lasting 10 sec each; currently the system performs a session every 45 minutes.

### 3.7 Software

At the software level, we built all application services on top of our TeenyLIME middleware (Costa et al. 2007), which provides an abstraction layer on top of the operating system running on each single node. The application modules interface with a shared memory space spanning neighbouring nodes in communication with each other. The interaction among components takes place by means of insertion, removal and reading of tuples, units of information arranged as ordered
sequences of typed fields; moreover, a reactive primitive enables listening for changes in the distributed tuple space. This software layer allows the design of decoupled and reusable application components resulting in a reduced implementation burden for the developer and a smaller memory footprint with respect to services built directly on top of the operating system. Based on this software architecture (Fig. 9), we implemented the modules required to satisfy the application needs.

To handle the sensor heterogeneity, we devised a data collection protocol that efficiently handles different traffic patterns (Ceriotti et al. 2009). The high volumes of data produced in bursts by the accelerometers demand highly delivery, as sample losses can damage signal reconstruction; whereas the lower sampling rate of temperature and deformation nodes sets lower demands as occasional losses are acceptable. The general system functions are also checked, and for example, the battery levels at each node were recorded. To achieve this, the routing protocol builds a tree topology, rooted at the sink, which is refreshed periodically to account for connectivity changes; the metric used to construct the paths is based on a link quality index that allows nodes to choose the routes with the highest probability of successful data forwarding (an example of routing topology is shown in Fig. 10). In addition, we apply a hop-by-hop recovery scheme to account for losses in the communication channel. In this scheme, each message sent from a child to its parent in the routing tree, is tagged with a sequence number; moreover, each node keeps a cache of the last messages forwarded. When the parent recognizes a gap in the sequence numbers of the messages received, it accesses the corresponding child cache, recovering the missing information.
When sampling vibration signals at multiple nodes, time synchronization is a common issue in WSN, which has to be properly addressed for an effective correlation analysis at different sensors. Among several available protocols, here we adopted a modified version of the solution described in the paper by Ganeriwal et al. (2003). The nodes are organized in hierarchies where the root provides the reference time. Each member periodically synchronizes with the next higher level in the hierarchy, preventing clocks from drifting too far from each other. With this simple solution it is easy and efficient to control the synchronization error within the time drift tolerance as required by the application. While this system component is typically placed near the operating system to provide the required accuracy, we efficiently and effectively implemented it on top of the TeenyLIME middleware.

Finally, the system provides a remote tasking functionality that disseminates throughout the network the operating parameters controlled by the user to tune the configuration of the network. This is particularly necessary not only in the cases where an adjustment is required due to unusual environmental effects, but also in daily maintenance of the whole network. All the tasks can be remotely established by the person responsible for the data analysis by means of a custom graphical user interface (Fig. 11), from which the data acquired from the network can be also visualized online.

4. Data collection and analysis

4.1 Overview of data recorded

The wireless sensing system was first installed in September 2008 and underwent an initial period of examination, debugging, adjustment and updating of the monitoring system.

After installation of the final version of the software, on April 15, 2009, the system worked continually save for battery replacement in August 2009. Data corresponding to environmental phenomena,
tower deformation and dynamic vibration behaviour were monitored and acquired continuously except during the maintenance periods. In order to check transmission reliability, data loss is monitored continuously. In recent months, the overall loss rate is assessed at less than 0.01%. This is good performance if compared with other long-term wireless sensor network deployments reported in current literature (Ceriotti et al. 2009).

In order to monitor the day by day level of vibration at ground level and on the top floor of the tower, every day a number of sampling sessions were acquired, each 30 seconds long. As an example, Fig. 12(a) shows part of one typical signal acquired in normal environmental conditions in three axes recorded at node #146 (located at the top floor) at time 11.38 AM. We see immediately that the amplitude of ambient acceleration is very low, less than 0.2 ms$^{-2}$. For a qualitative idea of the acceleration level recorded, compare Fig. 12(a) with the graph of Fig. 12(b), acquired under similar conditions with one person jumping near the sensor (in z direction). The graph of Fig. 13 shows the FFT of two of these signals expressed in spectral velocity and on a logarithmic scale (spectral velocity is the quantity commonly used by industrial standards to state vibration limits). On the same graph we also show the vibration limits, suggested by BS 7385-2 and DIN 4150-3 standards (BSI 1993, DIN 1999), for structures sensitive to vibration, such as an historic building. By examination of this graph, we observe that the typical ambient vibration recorded is well below the limits recommended, and lets us conclude that vibration is currently not a source of concern for the stability of the tower, nor even for integrity of the frescos.

To evaluate the response of the FOS, it is useful to compare the measured response with that estimated a priori before installing the monitoring system. A three-dimensional Finite Element Model (FEM) of the tower was developed in (Zonta et al. 2008) and used to simulate its response under different load and environmental conditions. The outcomes highlight that, compared with other effects such as wind and snow, thermal gradients produce the largest absolute strain in the tower, although only a minor part of this is stress-induced. For example, the thermal distortion of the crack is estimated as 0.157 mm on a summer day, and 0.069 mm in winter; while the response of the same sensor induced by a 10 mm settlement at the southwest foundation is estimated to be

![Sample acceleration signals recorded at node #146 under pure ambient vibration (a) and at node #145 when people walking nearby](image)
only 0.0023 mm. This and similar observations suggest the importance of temperature compensation for correct evaluation of structural response as provided by the monitoring system. Fig. 14 shows the deformation records from two FOS with their corresponding temperatures. Fig. 14(a) presents the deformation measured by the coil sensor (node #154) from September 2008 to September 2009. The daily variation is between 0.05 mm on a cloudy day and 0.30 mm when sunny, and this is in good agreement with the numerical results of the FEM model. Similarly, Fig. 14(b) shows the FOS elongation and temperature recorded at node #153 in the same period (observe that the long FOS...
was operating only after February 2009). Compared with the predicted value in the deformation presented in Zonta et al. (2008), the acquired measurements are of the same order of magnitude.

4.2 Temperature compensation

As mentioned, the main objective of monitoring is the preservation of the artistic frescos located at the second floor of the building. Damage to frescos is caused essentially by stress-induced strain: we must therefore compensate the strain measurements to eliminate the temperature effect. To do this, it is convenient to separate the temperature record into two components: the daily variation and the seasonal trend. Daily variation affects the tower in a non-uniform way, producing significant distortion of the tower; while the seasonal trend is a slow steady change in temperature, resulting in uniform expansion or contraction of the structure. The effect of daily and seasonal variation has been quantitatively explained in Zonta et al. (2008) with the support of the FEM.

A rough but effective way to extract the seasonal component is to select one sample per day at the time before sunrise; while evidently the daily excursion is given by the difference between the record and the seasonal trend. Fig. 15 illustrates this process as applied to sensor node #154, the coil sensor placed across the joint, in the period June 1 to July 31, 2009. By comparison of the elongation record shown in Fig. 15(a), with the daily and seasonal components of the temperature variation shown in Figs. 15(c) and (d), we can qualitatively appreciate how the structural deformation is mainly correlated to the daily variation.

In order to remove the temperature dependent variation from the raw elongation measurements,

![Fig. 15 Deformation history recorded by optical-coil sensor, (a) node #154, (b) temperature history recorded at the same node, (c) daily and (d) seasonal components](image-url)
we applied an algorithm based on Bayesian logic. Suggested readings for those interested in this topic, and its application to structural monitoring, are Sivia (2006), Beck and Katafygiotis (1998), Beck and Au (2002), Papadimitriou et al. (1997), Sohn and Law (1997). Here, we will follow the same general approach already proposed in Zonta et al. (2008): the thermometers are viewed as environmental sensors, recording the environmental action, while the two FOS are regarded as response sensors, recording the structural response of the tower to this action. In order to remove temperature dependent effects, we organize the time history into a series of time intervals of one day, with the assumption that this time span is small enough to consider the compensated response as constant within this interval. The recorded deformation history is assumed to have a linear relationship with both daily and seasonal temperature variation, although, because of the different mechanism explained above, the two linear coefficients are considered independent. Thus, the relation between a deformation sample \( m_T(t) \) recorded at day \( T \) and time \( t \), and the compensated response \( m_T^o \), supposed to be constant within day \( T \), can be formally written as

\[
m_T(t) = m_T^o + \alpha_T^d h_t(t - \Delta t_d) + \beta_T h_s(t - \Delta t_s) + n_T(t; \sigma_T)
\]

where: \( \alpha_T \) is the linear coefficient relating deformation and daily temperature variation \( h_t \); \( \beta_T \) is a linear coefficient between deformation and seasonal temperature variation \( h_s \); \( \Delta t_d \) and \( \Delta t_s \) are the time lags between the deformation and the two temperature components; and \( n_T \) is a Gaussian noise with zero mean value and standard deviation \( \sigma_T \) reproducing instrumental and environmental disturbances.

We can rewrite Eq. (1) for any of the samples acquired at day \( T \), obtaining a set of equations with unknown parameters \([m_T^o, \alpha_T, \beta_T, \Delta t_d, \Delta t_s, \sigma_T]\) which can be reasonably assumed constant within time interval \( T \). The above parameters, including the compensated deformation, all regarded as uncertain variables, can then be estimated by a classical Bayesian identification procedure. This procedure can be repeated day by day, eventually obtaining a record of compensated measurements.

![Fig. 16 Estimate of compensated deformation from optical coil sensor (node #154)](image-url)
As an example of this process, Fig. 16 illustrates how this procedure applies to the response of the coil FOS (node #154), in the period from June 1 to July 31. In detail, the red plot is the day-by-day best estimate of compensated deformation \( m_T^0 \) based on all the past information, while the blue lines indicate the best estimate plus or minus its standard deviation respectively, and give an idea of the degree of confidence of this information. More specifically, the system estimates \( \alpha_T \) to be 0.1 mm C\(^{-1}\) with standard deviation of 0.04 mm C\(^{-1}\), and \( \beta \) to be 0.05 mm C\(^{-1}\) with standard deviation of 0.02 mm C\(^{-1}\). It worth noting that during the updating process, coefficient \( \alpha_T \) is typically bigger than \( \beta \), which confirms that, as observed before, for identical temperature excursions, the daily component always produces greater changes in deformation than the seasonal. The observed variation of the compensated strain is relatively small, of the order of 0.2 mm, confirming, as expected, that so far the tower is not undergoing any significant deformation.

### 4.3 Data evaluation

To prevent possible damage to the frescos, specifically in view of the future tunneling that motivated the deployment of this system, it is important to recognize early any anomalous condition states of the tower. For example, linear trends in deformation are a typical sign of ongoing phenomena that should be under control. To recognize in real time a linear trend of deformation, we can further apply a Bayesian algorithm to the compensated records (Zonta et al. 2009). As the monitoring system continues to work, more and more data become available. A Bayesian algorithm lets us update the past estimate of the tower condition with the fresh data acquired. Here again we take deformation node #154 as an example to demonstrate the method. In principle, we expect the tower to behave according to one of the following two alternative scenarios: (1) the joint does not open, thus the deformation recorded at sensor #154 stays constant; (2) the joint is opening and the measurement exhibits a continuous increase. More formally, we can model the behavior of the joint in the two scenarios as follows

\[
\begin{align*}
\begin{cases}
m_T^0 = d_1 & \text{in } S_1 \\
m_T^0 = k \cdot T + d_2 & \text{in } S_2
\end{cases}
\end{align*}
\]

(2)

where \( d_1 \) is the constant deformation expected in scenario \( S_1 \), and \( d_2 \) and \( k \) are the offset and linear trend of deformation in scenario \( S_2 \). We recognize that each scenario depends on a set of parameters, which can be formally expressed as \( X_1 = [d_1] \) and \( X_2 = [k, d_2] \). Now, our problem is to estimate the probability of being in one scenario, \( S_1 \) or \( S_2 \), based on the fresh data acquired daily. Say that we are at day \( T \), and we acquire the new data \( m_T^0 \). Based on whole set of data \( \{m_T^0\}_{T=1} \) acquired up to the previous day \( T-1 \), we already have an estimate of the probability \( \text{prob}(S_n|m_T^0) \) of being in one of the two scenarios. This probability is regarded as prior probability, and represents our knowledge before analyzing the current data. Once acquired the last sample, Bayes’ theorem allows us to estimate the new (or posterior) probability based on the prior one, according to

\[
\text{prob}(S_n|m_T^0) = \frac{\text{PDF}(m_T^0|m_T^{-1}, S_n) \cdot \text{prob}(S_n|m_T^{-1})}{\text{PDF}(m_T^0|m_T^{-1})}
\]

(3)

where PDF is the short form for Probability Density Function. In order to make this algorithm work in practice, we need to calculate the different terms in Eq. (3). The first term in the numerator, referred to
as scenario evidence (sometimes also named scenario likelihood) of scenario \( S_n \), representing the probability of occurrence of the data if the specific scenario is given, can be calculated by integrating over the whole parameter domain \( DX_n \), using the marginalization and product rule

\[
PDF\left( m^* \mid \{ m^*_n \}, S_n \right) = \int_{DX_n} PDF\left( m^*_n \mid X_n, S_n \right) \cdot PDF\left( X_n \mid \{ m^*_n \}, S_n \right) \, dX_n
\]  

(4)

The denominator term, usually referred to as evidence, is a normalization term, that warrants that the sum of the probabilities of being in the different scenarios be 1. The prior probability at the first interval should reflect our prior judgment about the problem; in the absence of any other information a uniform distribution should be assigned. For details of the algorithm, the reader is referred to (Zonta et al. 2009).

Fig. 17 shows, again in the period from June 1 to July 31, how this approach applies to the compensated signal from deformation sensor #154. The first graph, Fig. 17(a), plots the posterior probability of scenario \( S_2 \) estimated day-by-day based on the past data: in simple terms, this graph quantifies the possibility of having a linear trend of deformation. As expected, to date this value

Fig. 17 (a) Posterior probability of Scenario 2, (b) best estimate and distribution of parameter \( d_1 \) (baseline deformation) in Scenario 1, (c) best estimate and distribution of offset \( d_2 \) and (d) linear trend \( k \) in Scenario 2
remains for most of the time close to zero; once only, when the deformation record exhibits sharp changes, this probability departs from zero reflecting some temporary concern, and immediately returns when new data are available. Using the same Bayesian approach, we can also calculate the posterior distribution of the scenario parameters. As shown in Fig. 17(b), assuming Scenario 1, ‘no trend’, to be correct, the estimated values of permanent deformation rapidly converge to 20 $\mu$m, with a standard deviation of 6 $\mu$m. It is likewise interesting to observe that, assuming correct Scenario 2, ‘linear trend’, the most likely estimate of the linear trend $k$ converges after 20 days to a value of 0.002 mm day$^{-1}$, corresponding to an annual trend of 0.29 mm year$^{-1}$. Of course, this value, and the corresponding likelihood, are both too small to call for an urgent action on the tower.

5. Conclusions

We presented an application of WSN technology to monitor permanently Torre Aquila. This effort was motivated by the need to keep under control the structural response of the tower, in terms of deformation and vibration, to preserve the integrity of the valuable artworks located inside, in view of possible future tunneling work.

The specific application, and the long-term requirement, demanded the development of customized hardware and dedicated software. As for hardware, the 3MATE! wireless sensor module was selected as the core platform, to allow reliable wireless communication at low cost and with a long service life. In terms of software, a multi-hop data collection protocol built atop of TeenyLIME was applied to improve the system's flexibility and scalability. The system has been operating since September 2008. After a period of debugging and adjustment, it now acquires data continuously with little or no interruption. In the last 5 months, the data loss ratio was estimated as less than 0.01%, which is good performance if compared with other long term wireless sensor systems deployed.

The data acquired so far are in agreement with the prediction estimated a priori from the 3-dimensional FEM. In particular, the effect of temperature on the deformation of the tower is in line with the estimate; we demonstrated the ability of the system to handle temperature effects, and to calculate compensated deformation records using a Bayesian algorithm. A Bayesian updating procedure is also employed to real-time estimate the probability of abnormal condition states. The proposed Bayesian identification procedure provides a good tool evaluating not only the occurrence of anomalous situations, but also the degree of confidence in this information. In the example reported, the system calculates that the probability of a trend in deformation is, based on the data available, close to zero. In general, the data recorded to date, both from the accelerometer and the deformation sensors, do not raise any special concern as to the safety of the tower. Nevertheless this first period of operation demonstrated the stability and reliability of the system, and therefore its ability to recognize any possible occurrence of an abnormal condition that could jeopardize the integrity of the frescos.

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Wireless sensor networks for permanent health monitoring of historic buildings


Wireless sensor networks for underground railway applications: case studies in Prague and London

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Abstract. There is increasing interest in using structural monitoring as a cost effective way of managing risks once an area of concern has been identified. However, it is challenging to deploy an effective, reliable, large-scale, long-term and real-time monitoring system in an underground railway environment (subway / metro). The use of wireless sensor technology allows for rapid deployment of a monitoring scheme and thus has significant potential benefits as the time available for access is often severely limited. This paper identifies the critical factors that should be considered in the design of a wireless sensor network, including the availability of electrical power and communications networks. Various issues facing underground deployment of wireless sensor networks will also be discussed, in particular for two field case studies involving networks deployed for structural monitoring in the Prague Metro and the London Underground. The paper describes the network design, the radio propagation, the network topology as well as the practical issues involved in deploying a wireless sensor network in these two tunnels.

Keywords: tunnel; wireless sensor network; monitoring.

1. Introduction

There is increasing demand in cities for space. This applies to the underground environment just as much as above ground, with more buried infrastructure required, deeper piles needed for tall buildings, deeper basements being constructed and even other transportation tunnels being built. This underground congestion has implications for underground railways (metros or subways) as it can change the loading on existing structures. These changing loads combined with the deterioration of these structures due to aging and natural variations mean that there are changing demands being placed on the structures of underground railways.

Monitoring is progressively being seen as a cost effective way to minimise identified risks and is increasingly deployed underground. It is challenging to deploy an effective, reliable, large-scale, long-term and real-time monitoring system in an underground railway environment. There exists a
number of potential hurdles to be overcome such as the underground environment that can be damp and even corrosive. Such an environment can impact reliability, which is a major concern for systems that are ‘safety critical’. There are also limits on the availability of electrical power and communications. The time available to deploy these systems is severely limited as well, normally being restricted to non-operating (engineering) hours. Installing the cables required to transmit both the power and data for the sensors can take a significant proportion of the overall installation time available. This is especially true in tunnels where the clearance between the tunnel lining and the trains may be limited and hence particular care has to be taken to keep the cables close to the walls.

The use of wireless sensor technology, which transmits the sensor data using radio, allows a rapid deployment due to elimination of some of the cabling and thus has significant potential benefits. Combined with microelectromechanical systems (MEMs) sensors, which can be cheaper and have the advantage of using less power, there is the opportunity for significant overall cost savings (for example, accelerometer (Lynch et al. 2006), acoustic emission (Glaser et al. 2007), Inclinometer (Yu et al. 2009)).

Although advantages of WSNs for conditioning monitoring of infrastructure have been identified, deployment of WSNs in real environment remains to be challenging (Barrenetxea et al. 2008, Houl et al. 2009a, Stajano et al. 2010). Current research investigating the use of WSNs for structural health monitoring (SHM) has focused mainly on bridges and acceleration monitoring e.g., Lynch et al. (2006), Glaser et al. (2007), Kim et al. (2007), Grosse (2008) and Whelan and Janoyan (2009). Very few groups, to our knowledge, have deployed WSNs with the goal of using them for long-term monitoring. Among those few are Feltrin et al. (2007) and here again the main parameter being measured is vibration.

While such research has helped to advance the state-of-the-art in WSN monitoring, the tunnel environment provides unique challenges (Akyildiz and Stuntebeck 2006, Bennett et al. 2009). Initial work was undertaken into the use of WSNs for monitoring in the London Underground as part of the Cambridge-MIT Institute project (Cheekiralla 2004). However, this work was limited both in terms of scale and time. The other past work includes detection of collapses in coal mines by sensing the removal of sensors in the collapsed area (Li and Liu 2007) and a wireless seismic array is under development at the Deep Underground Science and Engineering Laboratory (DUSEL) (Glaser and Parkkila 2009). There is also a larger body of work on radio propagation underground, with particular emphasis on telecommunication applications, but also applicable for WSNs (for examples, see proceedings of the international workshop and conference Wireless Communications in Underground and Confined Areas (Fares et al. 2005, Wu and Wassell 2009).

The current research seeks to determine what the issues are with using WSNs for SHM in an underground environment. This paper identifies various issues facing underground deployment of a wireless sensor network, based on two field case studies involving networks deployed for structural monitoring in the Prague Metro and the London Underground. The paper describes the network design and the radio propagation as well as the practical issues involved in deploying a WSN in these two tunnels.

2. Field trial sites

2.1 Prague Metro

First opened in 1974, the Prague Metro has three lines and consists of approximately 50 km of tracks, running mostly underground and 54 stations. In August 2002, the Metro suffered from the flooding that occurred across much of Central Europe. Fig. 1 shows the extent of flooding that
occurred on the Prague Metro. Nineteen stations were flooded and several building movements have been attributed to this event. The long term effects of the damages caused by the flooding are a major concern to the underground operator. In this study, an area of concern was identified in a section approximately 350 m from Nadrazi Holesovice station of Line C, towards Vltavska station, where cracks were visible in the lining. A wireless sensor network was designed to monitor this location and a control section further up the same tunnel, which had no signs of damage. The tunnel was constructed using the ‘Prague’ ring tunnelling method with a lining consisting of 200 mm thick reinforced concrete segments with an internal diameter of 5.1 m. The tunnel depth in this location is approximately 12.6 m. Further details of the site can be found in (Vanicek 2008).

2.2 London Underground

London currently has one of the most extensive networks and some of the oldest sections of underground tunnels in the world. London Underground Ltd. has 392 km of railway lines. Approximately 35% of the network (140 km) is underground tunnels and many of them are 75-100 years old. One of the significant areas of concern is a 200 metre section of expanded concrete tunnel on the Jubilee Line, where concrete spalling has been occurring at the radial joints of the precast tunnel lining panels. The cause of the spalling is high contact stresses, combined with a poor out-of-circular build which occurred as a result of difficulties encountered during construction in the mid 1970’s (Lyons 1979). In the area being studied the tunnel has a depth of approximately 35 m and is mostly in the top portion of the Lambeth Group strata, although the crown rises into the London Clay as shown in Fig. 2, which shows a geological section of the test site. As with most London Underground tunnels the tunnel diameter is quite small with an internal diameter of only 3810 mm and a 168 mm thick lining and the clearance between the linings and the trains is very small, which provides

Fig. 1 Flooding on Prague Metro (Vanicek 2008)
additional challenges in sensor deployment. Further details of the site can be found in (Bennett et al. 2009, Cheung et al. 2009).

3. Wireless sensor network hardware

The radio modules used in both trials were MICAz boards made by Crossbow, operating at 2.4 GHz and using the XMesh routing protocol also produced by Crossbow. This allows sensor motes to automatically form a ‘mesh’ network, in which motes can relay the messages from other motes. Interface boards were developed for the sensors required, i.e., crackmeters and inclinometers (Stajano et al. 2010, Hoult et al. 2009b). Low cost and low power sensors were used to extend the life of the batteries used to power the sensor motes.

The crackmeter module, as shown in Fig. 3, incorporates two linear potentiometric displacement transducers (LPDTs), one across the joint/crack under observation and one as a control, and two relative humidity and temperature sensors (one internal, one external to the protective box that the sensor node is placed in). The overall dimensions of the protective box are 145 mm × 220 mm × 50 mm; the 2 dBi / 5 dBi antenna extends a further 58 mm / 215 mm from the side. The smaller 2 dBi antennas were used in London, where clearance was more of an issue, and the 5 dBi antennas were used in Prague to provide longer radio communication range. In both sites, the antennas are located approximately 25 mm from the tunnel wall, i.e., half the thickness of the protective box.

The LPDTs have a total range of 12 mm and they act as a potential divider, with the output voltage varying linearly with displacement across the centre of this range. This output voltage is measured by a 10-bit ADC on the CPU of the MICAz giving a resolution of 0.012 mm. Both LPDTs are then mounted on a single circuit board, which is secured to the tunnel lining using drilled concrete anchors. The LPDTs are spring loaded and pressed against an angled plate that is also secured to the lining on the other side of the crack / joint. The cost of each LPDT is approximately $60. The relative humidity and temperature sensors come as a single unit: the Sensirion SHT11. The readings from all of the sensors are transmitted in the same data packet.
Fig. 3 Crackmeter module

Fig. 4 Inclinometer module
The inclinometer module, as shown in Fig. 4, also contains two Sensirion digital humidity and temperature sensors, monitoring the internal and external environment. The inclinometer sensor is a MEMS device (a VTI Technologies SCA103T-D04). It has a resolution of 0.001° with a ±15° range and costs approximately $60. To achieve this resolution the analogue output from the chip is measured by a 16-bit ADC external to the MICAz. An additional 9V battery is used only for the inclinometer and ADC, which are only powered briefly when taking a measurement. The overall dimensions of the installed module in its protective box are 90 mm × 145 mm × 50 mm; again the 2 dBi / 5 dBi antenna extends a further 58 mm / 215 mm from the side.

Additional modules were installed as relays and have the same form factor as the inclinometer module, but do not have sensors inside, only the radio module. For both the Prague and London networks the messages are received at a Gateway, the Crossbow MIB600, which in turn is linked via Ethernet cable to a single-board computer with a GPRS modem. All the measurement readings are time stamped to permit the data to be entered in the correct order into the database, enabling comparison between measurements made at different sensors. The data is transmitted via a modem and the Internet to a server at the University of Cambridge where it is stored as both text files and in a database. The readings are then displayed on a web page.

4. Network design

4.1 Radio propagation inside tunnels

In the London Underground and the Prague Metro, accurate measurements have been made of the received signal power with different transmission variables, for example, antenna position (both on the same side, on opposite sides or both in the centre of the tunnel), lining material and operating frequency. Rather than presenting the results in terms of the received power, the concept of propagation path loss (PL) is used to characterise the quality of the radio channel, since it is a dimensionless quantity that is independent of transmit power or antenna gain. That is, the greater the value of PL is, the worse the channel is and the greater the attenuation is. The PL can be related to the received signal power ($P_{Rx}$) in dBm as follows

$$P_{Rx}(\text{dBm}) = P_{Tx}(\text{dBm}) + G_{\text{ANT}} - L_{C} - P_{PL}$$

(1)

where $P_{Tx(\text{dBm})}$ is the transmit power in dBm, $P_{PL}$ is the PL (in dB), $L_{C}$ is the total cable loss (in dB), and $G_{\text{ANT}}$ is the overall antenna gain (in dBi). Fig. 5 shows the measured PL in the Bond Street London Underground tunnel with antennas located on the same side of the tunnel (Wu et al. 2009). This measurement was taken at a frequency of 2.45 GHz, with the transmit antenna spaced at 20 mm from the tunnel wall and the receive antenna at 110 mm from the tunnel wall. A radio receiver is specified to yield a particular data packet loss rate at a certain receiver input power level. However, if the received signal power is below the minimum sensitivity level of the receiver, then data packets will be lost at the receiver. The manufacturer usually specifies the minimum receiver sensitivity level, but if possible, it is also advisable to confirm it by measurement.

A line is drawn on Fig. 5 showing the maximum PL that can be tolerated for a specified receiver minimum sensitivity level, antenna gain and transmit power. Re-arranging Eq. (1) gives

$$P_{PL} = P_{Tx(\text{dBm})} + G_{\text{ANT}} - L_{C} - P_{Rx(\text{dBm})}$$

(2)
Wireless sensor networks for underground railway applications: case studies in Prague and London

where for example: \( P_{\text{Tx(dBm)}} = -9 \text{ dBm}; \) \( P_{\text{Rx(min.)}} = -90 \text{ dBm}; \) \( G_{\text{ANT}} = 4 \text{ dBi} \) (i.e., \( 2 \times 2 \text{ dBi} \)), and \( L_C = 0 \text{ dB} \), yielding a maximum tolerable PL for correct data transmission, \( P_{\text{PL(max.)}} = 85 \text{ dB} \). In this example it is assumed that the antennas are directly connected to the Radio Frequency (RF) connector on the radio modules, i.e., the cable loss is zero, \( L_C = 0 \text{ dB} \).

In addition to the gradual increase in PL with antenna separation observed in Fig. 5, there are local rapid variations in the received signal power owing to multi-path ‘fading’. At close antenna separations (region (a) in Fig. 5), losing a data packet is very unlikely since the PL is much less than the maximum tolerable PL, i.e., the probability of a fade being sufficiently deep to increase the PL to a value in excess of the maximum tolerable PL is very low in this region.

At greater antenna separations (the shaded area (b) in Fig. 5), there is a much greater chance that the PL will exceed that of the maximum tolerable PL. Consequently the probability of losing data packets will rise. At even greater antenna separations (region (c) in Fig. 5), the PL is always greater than the maximum tolerable PL. Hence, no successful transmission of data packets is possible.

At both sites a simple initial survey of the radio propagation environment was performed prior to installation using two MICAz modules, one programmed to transmit repeatedly and the other programmed to blink when the message is received. The transmitter was fixed to the tunnel lining while the receiver was moved away from the transmitter (while maintaining a position close to the tunnel wall) to investigate the effect of antenna separation on the loss of data packets. Based on these measurements and from the results shown in Fig. 5, the distance between wireless modules for both installations was chosen conservatively to be less than 20 m in order to guarantee a high probability of correct data transmission between the wireless modules.

From consideration of Eq. (2), it can be seen that increasing the antenna gain will raise the maximum level of PL that can be tolerated, i.e., it will increase the communication range. Alternatively, if it is necessary to maintain a particular range between a pair of modules, then increasing the antenna gain will improve the data packet loss rate (i.e., reduce the number of lost packets).

Although impractical, the best PL performance was obtained with transmitter and receiver antennas in the centre of the tunnel. Placing the antennas on the same side of the tunnel was
marginally advantageous over placing them on opposite sides of the tunnel. One significant reason why the maximum antenna separation is so much greater when both antennas are located in the centre of the tunnel is owing to the modification of the transmission radiation pattern of an antenna when it is placed close to a wall. The distance the antenna can be mounted away from the wall is constrained by the required clearance between the tunnel lining and the train, and is only ~50 mm in this section of tunnel. The issue of clearance is a particular problem in the London Underground since the tunnel diameters are very small, but even in the Prague Metro the distance the sensors could protrude was limited to a similar value so they could be placed at any point around the tunnel.

To determine what effect this offset distance has on the transmission radiation pattern, a Finite-Difference Time-Domain (FDTD) model was created where the parameters varied were (i) the spacing between the wall and the antenna and (ii) the wall material. Fig. 6 shows the radiation patterns predicted by the FDTD modeling for six different offsets and three different material types (concrete, cast-iron and plastic) (Wu and Wassell 2008). The wall is the vertical line that runs from 90° to -90° and the transmission frequency is 2.4 GHz. As shown in Fig. 6(a), if the antenna is offset from the wall by 6 mm, there is very limited signal strength along the wall. This means that on the flat wall of a tunnel, nodes in this plane will have their communication range impaired. At an offset of 20 mm (Fig. 6(b)) the range is still somewhat limited and it is not until the offset increases 31.25 mm (Fig. 6(c)) that the transmission strength along the wall starts to show significant increases. As such it is recommended that the antenna of the node be placed at least 30
mm away from the wall if transmission range along the wall is critical.

For metal structures, if the node is placed 125 to 250 mm away from the wall, the radiation pattern becomes significantly non-uniform. There are lobes that form between which the transmission strength falls dramatically. Whilst the transmission strength along the wall continues to be quite high, if the proposed WSN is to have nodes placed out of the plane of the wall, consideration must be given to where they will be located. Further details of transmission patterns close to walls can be found in (Wu et al. 2009, Wu and Wassell 2008).

4.2 Network geometry

The network design adopted for the Prague Metro is shown in Fig. 7. The WSN was installed in September 2008. A total of 28 motes were installed; 10 inclinometer motes, 2 crackmeter motes and 16 relay motes. From each sensor mote, a data packet was sent every 3 minutes. A mobile phone network is available to users in the stations, meaning that the computer and modem can be situated in the mouth of the tunnel in the vicinity of the station. Access to the WSN installation site was from a special train that has platforms at different levels allowing work to be conducted at varying
heights in the tunnel. This means placing sensors at the same height along the tunnel could be achieved with relative ease by moving the train down the tunnel. Electrical power is available in the tunnel with junction boxes situated every ~50 m. The computer/modem and MIB600 gateway are both powered from nearby junction boxes. The two areas of concern are linked by relays spaced by 20 m, allowing a network that uses extensive hopping to be tested.

In the London Underground there is no mobile phone coverage in the tunnels or the stations in the vicinity. The junction boxes can only be used during engineering hours as they are only turned on at this time and the sockets face into the tunnel meaning plugs must be removed because of
clearance issues when trains are running. Because the clearance is so tight no personnel are allowed in the tunnels when trains are moving and access must be from scaffold towers erected each night. The network designed to fit these constraints is shown in Fig. 8. A total of 25 motes were installed; 16 inclinometer motes, 5 crackmeter motes and 4 relay motes. From each sensor mote, a data packet is sent every 3 minutes.

The computer and mobile phone modem are located at the top of the closest vent shaft where there is mobile phone coverage and an electrical supply. These are connected to the MIB600 gateway using an Ethernet cable with relays which are all also powered by a DC supply from the top of the vent shaft. Using Ethernet cable rather than wireless relays allowed for faster installation for transmission along the tunnel where the cabling could be laid in the existing cable trays. This hybrid system therefore uses wireless for communications around the circumference of the tunnel in the area of interest where there are no cable trays, thus making the use of wireless modules a better choice. The WSN was installed in July 2008.

5. Network performance

5.1 System reliability and robustness

There are two main areas of concern when it comes to reliability/robustness of WSN systems: hardware and radio connectivity. The Prague and London Underground deployments have both suffered from hardware failures related to the gateways. The connection between the computer and the MIB600 has been identified as a weak link in both gateway systems. In the case of the Prague Metro a failure of the USB to Ethernet connection resulted in the gateway not logging data for several months until this hardware was replaced. In the London Underground a similar failure of the MIB600/Ethernet connection also resulted in interrupted data logging. The solution in both cases is the installation of a redundant gateway, which would be a prudent solution in any WSN system given the importance of the gateway.

Both networks also have experienced connectivity issues. The Crossbow software at each node (including relays) creates and transmits data packets, which contain information about the network connectivity. The time interval to send data packets was set to be 180 sec. Hence ideally the total number of data packet that the Gateway receives is 13,440 (480 data/day × 28 motes) for the Prague Metro WSN and 12,000 (480 data/day × 25 motes) for the London Underground WSN. An indicator for the connection quality is the ratio of the number of packet that are dropped (i.e. not transmitted) to the total expected number of packet transmitted. In this study, the data loss percentage is defined by the following equation:

\[
R_i(\%) = \frac{(E_i - N_i)}{E_i} \times 100
\]

where \(R_i\) is the data loss percentage for mote \(i\), \(E_i\) is expected value of the number of data packet from mote \(i\) and \(N_i\) is the measured number of data packet from mote \(i\). \(E_i\) is introduced by the time interval for transmitting data set on the motes \(\Delta t\) and a specific time volume during the investigation i.e., \(E_i = \frac{t}{\Delta t}\). The number of data packet from the motes is counted at the gateway, so the loss by traveling across several motes to reach to the gateway is also included in this ratio.

Fig. 9(a) shows the time history of the data loss ratio of motes having mote identification numbers 8209 and 8213, installed at the ring cluster 2 (control ring) in the Prague Metro WSN. The other
motes in the Prague Metro WSN showed similar time history trends. The data loss percentage during engineering hours is between 10 and 30%, whereas that during traffic hours is between 25 and 35% (note that the data missing between November 2008 and February 2009 is related to the gateway connection problem as discussed before). Fig. 9(b) shows the time history of the data loss percentage of motes having mote identification numbers 16562 and 16593, installed at the ring 1640 in the London Underground WSN during engineering hours (1:00am to 4:30am) and traffic hours (4:30am to 1:00am). The data loss percentage during engineering hours is between 0 and 10% and that during traffic hours is between 20 and 30%. The other motes in the London Underground WSN showed similar time history trends. Passing of trains during traffic hours influenced the transmission between motes, which increased the number of the lost data packets.

The difference in the data loss between the two networks is possibly related to communication distance and the number of hops. Fig. 10 shows the hop number versus distance to the gateway. In the Prague Metro WSN (Fig. 10(a)), the maximum communication distance is 170 m. The maximum distance for the one hop cases is 110 m, which corresponds well to the results of the radio propagation measurements shown in Fig. 5. For the mote placed at the maximum communication distance, three hops were necessary. In the London Underground WSN (Fig. 10(b)), the maximum communication distance is 27.5 m, which is much smaller than the Prague Metro WSN. The majority of the data packets travelled to the gateway by a single hop. Even the
mote placed at the maximum communication distance was able to be connected by a single hop to the gateway. The larger data loss observed in the Prague Metro WSN is mainly due to the larger communication distance.

If each data packet that was transmitted was critical, then this level of data loss percentage would be unacceptable. One solution would be to have each node retransmit the data packet until the receiving node sends an acknowledgement, but this increased reliability comes with a subsequent increase in power use. Further work is currently conducted to evaluate the causes of the data loss and to develop a WSN deployment method to reduce data loss percentage.
5.2 Network topology

Because of the layout of the sensors and the spaces of the relays was chosen to be conservative, there are many possible routes that individual data packet could take from the mote to the gateway. Fig. 11 shows the time history of the number of network patterns of health packet counted in one day.
day. The number of network pattern is between 50 and 200 for the London Underground WSN and between 400 and 700 for the Prague Metro WSN. The smaller number for the London WSN is due to a smaller network with less number of relay routes. For the Prague Metro WSN, it is interesting to note that the number decreased with time. The reason for this requires further investigation, but the decrease in battery power with time may have contributed to the removal of the network patterns that have long transmission distance.

As the sensor/relay spacing is conservative, relay motes are not always likely to be used, with some sensors being more likely to contact sensors closer to the gateway. The health packet from a mote has both a parent mote ID and a mote ID. From this information, it is possible to compute the probability of each link between motes. The probability of the link from mote \( i \) to mote \( j \) is introduced using the following equation

\[
P_{i\rightarrow j} = \frac{N_{i\rightarrow j}}{\sum_{k=1}^{n_i} N_{i\rightarrow k}}
\]

where \( P_{i\rightarrow j} \) is the possibility of the link from mote \( i \) to mote \( j \), \( N_{i\rightarrow j} \) is the number of health packets transmitted from mote \( i \) to mote \( j \), \( n_i \) is the total number of the motes which transmitted health packets to mote \( i \).

Fig. 12 shows all the communication links. The thick solid arrows are the links with a probability of above 50%, whereas the thin solid arrows are the links with a probability between 10% and 50%. The thin dotted arrows are the links with a probability below 10%; that is, there are many other links from these motes. Fig. 13 shows the most likely routes. Both figures illustrate that the communication between motes is quite busy and complicated. Both networks show that a large number of relay motes provides different possibilities for routing. In the case of the London Underground WSN, there is less number of relay motes and therefore some sensor motes are used for relaying the data. The sensor motes of the two rings located away from the gateway (Ring 1640 and Ring 1714 in Fig. 8) tend to send the data to one of the sensor motes and then the selected mote transmits the data to the gateway. It also appears that the present network protocol makes sensor motes to communicate directly to the gateway if possible, which may influence the data loss percentage when the communication distance is large. As shown in the Prague Metro WSN case, the data are hopped to the gateway only when sensor motes cannot communicate directly to the gateway.

The large number of changes does have the advantage that it helps even out the number of data packet individual sensor has to relay. If one sensor were to have to relay a large amount of data packets, its battery would go flat first. Hence, a more balanced network can go longer between battery changes. The optimisation of WSN network that provides redundancy and prolongs the lifetime requires further investigation (Hirai and Soga 2010).

5.3 Preliminary monitoring results

The WSN in the Prague Metro has not measured any movement of the tunnel lining. However, the results from the London Underground WSN do indicate movements of the tunnel lining, which will be discussed more in detail here.

The concrete lining ring at the London Underground WSN site consists of 20 segments plus 2 wedge blocks at knee level as shown in Fig. 14. The tunnel was constructed between 1973 and 1979 using conventional Greathead tunnelling shields. Most of the excavation was carried out
manually and by mechanical excavators in some cases. The tunnel lining construction was completed by first installing 168 mm thick concrete segments in position. They were then pushed by two wedge-key segments at knee level, and locked in compression against the ground.

Lyons (1979) reports that the major difficulty during the construction was the loss of ground above the shoulder level due to the low cohesion of the surrounding soil. As the Greathead shield method involves overcutting of the tunnel with the gaps filled by grout subsequently, it is likely that
the ring sections were not constructed within tolerance and therefore resulted in the ovalisation during the placement of the linings. The large manufacturing tolerances (±5 mm) of concrete segments at the radial joint as reported in Jobling (1980) is another probable reason of the poorly built tolerance of the tunnel ring.

Under the complex soil loading associated with variable geological conditions at the site (see Fig. 2), the large number of segments and joints makes the tunnel to behave in a very complicated manner. Furthermore, the possible spatial variation in construction quality can result in each ring behaving differently from the neighboring ones. For these reasons, performing a reliable engineering analysis for this tunnel section is considered to be difficult.
In order to assess the risk of lining movements, the tunnel maintenance contractor installed various instrumentation at joints (including this WSN system), which have already spalled or might be susceptible to spalling based on the surveyed joint orientations. In addition heavy steel strapping has been designed. If further monitored movements occur which are approaching a predetermined critical trigger level, it has been decided that the pre-fabricated strapping will be quickly installed.

The results for six months from ring 1714, the ring showing the largest movement, are shown in Fig. 15. The data shows the change in the readings from the sensors since they were installed. The position of the sensors is shown in Fig. 8. A positive trend on the crackmeters means that the crack / joint is opening / widening at the surface. A positive trend from the inclinometers indicates that the top of the inclinometer is moving away from the centre of the tunnel. The data from both the inclinometers and crackmeters is a good fit to a linear trend, but monitoring over a longer period will be required to check for annual fluctuations. Assuming a linear fit, the raw data from the inclinometers gives a standard error of 0.003°. The noise on the crackmeter is comparable with the resolution of the 10-bit ADC on the MicaZ (0.012 mm), so the readings appear ‘stepped’. However, the trend still appears to be good fit to a linear trend.
The movements for all the rings is summarised in Fig. 16 (Bennett et al. 2009). Some of the prototype inclinometers installed did not function properly and hence are represented by a cross. At present, it is difficult to determine the exact mechanism of tunnel movement from the readings taken to date. It is possible that the tunnel is tending to concertina or ‘squirm’. The data show that some rings such as No. 1661, 1689 and 1714 gradually squeezing along the vertical axis. In Ring 1640, on the other hand, the joint between segment F and G is behaving in the opposite direction compared to the other three rings. Based on the other instrumentation data (vibrating wire strain gauges and fibre optics distributed strain) (Bennett et al. 2009, Cheung et al. 2009), it is considered that complex behaviour of tunnel ling is observed due to the large number of segments per ring.

A denser array of monitoring points will be required to confirm the deformation mechanisms of these tunnel linings. One advantage of a WSN is that they can easily be expanded in areas of interest by simply attaching new modules. It is proposed to expand the WSN in the London Underground tunnel in the future by placing an inclinometer on every segment around a ring to gain a better understanding of the mechanisms involved.

6. Conclusions

This paper introduces some of the challenges involved with a WSN installation in an underground environment and shows how the design of a WSN can be adapted to suit the conditions. The case studies of two different field trials of WSN systems are described where the network design of the WSN was dictated by the constraints of the site.

In the Prague Metro where mains power and Internet access were available near one of the areas of interest, the main challenge was connecting together the two areas of interest using a series of relay nodes. In the London Underground, on the other hand, a lack of power and Internet connectivity
meant that the gateway had to be split into two pieces, one near the area of interest and one with access to power and the Internet, that were separated by hundreds of metres.

In both cases radio connectivity was potentially an issue that was averted by using the results of radio propagation testing to inform the network design. One of the key stumbling blocks in the way of commercial uptake of these systems is reliability. Several failures during the field trials have highlighted the need for robust systems.

A trial WSN installed in London Underground tunnel measured the response of four rings in an area where lining deformation has been occurring. The trends were found to be similar, even though the magnitudes differed as the sensors could not be collocated and the movement of the lining is complex with both radial and longitudinal rotations. The trial demonstrates the feasibility and advantages of wireless sensing in the underground environment, but further investigation is needed to evaluate its long-term performance.

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Design, calibration and application of wireless sensors for structural global and local monitoring of civil infrastructures

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Abstract. Structural Health Monitoring (SHM) gradually becomes a technique for ensuring the health and safety of civil infrastructures and is also an important approach for the research of the damage accumulation and disaster evolving characteristics of civil infrastructures. It is attracting prodigious research interests and the active development interests of scientists and engineers because a great number of civil infrastructures are planned and built every year in mainland China. In a SHM system the sheer number of accompanying wires, fiber optic cables, and other physical transmission medium is usually prohibitive, particularly for such structures as offshore platforms and long-span structures. Fortunately, with recent advances in technologies in sensing, wireless communication, and micro electro mechanical systems (MEMS), wireless sensor technique has been developing rapidly and is being used gradually in the SHM of civil engineering structures. In this paper, some recent advances in the research, development, and implementation of wireless sensors for the SHM of civil infrastructures in mainland China, especially in Dalian University of Technology (DUT) and Harbin Institute of Technology (HIT), are introduced. Firstly, a kind of wireless digital acceleration sensors for structural global monitoring is designed and validated in an offshore structure model. Secondly, wireless inclination sensor systems based on Frequency-hopping techniques are developed and applied successfully to swing monitoring of large-scale hook structures. Thirdly, wireless acquisition systems integrating with different sensing materials, such as Polyvinylidene Fluoride (PVDF), strain gauge, piezoresistive stress/strain sensors fabricated by using the nickel powder-filled cement-based composite, are proposed for structural local monitoring, and validating the characteristics of the above materials. Finally, solutions to the key problem of finite energy for wireless sensors networks are discussed, with future works also being introduced, for example, the wireless sensor networks powered by corrosion signal for corrosion monitoring and rapid diagnosis for large structures.

Keywords: wireless sensor network; structural health monitoring; civil infrastructure; energy optimization; wireless digital acceleration sensor; wireless inclination sensor; MEMS; PVDF; cement-based sensor.

1. Introduction

Civil engineering structures suffer from damages caused by environmental loads, fatigue, caustic effect and material aging, thus, their strength is reduced inevitably during their service time (Ou and Guan 1999). In order to assess these damages and make appropriate decisions to keep the structures in good service, it is essential to implement a damage detection strategy, this process is referred to as

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structural health monitoring, which is divided into global and local monitoring (Housner et al. 1997). One important element in a SHM system is the transmission of the measurement data from the sensors to the processing terminal, and wired networks are used for this task conventionally and most popularly. The wired sensors have many advantages: they transmit data with high fidelity, the products of wired sensors are mature, and they are inexpensive with a plenty of choices. However, with a great number of sensors for a large structure, a huge amount of wires is needed. As a result, installation time and costs can be very high, and this may also affect the reliability of the data transmission and increase the maintenance cost. Moreover, there may be cases in which wires cannot be placed in certain locations of a structure or even in the entire structure. Fortunately, with the development of technologies in sensing, wireless communication, and micro electro mechanical systems (MEMS), wireless sensor network technique has been developing rapidly, and is being used gradually in SHM for civil engineering structures for reducing the high capital costs associated with wire-based structural monitoring systems (Spencer 2003a).

Some of the first efforts in developing wireless sensors for applications to civil infrastructures were presented by Straser and Kiremidjian (1996) and Straser et al. (1998). Based on the above work, Lynch et al. demonstrated a proof-of-concept wireless sensor that uses standard integrated circuit components, and the sensor unit has been validated through various experiments in the laboratory (Lynch et al. 2001, 2003). Maser et al. (2003) proposed the Wireless Global Bridge Evaluation and Monitoring System to monitor the condition and performance of bridges remotely. Brooks (1999) emphasized the necessity of migrating some of the computational processing to the sensor board, calling them “Fourth-generation sensors”. Mitchell et al. (1999) presented a wireless data acquisition system for health monitoring of smart structures, and Mitchell et al. (1999) continued this work to extend cellular communication between the central cluster and the web server, allowing web-control of the network. Liu et al. (2001) presented a wireless sensor system that includes five monitoring stations. Ou and Li (2003) presented a wireless sensor network for the health monitoring of offshore platforms, and developed a laboratory prototype to demonstrate the feasibility of the proposed network. Yu et al. (2004), Shiraishi et al. (2005) and Glaser et al. (2007) presented more models of wireless sensor networks. Moreover, in 2000, the “Smart Dust” project was funded by the US Defence Advanced Research Projects Agency (DARPA). In this project, the ultimate goal was to develop a low-cost, small, and highly reliable wireless sensing system (Spencer 2003b). Now this system is now widely being used in theoretical research and practical applications.

In this paper, some recent advances in research, development and implementation of wireless sensors for the SHM of civil infrastructures in DUT and HIT in mainland China, are introduced. The main contents include wireless digital acceleration sensors for structural global monitoring; wireless inclination sensors systems based on Frequency-Hopping; wireless acquisition systems with different sensing material proposed for structural local monitoring.

2. Wireless digital acceleration sensors for structural global monitoring

2.1 Design of wireless digital acceleration sensor

On the basis of existing MEMS and embedded techniques, a wireless digital acceleration sensor is constructed by integrating several modules that include: a detection unit, a microprocessor unit, a wireless transceiver and a power unit.
The detection unit consists of an accelerometer and a temperature meter. For the first, a good choice is the ADXL202, a low-cost, low-power, and complete 2-axis accelerometer. It has a surface micromachined polysilicon structure built on top of a silicon wafer. A pin is available on each channel to allow the user to set the signal bandwidth of the device by adding a capacitor. This filtering improves the measurement resolution and helps to prevent aliasing. After being low-pass filtered, the analog signal is converted to a duty cycle modulated (DCM) signal, which can be decoded with a counter/timer or with a low-cost microcontroller. The DCM period is shown in Fig. 1, where T1 is Length of the “on” portion of the cycle and T2 is length of the total cycle.

The acceleration can then be determined by

\[
a = \frac{T_1}{T_2} - \frac{u_{0g}}{u_{1g}} = \frac{T_1 - T_{10g}}{T_{1g}}
\]

where

\[
u_{0g} = \frac{T_{10g}}{T_2}, \quad u_{1g} = \frac{T_{1g}}{T_2}
\]

and \(T_1\) is the measured value of the DCM output, \(T_{10g}\) is the DCM output at zero acceleration, \(T_{1g}\) is the DCM output at 1g acceleration, and \(T_2\) is the period of the DCM output. Although the typical value for \(u_{0g}\) is 0.5 and the one for \(u_{1g}\) is 0.125, both \(T_{10g}\) and \(T_{1g}\) are required to be calibrated according to the temperature before application. For \(T_{10g}\) and \(T_{1g}\) in Eq. (1), the theoretical values can be found from the specifications of the ADXL202 product. However, these values are temperature dependent, and must be revised based on a table stored in E²PROM of the microprocessor. According to the measured temperature, \(T_{10g}\) and \(T_{1g}\) are selected from the table, and then the acceleration value can be obtained from Eq. (1) based on the measured \(T_1\). Since most civil engineering structures have low natural frequencies, a bandwidth of 50 Hz will be sufficient for measuring their dynamic responses in practical applications. The noise level is 1.8 mg which is usually much lower than the amplitude of the signals. \(T_2\) is designed to be 1 ms, i.e., the DCM frequency is 1000 Hz. This will meet the requirement that the frequencies of the analog signals are less than 1/10 of the DCM frequency.

For the temperature meter, the TC1047 chip with low power consumption and a low power voltage between 2.7 V and 4.4 V is used. One advantage of the TC1047 is its linear relationship between the voltage output and the measured temperature. The typical slope of the voltage output vs. the temperature is 10 mV/°C, and the temperature measurement ranges from -40 °C to +125 °C. The TC1047 is in a small 3-Pin SOT-23B package, making it an ideal choice for space critical applications.

The microprocessor unit used in this design is the Atmega8l chip, which integrates a large storage memory and interface circuits. As a microprocessor with low cost, the chip adopts a small pin package. Its main features are as follows: 8 bit high performance, low cost AVR micro-controller with advanced RISC simplified instruction aggregation structure, a number of powerful external interface circuits, and five sleep modes including idle, ADC noise reduction, power-save, power-down and standby. As a processing unit for the wireless sensor, the Atmega8l could gather, pre-process the analog and digital output from the detection unit. And it could also exchange data with the wireless transceiver.
Wireless transceiver is used to transmit data collected by sensors to base station. In this research, wireless transceiver is developed on the basis of CC1020 radio frequency chip produced by Texas Instrument Corporation, which is a true single-chip ultra RF transceiver with high frequency and low power. The CC1020 circuit is mainly intended for the ISM(Industrial, Scientific and Medical) and Short Range Device frequency bands. Besides, CC1020 data rate is up to 153.6 kBaud. The CC1020 wireless transceiver is steady and its transmission distance is up to 500 meters.

For a wireless sensor, energy is usually provided through solar power (Kohvakka et al. 2003), structural vibration (Scott et al. 2001), chemical batteries or lithium batteries. In the present design, lithium batteries with charge circuits are used, taking into account their small volume and relatively long service time. The above units are integrated into a wireless digital acceleration sensor node. In addition to measuring the acceleration and the temperature, the wireless sensor also sets a limit for the acceleration and performs the alarm function using a buzzer. A computer connected with a wireless transceiver is a base station. The wireless digital sensor node is shown in Fig. 2, the wireless transceiver is in the upside of the node, and the detection unit and microprocessor unit are integrated into a printed circuit board which is put under the node.

The lithium battery used in the design has the specifications of 900 mAh and 3.6 V. It supplies power to the entire wireless sensor node. The current in the wireless sensor is 14.7 mA while it is collecting and transmitting data, and the sensor node could work for about 61 hours in this mode. When a wireless sensor is idle, its current is 152.5 μA, and the battery life is as long as about 246 days.

2.2 Calibration

The acceleration of the designed wireless digital sensor was tested using the device shown in Fig. 3. It is a servo-mechanism system consisting of an electromotor and a track for movement. The electromotor may move on the track back and forth to produce a periodic acceleration wave. In the test, the electromotor moves periodically with a frequency of 1 Hz.

A wireless sensor is put on the electromotor to measure the acceleration. For comparison purposes, a wired sensor is used as the reference sensor. The time histories of the reference and measured acceleration waves are depicted in Fig. 4. There exist minor differences because the wireless sensor with no encapsulation is possibly disturbed and its sample rate is low, but they match well generally. Fig. 5(a) and (b) show the power spectral density of the two acceleration processes, respectively. The peak frequency of the measured acceleration is 0.9825 Hz, while that of the reference acceleration is 0.9985 Hz. Such a small difference meets the requirement for the
2.3 Application: wireless sensors experimental system for ice-induced vibration monitoring of an offshore platform model

The wireless sensor test is finished on the offshore platform model of Bo Sea JZ20-2MUQ. The scale factor between the experimental model and the true offshore platform is 1/10. The model and its actual dimension are presented in Fig. 6. A wireless sensing test is performed to monitor the vibration of this model in different push ice and bend ice, with two wireless sensor nodes put respectively on the elevation height locations of 2.5 meters (node 1) and 2.85 (node 2) meters of this model. Wired acceleration sensors are also put in the corresponding place. The location of the ice loading is selected at the elevation height of 0.4 meters relative to the ground, which means that the location is corresponding to the ice loading of the practical offshore platform.
Two wireless sensor nodes and a base station composed of a wireless sensor network used for the structural health monitoring of offshore platform. The time histories and the power spectral density of the two wireless acceleration sensors and corresponding wired sensors are depicted in Fig. 7. Although minor differences are present in time histories, they agree relatively well. For the power spectral density: for Figs. 7(a) and (b), the peak frequency of the measured acceleration is 3.0127 Hz, while that of the reference acceleration is 3.1154 Hz; for Figs. 7(c) and (d), the peak frequency of the measured acceleration is 3.0064 Hz, while that of the reference acceleration is 3.1299 Hz.

3. Wireless inclination sensors systems based on frequency hopping technique for swing monitoring of large-scale hook structures

Large Scale Heavy Derrick Lay Barge is very important for sea work. Under intense wind and wave load, the hook on the barge will vibrate so large that it can not function in some cases. Through installing the Tuned Mass Damper (TMD) on the hook, the vibration will be reduced to an acceptable range to meet the demand on sea work, which is also important for increasing the efficiency of the sea work (Ou et al. 2006). To design the suitable TMD for the hook, the dynamical parameters should be specified beforehand, the related dynamical parameters such as the inclination and the acceleration are measured by wired sensors. However, due to the restrictions of the reality, the wired sensors are very hard to implement. Thus, wireless sensors have been presented to overcome the shortcomings of these wired ones. It is more suitable and also more convenient to utilize wireless sensors to acquire the useful data of large scale heavy derrick lay barge.

3.1 Wireless inclination sensors systems structure

Frequency-Hopping is one of the basic modulation techniques in wireless communication. It changes
Fig. 7 Graphics of acceleration collected by wireless and wired sensors network in an operating mode
carried frequency through and through for reliable signals transmission. The rate of Frequency-Hopping reflects the performance of the system: the faster Frequency-Hopping is, the better the performance we can get. The rate is up to ten thousands times a second in military communication, while the rate is about 50 times a second for commercial communication. Low rate wireless local area networks adopt slow Frequency-Hopping because of its easy implementation. Based on this idea, wireless inclination sensors systems with multi-frequency channels are proposed. Every wireless sensor has different communication channels, and base station have multiple communication channels covered with the wireless sensors’ ones. In this way, the base station can communicate with all nodes in separate channels using simple protocol.

Using recent developments in existing MEMS and wireless communication, the data transmission structure of wireless inclination sensors systems is as follow (Yu et al. 2009). The inclination data sensed by inclinometer MEMS chip is processed and transformed into serial data. Using the wireless communication module with a single special frequency channel, the serial data is transmitted to a wireless base station with multi-frequency channels. The status of the structure can be estimated by the method of diagnosis arithmetic based on the collected data.

3.2 Wireless inclination sensor

In this system, the wireless inclination sensor is integrated using a sensing disposal unit, a wireless communication unit and a power unit. A sensing disposal unit, consisting of an inclinometer chip and micro-processing unit circuits, can measure the swing and transform these data into a serial form for future transmission. The SCA100T chip, which is low-cost, low-power chip with 3D-MEMS-based dual axis, is selected in this design for swing monitoring. And the temperature compensation using the internal temperature sensor makes the inclination measure more precise. Connected with SPI of SCTA100T, the micro-processing unit can read and pre-process the inclination data, then transmit the data to wireless transceiver by using the RS485 signal format. In the present design, two groups of lithium batteries with charge circuits are being used as power units, taking into account their small volume and relatively long service time. One of the batteries outputs 5 V for wireless communication unit while the other one outputs 12 V for the sensing disposal unit. The integrated wireless inclination sensor and the base station are shown in Fig. 8. The sensing disposal unit and the power unit are put under the designed box. A wireless communication unit is deployed with a high-gain antenna outside the box to transmit data for farther distance.

3.3 Calibration

The calibration experiment is performed in a pendular experimental equipment shown in Fig. 9(a).
The wireless inclination sensor is put in the structure and a laser displacement sensor is used for measuring the structures’ displacement as a reference. For the laser displacement sensor, the relation between measuring displacement $\Delta$ and real swing angle $L$ is expressed in the following Eq. (3)

$$\sin \alpha = \frac{\Delta}{L}$$  \hspace{1cm} (3)

where $L$ is pendulum length. In this experiment, the pendulum length is about 91.97 cm, the pendular cycle is 1.9055s, and the wireless measure data and laser sensor’s angle are acquired by the designed data acquisition system. The experimental results are shown in Fig. 9(b). The maximal error is about 1% by analysis for the wireless inclination sensor while the laser sensor is used as a reference, this may meet the swing monitoring requirements. The wireless sensor node’s measuring range is $\pm 30^\circ$, and the frequency response is more than 20 Hz.

### 3.4 Application: wireless acquisition system experiment for swing monitoring of large scale Heavy Derrick Lay Barge’s hook model

As an ocean engineering boat, Lanjiang Heavy Derrick Lay Barge with main and assistant hooks has the strongest lifting capacity in Asia and can lay pipes in the seabed (shown in Fig. 10). Its sea work ability is the first in Asia and the sixth in the world. It can work at 150 meters below water and it can
also lift up to 3800 tons. However, the hook on the barge vibrates seriously in the case of intense wind and wave load. Sometimes it even fails to function properly and causes great economic lost. Thus, the hooks’ swing must be monitored with a wireless inclination sensor system and controlled by the dampers. On the basis of practical applications, an innovative gear-pendulum-type TMD control system is proposed. This system is more robust than the single pendulum TMD control system, as it avoids the requirement that the length of the pendulum TMD and the control system must be the same.

To validate the proposed TMD system, we used wireless inclination sensor to monitor the swing of the hooks with control and without control. The bridge crane with a lifting capacity of 10 tons is reconstructed into hook model. The scale factor between the experimental model and the true hook is 1:4, the scale factor of mass is 1:64, the scale factor of time is 1:2 and the scale factor of inclination and acceleration is 1:1. The designed control system is loaded on the hook model to control the swing angle of hook. The hook is influenced by the loads of wind, ocean wave at the lowest level. The wireless inclination sensors are also put on the model to monitor the swing. The actual hook structural model and their experimental system are shown in Fig. 11.

In this experiment, inclination of the model is gathered by wireless sensors in the status of with-control and without-control. Fig. 12 shows a continuous test of wireless inclination data: in the same working condition, the structural damp with control is larger than the one without control and the swing range is less. This shows the control effect of the control module.
4. Development of wireless sensor nodes based on different sensing materials for structural local monitoring

Base on the above idea of a wireless inclination sensor system, wireless acquisition systems of some sensing materials sensors (as shown in Fig. 13) are designed for structural local monitoring. The Modulation circuit of this system, which changes signals of sensing material into a standard voltage signal, is different from various kinds of sensors. The processing unit with the A/D function adopts atmega8l, and wireless communication module is based on CC1020 chip.

4.1 Analysis of PVDF's characteristics using wireless acquisition system

In recent decades, piezoelectric materials and devices are widely used in many technical areas (Kang et al. 1996). Among various piezoelectric polymers, PVDF film is well known for the advantages of good flexibility, strong corrosion resistance, low density, a few microns’ minimum thickness, and a high piezoelectric voltage constant with small disturbance to the performance of the monitoring structure. By means of piezoelectric characteristics, PVDF film can be applied to shape control, vibration control and active damper fields in the flexible structure. Moreover, PVDF film shows excellent properties in the transmission of strain, acceleration and force parameters, with a relatively simple signal processing system and is easy to implement. Therefore, the sensing properties of PVDF have gradually attracted more attention (Ju et al. 2004). However, PVDF and its frequency response analysis used in the structural monitoring field are still at the exploratory stage, and can not form a complete and mature system for structural monitoring. Based on this, analysis of PVDF’s characteristics used in civil strain monitoring and research of wired/wireless acquisition system are given as follows.

4.1.1 Development of measurement circuit module

Using PVDF’s piezoelectric effect, strain measurement can be carried out. However, charge signals must be converted into voltage signals through charge amplifier. The PVDF sensing module is
designed for enlarging the change of PVDF charge, mainly made up of two operational amplifiers. The wireless acquisition module is shown in Fig. 14, the standard voltage signal is input into A/D interface, and then is collected and pre-processed by micro-processing unit for further wireless transmission.

4.1.2 Experimental system and project
The structure of the experimental system is shown in Fig. 15(a). The Agilent 33220 Digital Synthesis Function Generator is used to generate sinusoidal signals. The JZK-10 is a modal vibration exciter driven by power amplifier YE5872A for signal amplification, so that the beam with a constant strength begins to deform. PVDF sensor and resistance strain gauge are attached on the beam in the experimental system. Measured signals of beam deformation are converted into voltage signals and amplified respectively by the charge amplifier YE5850 and dynamic strain indicator YE3835. Then the amplified voltage signals are transmitted to the computer PC in wired or wireless mode to realize real-time data display, storage and analysis. Sensors layout is shown in Fig. 15(b).

As shown in the arrangement of sensors, the direction along the beam is known as the PVDF-0 and resistance strain gauge-0, while the direction perpendicular to the beam is known as PVDF-90 and resistance strain gauge-90. By using a number of sensors, vibration exciter loading tests on the beam were carried out to complete the following projects: comparing the response characteristics of the PVDF-0 and the resistance strain gauge-0; comparing the PVDF-0 and PVDF-90 to study the tensile direction of PVDF; analyzing the frequency characteristics of PVDF and resistance strain gauge, and exploring the appropriate strain measuring range of the PVDF and the resistance strain gauge.

4.1.3 Characteristics analysis

4.1.3.1 Vibration detection using PVDF-0 and the resistance strain gauge-0
As shown in Fig. 16, in the same frequency, the output of PVDF film and resistance strain gauge show a linear relationship with the growth of drive signal. The actual measurement of PVDF film with the theoretical values calculated is shown in Fig. 17. The two curves show the same trend, but the measured value is smaller than the theoretical value as the actual leakage of charge.

4.1.3.2 The effect of the tensile direction of PVDF film to the measurement
Through loading drive of different amplitude on the beam, Fig. 18 uses the resistance strain gauge as

---

**Fig. 15 Experimental facilities**
4.1.3.3 Sensitivity experiment of PVDF

To analyze and study the dynamic response of PVDF film, response signals of two sensors are collected in different frequencies. Through the processing of acquired signals, the dynamic sensitivity of PVDF sensors is calculated. PVDF's strain sensitivity is defined as the ratio of output voltage change caused by the strain change

\[ S = \frac{\Delta V}{\Delta \varepsilon} \]  

(4)

where \( S \) is strain sensitivity, \( \Delta V \) is voltage change, \( \Delta \varepsilon \) is strain change. Under different excitation frequency (0.1 Hz-40 Hz), the amplitude-frequency characteristic curve of PVDF film is shown in Fig.
19. The sensitivity is low under 0.5 Hz, but relatively stable around 0.5 Hz. PVDF film has high signal sensitivity during the dynamic strain measurement, and the higher the frequency, the more stable the performance of collecting strain.

4.2 Experiment of wireless strain sensor system on a typical concrete beam structure

While using the strain gauge as a sensor and the bridge circuit as a modulation circuit (Yu and Ou 2009), there are mainly the circuits of amplification and filtering. As micro-changing signals are sampled in amplification, the instrument amplifier AD623 is selected. The two steps of Butterworth circuits are used for a filtering circuit. The signals of the civil engineering structures belong to low frequency ones, so the bandwidth within 20 Hz can already meet the requirement. Using the above modulation circuit, the change of the strain gauge could be output by a standard voltage signal.

The experiment of the wireless strain sensor system is finished on a typical concrete beam structure shown in Fig. 20. The strain gauge is affixed on a concrete beam, which could change regularly while the beam is loaded in rule. Furthermore, the change could be collected, disposed and transmitted wirelessly. In this test, the beam is loaded gradually up to the rate of 1000 kg. The measured data processed by using the data fusion method and the arithmetic average value method is compared and analyzed. In Fig. 21, results show that the wireless strain sensor can be installed easily and applied compatibly to local monitoring in civil engineering. The strain signal processed by the data fusion method is more accurate than the one processed by the arithmetic average value method. Thus, the proposed data fusion method is suitable for processing such slowly-changing signals as strain.
4.3 Wireless stress/strain measurement system integrating with nickel powder-filled cement-based composite sensor

A wireless stress/strain measurement system, shown in Fig. 22 (Han et al. 2008), is developed by integrating pressure-sensitive sensors for the health monitoring of concrete structures. The pressure-sensitive stress/strain sensors are fabricated by using nickel powder-filled cement-based composite and modulation circuits which adopt the direct-current four-electrode method to measure the fractional
change in electrical resistivity (i.e., the output signal) of the piezoresistive nickel powder-filled cement-based stress/strain sensors (Han et al. 2007, Ou and Han 2009).

The wireless stress/strain measurement system integrated with these sensors is tested with compressive stress/strain in the range from 0 MPa/0 με to 2.5 MPa/311.5 με for performance evaluation. Experimental results in Fig. 23 indicate that the electrical resistivity of pressure-sensitive nickel powder-filled cement-based stress/strain sensors decreases linearly and reversibly with the compressive stress/strain, and its fractional change goes up to 42.719% under uniaxial compression. The relationship between the input (compressive stress/strain) and the output (the fractional change in electrical resistivity) of the wireless stress/strain measurement system integrated with pressure-sensitive sensors is \( \Delta \rho = \frac{-0.16894 \sigma}{\Delta \rho} = -1336.5 \epsilon \). The wireless stress/strain measurement system can be used to achieve a sensitivity of stress/strain of 16.894% MPa\(^{-1}\)/0.13365%με\(^{-1}\) (a gauge factor of 1336.5) and a stress/strain resolution of 150 Pa/0.02 με. The newly developed wireless stress/strain measurement system integrated with pressure-sensitive nickel powder-filled cement-based sensors has such advantages as high sensitivity to stress/strain, high stress/strain resolution, simple circuit and low energy consumption.

5. Discussion and future works

5.1 Energy optimization

Due to the essence of the wireless sensing system, an external power connected by wires will not be used to supply the energy. Thus, it becomes an important issue to optimize the energy and reduce its consumption in wireless sensing technology. The problem of energy consumed is discussed from the point of node and network.

1. For a node, the strategies of hardware, software, their cooperation are brought forward. For hardware of a wireless sensor node: Electronic components with low power consumption and high reliability are selected to integrate a wireless node, which reduces the overall power consumption and requires an energy source with high capacity. Regarding embedded software, it is known that a factor which plays an important role in the energy consumption is the volume of the transmitted data. The larger the volume is transmitted, the more energy is required. In this design, the data collected by the sensors are processed first, and only those describing the essential characteristics of the measured data are kept. This data are then packed and transmitted to the base station. In this way, the transmitted data volume is substantially reduced and energy is saved. To summary, saving power is accomplished by the cooperation between hardware and software.

2. For the overall network, good algorithms with MAC and routing protocol are necessary for saving power. For example, in the time-sharing TDMA communication between the base station and the sensor nodes, only one sensor node is working at a time. The other sensor nodes are in idle, power-save, power-down or standby mode. In this way, the microprocessor and wireless transceiver in the working sensor becomes the main consumer of energy. The energy consumption of the overall network is reduced. In addition, an innovative method of Power Saving Ant Colony Optimization based on powers is presented and simulated in paper (Yu 2006), and the research shows that the above saving energy strategies can extend the work life of wireless sensor network.
5.2 Future works

The authors are trying to develop a kind of wireless array acceleration sensors with quick deployment and super low frequency sensing unit to monitor the vibration characteristic of offshore platform in deep sea so that the damage can be detected and repaired quickly. The authors are also designing a kind of wireless self-power corrosion monitoring system in concrete. All the components are embedded in monitored structure. Corrosion produces not only sensor signal but also charge power stored in a special capacitor, which means that wireless self-power corrosion monitoring system works while there is corrosion in concrete.

6. Conclusions

Some recent advances in research, development and implementation of wireless sensors networks for SHM of civil infrastructures are introduced. The following conclusions can be drawn:

(a) The wireless digital acceleration sensor may calibrate acceleration by itself according to the measured temperature to receive more accurate values, and the designed wireless sensor can measure the acceleration of a structure well.

(b) Wireless inclination sensors systems based on Frequency-Hopping can overcome the monitoring errors of unaided eyes without affecting the normal work of the monitored objective. Further experiment validates the effect of the proposed TMD control device.

(c) The proposed wireless acquisition systems of some sensing materials are used easily for the analysis of the characteristics of these materials for structural local monitoring.

(d) The problem of energy consummation is discussed from the point of node and network. In order to finish energy optimization, the wireless sensor can pre-process and pack the measured data to reduce the data volume to be transmitted. Its micro-processing unit can choose between the working mode and different sleeping modes. And the routing algorithm is very important for energy conservation.

In general, the wireless sensors designed for structural global and local monitoring of civil engineering structures are feasible. The design is preliminary and the improvement is necessary. More importantly, more tests and practical use need to be carried out.

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Multi-scale wireless sensor node for health monitoring of civil infrastructure and mechanical systems

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Abstract. This paper presents recent developments in an extremely compact, wireless impedance sensor node (the WID3, Wireless Impedance Device) for use in high-frequency impedance-based structural health monitoring (SHM), sensor diagnostics and validation, and low-frequency (< ~1 kHz) vibration data acquisition. The WID3 is equipped with an impedance chip that can resolve measurements up to 100 kHz, a frequency range ideal for many SHM applications. An integrated set of multiplexers allows the end user to monitor seven piezoelectric sensors from a single sensor node. The WID3 combines on-board processing using a microcontroller, data storage using flash memory, wireless communications capabilities, and a series of internal and external triggering options into a single package to realize a truly comprehensive, self-contained wireless active-sensor node for SHM applications. Furthermore, we recently extended the capability of this device by implementing low-frequency analog-to-digital and digital-to-analog converters so that the same device can measure structural vibration data. The compact sensor node collects relatively low-frequency acceleration measurements to estimate natural frequencies and operational deflection shapes, as well as relatively high-frequency impedance measurements to detect structural damage. Experimental results with application to SHM, sensor diagnostics and low-frequency vibration data acquisition are presented.

Keywords: structural health monitoring; impedance method; piezoelectric active-sensors; sensor diagnostics; wireless hardware.

1. Introduction

Structural health monitoring (SHM) is the process of detecting damage in structures. The goal of SHM is to improve the safety and reliability of aerospace, civil and mechanical infrastructure by detecting damage before it reaches a critical state. To achieve this goal, technology is being developed to replace qualitative visual inspection and time-based maintenance procedures with more quantifiable and automated damage assessment processes. These processes are implemented using both hardware and software with the intent of achieving more cost-effective condition-based maintenance. A more detailed general discussion of SHM can be found in Worden and Dulieu-Barton (2004).

The implementation of SHM is an integrated paradigm of networked sensing and actuation, data interrogation (signal processing and feature extraction), and statistical assessment (classification of

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damage existence, location and/or type) that treats structural health assessments in a systematic way. An appropriate sensor network is always required as a first line of attack in observing the structural system behavior in such a way that suitable signal processing and damage-sensitive feature extraction on the measured data may be performed efficiently.

A specific topic that has not been extensively addressed in the SHM literature is the development of rigorous approaches to designing the data acquisition portion of SHM sensing system. To date, almost all such system designs are done somewhat in an *ad hoc* manner where the engineer picks a sensing system that is readily available and with which they are familiar, and then attempts to demonstrate that a specific type of damage can be detected with that system. In many cases, this approach has been shown to be ineffective. As a result, researchers have begun to develop sensor networks suited for SHM objectives. Because the cost of implementing a vast network of sensors using traditional wired systems can become prohibitively high, there has been a recent shift toward the use of wireless sensor nodes, which are well-summarized by Spencer *et al.* (2004) and Lynch and Loh (2006). Advances in wireless communications and low power electronics have enabled the development of power efficient, compact sensor nodes for SHM and other engineering applications.

This paper presents an overview of a wireless sensor node specifically designed for structural health monitoring and sensor diagnostics in both a relatively high frequency regime, wherein the impedance method is typically used, as well as a relatively low-frequency regime, wherein traditional sensing methods such as modal analysis and time-domain identification methods are used.

### 2. Hardware design and capabilities

The wireless impedance device (WID) was originally developed based on capabilities demonstrated in previous studies of the impedance-based structural health monitoring method (Park *et al.* 2003, Park *et al.* 2006c, Bhalla and Soh 2004, Giurgiutiu *et al.* 2004). The basic concept of the impedance method is to use high-frequency (tens to hundreds of kHz) vibrations to monitor the local area of a structure for changes in structural impedance that would indicate damage or imminent damage. This process is possible using piezoelectric sensor/actuators whose electrical impedance is directly related to the structure’s mechanical impedance through bonding. This electromechanical coupling is exploited to detect how changing mechanical system parameters that may correlate with damage, such as resonant frequencies or modal damping, reflect in measurable voltage potentials in the bonded sensor. Another critical aspect of the impedance method is that it can be implemented with relatively low power, compared to other active-sensing SHM techniques such as Lamb wave-based methods. The hardware required for implementing Lamb wave propagations needs much higher sampling rates and higher peak-power capabilities, compared to that of impedance methods. The impedance method also has applications in sensor self-diagnostics in determining the operational status of piezoelectric active-sensors used in SHM (Park *et al.* 2006a, 2006b, Park *et al.* 2009b, Overly *et al.* 2009).

In the past, several research efforts have focused on the development of wireless sensor nodes that capitalize on the capability of the impedance method. Grisso and Inman (2008) developed a stand-alone prototype of active-sensing unit, incorporating impedance data acquisition, local-computation, wireless communication of the results and a renewable power supply via several different types of energy harvesting techniques. This prototype has been substantially improved by Kim *et al.* (2009) and Zhou *et al.* (2009). This new prototype eliminates the use of a digital-to-analog converter which
requires a large memory space and power consumption, allowing for extremely low-power operation (<18 mW). Wang and You (2008) also introduced a new circuit implementation for electrical impedance monitoring coupled with the use of wireless telemetry.

The core component of WID is the Analog Devices AD5933 impedance chip, which is capable of resolving impedance measurements up to 100 kHz. The use of AD5933 for measuring impedance signatures for SHM is firstly proposed by the authors (Mascarenas et al. 2006), and substantially investigated producing several versions of snap-on hardware with experimental validation. (Mascarenas et al. 2007, Overly et al. 2008, Taylor et al. 2009). By following the similar concept, several different prototypes were also produced by other researchers using the AD5933 chip (Park et al. 2009a, Kim et al. 2010).

The first generations of the WID, the WID 1.5 and 2.0, developed by our research team (Mascarenas et al. 2007, Overly et al. 2008) are shown in Fig. 1 (left), along with the current version WID 3.0. The WID 2.0 was developed to address some of the limitations of the WID 1.5, including the ability to monitor only a single active-sensor, limited triggering capabilities, and the high power demands of the wireless telemetry components. The WID 3.0 provides further increased capabilities over the previous generations, with advanced communication capabilities, increased triggering options, more data storage capabilities, as well as multiple power options coupled with a power conditioning component that allows the use with a variety of energy harvesting options. The WID 3.0 can self-configure into a network with neighboring sensor nodes at fixed time intervals or in the presence of a ‘mobile host’ that is brought in to interrogate the sensor network. The WID 3.0 has been designed to operate using multiple power options, including the ability to store energy harvested from the environment and/or energy received through radio frequency (RF) energy transmission.

In addition to improving the capabilities and functionality of the previous WID versions, the WID 3.0 has been designed to function as part of a modular hardware platform that incorporates other sensing capabilities on separate boards, such as time-domain measurement capabilities. By combining modules, resources such as the telemetry, processing, data storage and respective measurement capabilities of each module may be shared, resulting in a highly functional sensor node. One such configuration is shown in Fig. 1 (right), where the WID3 has been combined with the Wireless Data Acquisition (WiDAQ) board. This integrated sensor node combines both actuation and sensing capabilities into a single package with the ability to implement multiple SHM techniques for the rapid health assessment of civil, aerospace and mechanical infrastructure.
2.1 WID 3.0 hardware and capabilities

The major hardware components of the WID 3.0 are shown in Fig. 2. Like the previous generations, the WID 3.0 is controlled by an ATmega1281v microcontroller. The WID 3.0 uses a ZigBit module which integrates the ATmega1281v microprocessor with Atmel’s AT86RF230 transceiver module within a single compact package. The microcontroller itself is manufactured by Atmel and is part of their 8-bit AVR line. This microcontroller contains 128 kB of program memory allowing for complex and robust algorithms to be loaded on the chip. It also contains 8 kB of memory for computational requirements. The ATmega1281 comes from a line of microprocessors that have available to them a large open source development community. Atmel is developing future versions with enhanced capabilities, which include more memory and EEPROM, while maintaining the same form factor that would allow for pin compatibility. These features would help with applications and expansion of capabilities in future versions of the WID. The wireless data transmission solution is also produced by Atmel and integrated within the ZigBit module. This solution is an 802.15.4 compliant radio, which uses an open MAC protocol distributed by ZigBit. The availability of the MAC table facilitates programming to the wireless standard for robust data transmission. The AT86RF230 has very low energy requirements and low external component counts, making it particularly attractive for an SHM device.

The key measurement component of the WID systems is the AD5933, an integrated circuit (IC) for impedance measurements. This IC has the ability to measure electrical impedance up to 100 kHz and was chosen because it lowers the total power requirements and chip count of the WID. It has many functions built in that would ordinarily require several additional components, including a signal generator, high-speed analog-to-digital converter (ADC), fast Fourier transform (FFT) analyzer, high-speed digital-to-analog converter (DAC), and anti-aliasing filter.

There are two main options for data storage on the WID 3.0: (1) internal EEPROM that is on the ATmega1281v, and (2) a flash memory module, the Atmel AT26F004. The data storage available in these locations is 8 kB and 500 kB, respectively. This amount is not a vast quantity of storage, but it is sufficient for the type of measurements being made. The measured data are in the frequency domain, and therefore of much smaller size compared to the time series data of other methods. If the data is analyzed before storage, for example with a root mean standard deviation or cross-correlation coefficient, features typically used in impedance methods, and only the analyzed data is stored, the internal EEPROM and flash modules would be able to contain 4000 and 500,000 data points of double precision floating point numbers.

![Fig. 2 Major components of the WID3](image-url)
The previous version of the WID (Mascarenas et al. 2007) had the ability to measure only a single sensor, and it also required manual selection of the bypass resistor for range selection. Both of these shortcomings have been addressed with the current WID 3.0 with the addition of two low-power and low-resistance multiplexers, which are shown in Fig. 2. Each multiplexer has eight total inputs, which allows for four resistor ranges and seven sensors to be measured. One of the sensor ports is required for a calibration cycle, which reduces the available sensors from eight to seven.

The WID 3.0 has very low power consumption, especially considering the active nature of its measurements. The WID 3.0 operates at as low as 2.7 V, and it requires 16 seconds to measure four sensors with 100 points and four averages per point. With data reduction, only a few seconds would be required to transmit the data off of the WID to base station, or a few microseconds to store the data on the onboard locations. Initial testing indicates that the current draw could be reduced to approximately 0.01 mA with proper use of sleep modes. At this extremely low power level, the WID could also be powered by a wide range of energy harvesting methods. The current draw of various electronic components is shown in Table 1. The voltage supply for WID3 is designed to provide 2.7 V.

The WID 3.0 can be awakened from sleep states in several ways depending on the capabilities required. The WID3 includes a low frequency (LF) wake-up chip that monitors an inductor low-frequency RF wake-up signal. This monitoring occurs at very low power (0.28 μW), but at limited range of only 2.5 m. This chip is indicated in Fig. 2, and the inductor coil located above the AD5993 impedance chip. This wake-up capability would be used for on-demand measurements wirelessly triggered by a mobile base station capable of recording the measurements. The second option is an internal timer in the ATmega1281v that can wake the WID3 at intervals on the order of a few seconds to a few weeks. With these solutions available it is conceivable that the WID could run in low-duty cycle operation for decades on a limited power supply. The table below summarizes the power consumption for various modes of operation, and compares these values to those for the

<table>
<thead>
<tr>
<th>Mode</th>
<th>WID3</th>
<th>WID2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement</td>
<td>55</td>
<td>56</td>
</tr>
<tr>
<td>Transmit</td>
<td>70.5</td>
<td>61.6</td>
</tr>
<tr>
<td>Receive</td>
<td>67.5</td>
<td>N/A</td>
</tr>
<tr>
<td>Store</td>
<td>42</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 1 Current draw for the WID 3 components

<table>
<thead>
<tr>
<th>Component</th>
<th>Current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microcontroller ATmega1281</td>
<td>7</td>
</tr>
<tr>
<td>Telemetry chip (3 dBm) AT86RF230</td>
<td>15.5/16.5 (RX TX)</td>
</tr>
<tr>
<td>Impedance chip AD5933</td>
<td>10</td>
</tr>
<tr>
<td>DataFlash (writing) AT26F004</td>
<td>7</td>
</tr>
<tr>
<td>Multiplexer 1 ADG708</td>
<td>0.003</td>
</tr>
<tr>
<td>Multiplexer 2 ADG709</td>
<td>0.003</td>
</tr>
<tr>
<td>Wake-up chip ATAK5278</td>
<td>0.09</td>
</tr>
</tbody>
</table>
previous version, WID2. It can be seen in the table that the power requirement for WID2 and WID3 are comparable. While the requirement for the WID3 is slightly higher, its increased functionality compensates for its modest increase in power consumption.

2.2 WiDAQ hardware components and capabilities

The capabilities of the WID3 have been further extended to be able to take low frequency measurements from a variety of sensors, such as accelerometers, by combining it with the Wireless Data Acquisition (WiDAQ) board. The combined modular sensor node is shown in Fig. 1 (right). The major components of the WiDAQ are shown in Fig. 3. The WiDAQ is also controlled by an ATmega1281 microcontroller, although it lacks the wireless telemetry capabilities of the WID3. Having its own microcontroller, the WiDAQ can function as a stand-alone device using wired communication, but is primarily intended to be used in combination with the WID3, as shown in Fig. 1 (right). The module connectors, indicated in Figs. 2 and 3, provide each module with the ability to share resources, such as processing power, data storage, and wireless communications. Because each module is equipped with its own microcontroller, both modules need not be awake simultaneously; one module can perform a task and wake the other when it is needed, thereby reducing overall power consumption.

The primary functions of the WiDAQ are data acquisition and signal generation, so the key components on the WiDAQ board are the Analog Devices AD7924 analog-to-digital converter (ADC) chip and the Analog Devices AD5621 digital-to-analog converter (DAC) chip. By excluding sensor-specific conditioning circuitry from the WiDAQ board, sensor data can be acquired from any transducer that provides a voltage output. Sensor-specific conditioning, such as that required for ICP accelerometers, can be included on a third module. The four-channel AD7924 has a 12-bit resolution over a range from zero to 2.5 Volts, and it would consume a maximum of 6 mW while sampling at one million times per second. Because the microcontroller must handle both measurement and telemetry tasks, the full ability of the AD7924 cannot be utilized in the absence of a second dedicated microcontroller. As a result, the effective sampling rate for the WID3 is limited to about 40 kHz, which must be shared among the four channels of the AD7924. With four sensing channels, the effective sampling rate per channel would then be 10 kHz.
The WiDAQ is designed for both passive and active sensing. In addition to the AD7924, an Analog Devices AD5621 D/A converter provides the excitation signal necessary for active sensing using piezoelectric patches. The AD5621 has a 12-bit resolution with an output range of zero to 2.5 Volts, consumes a maximum of 0.5 mW. Each WiDAQ is capable of simultaneously providing an excitation signal through the AD5621 while measuring the response on each of the AD7924’s four channels. However, the maximum sampling frequency of 40 kHz must still be shared between the A/D and D/A converters.

Because the WiDAQ does not include any sensor-specific conditioning circuitry, the WiDAQ ICP module has been designed to allow the combined sensor node to function as a complete wireless data acquisition system for ICP accelerometer measurements. The WiDAQ ICP and the complete wireless data acquisition system for ICP accelerometer measurements are pictured in Fig. 4.

3. Impedance measurements for SHM

The experimental verification of the WID for SHM has been reported in the previous papers on monitoring of joint frame structures (Mascarenas et al. 2007, 2009), corrosion detection (Overly et al. 2008). The performance was also verified in the filed test at the Alamosa Canyon Bridge in Southern NM, where we showed that the joints in the bridge could be efficiently monitored with several different WID’s operation schemes, including wireless triggering, local networking and wireless energy transmission to power this sensor node (Taylor et al. 2009).

4. Sensor diagnostics

This section presents the sensor diagnostic capability of WID3. The WID3 is able to perform sensor diagnostics, where the functionality of sensors/actuators is confirmed to be operational. Validation of the sensor/actuator functionality during SHM operation is a critical component to successfully implement a complete and robust SHM system, especially with an array of PZT active-sensors involved. The basis of this method is to track the capacitive value of PZT transducers, which manifests in the imaginary part of the measured electrical admittance (Park et al. 2006a, 2006b). Both degradation of the mechanical/electrical properties of a PZT transducer and the bonding defects between a PZT patch and a host structure can be identified by this process. It is
however found that temperature variations in sensor boundary conditions manifest themselves in similar ways of sensor failures in the measured electrical admittances. Therefore, we have developed an efficient signal processing tool that enables the identification of a sensor validation feature that can be obtained instantaneously without relying on pre-stored baselines and be immune to temperature variations (Overly et al. 2009). This diagnostics tools are incorporated in the SHMTools software package, currently under development by the authors. These tools were extended to utilize data collected with the WID3 system.

A sensor diagnostics demonstration plate, shown with the WID3 in Fig. 5, was constructed to test the sensor diagnostics capability. Twelve circular piezoelectric patches are mounted using super-glue on one surface of an Aluminum plate (30 × 30 × 1.25 cm). The size of the circular PZT patch is 5.5 mm diameter with 0.2 mm thickness. Patches had a different bonding condition, perfect bonding, debonding and sensor breakages. Six patches were under perfect bonding condition, three of them were under the different degree of debonding conditions (25%, 50% and 75% area debonding), and the remaining three were under different fracture conditions (25%, 50% and 75%). To implement the partially bonded samples, a release paper was used to restrict adhesion to only the desired contract regions. Specifically, the PZT patches were bonded to the plate with a corresponding percent of the total area separated by a double layer of release paper. The broken condition was imposed by using a chisel to cut at specific percentages of their total surface area. Admittance measurements in the frequency range of 5-30 kHz were made to each PZT patch after installation.

Fig. 5 Sensor diagnostics demonstration plate with healthy, debonded and broken sensors

Fig. 6 Raw impedance data collected with the WID3 and auto-classification results from SHMTools for debonded sensors
Multi-scale wireless sensor node for health monitoring of civil infrastructure and mechanical systems

Typical experimental results are illustrated in Figs. 6 and 7. In each scenario, the WID3 is connected to five healthy sensors and two faulty sensors. With induced de-bonding, the slope of the measured admittance is different from the perfect bonding condition (upward shifts), and as the debonding area increases, there is a corresponding increase in the slope as shown in Fig. 8 (left). At the same time, one can clearly observe in the Fig. 9 that, the slope change (downward shift) of the imaginary admittance is proportional to the breakage percentage. As the breakage percent increases, corresponding decreases in slope were observed. The theoretical basis for this reduction is detailed in the reference (Park et al. 2006a). The right side of Figs. 8 and 9 illustrates the results from the SHMTools sensor diagnostics functions using data collected by the WID3. All the sensor conditions were correctly identified with the use of signal processing algorithm developed by the authors, which does not rely on pre-stored baseline measurements. The theoretical basis for the signal processing tools is detailed in the reference (Overly et al. 2009). In short, with an array of sensors, this signal processing tool instantaneously identifies a common feature of healthy sensors and applies a process of outlier detection. Sensors with errant bonding or degraded mechanical/electrical properties could be separated by this process. The method is attractive as an array of sensors is typically deployed in active sensing SHM methods. Care does have to be taken to make sure that the sensors being analyzed are exposed to the same environmental conditions and one must use and compare the same size/materials of PZT transducers in order to efficiently use this process and to minimize the variations not related to the sensor conditions (Overly et al. 2009).
5. Low frequency vibration measurements

This section describes the laboratory testing using the WID3/WiDAQ system to collect time-domain vibrational data for modal analysis. The experimental setup with the sensor node network and test structure is shown in Fig. 8. Two WID3/WiDAQ nodes with ICP conditioning boards were wirelessly networked with a MeshBean board, which served as the network coordinator. In this experiment, the sensor nodes were powered exclusively by batteries. The sensor node network is visible in the figure below (left). Four accelerometers mounted on the test structure were connected to Node A. The accelerometers used were PCB 352A24 “teardrop” accelerometers with a nominal sensitivity of 110 mV/g. An impact hammer was connected to Node B. The impact hammer used was a PCB 086C03, with a nominal sensitivity of 10 mV/lbf.

The wireless network implemented in this experiment utilized a “star” topology, in which the coordinator node communicated directly with each sensor node. Because the modal testing was implemented with a star topology, the command broadcast by the coordinator was received simultaneously by each end device to begin recording. The data could then be handled as digital sequences with identical indices. If the network were more complicated, such as a tiered or mesh network, each device would have to “time-stamp” the recorded data according to a master clock. The accuracy of that clock would then limit the frequency range over which valid measurements could be obtained. The coordinator was connected to a laptop computer using a serial port. At a command from the computer, the coordinator broadcast an instruction to the two sensor nodes to begin recording sensor data simultaneously. The sensor nodes were preprogrammed to record data at 969 Hz for just over 4 seconds and store the results in the onboard flash memory chips. In this experiment, the measurement parameters were preprogrammed; however, a flexible testing method in which the coordinator also passes commands such as sampling rate and duration could easily be implemented. After storing the data record, each sensor node transmitted its results to the coordinator, which in this case, relayed the data to the laptop computer for later analysis. A sample of the data collected is shown in Fig. 9.

Frequency response functions were estimated using the recorded data, and the test structure’s
resonant frequencies and mode shapes were extracted using the rational polynomial curve-fitting method (Richardson and Formenti 1982) implemented in DIAMOND, a modal analysis software package developed at Los Alamos National Laboratory (Doebling et al. 1997). The extracted resonant frequencies and mode shapes were compared with those obtained using data collected using a 4-channel Dactron™ data acquisition system. The extracted resonant frequencies using each system are shown in Table 3 for the first four modes of vibration. The modal assurance criterion (MAC) was

![Fig. 10 Line plots of the first four mode shapes obtained using the Dactron and WID3/WiDAQ systems](image-url)

Table 3 Comparison of measured natural frequencies using Dactron and WID3/WiDAQ systems

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Dactron</th>
<th>WID3/WiDAQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>71.42</td>
<td>70.94</td>
</tr>
<tr>
<td>2</td>
<td>106.02</td>
<td>105.98</td>
</tr>
<tr>
<td>3</td>
<td>185.82</td>
<td>185.68</td>
</tr>
<tr>
<td>4</td>
<td>287.26</td>
<td>287.27</td>
</tr>
</tbody>
</table>

Table 4 Comparison of measured natural frequencies using Dactron and WID3/WiDAQ systems

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Dactron Auto-MAC</th>
<th>Dactron and WID3/WiDAQ Cross-MAC</th>
<th>WID3/WiDAQ Auto-MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00 0.00 0.00 0.19</td>
<td>0.97 0.01 0.00 0.15</td>
<td>1.00 0.00 0.02 0.21</td>
</tr>
<tr>
<td>2</td>
<td>0.00 1.00 0.70 0.00</td>
<td>0.00 0.94 0.68 0.00</td>
<td>0.00 1.00 0.70 0.02</td>
</tr>
<tr>
<td>3</td>
<td>0.00 0.70 1.00 0.00</td>
<td>0.01 0.68 0.98 0.01</td>
<td>0.02 0.70 1.00 0.01</td>
</tr>
<tr>
<td>4</td>
<td>0.19 0.00 0.00 1.00</td>
<td>0.19 0.00 0.00 0.88</td>
<td>0.21 0.02 0.01 1.00</td>
</tr>
</tbody>
</table>

Fig. 10 Line plots of the first four mode shapes obtained using the Dactron and WID3/WiDAQ systems
also computed to compare the mode shapes extracted using the WID3/WiDAQ system with those extracted using the Dactron system. The MAC provides an indication of the degree to which two vectors are aligned; the resulting MAC matrix would be unity on the diagonal for completely correlated vectors, and it would have zeros on the off-diagonals for orthogonal vectors. The auto-MACs for the mode shapes extracted using each system and their cross-MAC are shown in Table 4.

In a controlled laboratory experiment, the correlation between two sets of mode shapes extracted using two different data acquisition systems should be very near unity. For this test, the diagonal MAC values were near unity except for the fourth mode, which had a value of 0.88. Some discrepancies between the mode shapes extracted using the traditional data acquisition system and the WID3/WiDAQ systems, while not significant, can be seen in a line plot of the deformed structure, shown in Fig. 10. These discrepancies could be removed by the use of a higher resolution (such as 16 bit) ADC, but it would require higher power consumption, reducing the effectiveness of the system in areas without access to a constant power supply.

6. Conclusions

Recent developments in the compact wireless impedance device (WID3) have been presented, and the new functionality has been demonstrated. The WID3’s most basic capability involves measuring the coupled electromechanical impedance of a structure, capitalizing on the well-established impedance-based structural health monitoring technique to monitor the condition of a structure. The low-power sensor node’s capabilities have been extended through improved networking capabilities, increased data storage options, multiple powering options that allow for energy harvesting integration, and increased triggering options that allow for better control of sleep modes, reducing overall power consumption. The capability of this device is demonstrated in structural health monitoring and sensor diagnostic applications. Furthermore, the node’s capabilities have been extended through use of a wireless data acquisition (WiDAQ) module to be capable of collecting low-frequency time-domain data from a variety of sensors. To demonstrate this capability, structural vibration data were collected for modal analysis, and the resulting measured natural frequencies and mode shapes were compared to those measured using a traditional data acquisition system. The WID3/WiDAQ serves as a multi-scale sensing module, carrying out an efficient SHM and sensor diagnostic process in high-frequency regimes, as well as monitoring the effects of damage on system-level performance by measuring low-frequency vibration responses. This coupled and multi-scale sensing capability is currently being utilized by the authors for SHM investigations including wind turbine applications, and it will be a subject of subsequent papers.

References


Ultra low-power active wireless sensor for structural health monitoring

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Abstract. Structural Health Monitoring (SHM) is the science and technology of monitoring and assessing the condition of aerospace, civil and mechanical infrastructures using a sensing system integrated into the structure. Impedance-based SHM measures impedance of a structure using a PZT (Lead Zirconate Titanate) patch. This paper presents a low-power wireless autonomous and active SHM node called Autonomous SHM Sensor 2 (ASN-2), which is based on the impedance method. In this study, we incorporated three methods to save power. First, entire data processing is performed on-board, which minimizes radio transmission time. Considering that the radio of a wireless sensor node consumes the highest power among all modules, reduction of the transmission time saves substantial power. Second, a rectangular pulse train is used to excite a PZT patch instead of a sinusoidal wave. This eliminates a digital-to-analog converter and reduces the memory space. Third, ASN-2 senses the phase of the response signal instead of the magnitude. Sensing the phase of the signal eliminates an analog-to-digital converter and Fast Fourier Transform operation, which not only saves power, but also enables us to use a low-end low-power processor. Our SHM sensor node ASN-2 is implemented using a TI MSP430 microcontroller evaluation board. A cluster of ASN-2 nodes forms a wireless network. Each node wakes up at a predetermined interval, such as once in four hours, performs an SHM operation, reports the result to the central node wirelessly, and returns to sleep. The power consumption of our ASN-2 is 0.15 mW during the inactive mode and 18 mW during the active mode. Each SHM operation takes about 13 seconds to consume 236 mJ. When our ASN-2 operates once in every four hours, it is estimated to run for about 2.5 years with two AAA-size batteries ignoring the internal battery leakage.

Keywords: structural health monitoring; SHM; wireless sensor node; impedance-based method; temperature compensation.

1. Introduction

Structural Health Monitoring (SHM) is the science and technology of monitoring and assessing the condition of aerospace, civil and mechanical infrastructures using a sensing system integrated into the structure. SHM is capable of detecting, locating and quantifying various types of damage such as cracks, holes, corrosion, collisions, delimitations, and loose joints, and can be applied to various kinds of infrastructures such as buildings, railroads, windmills, bridges and aircrafts. A
variety of approaches for SHM have been proposed and investigated. The impedance method based on using piezoelectric wafers, such as PZT (Lead Zirconate Titanate), is proven to be effective for in-situ local damage detection. Unlike passive sensing methods, the impedance-based method combines sensing with actuation, which sweeps a certain frequency range to measure the impedance profile of a structure. In spite of its effectiveness, the PZT based SHM approach still has not been deployed in large-scale applications.

Major roadblocks for field deployment include high hardware complexity and high installation cost (including laying out cables for power supply and data collection). High hardware complexity is attributed to the need for generation of an excitation signal, collection of the response signal, and processing of the collected data. Existing SHM prototypes rely on expensive instruments and/or high-speed DSP chips. High hardware complexity incurs high power consumption, a large form factor and high cost. Among them, power consumption is especially problematic for many SHM applications, where line power is unavailable (such as a blade of a windmill) or laying out cables is undesirable (such as wings of an airplane). Even if line power is available (such as a bridge with street lights), drawing a cable to a sensor node is costly. Ideally, an SHM node/system dissipates extremely low power, so that it can run on a small-size battery for several years or run on energy harvested from ambient sources, such as solar, thermal or vibration. In such a case, wireless transmission of the SHM data to the host computer is essential to remove wires from the node to the host.

In this paper, we present a low-power wireless autonomous and active SHM node called ASN-2, which is based on the impedance method. Our system incorporates three methods for reduction of power, and experimental results show our system is highly efficient in power. It should be noted that the focus of the paper is low-power design of our SHM system, not wireless networking nor the impedance method itself. The paper is organized as follows: Section 2 provides background and preliminaries necessary to understand our work. We also review a few existing SHM systems relevant to our system. Section 3 presents three power saving methods, which are incorporated into ASN-2. Section 4 describes details about ASN-2 such as its architecture, system operation, temperature compensation and wireless networking. Section 5 presents experimental results including a power dissipation profile. Finally, we conclude the paper in Section 6.

2. Preliminaries

We describe the impedance-based method and review a few relevant SHM systems in this section. Fig. 1 shows a model of an impedance-based SHM, in which an electrical sinusoid signal \( V(\omega) \) actuates the PZT. The PZT transforms the electrical signal into the mechanical strain. The admittance of the piezoelectric patch \( Y(\omega) \) is a combined function of the impedance of the PZT actuator \( Z_a(\omega) \) and that of the host structure \( Z(\omega) \) is given by

\[
Y(\omega) = j \omega a \left( \varepsilon_{33}^T (1 - \delta) - \frac{Z(\omega)}{Z(\omega) + Z_a(\omega)} d_{33}^e Y_{xx}^e \right)
\]

where \( a, d_{33}^e, \delta, Y_{xx}^e \) and \( \varepsilon_{33}^T \) are the geometry constant, the piezoelectric coupling constant, the dielectric loss tangent, Young’s modulus, and the complex dielectric constant of the PZT at zero stress, respectively (Park et al. 2003). The first term in the equation is the capacitive admittance of a free piezoelectric patch, and the second one is the result of the electromechanical interaction of the
piezoelectric patch with the host structure (Sun et al. 1995).

Previous studies indicate that the real part of the admittance given in (1) is more sensitive to damage of the structure, while the imaginary part to the temperature variation (Park et al. 1999). Hence, it is desirable for an SHM system to be sensitive to the real part and to suppress the side effect caused by the imaginary part. Krishnamurthy et al. (1996) showed through experiments that the magnitude of impedance peaks shrink as the temperature increases, while peaks of the imaginary part shift towards a lower frequency. Consequently, an impedance-based SHM requires a mechanism to compensate the temperature variation.

Conventional impedance-based SHM methods rely on impedance analyzers. Such instruments provide high precision measurements for a large frequency range, but they are bulky and, hence, not suitable for in-situ applications. Analog Device, Inc. introduced an impedance analyzer chip AD5933, which dissipates about 30 mW. The chip includes a digital-to-analog converter to generate an excitation signal up to 100 kHz, a 12-bit analog-to-digital converter, and supports on-chip Fast Fourier Transform (FFT) operation. Park et al. (2008a, b, 2009) integrated this chip with a microcontroller ATMega128 and an XBee wireless transceiver. They showed that the system could be applicable for various SHM applications, but high-power consumption is a major issue. Researchers from Los Alamos National Lab have worked on a series of wireless SHM sensor systems embedded with Analog Device’s impedance analyzer chips AD5933 for years and developed the third generation of the sensor system called Wireless Impedance Device (WID-3) in 2009 (Overly et al. 2008, Mascarenas et al. 2007, Taylor et al. 2009a). The power consumption of WID-3 is around 70 mW during measurement and wireless transmission (Farinholt et al. 2009, Taylor et al. 2009b). Our team also developed an impedance-based SHM system using a Texas Instrument DSP evaluation board. The SHM system verifies effectiveness of rectangular pulse trains as the excitation signal, but consumes about 800 mW due to unnecessary chips and components embedded on the evaluation board (Kim et al. 2007a, b).

3. Proposed methods for low-power system design

In this section, we present three methods employed for low-power design of our wireless SHM sensor node. The first method is on-board data processing to reduce the radio transmission time, which substantially reduces the power dissipated by the radio. The second method is elimination of a digital-to-analog converter (DAC) for excitation signal generation, and the third one is elimination of an analog-to-digital converter (ADC) for response sensing.
3.1 On-board data processing

The major source of power consumption for a wireless sensor node is the radio. For example, a microcontroller unit TI MSP430 from Texas Instruments used for our SHM sensor node dissipates 3 mW under a low-power operation mode, while a low-end radio CC2500 from Texas Instruments embedded in the sensor node dissipates 65 mW during transmission. So, it is essential to reduce the radio transmission time for a low-power wireless SHM sensor node. We adopt an on-board data processing approach for our SHM sensor node, which processes the data on the board and sends only the final outcome (healthy or damaged) of the SHM operation to the control center. So, the radio for our sensor node transmits only three bytes of data, including the outcome of the SHM operation and the ambient temperature.

3.2 Elimination of a DAC for generation of an excitation signal

A sinusoidal signal sweeping a certain frequency range is usually used to excite a PZT patch for the impedance method. Generation of a sinusoidal signal usually relies on a DAC. Sampled values of a sinusoidal signal are pre-stored in a memory, and a processor reads the pre-stored data and applies it to a DAC to generate the corresponding analog signal. This method is straightforward, but it requires a DAC and a large memory space for a large-frequency sweeping range.

Our method is to employ a rectangular pulse train rather than a sinusoidal signal. A rectangular pulse train illustrated in Fig. 2(a) has the duty cycle of 0.5, and its fundamental frequency (which is given as $1/t_p$, where $t_p$ is the pulse period) sweeps a certain desired frequency range. The Fourier transform of a pulse train with a pulse period $t_p$ and a duty cycle of 0.5 has odd harmonics $k f_o$, $k=1, 3, 5...$, where $f_o=1/t_p$. Fig. 2(b) illustrates frequency components of a pulse train with the fundamental frequency ranging from 40 kHz to 50 kHz. The magnitude of the third harmonic is about 33 percent of the fundamental frequency, and the fifth one about 20 percent.

A rectangular pulse train is digital, and hence a processor can directly generate such a signal. Since generation of a rectangular pulse train does not require a DAC, it reduces power consumption of an SHM sensor node. One potential issue is existence of harmonics on the signal. Note that our

![Fig. 2 Rectangular pulse train](image)

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1This value is from the data sheet.
interest is to detect the difference between the baseline impedance profile and a currently measured one. Since both profiles are under the subject of the same frequency terms, the sensitivity for detecting the difference may not be affected by harmonics. Further, harmonic terms decrease rapidly, and some harmonic terms may be out of the interested frequency range. Our experimental results reveal that use of a rectangular pulse train does not incur any noticeable deterioration of the performance for the impedance method (Kim et al. 2007a).

3.3 Elimination of an ADC for response signal sensing

Existing methods such as Analog Device’s impedance analyzer chips sample the response signal using an ADC and performs a Fast Fourier Transform (FFT) to extract the impedance component of the frequency. A typical ADC used for an SHM system consumes large power, possibly next to a radio and a processor, and FFT is also computationally intensive to increase power dissipation. Our method is to eliminate an ADC and the FFT operation by sensing the phase, not the magnitude, of the response signal.

The electrical admittance is expressed as $Y(jf) = G(f) + jB(f)$, where $G(f)$ and $B(f)$ are conductance and susceptance terms, respectively. It is known that the conductance term of a PZT patch is more sensitive to damage (Park et al. 2003). Let $G_{\text{bad}}(f)$ denote the baseline conductance obtained from a healthy structure and $G_{\text{SUT}}(f)$ be the conductance of a structure under test (SUT). The difference of the two conductance terms $G_{\text{bad}}(f) - G_{\text{SUT}}(f)$ is used for existing impedance-based SHM systems to detect damage. Our earlier work showed that

$$G_{\text{bad}}(f) - G_{\text{SUT}}(f) \approx C \sin[\phi_{\text{bad}}(f) - \phi_{\text{SUT}}(f)]$$

(2)

where $C$ is a constant, assuming all parameters other than the two impedance terms or $Z_a(\omega)$ and $Z(\omega)$ in expression (1) are constant, and $\phi_{\text{bad}}(f)$ and $\phi_{\text{SUT}}(f)$ are the phase of the baseline admittance and the SUT admittance, respectively. Expression (2) suggests that difference of the phases, instead of the conductance $G(f)$’s, can be sensed for the impedance method.

The phase of an admittance $\phi(f)$ for a frequency $f$ can be expressed as in (3), where $T_d(f)$ is the time difference between the voltage and the current

$$\phi(f) = 2\pi f \times T_d(f)$$

(3)

When both the voltage and current are represented as binary signals, the phase difference of the two signals is obtained using an exclusive-OR (XOR) operation as illustrated in Fig. 3. A processor can

![Fig. 3 Phase difference measured by sampling the output of the XOR operation](image-url)
measure the time delay by sampling the output of the XOR operation at a system clock frequency, where the system clock frequency is typically much higher than the frequency $f$ of the admittance under consideration.

Fig. 4 shows a simplified circuit diagram for a phase measurement. A rectangular pulse train $V_{in}(t)$ is buffered by an operational amplifier (opamp) and applied to the PZT attached to the structure. The output of opamp OP3 is the current through the PZT, which is delayed in time by a certain amount. The reference voltage $V_{ref}$ shifts the DC level of the applied input voltage, and it is set to one half of the peak-to-peak voltage of input signal $V_{in}(t)$. OP4 is a comparator, which shapes the current waveform into digital. The XOR gate detects the difference between the input voltage and the current through the PZT. OP1 is necessary to drives a highly capacitive PZT, and OP2 is added to delay the excitation signal by the same amount as OP1.

4. ASN-2: wireless autonomous SHM node

We developed an autonomous SHM node called ASN-2, which is an improved version of our earlier one reported in (Kim et al. 2007a). The major focus of ASN-2 is low-power design of an SHM system based on the impedance method, not wireless networking nor the impedance method itself. ASN-2 incorporates the low-power design methods described in Section 3 and was developed using a low-power microcontroller evaluation board. We describe ASN-2 in this section including its architecture, system operation, damage metric, temperature compensation and wireless networking.

4.1 Architecture and prototype

ASN-2 was developed using a TI MSP430 low-power microcontroller from Texas Instruments, which contains an embedded temperature sensor. The maximum clock frequency of MSP430 is 16 MHz. We chose a low clock frequency of 1.2 MHz to save power, but the frequency is high enough for generation of a pulse train in our desired frequency range. The microcontroller can be programmed to operate in several modes with different levels of power consumption. It consumes about 3 mW in the active mode for ANS-2 and only 3 $\mu$W in the sleep mode.

The microcontroller evaluation board ez430-RF2500 used for ASN-2 has a radio called CC2500 operating at 2.4 GHz. The data rate of the radio is programmable and can reach up to 500 kbps, and its coverage is less than 20 meters for an outdoor environment. Also, the radio can be configured to operate in the active mode or sleep mode. It consumes 65 mW during transmission, and as low as 1.2 $\mu$W in the sleep mode. The architecture of our SHM sensor node based on TI MSP430 microcontrollers is shown in Fig. 5.
A prototype for ASN-2 is shown in Fig. 6. The top part is the interface analog circuit, and the bottom part is the evaluation board and two AAA-size batteries. The size of the prototype is 4.5 cm \times 7 \text{ cm} \times 3 \text{ cm}, and it runs on two AAA-size batteries.

4.2 System operation

Fig. 7 shows the system operation of ASN-2. The microcontroller sweeps a user specified frequency range and measures the phase profile of a baseline or SUT for the frequency range. It repeats the same operation four times and takes the average value to obtain the phase profile. Each SHM operation including four repeated measurements and processing of the response data, takes about 13 seconds for a frequency range from 12 KHz to 35 KHz. After an SHM operation, ASN-2 goes into the sleep mode for a predetermined time period controlled by an internal timer. During the sleep mode, most components such as the CPU, opamps, and the built-in ADC (used to sample temperature sensor values for ASN-2) are turned off, and some other components such as the timer and the radio are set to a lower clock frequency or the sleep mode.

4.3 Damage metric

The damage metric (DM) for our system is defined as a normalized absolute sum of differences between the phase profiles of the baseline and of the SUT given by

$$DM = \frac{\sum_{f_1}^{f_h} |\phi_{\text{base}}(f_i) - \phi_{\text{SUT}}(f_i)|}{M(f_1, f_h)}$$

(4)
where \( M(f_l, f_h) \) is the number of frequency points from the lowest frequency \( f_l \) to the highest frequency \( f_h \). The DM of a SUT is compared against a threshold value, whose value may be set based on field experience. If the DM is lower than the threshold value, the SUT is considered healthy. Otherwise, it is damaged. It is important to note that fixed-point calculations without involving multiplications or division are sufficient for Expression (4) provided \( M(f_l, f_h) \) is set to power of 2. So, a simple fixed-point processor, rather than a floating-point processor, can be used for our SHM system to save power. Adoption of a more sophisticated DM is possible for ASN-2 to improve the SHM performance, but it is not the objective of ASN-2.
4.4 Temperature compensation

A PZT is sensitive to temperature variations, and Fig. 8 presents our measurements showing the phase sensitivity of the PZT admittance to temperature (Zhou et al. 2009a). The Y-axis is the cumulative number of system clock samples for a given frequency $f$, which represents the phase of the PZT admittance. (Refer to Fig. 3). The trend observed from the measurements is that as temperature increases (i) the magnitude of a peak shrinks and (ii) the frequency shifts toward a lower frequency.

A straightforward solution to the temperature dependency is to store all baseline profiles for the entire temperature range with a small increment of the temperature. During an SHM operation, the ambient temperature is measured, and the baseline profile corresponding to the temperature is referenced for the SHM operation. The solution requires a large memory, which is undesirable for low-end processors with a limited memory space such as microcontrollers. Another approach is to compensate temperature variations. It assumes a linear relationship between a baseline and its temperature variations (Krishnamurthy et al. 1996, Park et al. 1999), but a linear relationship is overly simplified and results in large errors. We proposed a new method, in which a few baseline profiles at critical temperatures are judiciously selected and used to construct baseline profiles at other temperatures (Zhou et al. 2009a). A new baseline is constructed based on a linear interpolation between two baseline profiles at neighbor temperatures. Our method reduces the total number of baseline profiles stored by more than 40 percent, which makes it suitable for a microcontroller with a small memory space. Refer to (Zhou et al. 2009a) for details on our experimental results.

4.5 Wireless networking

The radio included in ASN-2 is a low-power wireless transceiver CC2500 developed by Texas Instruments. It operates in the band of 2400 MHz to 2483.5 MHz with power dissipation of 65 mW during transmission. The maximum number of sensor nodes supported by current prototype of ASN-2 is ten, and the maximum communication distance between a node and a control center is 10 meters indoors.

A network protocol SimplicTI developed by Texas Instruments targets low-power wireless sensor networks and is adopted for ASN-2. There are three major layers defined for the protocol, the data link/PHY layer, the network layer, and the application layer. ASN-2 adopts a star network topology and a token-based algorithm to avoid conflicts. The control center node assigns a token with a sensor node ID number, and the sensor node with the matching ID number grabs the token, synchronizes its clock with that of the control center, and transmits the data. The data is three bytes long, including the outcome of the SHM operation and the ambient temperature. The transmission data rate is set to 250 kbps for ASN-2, and transmission of one message takes about 30 msec.

5. Experimental results

In this section, we present experimental results and a power dissipation profile of ASN-2 during an SHM operation.

5.1 Test structure and environment

The test structure for our experiments is an aluminum beam with a PZT patch attached at one
end. The test structure is hung in free air at the room temperature of around 20 °C. A pair of identical magnets are placed on both sides of the beam at a certain position, and the pressure applied to the structure simulates damage. The size of the test beam and four different positions of the two magnets considered for our experiments are shown in Fig. 9.

To identify a sensitive frequency range of the test beam, we measured the impedance of the healthy beam with an impedance analyzer, Agilent 4294A. The impedance profile of the healthy

![Fig. 9 Test structure and positions of magnets](image)

![Fig. 10 Impedance of the healthy structure](image)
beam is shown in Fig. 10. As shown in the figure, the phase of the measured impedance is sensitive in the frequency range from 12 kHz to 35 kHz, and hence the range is set for our experiments.

5.2 SHM performance

We performed SHM operations with ASN-2, in which the excitation pulse train sweeps from 12 KHz to 35 KHz. Since the phase profile of a SUT changes from one measurement to the next due to noise or other environment changes, we conducted 20 experiments for the baseline and for each damage, i.e., each position of the magnets, and computed the DM values using expression (4). Statistical data for the DM values are tabulated in Table 1 and presented in Fig. 11.

The average DM value of the baseline structure is 3.4, while those for damaged structures range from 15.6 to 24.2. The large difference in the averages values of the baseline and of damaged structures combined with small standard deviations assures detection of damage with high confidence for ASN-2. If the threshold is set between 6.7 and 15.2, ASN-2 does not incur any false alarm for the particular damages, and the dotted line Fig. 11 indicates the optimal DM value (which is the middle point between 6.7 and 15.2). It should be noted that the DM value decreases from Position 1 to Position 3, but increases sharply at Position 4. The result indicates that the proposed damage metric cannot be used to locate damage.

Table 1 DM values for 20 experiments

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Position 1</th>
<th>Position 2</th>
<th>Position 3</th>
<th>Position 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>3.4</td>
<td>19.2</td>
<td>16.9</td>
<td>15.6</td>
<td>24.2</td>
</tr>
<tr>
<td>Maximum</td>
<td>6.7</td>
<td>22.6</td>
<td>17.6</td>
<td>15.9</td>
<td>25.5</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.3</td>
<td>18.1</td>
<td>16.3</td>
<td>15.2</td>
<td>23.1</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.72</td>
<td>1.29</td>
<td>0.41</td>
<td>0.23</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Fig. 11 Difference of DM values between the baseline and the four damages
5.3 Power profile

The supply voltage of two AAA-size batteries remained at constant 3 V during our experiments, and so we measured only the current flowing into ASN-2. The measured current profile over one SHM operation of ASN-2 is shown in Fig. 12. The current under the inactive mode is about 50 $\mu$A resulting in 0.15 mW of power consumption. The current increases to an average of 6 mA during the active mode with the radio off, which dissipates 18 mW. The active mode lasts for about 13 seconds consuming 234 mJ of energy. When the radio is turned on at the end of the active mode, the current jumps abruptly to 23 mA causing 70 mW of power consumption. However, the period lasts for about 30 msec resulting in 2.1 mJ of energy consumption.

When ASN-2 operates once in every four hours, the average power consumption is 0.16 mW. Considering the typical capacity of an AAA-size battery is about 1200 mAh, ASN-2 can run for about 2.5 years ignoring the internal battery leakage. It is feasible for ASN-2 to be powered by energy harvested from ambient sources such as solar, thermal or vibration. We conclude this section by noting that the above power consumption is limited for our experiments. The power consumption of ASN-2 varies widely depending on multiple parameters such as the frequency of SHM operations per a given period, the amount of data to be transmitted, and the topology of the network.

6. Conclusions

We presented a low-power wireless autonomous and active SHM node ASN-2, which is based on the impedance method. We incorporated three methods to save power. First, the entire data processing is performed on-board, which minimizes the radio transmission time. Considering the radio of a wireless sensor node consumes the most power, reduction of the transmission time saves substantial power. Second, a rectangular pulse train is used to excite a PZT patch instead of a sinusoidal signal. This eliminates a DAC and reduces the memory space. Third, it senses the phase of the response signal instead of the magnitude. Sensing the phase of the signal eliminates an ADC and FFT operation, which not only saves power, but also enables us to use a low-end low-power
Ultra low-power active wireless sensor for structural health monitoring

Our SHM sensor node ASN-2 is implemented using a TI MSP430 microcontroller evaluation board. A cluster of ASN-2 nodes forms a wireless network. Each node wakes up at a predetermined interval such as once in four hours, performs an SHM operation, reports the result to the central node wirelessly, and returns to sleep. The power consumption of our ASN-2 is 0.15 mW during the inactive mode and 18 mW during the active mode. Each SHM operation takes about 13 seconds to consume 236 mJ. When our ASN-2 operates once in every four hours, it can run for about 2.5 years with two AAA-size batteries ignoring the internal battery leakage.

References


Development of a low-cost multifunctional wireless impedance sensor node

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Abstract. In this paper, a low cost, low power but multifunctional wireless sensor node is presented for the impedance-based SHM using piezoelectric sensors. Firstly, a miniaturized impedance measuring chip device is utilized for low cost and low power structural excitation/sensing. Then, structural damage detection/sensor self-diagnosis algorithms are embedded on the on-board microcontroller. This sensor node uses the power harvested from the solar energy to measure and analyze the impedance data. Simultaneously it monitors temperature on the structure near the piezoelectric sensor and battery power consumption. The wireless sensor node is based on the TinyOS platform for operation, and users can take MATLAB\textsuperscript{®} interface for the control of the sensor node through serial communication. In order to validate the performance of this multifunctional wireless impedance sensor node, a series of experimental studies have been carried out for detecting loose bolts and crack damages on lab-scale steel structural members as well as on real steel bridge and building structures. It has been found that the proposed sensor nodes can be effectively used for local wireless health monitoring of structural components and for constructing a low-cost and multifunctional SHM system as “place and forget” wireless sensors.

Keywords: structural health monitoring; piezoelectric sensor; electromechanical impedance; wireless sensor node; multifunctional system.

1. Introduction

On-line structural health monitoring (SHM) has become an important issue in civil, mechanical and aerospace engineering fields. Particularly, the interest in health monitoring for critical members of large structures is dramatically growing with increasing social needs. To date, numerous techniques and algorithms have been proposed for local SHM with smart sensors including fiber optic sensors and piezoelectric sensors. Among them, the electromechanical (E/M) impedance-based SHM has shown promising results for steel structures (Park et al. 2003, Park et al. 2005, Koo et al. 2009, Park et al. 2009a, Taylor et al. 2009a, b). The technique utilizes small piezoelectric sensors such as piezoceramic (PZT) and macro-fiber composite (MFC) patches attached to a structure as self-sensing actuators to both excite the structure with high-frequency sweeping and monitor any changes in structural mechanical impedance (Giurgiutiu et al. 1999, Park et al. 2003, Park et al. 2009a). By monitoring the

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electrical impedance of the PZT, assessments can be made about the integrity of the structure. Recent advances in online SHM, including actuation and sensing, on-board computing, and radio-frequency (RF) telemetry, have improved the accessibility of the impedance method for in-field measurements. Lynch et al. (2004) designed a wireless active sensing unit to monitor civil structures, which was constructed of off-the-shelf components and had the ability to command active sensors and actuators from a computational core combined with wireless transmission and sensing circuits, embedded algorithm to process the acquired data, and structural status broadcasting. Grisso and Inman (2005) designed a DSP (Digital Signal Processor) based prototype to provide wireless assessment of thermal protection systems. It was able to directly detect damages by analyzing variations of the electrical impedance of PZT sensors bonded to the structure. The obtained impedance signals were compared with the pre-stored baseline and a statistical damage index was calculated. Mascarenas et al. (2007) proposed a wireless sensor node which consists of a miniaturized impedance measuring chip, a microprocessor, and a radio-frequency identification (RFID) module. Low cost impedance measuring chip actuated the structure through a PZT and measured the structural impedance response, and RFID module delivered the diagnostic result to a base station. Park et al. (2009a) improved the wireless sensor node of Mascarenas et al. (2007) by adding two multiplexer IC chips for 16 channels for the cases of multiple sensors in a small region and by embedding signal processing algorithms in the microcontroller unit (MCU) for both structural damage identification and sensor self-diagnosis. Research groups at Los Alamos National Lab recently developed a compact impedance-based wireless sensing device (WID3) for low power operation (Overly et al. 2007, 2008), which requires around 60 mW of power to operate. Here, a wake-up capability was combined for low power operation. Taylor et al. (2009a, b) extended the capability of the WID3 by implementing a module with low-frequency A/D and D/A converters to measure low-frequency vibration data for multiple SHM techniques. It is wirelessly triggered by a mobile agent for use in the mobile-host-based wireless sensing network. The mobile agent also provides computational power to real-time assessments on the structural conditions.

Based on these prior researches, this paper extends the impedance-based wireless SHM node for the purpose of multifunctional and environment-friendly uses in SHM applications. More specifically this study focuses on the following three objectives: (1) to develop in-field adjustable impedance-based wireless sensor nodes with on-board algorithms for structural and sensor-self diagnosis, (2) to incorporate the energy scavenging system for maintenance-free wireless sensor node, and (3) to investigate the feasibility of the impedance-based SHM system to real structures. A series of experimental studies are performed to determine the capability of the sensor node to monitor the health of sensors and structures. First, lab tests are carried out to validate the acquired data from the developed wireless sensor nodes. Tests are done for detecting a growing crack on a steel truss member, and for monitoring the sensor fracture and the bonding layer damage for sensor self-diagnosis. Finally, the wireless system is utilized in an attempt to detect loose bolts and crack damages occurrence in real buildings and bridge structures.

2. Theoretical backgrounds

2.1 Electromechanical impedance-based SHM techniques

The E/M impedance-based SHM techniques have been developed as a promising tool for real-time structural damage assessment on critical members of large structural systems (Park et al. 2003, Koo et
al. 2009, Taylor et al. 2009a, b, Mascarenas et al. 2009). They make use of piezoelectric sensors such as piezoceramic (PZT) and macro-fiber composite (MFC) patches, which form a collocated sensor and actuator, often referred to as a self-sensing actuator (Giurgiutiu 2008). The basis of this active sensing technology is the energy transfer between the actuator and the host mechanical system. If a PZT attached on a structure is driven with a sinusoidal voltage, it causes the local area of the structure to vibrate (the converse piezoelectric effect). And the structural response causes an electrical response in the PZT (the direct piezoelectric effect). Liang et al. (1994) first proposed a one-dimensional analytical model of this setup as in Fig. 1, and showed that the electrical admittance (inverse of the electrical impedance), \( Y(\omega) \), of a PZT is directly correlated to the local mechanical impedance of the host structure, \( Z_s(\omega) \), and that of a PZT patch, \( Z_a(\omega) \), in most applications as
\[
Y(\omega) = G(\omega) + jB(\omega) = j\omega C \left( 1 - \kappa_{31}^2 \frac{Z_s(\omega)}{Z_s(\omega) + Z_a(\omega)} \right)
\]  
where \( G \) is the conductance (real part); \( B \) is the susceptance (imaginary part); \( C \) is the zero-load capacitance of a PZT; and \( \kappa_{31} \) is the electromechanical coupling coefficient of a PZT. Given that the mechanical impedance and the material properties of the PZT stay constant, the equation shows that a change in the structure’s mechanical impedance directly results in a change in the electrical impedance measured by the PZT. Since damages cause a change in the structure’s local mass, stiffness, or damping properties and consequently its mechanical impedance, the structure’s mechanical integrity can be assessed by monitoring the PZT’s electrical impedance. It should be noted that the admittance function, \( Y(\omega) \), is a complex number. Bhalla et al. (2002) demonstrated that the real part of the measured admittance is more sensitively changed due to the structural damage condition as compared to the imaginary part. On the other hand, Park et al. (2006) found out that the imaginary part can be more effectively used for piezoelectric sensor self-diagnosis.

2.2 Statistical damage indices for damage detection: RMSD and cross-correlation coefficient

By observing some changes of the E/M impedance acquired from a PZT attached on a host structure, assessments can be made about the integrity of the host structure. Since the impedance changes provide only a qualitative assessment for damage detection, several scalar damage metrics have been used for quantitative measure of structural damages. Peairs et al. (2006) compares several damage metrics, while the most commonly used indices for the impedance method are the root mean square deviation (RMSD) and the cross-correlation coefficient (CC) as
where $Z_0(\omega)$ is the impedance of the PZT measured in the healthy condition (baseline); $Z_1(\omega)$ is the impedance in the concurrent condition; $n$ is the number of frequency points; $\bar{Z}_0$ and $\bar{Z}_1$ are the mean values of the real parts of $Z_0(\omega)$ and $Z_1(\omega)$; and $\sigma_{Z_0}$ and $\sigma_{Z_1}$ are the standard deviations of the real parts of $Z_0(\omega)$ and $Z_1(\omega)$. These metrics are scaled by the baseline measurement, $Z_0(\omega)$, and are corrected for the vertical shift between measurements by subtracting mean values. The vertical shift is mainly caused by changes in environmental conditions such as temperature and humidity (Koo et al. 2009). Greater numerical value of the RMSD metric indicates larger difference between the baseline reading and the subsequent reading, which indicates clearer presence of damage in the structure. On the other hand, smaller value of the CC metric indicates larger difference between the impedances and clearer presence of damage.

Temperature variation due to surrounding changes should be considered with careful attention because it may result in a significant impedance variation, particularly a frequency shift in the impedance, which may lead to erroneous diagnostic results of real structures. To date, several studies have been reported to avoid the temperature variation effects on the impedance measurement. Bhalla et al. (2002) investigated the influence of the structure-actuator interactions and temperature variation on the impedance signatures. Koo et al. (2009) proposed the effective frequency shift (EFS; $\omega$) method in order to compensate temperature effects on impedances, which is based on the frequency shift giving the maximum cross-correlation coefficient between the baseline impedance data, $Z_0(\omega)$, and the concurrent impedance data, $Z_1(\omega)$, as

$$CC = \max_{\tilde{\omega}} \left\{ \frac{1}{N} \sum_{i=1}^{N} \frac{\{ \text{Re}(Z_0(\omega_i)) - \bar{Z}_0 \} \{ \text{Re}(Z_1(\omega_i)) - \bar{Z}_1 \}}{\sigma_{Z_0} \sigma_{Z_1}} \right\}$$

(4)

Fig. 2(a) shows that the temperature change causes considerable variation with both vertical and horizontal shifts on two impedance measurements at the same damage condition. As the EFS method is applied to compensate the temperature effect, excellent match can be obtained between two signatures as shown in Fig. 2(b). Here, the effect of the vertical shift in the measured signal is automatically compensated by subtracting the mean values as in Eqs. (3) and (4).

### 2.3 Piezoelectric sensor self-diagnosis

PZT sensors attached to a structure play a major role in the successful operation of a health monitoring and damage-detection system. The integrity of the sensor and the consistency of the sensor/structure interface are essential elements that can ‘make or break’ structural monitoring (Giurgiutiu 2008). For real structures, the duration of the monitoring process is extensive and
can span several years. It also encompasses various service conditions and several loading cases. Therefore, the sensor self-diagnostic procedure, where sensors/actuators are confirmed to be operational, is critically important for the successful implementation of the SHM system. Since most of the PZT patches are brittle, sensor fracture and subsequent degradation of mechanical/electrical properties are common types of the PZT sensor failures. In addition, the integrity of the bonding layer between a PZT and a host structure should be maintained and monitored throughout their service lives.

Saint-Pierre et al. (1996) and Giurgiutiu et al. (2002) proposed a de-bonding identification algorithm by monitoring the resonance of a PZT sensor measured by electrical impedances. As the de-bonding area between the PZT and the host increases, the shape of the PZT’s resonance becomes sharper and more distinctive, and the magnitudes of the host resonances get reduced. Park et al. (2006) introduced a piezoelectric sensor-diagnostic procedure based on tracking the imaginary part of the measured electrical admittance, which can be justified by the fact that the PZT is a capacitive device and its admittance is dominated by the imaginary part ($j\omega C$) in Eq. (1). This study demonstrated that bonding defects affect the measured admittance and can be identified by monitoring the slope of the admittance. Bonding defects would cause an upward shift in the slope of the imaginary part of the admittance, while sensor breakage would cause a downward shift in the slope implying the decrease of the capacitive value of the PZT. Therefore, sensor functionality including the sensor breakage and the degradation of the bonding condition could be assessed by monitoring the imaginary part of the admittance. Park et al. (2009b) proposed a modified impedance model adding three parameters to Eq. (1) for PZT sensor self-diagnosis, which considers the effect of the bonding layer between a PZT and a host on the dynamic interaction in the coupled electromechanical system as

\[
\tilde{Y}(\omega) = j\omega a C \left(1 - b K_s^2 \frac{\xi \cdot Z_s(\omega)}{Z_s(\omega) + Z_a(\omega)} \right)
\]

where $a$ is the sensor quality index ($0 \leq a \leq 1$); $b$ is the bonding degradation index ($0 \leq b \leq 1$); $\xi = 1 / (1 + K_s/K_b)$ is the shear-lag index between a bonding layer and a host structure ($0 \leq \xi \leq 1$); and $K_s$ and $K_b$ are dynamic stiffnesses of the host structure and the bonding layer, respectively.
3. Development of wireless impedance sensor nodes

3.1 Subsystems of wireless impedance sensor nodes

To measure the E/M impedances, impedance analyzers such as HP4194A/HP4294A are conventionally used. However, they are not quite suitable for field applications to online SHM because they are bulky (approximately 25 kg) and expensive (approximately 40,000 USD). Thus, research on the impedance-based SHM technique trends toward development of self-contained sensors and wireless active sensor nodes with all required functions including actuating/sensing, data processing, damage assessments and sensor self-diagnostics on the sensor board as well as power management with energy harvesters. Recently, Analog Devices® developed an integrated impedance converters, AD5933 (www.analog.com). It is equipped with a 12-bit analog-to-digital converter (ADC), a digital-to-analog converter (DAC) and a discrete Fourier transform (DFT) functionality. The frequency generator allows an external complex impedance with range of $100 \Omega$ to $10 \text{ M}\Omega$ to be excited with a known frequency of up to 100 kHz. AD5933 is just of a penny size, thus it provides a solution for self-contained miniaturized impedance measuring. Therefore, AD5933 has been used as a core component in developing a wireless impedance sensor node for SHM applications (Mascarenas et al. 2007, 2009, Overly et al. 2007, 2008, Taylor et al. 2009a, b, Park et al. 2009a).

The wireless sensor node, proposed in this paper, has extended the previous researches for multifunctional and environment-friendly uses in the impedance-based SHM (Mascarenas et al. 2007, Park et al. 2009a). It was designed by adding: (1) optimal arrangement of each chip for low power consumption, (2) energy harvester equipped with solar panels, (3) peer-to-peer communication by using a RF transceiver of CC2420, which enables to construct the ubiquitous sensor network, (4) internal algorithms for operations, which are optimized by using microcontroller-dependent instruction codes to boost the sensor node’s capability and (5) miniaturized hardware system fabricated as a printed circuit board (PCB) for a high quality prototype and enclosed by waterproof plastic box for applications to real structures.

The proposed wireless sensor node is composed of four functional subsystems: (1) sensing interface, (2) computational core, (3) wireless transceiver and (4) power supply. The “sensing interface” includes an interface to which a piezoelectric sensor and a temperature sensor can be connected, and an impedance chip (AD5933) for exciting a piezoelectric sensor and measuring the impedance signals. Here, NTC (Negative Temperature Coefficient) disc thermistor is equipped for temperature sensing on the structure near a piezoelectric sensor. It is a low-cost and small-size resistance type device, and is suitable for temperature ranges from $-20 ^\circ \text{C}$ to $+120 ^\circ \text{C}$ with reference resistance of 10 k$\Omega$ at $25 ^\circ \text{C}$. The “computational core” consists of a microcontroller and a serial flash memory for computational tasks and system operations with various embedded algorithms. Through embedding technologies in microcontroller, the wireless traffic can be reduced and the survival rate of transmitted data can be increased. In this sensor node, ATmega128L is adopted because it is one of high performance and low power 8-bit microcontrollers, and has 128 kilobytes of in-system self-programmable flash program memory (www.atmel.com). The “wireless transceiver” is an integral component of the wireless system, which is composed of a RF transceiver (CC2420), a balun transformer, and an antenna to communicate with a base station (Kmote-B radio module) and/or other wireless sensor nodes and to broadcast the structural condition. CC2420 is a single chip 2.4 GHz IEEE 802.15.4 compliant RF transceiver designed for low-power and low-voltage wireless applications (www.ti.com). It provides a low-cost and highly integrated solution for robust wireless communication and extensive hardware support for
Development of a low-cost multifunctional wireless impedance sensor node

Packet handling, data buffering and burst transmission. These features reduce the load on the host controller and allow CC2420 to interface low-cost microcontrollers. The sensor node can be operated by one of three type “power supply” systems: 5 V AC-plug DC adapter, 3.6-7.2 V battery, or 5 V solar power system. The power can be monitored on the microcontroller using a general ADC, which transforms the analog signals acquired from batteries to the digital signals. For stable power supply to the sensor node during operations, LDO (Low-dropout regulator) is mounted for providing a fixed 3.3 V reference output to the sensor node. Solar power system for energy harvesting consists of single crystalline silicon solar cells (120 × 60 mm²) to generate the maximum power for its size, two AA Ni-MH rechargeable batteries to stand high temperature and overcharging under sunlight and to last up to 1000 charge/discharge cycles, and a step-up DC/DC solar controller to protect the appliances and the batteries with over discharge prevention circuit. Fig. 3 shows the impedance sensor node developed in
Jiyoung Min, Seunghee Park, Chung-Bang Yun and Byunghun Song

Table 1 Features of the proposed wireless impedance sensor node

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output frequency range</td>
<td>1 ~ 100 kHz</td>
</tr>
<tr>
<td>Output frequency resolution</td>
<td>&gt; 1 Hz</td>
</tr>
<tr>
<td>Impedance range</td>
<td>1 kΩ ~ 1 MΩ</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-20 ~ 120 ºC</td>
</tr>
<tr>
<td>Temperature resolution</td>
<td>&gt; 0.03 ºC</td>
</tr>
<tr>
<td>On-board processing</td>
<td>Yes (MCU : ATMega128L)</td>
</tr>
<tr>
<td>Operating frequency</td>
<td>2.4 GHz IEEE 802.15.4 / Zigbee RF transceiver</td>
</tr>
<tr>
<td>Outdoor transmission range</td>
<td>150 m (2dBi Dipole Antenna)</td>
</tr>
<tr>
<td>Power supply options</td>
<td>5V AC-plug DC adapter; 5 V AC-plug DC adapter;</td>
</tr>
<tr>
<td></td>
<td>Commercial batteries (3.6-7.2 V); Ni-MH rechargeable batteries with solar panels (5 V)</td>
</tr>
<tr>
<td>Feature</td>
<td>150 × 100 × 70 (mm); 310 (g)</td>
</tr>
</tbody>
</table>

this study and its block diagram, and the features are described in Table 1.

The developed impedance sensor node was tested on the several operational conditions to determine the actual in-service power consumption. A multimeter was placed in line on the node’s positive voltage terminal. The current draw during each condition was recorded as: 1.3 mA in idle state, 25.8 mA during measurement, 15.2 mA during calculation, and 27.3 mA during transmission, which indicates that the maximum required power is approximately 90 mW with 3.3 V. It is slightly larger than the required power of 60 mW by Overly et al. (2008), which may be caused by additionally equipped NTC thermistor for temperature sensing, three LEDs for informing the node status by twinkling with different colors, and other operation subsystems. The required power may be reduced further with proper use of sleep modes in Overly et al. (2008).

3.2 Data control and on-board data analysis

TinyOS is the most typical open-source operating system designed for wireless embedded sensor networks. It features a component-based architecture which enables rapid innovation and implementation while minimizing code size as required by the severe memory constraints inherent in sensor networks. The proposed sensor node is based on TinyOS for system operation. On the other hand, the server is controlled by users through MATLAB® software, which is a high-level language and interactive environment to perform computationally intensive tasks faster than traditional programming languages such as C, C++, or FORTRAN, and includes a number of mathematical functions including Fourier analysis, filtering, signal processing and serial communications. Moreover, it provides GUI (graphical user interface) development environment, from which the user can easily change the control variables and monitor the wirelessly transmitted raw and/or processed data, temperature and node status such as battery condition. The serial communication is established between a server and a base station using two service daemons, which are cross-compiled using Cygwin. These daemons provide a Linux-like environment for Windows, and enable to communicate between MATLAB® (Windows) and base station/sensor node (TinyOS).

For continuous and autonomous SHM using wireless sensor nodes, it is strongly required to construct the embedded data analysis system. More power-efficient wireless SHMs could be achieved, if the measured impedance is analyzed on microcontroller of the sensor node and only the analyzed results
could be wirelessly sent to a base station. Especially, this fact is crucial for self-powered wireless sensor nodes incorporating several kinds of energy harvesters. In the proposed sensor node, multifunctional algorithms are implemented for temperature/power measurement, impedance measurement and analysis engine for both structural damage detection and sensor self-diagnosis, as shown in Fig. 4. The impedance measurement block consists of the TWI library, AD5933 control library and the default sweep function (512 points) library. Using raw data from the impedance measurement block, the embedded analysis engine optionally performs the analysis for structural damage detection and sensor self-diagnosis. Two algorithms are embedded on the microcontroller for the structural status monitoring: the RMSD metric and the temperature compensated CC metric calculated by EFS method. Sensor self-diagnosis is simply carried out calculating the slope of the imaginary part of admittance. Here, the baseline impedance is stored at the serial flash memory. Depending on input arguments, the users can get raw or processed data from the designated sensors.

3.3 Self-powered wireless system incorporated with solar cells

Power scavenging enables “place-and-forget” wireless sensor node. Considering that the necessary cost and efforts for battery maintenance and replacement may over-shadow the merits of the wireless SHM system, the ability to scavenge energy from the environment is a quite important and it permits deploying self-powered sensor nodes onto inaccessible locations. Thus, many researchers have shown interest in power scavenging and the related technologies have steeply grown. Especially, the solar power is most often used, which is produced by collecting sunlight and converting it into electricity. This is done by using solar panels, which are large flat panels made up of many individual solar cells.

In this study, a solar power system for operating a wireless sensor node is designed with single
crystalline silicon solar cells (120 × 60 mm$^2$), two AA Ni-MH rechargeable batteries (1.2 V × 2ea), and a step-up DC/DC solar controller, considering one-time measurement per day. A step-up DC/DC solar controller offers 4.8 V reference output from a lowered battery voltage of more than 2 V. This solar power system provides maximum 750 mW, which may be enough to operate the developed sensor node of 90 mW. If the larger power is needed for more frequent measurements per day, the recharging capacity of the solar power system may be increased by using higher-efficient and bigger-size solar panels and higher-voltage batteries. To validate the ability of the solar power system, a simple experiment has been carried out on an aluminum plate as shown in Fig. 5. A macro-fiber composite (MFC) patch of 47 × 25 × 0.267 mm$^3$ (2814P1 Type; Smart Material©) was surface-bonded to the aluminum specimen of 50 × 1,000 × 4 mm$^3$. The MFC is a relatively new type of PZT transducer that exhibit superior ruggedness and conformability compared to traditional piezoceramic wafers.

At the beginning, the batteries were fully recharged by an electric battery charger. Then, the experiment started at 00:00 am on 6 September, 2009. Raw impedance signals and the processed structural damage detection results were wirelessly transmitted to a base station at every 10:00 am for five days. The weather condition was changed in five days as follows: sunny (19.6-31.1 °C; cloud 0.8),

![Fig. 5 Sensor node with a solar panel](image)

![Fig. 6 Voltage monitoring of a wireless SHM system with solar cells](image)
mostly cloudy (20.9-27.9 °C; cloud 7.6), partly cloudy (21.0-29.8 °C; cloud 5.3), partly cloudy (17.9-28.6 °C; cloud 4.3), and partly cloudy (14.5-28.5 °C; cloud 6.8). Fig. 6 shows the voltage level in two AA rechargeable batteries during five days, which was measured every one hour. Although the voltage steeply declined during the measurement of impedances and on-board calculation of damage index, it was almost fully recovered in one hour under sun light. It may indicate that it is able to operate the sensor node several times per day. The recharged voltage remained on stable condition under sun light, but it decreased at 0.005 V/hour at night. When cloudy, the solar cells could not be recharged due to the lack of sun light, but it shortly returned to stable condition as the sun rose. From the above results, it may be concluded that the solar power system is able to provide a solution for maintenance-free wireless sensor nodes in spite of sensitive reaction to the environment, which would be complemented by development of the more efficient energy scavenging technologies.

4. Performance validation of wireless impedance sensor node

To investigate the performance of the wireless impedance sensor node designed and fabricated in this study, a series of experiments have been performed for structural damage identification and sensor self-diagnosis. First, the performance for impedance measurement was evaluated on an aluminum plate. Impedances measured using the wireless sensor node were compared with the impedance measured using the conventional impedance analyzer, HP4294A. Second, damages detection was carried out on a steel truss member to validate the embedded software in the sensor node. Third, experiments for sensor self-diagnosis were carried out to detect PZT sensor’s defects and bonding layer’s defects. For all of the testing performed, the wireless sensor node was powered by one 3.6 V battery. Once the measurement and data analysis were carried out in the sensor node, they were wirelessly sent to a Kmote-B radio module with a CC2420 RF transceiver that was used as a serial port interface. MATLAB® was used to import both raw data and/or on-board processed CC indices from the RF communications and to plot all the results on the end-user server PC.

4.1 Evaluation of impedance measurements on an aluminum plate

It is crucially important to validate how exactly the impedance sensor node can measure the E/M impedances for SHM applications. Therefore, the measured impedance signatures have been examined on a simple plate made from a 6063 T5 aluminum alloy. A MFC patch of 47 × 25 × 0.267 mm³ (2814P1 Type; Smart Material®) was surface-mounted using superglue (cyanoacrylate adhesive) on the specimen of 25 × 275 × 1 mm³. The test setup is shown in Fig. 7.

The impedances were recorded in a frequency range of 40-80 kHz using both a conventional impedance analyzer (HP4294A) and the wireless impedance sensor node utilizing AD5933. Fig. 8 shows the real parts and the imaginary parts of impedances obtained from both equipments. In these figures, same peak frequencies can be observed at two signatures measured by HP4294A and AD5933, although the magnitudes of the peaks and the shapes of the troughs are quite different. The difference in two signatures may be caused by the A/D conversion and the inherent electrical impedances of the internal chips. The sensing resistor of AD5933 to estimate the impedance value in the sensor node also contributes to the differences in magnitude (Overly et al. 2008). However, it does not seem to cause significant problems for SHM, because the impedance-based SHM is based on the relative difference between two normalized signals in the healthy and the concurrent conditions and
Jiyoung Min, Seunghee Park, Chung-Bang Yun and Byunghun Song

The inherent differences in magnitude may be canceled out. Furthermore, the damage indices in Eqs. (2) and (3) are based on the sum of squares of the differences, so possible errors in the measurements around the troughs do not cause significant effect to the damage indices. The current wireless sensor node is very cost-effective for real SHM applications to large structures considering that its cost is approximately 300 USD, while the cost of HP4294A is about 40,000 USD.

4.2 Damage detection on a steel truss member

The second experiment was carried out to check the feasibility of damage detection on a steel truss member under temperature varying condition. A MFC patch of $47 \times 25 \times 0.267$ mm$^3$ (2814P1 Type; Smart Material®) was mounted using superglue on the surface of the laboratory-scale model ($150 \times 150 \times 530$ mm$^3$) of a vertical truss member of Seongsu Bridge, Korea, which caused the collapse the bridge in 1994. The specimen is composed of two segments with wide flange sections of different flange thicknesses of 6 and 3 mm welded together as in Fig. 9. An artificial crack was inflicted by
cutting the flanges sequentially (10, 20, 30 and 40 mm) using electric saw on the left side of the welded zone. The MFC patch was attached at a location 120 mm apart from the crack. Then the increase of the crack length is monitored using the wireless sensor node. The maximum temperature variation obtained from a NTC thermistor was 10 ºC.

To test the ability of the embedded structural damage diagnosis algorithm in the microprocessor, the impedance measurements in the frequency range of 46.5-51.5 kHz were taken for an intact and each of four damage cases as shown in Fig. 10. It is clear from this figure that real parts of impedances show large variations of peaks in the whole frequency range as the level of the crack length is also increased, while imaginary parts do not change remarkably. It means that the damage mainly affects on the real part of the impedance rather than on the imaginary part (Bhalla et al. 2002). Then, both conventional and temperature-compensated CC values, defined in Eqs. (3) and (4), were calculated using real parts of impedances as shown in Fig. 11. It should be noted that temperature-compensated CC values were computed in the microprocessor of the sensor node. The conventional CC metric showed fairly large fluctuation due to the temperature variation even at the same damage condition and could not correctly distinguish Cases II and III, but the temperature-compensated CC damage metric clearly identified the all damage cases by showing significant distinctions for different damage severities.

![Fig. 9 Laboratory-scale model of a steel truss member of Seongsu Bridge](image1)

![Fig. 10 Measured impedance signatures at baseline and damage cases](image2)
4.3 Sensor self-diagnosis using embedded software

A piezoelectric sensor diagnostic procedure based on electrical admittance measurements was implemented in the developed sensor node. The basis of the sensor diagnostic procedure is to track changes in the capacitive value of piezoelectric materials manifested in the imaginary parts of the measured electrical admittances. The structural damage induces changes in the real parts of the admittance signatures, while the sensor failure results in changes to the imaginary parts of the admittance signatures distinctively causing a decrease (sensor breakage) and an increase (de-bonding between PZT transducers and the host) in the capacitive value (Park et al. 2006).

In order to determine the performance of the sensor node in sensor diagnosis, an experiment was carried out on an aluminum plate of $1000 \times 1100 \times 1 \text{ mm}^3$ as in Fig. 12. First, four PZTs (PIC151 Type; PI©) with different sizes (1/4-, 1/2-, 3/4- and full sized) were surface-attached using superglue on an aluminum plate to investigate the effects of sensor’s fracture. The perfect size of the sensor is $10 \times$
Development of a low-cost multifunctional wireless impedance sensor node

10 × 0.2 mm³. Second, other four PZTs (PIC151 Type; PI©) with different bonding area (1/4-, 1/2-, 3/4- and perfect bonding) were also attached on the surface of the same aluminum plate to see the effects of the bonding layer’s defects. Cellular tapes were used between the sensors and the plate to simulate different de-bonding areas. Admittances were measured in the frequency range of 5-20 kHz using the sensor node. All experiments were carried out under the same temperature environment (approximately 24 °C).

Fig. 13 shows that the slope of the imaginary parts of the measured admittances decreases, as the severity of the PZT fracture increases. The sensor breakage causes a reduction in the capacitance of the PZT, which is related to the sensor quality index, α, in Eq. (5). In contrast, the increase of the de-bonding area makes slope of the imaginary parts of the admittances to increase, as shown in Fig. 14. The bonding layer’s defects are related to the bonding degradation index (β) and shear-lag index (ξ) between the bonding layer and the host structure. The present results are well-consistent with the

![Fig. 13 Effects of PZT sensor’s fracture](image1)

![Fig. 14 Effects of de-bonding of PZT sensor](image2)
previous experimental and numerical investigations of other researchers (Park et al. 2006, Overly et al. 2008, Park et al. 2009b).

5. Field applications

For the case of steel structures, most common damage types would be: 1) loose bolts at bolt-jointed members, 2) fatigue cracks at the critical members, and 3) welding defects. In this study, a series of experimental works were performed using the developed impedance sensor node to detect loosened bolts and artificial crack damages inflicted on real building and bridge structures. For all of the testing performed, the wireless sensor node was powered using one 3.6 V battery. The temperature on the structure near a PZT sensor and the voltage of the battery were monitored before impedance measurement. Temperature-compensated CC indices calculated in the microprocessor using measured impedance signals were wirelessly sent to a Kmote-B RF module. MATLAB® imported on-board processed CC values from the RF communications and plotted the results on the end-user server PC.

5.1 Loose bolt detection at the base of a steel column

The first test was carried out to monitor loosened bolts at the base of an inclined steel column (diameter of 180 mm) for a building roof as shown in Fig. 15. The base plate ($600 \times 300 \times 10 \text{ mm}^3$) is fixed to a concrete base by four bolts with a diameter of 19 mm. One sensor node was installed beside the concrete base, and connected to a PZT of $30 \times 30 \times 0.5 \text{ mm}^3$ (PIC151 Type; PF©) and a NTC thermistor bonded near Bolt #1. The monitoring of the bolted base plate started with the as-built condition without measuring the torques on the bolts. The test was carried out for 2 days. The maximum temperature variation obtained from a NTC thermistor was approximately 15 ºC.

Assuming that all the bolts were on healthy condition, E/M impedances were measured at a frequency range of 45-50 kHz and their averaged data was stored as a baseline data. This frequency range was chosen as it contains a significant dynamic interaction between the PZT and the structure with multiple resonant peaks. Then, four damage scenarios were imposed by increasing the number of bolts loosened by one full rotation in a sequence, of which the locations are described in Fig. 15. Twenty measurements were carried out for each damage case. Each measurement took about 1.5 minutes, and the interval of measurements was 25 minutes. Fig. 16 shows one set of impedance records for 5 damage cases. Then, temperature-compensated CC indices of Eq. (4) were calculated in the microcontroller unit of the sensor node and were wirelessly transmitted to the base station. Fig. 17
Development of a low-cost multifunctional wireless impedance sensor node

shows that CC values decrease significantly and consistently, as the number of loosened bolts increases. During the tests for 100 measurements in 2 days, the voltage drop in the battery was only 0.004 V from 3.483 V to 3.479 V.

5.2 Multiple damage detection on a steel girder of bridge structure

As another application for detecting damages including loosened bolts and notches, a field test has been performed on the Ramp-G bridge in Incheon, Korea. The bridge is a conventional steel box girder bridge with a reinforced concrete deck as shown in Fig. 18. It has 2 continuous spans with a total length of 90 m. The bridge has been decommissioned, so small damages could be inflicted with an authorization of the Korea Expressway Corporation. One sensor node was installed near the bolted
joint of the outer girder and connected to a PZT patch of 50 \times 50 \times 0.5 \text{ mm}^3 (\text{PIC151 Type; PI}^\text{®}) and a NTC thermistor surface-mounted at a distance of 200 mm from the bolted joint using epoxy glue. The maximum temperature variation measured from a NTC thermistor was 15 °C during the test of 2 days, and the voltage drop in the battery was 0.004 V from 3.476 V to 3.472 V.

The E/M impedances were measured at a frequency range of 45-50 kHz for the baseline. The frequency range was chosen as it contains a significant dynamic interaction between the PZT and the structure. Here, it was assumed that there were no damages in the initial condition (Case I). A series of damages were imposed as in Table 2, and tests were carried out for each case. The first damage was simulated by loosening Bolt #1 by two rotations, and then Bolt #1 was hand-tightened using a wrench. Cracks and multiple damages were induced in a sequence. Measurements were carried out 10 times for each damage case. Example cases of the measured impedance signals at different damage conditions were compared with the baseline data in Fig. 19, from which significant variations are observed for different damage cases. Fig. 20 shows temperature-compensated CC values, which were computed in the on-board microcontroller and wirelessly transmitted to a base station. It can be observed that the CC value decreases when Bolt #1 gets loosened, and it recovers almost fully as the bolt is hand-tightened. Then, the CC value decreases consistently as the damage severity increases by additional loosened bolts and artificial notches. The CC metrics for Cases 5 and 6 are found to be similar, which may be because Bolt #2, which got loosened in Case 6, is located fairly far from the sensor.
6. Conclusions

This paper presented the development of a low cost, low power but multifunctional wireless impedance sensor node for online structural health monitoring, which is incorporating an impedance chip (AD5933) for exciting a PZT sensor and measuring the impedance signals, a microcontroller (ATmega128L) for controlling and on-board signal processing, and a RF module (CC2420) for wirelessly transmitting the data to end-user PC. This sensor node can be operated using the power harvested from solar energy. For on-board signal processing, algorithms for the temperature-compensated damage detection and sensor-self diagnosis are embedded in the microcontroller based on an open-source operating system, TinyOS. Monitoring capability for temperature and power consumption is added. MATLAB®-GUI is utilized to import the raw and/or processed data from the RF communications, and plot the data on the end-user server PC. The applicability of the proposed wireless sensor node was
successfully demonstrated through a series of experimental studies for detecting loosened bolts and crack damages on laboratory-scale steel structural members and members of real building/bridge structures. The results indicate that the current wireless impedance sensor node can effectively detect structural damages and sensor damages. It is expected that the wireless impedance sensor node plays an important role in the development of cost-effective online SHM system for critical structural members.

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References


Development of a low-cost multifunctional wireless impedance sensor node


Autonomous smart sensor nodes for global and local damage detection of prestressed concrete bridges based on accelerations and impedance measurements

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Abstract. This study presents the design of autonomous smart sensor nodes for damage monitoring of tendons and girders in prestressed concrete (PSC) bridges. To achieve the objective, the following approaches are implemented. Firstly, acceleration-based and impedance-based smart sensor nodes are designed for global and local structural health monitoring (SHM). Secondly, global and local SHM methods which are suitable for damage monitoring of tendons and girders in PSC bridges are selected to alarm damage occurrence, to locate damage and to estimate severity of damage. Thirdly, an autonomous SHM scheme is designed for PSC bridges by implementing the selected SHM methods. Operation logics of the SHM methods are programmed based on the concept of the decentralized sensor network. Finally, the performance of the proposed system is experimentally evaluated for a lab-scaled PSC girder model for which a set of damage scenarios are experimentally monitored by the developed smart sensor nodes.

Keywords: autonomous; wireless; smart sensor node; prestressed concrete bridge; structural health monitoring.

1. Introduction

Structural health monitoring (SHM) systems are widely adopted to monitor the structural responses, to detect damage, and to assess the effect of damage on the structural integrity. Many researchers have developed novel sensing technologies and damage monitoring techniques for the practical SHM applications. The SHM system for long-span bridges mainly includes a number of sensors, a huge amount of signal transmitting wires, data acquisition (DAQ) instruments, and one or more centralized data storage servers. The stored data in the centralized servers are handled for off-line signal and information analysis for damage monitoring and safety evaluation. However, the costs associated with installation and maintenance of SHM systems can be very high. The high costs associated with wired SHM systems can be greatly reduced through the adoption of wireless sensors (Straser and Kiremidjian 1998, Spencer et al. 2004, Lynch et al. 2006, Nagayama et al.)

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2007, Krishnamurthy et al. 2008, Cho et al. 2008). One of great advantages for using wireless sensors is that autonomous operations for the SHM can be implemented by embedding advanced system technologies. Therefore, the new paradigm by adopting smart sensor nodes may offer an autonomous and cost-efficient SHM.

For the autonomous and cost-efficient SHM, the development of wireless sensor nodes as much as the selection of embedding SHM algorithms are important topics (Lynch et al. 2003, Nagayama 2007, Wang et al. 2007, Zimmerman et al. 2008, Lu et al. 2008). To date, many SHM algorithms have been developed to monitor the location and the severity of damage in structures (Adams et al. 1978, Stubbs and Osegueda 1990, Yun and Bahng 2000, Kim et al. 2001, 2002, 2003a, 2003b, 2010). Most of the SHM algorithms are dependent on structural types, damage characteristics and available response signals. In this study, prestressed concrete (PSC) bridges were selected as the target structural type. For the PSC bridges, the prestress force in tendon and the structural properties (i.e., mass, damping and stiffness) in concrete girder are important parameters that should be secured for its serviceability and safety against external loadings and environmental conditions.

Since 1990s, several researchers have focused on using vibration characteristics of a PSC bridge as an indication of its structural damage (Saiidi et al. 1994, Miyamoto et al. 2000, Kim et al. 2004, Jeyasehar and Sumangala 2006). Based on the previous works, however, vibration-based approaches cannot easily distinguish the two damage-types, girder damage and tendon damage, unless the information on real damages is known. The pattern of one damage-type is hard to be distinguished from another since the change in vibration characteristics may be attributed to both damage-types. These make the vibration-based structural health monitoring difficult with a single sensing device to extract vibration characteristics. Therefore, other nondestructive evaluation techniques which are complementary to vibration-based approaches should be sought.

Recently, electro-mechanical impedance-based monitoring has shown the promising success to detect minor incipient change in structural integrity at local subsystems (Liang et al. 1994, Sun et al. 1995, Park et al. 2000, Bhall and Soh 2003, Park et al. 2006). Compared to vibration-based approaches, the impedance-based method has the capability of more precisely locating damage such as crack and prestress-loss on small scale. Moreover, its local monitoring cannot characterize the entire structure, which means the global healthy state would not be easily captured to couple with the local monitoring information. Using those characteristics of the impedance-based methods, Kim et al. (2006) first proposed a combined SHM system with global vibration-based techniques and local impedance-based techniques. Also, Kim et al. (2009) used the combined system for prestress-loss monitoring in PSC bridges and Kim et al. (2010) proposed a serial hybrid SHM scheme using the global and local techniques for monitoring of PSC bridges.

This study presents the design of autonomous smart sensor nodes for damage monitoring of tendons and girders in PSC bridges. In order to achieve the objective, the following approaches are implemented. Firstly, acceleration-based and impedance-based smart sensor nodes are designed for global and local SHM. Secondly, global and local SHM methods which are suitable for damage monitoring of tendons and girders in PSC bridges are selected to alarm damage occurrence, to locate damage and to estimate severity of damage. Thirdly, an autonomous SHM scheme is designed for PSC bridges by implementing the selected SHM methods. Operation logics of the SHM methods are programmed based on the concept of the decentralized sensor network. Finally, the performance of the proposed system is experimentally evaluated for a lab-scaled PSC girder model.
Autonomous smart sensor nodes for global and local damage detection of prestressed concrete bridges

2. Design of smart sensor nodes

A smart sensor node is defined as a sensor node with the following five essential features (Nagayama 2007): 1) on-board microprocessor, 2) sensing capability, 3) wireless communication, 4) battery powered and 5) low cost. Therefore, the smart sensor node should be composed of sensors, data acquisition unit, embedded software for damage detection and wireless radio. The data acquisition system includes amplifier, anti-aliasing filter and microcontroller. The on-board computation capacity of the microcontroller satisfies for signal processing as well as information analysis for damage monitoring.

2.1 Acceleration-based smart sensor node

Based on the original design of wireless sensor node by Lynch et al. (2006), in this study, an acceleration-based smart sensor node (Acc-SSN) was designed by modifying anti-aliasing filter, MEMS (micro electro-mechanical system) accelerometer and wireless radio capacity. As shown in Fig. 1, the Acc-SSN was consisted of eight (8) components: power supply, MEMS accelerometer, coupling capacitor, amplifier, anti-aliasing (AA) filter, analog-to-digital (A/D) converter, microcontroller and wireless radio. Coupling capacitor was designed by using a high pass-filter with a cutoff-frequency of 0.1 Hz. An operational amplifier (OP-AMP) was used to amplify low-level signals such as ambient vibration signals of civil structures.

For civil structures, high-resolution A/D converters are broadly employed for SHM systems. Even though the microcontroller has an embedded A/D converter of 10 bits and 8 channels, its resolution is relatively low due to quantization error. In order to solve the problem, a four-channel 16-bit A/D converter ADS8341 (Texas Instruments Inc.) was utilized. The performance of ADS8341 was evaluated by Lynch et al. (2006). An 8-bit microcontroller ATmega128 (ATMEL co.) with low-power consumption and low-cost was selected for the Acc-SSN. The microcontroller runs for multiple tasks which include operation schedule, system control (e.g., A/D converter and wireless radio), and radio transmission. The ATmega128 has the capacity enough to perform signal processing and information analysis based on 4-byte floating-point computation. Lynch et al. (2003) evaluated the computational capacity of ATmega128 for embedded fast Fourier transform (FFT) and autoregressive (AR) model. For signal processing and information analysis, an external memory of 32 kB was adopted for the sensor nodes.

For large civil infra-structures, long-range wireless radios are generally required to ensure that smart sensor nodes can be spaced adequate distances apart. Lynch et al. (2006) selected a wireless radio 9XCite (Digi International Inc.) of 900 MHz frequency for monitoring of large civil structures. In Korea, however, wireless radios using 2.4 GHz frequency band are legally allowed to be used outdoor. Therefore, we selected a wireless radio using 2.4 GHz frequency, XBee™ (Digi International Inc.). The outdoor line-of-sight range of the wireless radio is up to 100 m. The power requirements

Fig. 1 Schematic of acceleration-based smart sensor node (Acc-SSN)
of the radio are 45 mA @ 3.3 V, 50 mA @ 3.3 V and 0.01 mA @ 3.3 V when transmitting, receiving and sleep-mode, respectively. As an anti-aliasing (AA) filter, the Butterworth low-pass filter was selected to avoid the aliasing problem. Butterworth low-pass filter is often used as anti-aliasing filter in data converter applications in which precise signal levels are required across the entire band-pass. An 8th order Butterworth low-pass filter with a cut-off frequency of 100 Hz was designed for SHM applications in civil structures.

For SHM in civil structures, ICP (integrated circuit piezoelectric) accelerometers have been broadly used due to their robustness with low-noise and high sensitivity characteristics. However, the ICP accelerometers are not suitable for smart sensor applications since they are expensive and also consume too much electrical-power relatively. Recently, MEMS accelerometers have been

Table 1 Comparison of acceleration-based smart sensor nodes

<table>
<thead>
<tr>
<th>Sensor Node</th>
<th>Lynch et al. (2006)</th>
<th>Acc-SSN (this study)</th>
</tr>
</thead>
</table>
| Microcontroller | ATmega128L (Atmel)  
- Bus Size: 8 bits  
- Clock Speed: 0 - 8 MHz  
- Flash: 128 kB  
- RAM: 128 kB (Ext.)  
- Power: 2.7-5.5 V / 5.5 mA@Active 4 MHz | ATmega128 (Atmel)  
- Bus Size: 8 bits  
- Clock Speed: 0 - 16 MHz  
- Flash: 128 kB  
- RAM: 32 kB (Ext.)  
- Power: 4.5-5.5 V / 19 mA@Active 8 MHz |
| A/D Converter | ADS8341 (Texas Instruments)  
- Resolution: 16 bits | ADS8341 (Texas Instruments)  
- Resolution: 16 bits |
| AA Filter | 4-pole Bassel Filter | 8-pole Butterworth Filter |
| Accelerometer | 3801D1FB3G (PCB Piezotronics)  
- Sensitivity: 700 mV/g  
- Range: ±1.5 g  
- Bandwidth: 80 Hz  
- Noise Floor: 150 μV/√Hz | SD1221 (Silicon Designs)  
- Sensitivity: 2000 mV/g  
- Range: ±2 g  
- Bandwidth: 400 Hz  
- Noise Floor: 5 μV/√Hz |
| Radio | 9XCite (Digi International)  
- Radio Freq.: 900 MHz  
- Data Rate: up to 57.6 kbps  
- outdoor range: 300 m  
- Power: 2.85 - 5.5V / 35 mA(RX), 50 mA(TX) | XBee (Digi International)  
- Radio Freq.: 2.4 GHz  
- Data Rate: up to 250 kbps  
- outdoor range: 100 m  
- Power: 2.8 - 3.4 V / 50 mA(RX), 45 mA(TX) |
Autonomous smart sensor nodes for global and local damage detection of prestressed concrete bridges

...developed for low costs, low power consumption and small size. Many researchers have attempted to implement the MEMS sensors for SHM in civil infrastructures. (Lynch et al. 2003, Ruiz-Sandoval et al. 2006, Nagayama 2007, Rice and Spencer 2008). In this study, SD1221 (by Silicon Designs Inc.) was selected for its high-sensitivity (2000 mV/g), low-noise density (5 μg/√Hz), and low-cost. Fig. 2 shows a prototype of the Acc-SSN developed in this study. The Acc-SSN consists of 2 layers as depicted in Fig. 2. The lower layer includes power supply (i.e., 6 V by 4 AAA batteries with 1.5 V for each battery), amplifier, AA filter, and A/D converter, while the upper layer functions for microcontroller and wireless radio chip. As summarized in Table 1, the specification of the developed Acc-SSN was compared with one by Lynch et al. (2006).

2.2 Impedance-based smart sensor node

Mascarenas et al. (2007) has worked on design of impedance-based smart sensor node (Imp-SSN). The design of the Imp-SSN is simpler than the Acc-SSN due to the multi-functional capability of AD5933 (Analog Devices) impedance chip. The AD5933 impedance chip has the following embedded multi-functional circuits: function generator, digital-to-analog (D/A) converter, current-to-voltage amplifier, anti-aliasing filter, A/D converter and discrete Fourier transform (DFT) analyzer. The AD5933 outputs real and imaginary values of impedance for a target frequency of interest and transmits the values into a microcontroller.

As a modified version, an Imp-SSN was designed as shown in Fig. 3. In the figure, two resistors are pull-up resistors for two wired interface (TWI) communication. The Imp-SSN was consisted of power supply, PZT sensor, impedance chip, microcontroller, and wireless radio. The same microcontroller (i.e., ATmeg128) and wireless radio (i.e., XBee™) used for the Acc-SSN were also adopted for the...
Imp-SSN. The microcontroller runs for multiple tasks which include operation schedule, system control (e.g., AD5933 impedance chip and wireless radio), and radio transmission. A prototype of the Imp-SSN developed in this study is shown in Fig. 4. As summarized in Table 2, the specification of the developed Imp-SSN was compared with a commercial impedance analyzer HIOKI 3532-50 (HIOKI E.E. Co.). Note that the measurable frequency range of the Imp-SSN is quite narrower than the commercial impedance analyzer.

Output values from the AD5933 impedance chip should be calibrated by using a feedback resistor (RFB), sensing on-board temperature, and measuring a resistor for the calibration (Analog Devices 2009). Furthermore, the output values were calibrated by comparing to impedance signals of the commercial impedance analyzer, HIOKI 3532-50.

### Table 2 Specification of impedance-based smart sensor node (Imp-SSN) and commercial impedance analyzer (HIOKI 3532-50)

<table>
<thead>
<tr>
<th></th>
<th>Imp-SSN</th>
<th>HIOKI 3532-50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impedance range</td>
<td>1 kΩ - 10 MΩ</td>
<td>10 mΩ - 200 MΩ</td>
</tr>
<tr>
<td>Frequency range</td>
<td>1 kHz - 100 kHz</td>
<td>42 Hz - 5 MHz</td>
</tr>
<tr>
<td>Excitation voltage</td>
<td>1.98 Vp-p</td>
<td>14 Vp-p</td>
</tr>
<tr>
<td>Cost</td>
<td>US $ 100</td>
<td>US $ 15,000</td>
</tr>
</tbody>
</table>

The selection of SHM methods for the smart sensor nodes should be based on target structures, their inherent damage types, and the variety of extracted features. In this study, global and local SHM methods which are suitable for monitoring of PSC bridges were selected to alarm the occurrence of damage, to detect the location of damage, and to estimate the severity of damage. The selected global SHM methods are frequency response ratio assurance criterion, prestress-loss prediction model, and modal strain-energy (MSE)-based damage index. Also, the selected local SHM method is an impedance-based method using root-mean-square deviation. For each SHM method, the theory of approach is described in detail.

#### 3.1 Frequency response ratio assurance criterion (FRRAC)

Kim et al. (2009) proposed a global damage alarming indicator using the displacement ratio in frequency domain (i.e., frequency-response-ratio, FRR) between two outputs at difference locations. A frequency-response-ratio (FRR) function between the locations $i$ and $i+1$ is defined as

\[
FRR_{i,i+1}(\omega) = \frac{S_{i,i+1}(\omega)}{S_{i+1,i+1}(\omega)} = \frac{H_i(\omega)}{H_{i+1}(\omega)}
\]  

where $H_i(\omega)$ and $H_{i+1}(\omega)$ are frequency response functions (FRFs) measured at locations $i$ and $i+1$, respectively; and $S_{i+1,i+1}(\omega)$ and $S_{i,i+1}(\omega)$ are cross-spectral and auto-spectral density functions, respectively. By comparing a frequency-response-ratio measured at an undamaged baseline state to the corresponding one at a subsequent damaged state, a frequency-response-ratio assurance criterion (FRRAC) can be defined as follows...
where the subscripts \( b \) and \( d \) denote the undamaged baseline state and its corresponding damaged state, respectively. Eq. (2) represents the linear relationship between the pre-damaged frequency-response-ratio, \( FRR_b \), and the post-damage frequency-response ratio, \( FRR_d \). The FRRAC equals to the unity if no damage. Otherwise, the FRRAC is less than the unity.

In real applications, however, the FRRAC may be less than 1.0 although damage is not occurred. This is due to experimental and environmental errors. In order to discriminate damage occurrence from those errors, the control chart analysis is utilized (Sohn et al. 2003). By noticing the nature of the FRRAC, the lower control limit (LCL) was adopted as follows

\[
LCL_{FRRAC} = \mu_{FRRAC} - 3 \sigma_{FRRAC}
\]

where \( \mu_{FRRAC} \) and \( \sigma_{FRRAC} \) are mean and standard deviation of FRRACs, respectively. The occurrence of damage is indicated when the FRRAC is beyond (i.e., less than) the bound of the LCL. Otherwise, there is no indication of damage occurrence.

### 3.2 Prestress-loss prediction model

For PSC bridges, Kim et al. (2004) proposed a frequency-based prestress-loss prediction model based on the concept of equivalent flexural rigidity for cable under uniform tension. The relative change in prestress forces is estimated by the fractional change in natural frequencies measured from the PSC beam.

\[
\left( \frac{\delta N}{N} \right)_n = \frac{\delta \omega_n^2 - \delta \sigma_n^2}{\omega_n^2 - \sigma_n^2}
\]

where \( N \) is the prestress force; \( \omega_n \) is the eigenvalue for the \( n^{th} \) mode; and \( \sigma_n \) is the \( n^{th} \) eigenvalue of the beam with zero prestress force. From the Eq. (4), the relative change in prestress force can be estimated by measuring changes in natural frequency due to changes in prestress forces. Eq. (4) can be simplified by further assuming no change in concrete flexural rigidity occurred due to the prestress-loss, i.e., \( \delta \sigma_n = 0 \). In existing real structures, however, \( \sigma_n \) may not be available unless measured at as-built state. As an alternative way, \( \sigma_n \) can be estimated from a numerical analysis using system identification process.

### 3.3 Modal strain energy-based damage index

Modal strain energy (MSE) is one of the damage sensitive features because it uses mode-shape curvatures. The MSE-based damage index method is based on the decrease in modal strain energy between two structural DOFs (Kim et al. 2003). The MSE-based damage index is defined as

\[
\beta_j = \frac{E_i}{E_j} \frac{\Phi_i^T \Phi_j}{[\Phi_i^T[K_0 \Phi_j]^{-1}] K_j}
\]

where \( \beta_j \) and \( E_j \) represent the MSE-based damage index and material stiffness for the \( j^{th} \) member, respectively. The symbol \( \Phi_i \) represent the \( i^{th} \) modal vector; \( K_0 \) involves only geometric quantities; and
$K_i$ is $i^{th}$ modal stiffness and the symbol (\textasciitilde) denotes damaged state. The damage indices are also normalized according to the standard rule as

$$Z_j = \frac{(\beta_j - \mu_\beta)}{\sigma_\beta}$$

(6)

where $Z_j$ is the standard normalized damage index of the element $j$. The symbols $\mu_\beta$ and $\sigma_\beta$ represent the mean and standard deviation of the collection of $\beta$ values, respectively. The beam elements are next assigned to a damage class by utilizing hypothesis testing. The null hypothesis (i.e., $H_0$) is taken to be the structure undamaged at the $j^{th}$ element and the alternate hypothesis (i.e., $H_1$) is taken to be the structure damaged at the $j^{th}$ element. In assigning damage to a particular location, the following decision rule was utilized: (1) choose $H_1$ if $Z_j \geq z_o$; and (2) choose $H_0$ if $Z_j < z_o$, where $z_o$ is number which depends upon the confidence level of the localization test. Then damage is assigned to a particular location $j$ if $Z_j$ exceeds the confidence level.

3.4 Root-mean-square-deviation (RMSD) of impedance signature

Impedance-based damage detection techniques utilize piezoelectric materials as sensors and actuators (Liang et al. 1994, Park et al. 2000, Bhalla and Soh 2003, Park et al. 2006). The electrical impedance of the piezoelectric patch bonded onto a host structure is directly related to the mechanical impedance of the structure. When damage occurs to a structure, its mechanical impedance will be changed. Hence, any changes in the electrical impedance signature (such as magnitude of admittance and resonant frequency) are attributed to damage or changes in the structure.

To quantify the change in impedance signature due to damage in the structure, the root-mean-square-deviation (RMSD) of impedance signatures measured before and after damage (Sun et al. 1995) was used in this study. The RMSD is calculated from impedance measurements before and after damage as

$$RMSD = \sqrt{\frac{1}{N} \sum_{i=1}^{N} [Z'(\omega_i) - Z(\omega_i)]^2 / \sum_{i=1}^{N} [Z(\omega_i)]^2}$$

(7)

where $Z(\omega_i)$ and $Z'(\omega_i)$ are impedances measured before and after damage for $i^{th}$ frequency, respectively; and $N$ denotes the number of frequency points in the sweep. The $RMSD$ equals to 0 if no damage. Otherwise, the $RMSD$ is larger than 0.

Due to experimental and environmental errors, however, the RMSD may be larger than 0 although damage is not occurred. By noticing the nature of the RMSD values, the upper control limit (UCL) is adopted for alarming damage occurrence, as follows

$$UCL_{RMSD} = \mu_{RMSD} + 3\sigma_{RMSD}$$

(8)

where $\mu_{RMSD}$ and $\sigma_{RMSD}$ are mean and standard deviation of RMSDs, respectively. The occurrence of damage is indicated when the RMSD values are beyond (i.e., larger than) the bound of the UCL. Otherwise, there is no indication of damage occurrence.
4. Autonomous SHM scheme for smart sensor nodes

The autonomous SHM scheme used for smart sensor nodes are based on the decentralized wireless sensor network, as schematized in Fig. 5(b). Compared to the centralized sensor network as shown in Fig. 5(a), each sensor node in the decentralized network performs multiple tasks including acquiring signals, analyzing information and computing data for decision-making process. In this study, the autonomous SHM scheme includes three vibration-based SHM methods and one impedance-based SHM method, as described previously. Note that the vibration-based SHM methods are embedded in the acceleration-based sensor nodes (i.e., Acc-SSNs) and the impedance-based SHM method is embedded in the impedance-based sensor node (i.e., Imp-SSNs). For the autonomous SHM, operation logics of the SHM methods are programmed for embedding into the smart sensor nodes. Finally, an autonomous SHM scheme is designed for PSC bridges by implementing the operation logics of the SHM methods.

4.1 Operation logics of SHM methods

4.1.1 FRRAC

The operation logic of FRRAC was designed as shown in Fig. 6. For the FRRAC, two sensor nodes (i.e., Acc-SSN \(i\) and Acc-SSN \(j\)) installed at damage-sensitive locations should be selected. The smart sensor nodes operate: 1) to acquire acceleration signals \(\{y_i(t)\}\) \(y_j(t)\), 2) to compute frequency responses \(\{Y_i(\omega)\} Y_j(\omega)\), 3) to calculate FRR of Eq. (1), 4) to calculate FRRAC of Eq. (2) and 5) to determine the occurrence of damage by control chart analysis (i.e., Eq. (3)).

4.1.2 Prestress-loss prediction model

As shown in Fig. 7, the operation logic of prestress-loss prediction model was designed by using the peer-to-peer network. For the prestress-loss prediction model, one (1) sensor node (i.e., Acc-SSN \(i\)) installed at a damage-sensitive location should be selected. Then, the smart sensor node operates: 1) to acquire acceleration signals \(y_i(t)\), 2) to compute frequency response \(Y_i(\omega)\), 3) to extract natural frequencies and 4) to estimate prestress-loss by the prestress-loss prediction model of Eq. (4).

Fig. 5 Comparison of centralized and decentralized wireless sensor networks
4.1.3 MSE-based damage index

In order to calculate MSE-based damage index, modal parameters such as natural frequencies and mode shapes of a structure should be extracted. In this study, the frequency domain decomposition...
Autonomous smart sensor nodes for global and local damage detection of prestressed concrete bridges

(FDD) technique (Yi and Yun 2004) was employed for modal parameter extraction. Based on the decentralized wireless sensor networks, the operation logic of MSE-based damage index was designed as shown in Fig. 8. The captain sensor node (Acc-SSN i) should be located at a sensitive point in order to measure appropriate vibration modes with less noise effect. The smart sensor nodes operate: 1) to acquire acceleration signals \( y_k(t), k = 1, \ldots, n \), 2) to compute frequency responses \( Y_k(\omega), k = 1, \ldots, i, \ldots, n \), 3) to compute cross-spectral densities between two FFT results \( CSD(k,i) \), \( k = 1, \ldots, n \), 4) to extract modal vectors by the FDD technique, 5) to assemble the received modal vectors and calculate MSEs and 6) to locate damage by using the MSE-based damage index (i.e., Eqs. (5) and (6)).

4.1.4 RMSD of impedance signature

Based on the wireless sensor network, the operation logic of impedance-based method using RMSD was designed as shown in Fig. 9. The Imp-SSNs are installed near the tendons to monitor prestress-loss of PSC bridges. The smart sensor nodes operate: 1) to acquire impedance signatures \( Z_i(\omega), i = 1, \ldots, n \), 2) to compute RMSD of impedance features, 3) to determine the occurrence of damage by control chart analysis (i.e., Eq. (8)) and 4) to assemble the damage detection results and determine damaged members.

4.2 Autonomous SHM scheme

Based on the hybrid SHM method proposed by Kim et al. (2010), a modified SHM scheme was
designed to monitor PSC bridges. The basic idea of the scheme is that the global SHM method is used for alarming damage occurrence in global structure level and, at the same moment, the local SHM method is used for pin-pointing damage occurrence at prescribed local member level. Note that global methods using accelerations can detect structural changes (e.g., crack, added-mass and tension loss of tendon) from a sensor in an overall structure, while local methods using impedances can detect damage in only a specific structural member (or sub-structure) near an attached sensor. Then, the type of alarmed damage is classified by recognizing the patterns of the SHM results. In this study, the autonomous operation scheme for hybrid SHM was designed based on the four operation logics of SHM methods, as described previously (i.e., Figs. 6-9). The scheme consists of three phases, in which each operation phase is described in detail as follows:

**Phase I: Global and local alarming process**

Step 1) Acc-SSNs and Imp-SSNs measure acceleration and impedance signals, respectively.
Step 2) Acc-SSNs calculate frequency response ratio (FRR) of Eq. (1), natural frequencies, and mode shapes, and Imp-SSNs calculate RMSD of Eq. (7).
Step 3) Acc-SSNs compute FRRAC indices of Eq. (2) and their control limits of Eq. (3) to monitor global damage alarming. Imp-SSNs calculate their control limits of Eq. (8) to monitor local damage alarming.

**Phase II: Damage classification process**

Step 4) The captain Imp-SSN transmits local damage information to the captain Acc-SSN. Then, the captain Acc-SSN assembles the global and local damage information;
Step 5) By making decision based on the global alarming of Acc-SSNs and the local alarming of Imp-SSNs, the captain Acc-SSN classifies the damage into one of four classes;

1. Class 1: ‘No Damage Occurrence’ if the global alarming indicates ‘OFF’ and the local alarming also indicates ‘OFF’.

![Fig. 9 Operation logic of impedance-based method using RMSD](image)
Class 2: ‘Occurrence of Girder Damage and Tendon Damage’ if the global alarming indicates ‘ON’ and the local alarming also indicates ‘ON’.

Class 3: ‘Occurrence of Girder Damage’ if the global alarming indicates ‘ON’ but the local alarming indicates ‘OFF’.

Class 4: ‘Occurrence of Minor Tendon Damage’ if the global alarming indicates ‘OFF’ but the local alarming indicates ‘ON’.

Phase III: Detailed damage estimation process
Step 6) The captain Acc-SSN performs detailed damage estimation for the classified damage. Tendon damage is estimated by the frequency-based prestress-loss prediction model of Eq. (4). Girder damage is estimated by the MSE-based damage index of Eqs. (5) and (6).
Step 7) The captain Acc-SSN transmits the monitoring results to the Remote Control Server.

5. Experimental evaluation

5.1 Experimental setup and preliminary tests

A lab-scaled PSC girder model was used to verify the proposed autonomous operation schemes using the smart sensor nodes. The girder with T-beam section has the span length of 6 m (see the Kim et al. (2010) for detailed description on the structure). Locations and arrangements of the acceleration-based smart sensor nodes (Acc-SSNs) and conventional accelerometers on the test structure were designed as shown in Fig. 10. Seven Acc-SSNs (Acc-SSN 1–7) were placed along the girder with constant interval. As shown in Fig. 10, seven conventional accelerometers PCB393B04 (PCB 1–7) were also located at the side of the Acc-SSNs. The conventional accelerometers were used to compare the performance of the developed Acc-SSNs.

The impact excitation was applied by an electro-magnetic shaker (VTS100) at a location 1.7 m distanced from the right edge. Impact force, which has 444.5 N intensity, was applied to the PSC girder by the electro-magnetic shaker. As shown in Fig. 11(a), dynamic responses in vertical direction were measured from the Acc-SSNs and the corresponding 7 commercial sensors with a sampling frequency of 500 Hz. The commercial data acquisition system includes a 16-channel signal conditioner (PCB 481A03), a 16 channel DAQ (NI-6036E) card, and a laptop with MATLAB. Fig. 11(b) shows frequency responses acquired from the Acc-SSNs and the commercial system. The
responses from the Acc-SSNs and the commercial system show good matches with little difference.

For impedance measurement, two PZT sensors, PZT 1 and PZT 2, were placed on the anchor plate and the interface washer, respectively, as shown in Fig. 12(a). In this study, an aluminum plate was installed as the interface washer between the anchor plate and the wedge of tendon. The interface washer was specially adopted to improve the sensitivity of the Imp-SSN which has the limited measurable frequency range. The PZT sensors, both PZT 1 and PZT 2, were 25 × 25 mm, PZT 5A type patch. Also, the Imp-SSN was placed near the PZT sensors as shown in Fig. 12(b). A set of sweep tests was performed by using a commercial impedance analyzer in order to determine the range for frequency sweep between 10 kHz and 100 kHz. The commercial data acquisition system includes an impedance analyzer HIOKI 3532, a GPIB interface, and a laptop computer with LabVIEW software. The input voltage into the PZT sensor by the HIOKI 3532 was set up as 1.98 \( V_{p-p} \), which is the same as the maximum output voltage of the Imp-SSN as listed in Table 2.

Fig. 13(a) shows the impedance signatures measured from the PZT 1 sensor on the anchor plate. In the figure, no peak point was meaningfully recurred, from repeated measurements, in the scanned 10 kHz - 23 kHz frequency range. Fig. 13(b) shows the impedance signatures measured from the PZT 2 sensor on the interface washer. In the figure, a recurring peak point, from repeated sweep tests, was found in a narrow range of 16.5 - 17.5 kHz in the scanned 10 kHz - 23 kHz frequency range.
From these sweep test results, the PZT 2 sensor on the interface washer was selected to monitor the change in impedance signatures due to damage occurrence in tendon-anchor subsystems. From the measurements by the Imp-SSN and the commercial analyzer, as shown in Fig. 14, a feasible peak point was coincided at 17.1 kHz in the narrow frequency range of 16.5 - 17.5 kHz. Those two impedance signals show good matches with little difference. The change in impedance signatures due to change in structural condition is more sensitive near the peak point.

### Table 3 Damage scenarios for girder and tendon (GT)

<table>
<thead>
<tr>
<th>Damage case</th>
<th>Prestress force (kN)</th>
<th>Added Mass (kN)</th>
<th>Girder damage</th>
<th>Location (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undamage</td>
<td>98.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GT1</td>
<td>98.0</td>
<td>1.2</td>
<td>2.7 - 3.2</td>
<td></td>
</tr>
<tr>
<td>GT2</td>
<td>88.2</td>
<td>0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>GT3</td>
<td>78.4</td>
<td>2.4</td>
<td>2.7 - 3.2</td>
<td></td>
</tr>
</tbody>
</table>
As shown in Table 3, a few mixed damage scenarios combining girder damage and tendon damage. Damage scenarios are three cases: GT1, GT2 and GT3. The first damage case (GT1) is to simulate the girder damage by added mass (Kim et al. 2010). The added mass may not be referred as damage; however, it was treated as a damaging event for the evaluation purpose since the increment of mass results in similar effect as the decrement of stiffness caused by a crack. The second damage case (GT2) is to introduce tendon damage by prestress-loss. The last case (GT3) is to simulate girder and tendon damages simultaneously occurred in the PSC girder model.

5.2 SHM results of smart sensor nodes

For the three damage cases (i.e., GT1, GT2 and GT3), the autonomous operation scheme embedded in the smart sensor nodes were performed for damage occurrence monitoring, damage classification, and detailed damage estimation for the PSC girder model. The seven Acc-SSNs shown in Fig. 10 were used for the global health monitoring. Also, an Imp-SSN installed only at the tendon anchor as shown in Figs. 10 and 12 was used for the local health monitoring.

For the damage case GT1, as shown in Fig. 15, the global alarming results and the local monitoring results were obtained by the Acc-SSNs and the Imp-SSN, respectively. First, FRRAC values were obtained from Acc-SSN5 and Acc-SSN6. As shown in Fig. 15(a), the monitored FRRAC values are beyond the bound of lower control limit (LCL). This indicates that the damage is globally alarmed by the Acc-SSNs. Next, as shown in Fig. 15(b), the RMSD values monitored from the Imp-SSN are within the bound of upper control limit (UCL). This indicates that the damage is not locally alarmed by the Imp-SSNs. Upon receiving monitoring results (i.e., Global Alarming ‘ON’ and Local Alarming ‘OFF’ as described in Chapter 4), the captain Acc-SSN5 classified the situation as ‘Class 3: Occurrence of Girder Damage’, as categorized in Section 4.2. Next, Acc-SSNs performed the detailed damage estimation by using the MSE-based damage index method for girder damage. As shown in Fig. 15(c), the damage was accurately located by the MSE-based damage index method embedded in the captain Acc-SSN5.

For the damage case GT2, as shown in Fig. 16, the damage alarming results were obtained by the Acc-SSNs and the Imp-SSN, respectively. First, as shown in Fig. 16(a), the FRRAC values are beyond the LCL bound. Next, as shown in Fig. 16(b), the RMSD values are also beyond the UCL bound. Note that the LCL and UCL values in Figs. 16(a) and (b) were recalculated from measured data after removing the added mass in the damage case GT1, so that the values are different from the values in Figs. 15(a) and (b). Upon receiving those monitoring results (i.e., Global Alarming ‘ON’
Autonomous smart sensor nodes for global and local damage detection of prestressed concrete bridges

and Local Alarming ‘ON’), the captain Acc-SSN5 classified the situation as ‘Class 2: Occurrence of Tendon Damage and Girder Damage’. Next, Acc-SSNs performed the detailed damage estimation by using both the MSE-based damage index method for girder damage and the frequency-based prestress-loss prediction model for tendon damage. Fig. 16(c) shows damage estimation results by the MSE-based damage index method. Fig. 16(d) shows damage estimation results by the prestress-loss prediction model. The tendon damage was estimated with good accuracy; however, the girder damage was indicated near mid-span even though there was no girder damage inflicted to the test (i.e., false positive prediction).

For the damage case GT3, as shown in Fig. 17, the damage alarming results were obtained by the Acc-SSNs and the Imp-SSN, respectively. The FRRAC values were beyond the LCL bound as indicating the occurrence of global damage. The RMSD values were beyond the UCL bound, as also indicating the local damage occurrence. Note that the LCL and UCL values in Figs. 17(a) and (b) were recalculated from measured data after resetting the reduced prestress-force in the damage case GT2, so that the values are different from the values in Figs. 16(a) and (b). Upon receiving those monitoring results (i.e., Global Alarming ‘ON’ and Local Alarming ‘ON’), the captain Acc-SSN5 classified the event as ‘Class 2: Occurrence of Tendon Damage and Girder Damage’. Next, the Acc-SSNs performed detailed damage estimation as shown in Figs. 17(c) and (d), respectively. Fig. 17(c) shows damage estimation results by the MSE-based damage index method. Fig. 17(d) shows
damage estimation results by the prestress-loss prediction model. The girder damage was located with good accuracy; however, the tendon damage was estimated with very large error since the girder damage as well as the tendon damage causes the change in natural frequencies of the PSC girder model.

6. Conclusions

In this study, autonomous smart sensor nodes were designed for damage monitoring of tendons and girders in PSC bridges. To achieve the objective, the following approaches were implemented. Firstly, acceleration-based and impedance-based smart sensor nodes were designed for global and local SHM. Secondly, global and local SHM methods suitable for damage monitoring of tendons and girders in PSC bridges were selected. Thirdly, an autonomous SHM scheme was designed for PSC bridges by implementing the selected SHM methods. Operation logics of the SHM methods were programmed based on the concept of the decentralized sensor network. Finally, the performance of the proposed system was experimentally evaluated in a lab-scaled PSC girder model.

From the experimental evaluation, the smart sensor nodes accurately alarmed the occurrence of damage in tendon and girder of the PSC girder model. In the case of girder damage, the smart sensor nodes successfully classified its damage type and detected damage location with good accuracy. In
the case of tendon damage, the prestress-loss was estimated with good accuracy; however, the girder
damage was false-alarmed. In the mixed case of tendon damage and girder damage, the girder
damage was located near mid-span with good accuracy but the prestress-loss was estimated with
relatively large error.

In order to improve the accuracy of damage estimation, the autonomous SHM scheme embedded
in smart sensor nodes should be improved to appropriately reflect the mixed damage scenarios of
the PSC bridges. Furthermore, the smart sensor nodes should be improved for field applications by
dealing with temperature-induced uncertainty and power management problem. Energy harvesting
may be considered in conjunction with the smart sensor nodes to overcome the limitation of power
supply.

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Concrete structural health monitoring using piezoceramic-based wireless sensor networks

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Abstract. Impact detection and health monitoring are very important tasks for civil infrastructures, such as bridges. Piezoceramic based transducers are widely researched for these tasks due to the piezoceramic material’s inherent advantages of dual sensing and actuation ability, which enables the active sensing method for structural health monitoring with a network of piezoceramic transducers. Wireless sensor networks, which are easy for deployment, have great potential in health monitoring systems for large civil infrastructures to identify early-age damages. However, most commercial wireless sensor networks are general purpose and may not be optimized for a network of piezoceramic based transducers. Wireless networks of piezoceramic transducers for active sensing have special requirements, such as relatively high sampling rate (at a few-thousand Hz), incorporation of an amplifier for the piezoceramic element for actuation, and low energy consumption for actuation. In this paper, a wireless network is specially designed for piezoceramic transducers to implement impact detection and active sensing for structural health monitoring. A power efficient embedded system is designed to form the wireless sensor network that is capable of high sampling rate. A 32 bit RISC wireless microcontroller is chosen as the main processor. Detailed design of the hardware system and software system of the wireless sensor network is presented in this paper. To verify the functionality of the wireless sensor network, it is deployed on a two-story concrete frame with embedded piezoceramic transducers, and the active sensing property of piezoceramic material is used to detect the damage in the structure. Experimental results show that the wireless sensor network can effectively implement active sensing and impact detection with high sampling rate while maintaining low power consumption by performing offline data processing and minimizing wireless communication.

Keywords: wireless sensor network; impact detection; structural health monitoring; embedded system; piezoceramic sensor.

1. Introduction

Structural Health Monitoring (SHM) systems are important for structures, such as buildings and bridges, since they can diagnose the condition of structures and prevent the potential danger of collapse by detecting structural faults at early stages (Farrar and Worden 2007). Piezoelectric materials, due to their advantages of active sensing, low cost, quick response, availability in different shapes, and simplicity for implementation (Viscardi and Lecce 2002), have been successfully applied to structural health monitoring of concrete structures in either impedance-based methods (Bahel-el-din et al. 2003,
Tseng and Wang 2004) or vibration-characteristic-based methods (Mevelet et al. 2000, Song et al. 2005, Song et al. 2008). Piezoceramic-based smart aggregate (SA) is a single transducer which can perform early-age strength monitoring (Gu et al. 2006), impact detection (Song et al. 2007c), and structural health monitoring for concrete structures (Song et al. 2007a, Song et al. 2008), especially for concrete infrastructures, such as concrete bridges. A smart aggregate (SA) is a one-cubic inch precast concrete block with a wired embedded PZT (Lead Zirconate Titanate, a type of piezoceramic) patch (Song et al. 2007b).

Most existing SHM implementations use wired data network systems to collect structural health information. A wired sensor network simplifies the hardware design of the system; however, it generates additional problems, such as wiring and maintenance of the network. Installing a large scale wired networked data acquisition system may sometimes take several weeks and often turns out to be prohibitively expensive (Pottie and Kaiser 2000). Wiring sensors to a central node in a large structure is cumbersome and sometimes the wires may cost more than the sensors and the controllers. Recent advances in sensing and networking technologies have led to the emergence of wireless sensor networks (WSNs). Composed of a large number of small, intelligent sensor nodes, WSNs have started replacing centralized sensing and control systems with a distributed alternative (Mechitov et al. 2004).

Data acquisition systems based on WSNs promise enormous benefits, such as easy and flexible deployment in addition to low maintenance and deployment costs. WSNs are also attractive since they offer increased robustness through decentralization. For example, a distributed sensor network would continue to function at diminished capacity even when it experiences the failure of a large fraction of the sensors. Although WSNs bring much benefit, transferring data wirelessly tends to be more complex than that in wired systems. Wireless protocols have stringent demands on frequencies, data formats, timing of data transfers, security and other issues. Application development must consider the requirements of the wireless network in addition to product functionalities and user interfaces. The key design requirements for the wireless sensor nodes are cost, size, power, heterogeneity and robustness (Wu et al. 2007).

The goal of structural health monitoring (SHM) is to determine the condition of the monitored structure and identify potential problems at an early stage by examining the output of sensors attached to or embedded in the structure. In this paper, piezoelectric based smart aggregates (SAs) are used to form a distributed intelligent wireless sensor network (WSN) to address the important issues associated with concrete structures. Structural health monitoring is addressed via the active sensing approach where a swept sine signal is used to excite the SA as an actuator. Impact detection is performed by using the SA’s passive sensing capacity, which is an inherent property of a piezoceramic material. Piezoceramic-based structural health monitoring systems have special requirement for the data acquisition systems, such as high sampling rate and high computational power for data processing, all of which require a relatively powerful processor. On the other hand, the battery powered wireless sensor network has strict limitation on power consumption to achieve longer life cycles. The design of the embedded wireless system for structural health monitoring must balance between the computational power and the power consumption to achieve optimal performances. In this paper, a wireless network is specially designed for piezoceramic transducers to implement impact detection and active sensing for structural health monitoring. A power efficient embedded system is designed to form the wireless sensor network that is capable of high sampling rate while maintaining low power consumption. Detailed design of the hardware system and software system of the wireless sensor network is presented in this paper. A two-story concrete frame with embedded SAs is used as the test structure to evaluate the developed wireless sensor network.
2. Basics about the piezoceramic-based smart aggregate

In this paper, the smart aggregates (SAs) shown in Fig. 1 were formed by embedding a water-proof piezoceramic patch with lead wires into a small concrete block before casting the smart aggregate into a larger concrete structure. Piezoceramic transducers are very fragile and can be easily damaged by the vibrator during the casting of concrete structures. In order to protect the fragile piezoelectric transducer, the piezoceramic patch is first coated with insulation to prevent water and moisture damage then embedded into a small concrete block to form a smart aggregate, as shown in Fig. 2. The piezoceramic material will generate electric charge when it is subjected to a stress or strain (the direct piezoelectric effect); the piezoceramic material will also produce a stress or strain when an electric field is applied to a piezoelectric material in its poled direction (the converse piezoelectric effect). Due to this special piezoelectric property, piezoelectric material can be utilized as both an actuator and a sensor. In this research, PZT (Lead Zirconate Titanate) type of piezoceramic material is used due to its advantage of high piezoelectric effect, high bandwidth and close-to-linear operation. The smart aggregate has been successfully used in the health monitoring of various concrete structures, such as concrete bridge bent-cap (Song et al. 2007b), shear wall (Yan et al. 2009), concrete column (Liao et al. 2008) and concrete frame (Laskar et al. 2009).

3. Principle for wireless SHM

The smart aggregate-based wireless active sensing system, as shown in Fig. 3, uses one smart aggregate as an actuator to generate excitation waves. The piezoceramic transducers in the other, distributed smart aggregates are used as sensors. The crack or damage inside the concrete structure
acts as a stress relief in the wave propagation path. The amplitude of the wave and the transmission energy will decrease due to the existence of crack. The drop value of the transmission energy will be correlated with the degree of the damage inside (Song et al. 2008). The signal is captured by the smart aggregate sensors and sent back wirelessly to the network coordinator. Through the serial communication, the network coordinator sends the data to PC for post signal analysis. Wavelet packet analysis is used as the signal processing tool to capture the damage features. In the proposed health monitoring approach, a swept sine signal will be used as the excitation source for the smart aggregate actuator. The swept sine starts from 500 Hz and ends at 3 KHz with the period of 1.2 seconds. The swept sine response reveals the frequency response of the structure in a wide frequency range, which benefits the damage feature extraction through the wavelet packet analysis (Song et al. 2008, Laskar et al. 2009).

4. WSN hardware system design

In this project, two types of wireless devices, the wireless coordinator and the wireless nodes are designed and implemented for SHM and impact detection. The wireless coordinator is used to organize and manage the wireless network and it also controls the performance of all the nodes in the network. The function of the wireless nodes is to sense the impact, perform data acquisition and send data back to wireless coordinator wirelessly. The wireless coordinator is composed of three parts, the amplifier, the Swept Sine Module (SSM), and the wireless microcontroller. The wireless nodes are composed of the signal conditioner, the impact detector and the wireless microcontroller. The SA based wireless strength monitoring system is illustrated in Fig. 4.

4.1 Energy-efficient impact detection circuit

Impact detection is very important for civil structures since a large impact can possibly produce
permanent damage and may result in the failure of the structure (Champaigne and Sumner 2007). Based on the measured physical variable, existing impact detection methods for structures can be classified into three major categories: the acceleration-based approach (Bernard et al. 1988), the impact force-based approach (Fujii and Fujimoto 1999, Song et al. 2007a), and the strain-based approach (Yang and Han 2002, Staszewski et al. 2000). Often piezoceramics (Staszewski et al. 2000, Song et al. 2007a) and fiber optic sensors (Yang and Han 2002) are employed for impact detection. The piezoelectric based method, which is used in this paper, has the advantage of low cost, quick response, near-linear response, simple implementation, and sensing and actuating functions. A piezoceramic sensor is suitable for either surface mount or embedment. PZT based SAs embedded in the structure are used to capture the vibration caused impacts, and the impact can be analyzed from the vibration signal it captured. PZTs can be used to evaluate the impact force since the open-circuit voltage yield by a PZT transducer is proportional to the compression force, as shown below:

\[ V = g_{33}Ft/A \]  

(1)

where A is the area of the PZT patch, t is its thickness, and \( g_{33} \) is the piezoelectric voltage constant, which is defined as the electric field generated in a material per unit mechanical stress applied to it. Therefore, as long as the open circuit voltage is measured, the impact force on the structure can be determined. With PZT sensors, impact detection is not a difficult issue for continuously powered systems since the processor can remain powered to capture and record impact events. However, for a battery powered wireless network, where power consumption is a critical issue, the processor cannot be powered continuously. Actually the processor is placed in a sleep mode for most of the time to preserve energy. It only wakes up when necessary to perform certain tasks. Hence the onset of an impact must be detected and transformed into a wake up signal, which can trigger a system interrupt to the processor. An impact detection circuit is designed and fabricated for the PZT sensor to accomplish this task. Fig. 5 shows the impact detection circuit. In Fig. 5, the J1 is connected to the smart aggregate sensor, which sends out a charge signal to the impact detection circuit. The 1M ohm resister (R1) and the op-amp
convert the charge signal to a voltage signal. The diode and the RC circuit is basically a peak detector, which convert the impact to a peak voltage signal. The inverter makes the analogue signal compatible with a digital interface so that when the input is large enough an interrupt can be generated to the microcontroller.

4.2 Signal conditioning

The amplitude of the charge and therefore the current generated by a PZT is proportional to the magnitude of the stress wave in the structure. The simplified model considers the PZT element as a high impedance current source. The current generated from the PZT sensor is usually very small (a few microamperes), therefore proper amplification and signal conditioning are necessary for later sampling and processing by a microcontroller. One resister with a large resistance is used to convert the current to a voltage signal. The PZT sensor here is used to measure dynamic signals: vibrations, not static signals, therefore this design does not require the PZT to hold the charge and the charge leakage will not be an issue. There are several ways to measure the charge signal. One common method is to use the so called integration circuit to convert charge into current, and then to a voltage signal. This method can solve the problem of the high-impedance feature of a PZT sensor. However, it causes another major problem: saturation of the capacitor in the circuit. This requires the circuit parameters to be tuned for certain range of inputs. If the amount of charge has dramatic changes, which fits our case, it is not suitable to use the integration circuit. Therefore, the method of using a large resistor to transform the charge signal to the voltage signal is adopted in this paper. Although the impedance of the PZT is large, it does not affect the charge to be converted to voltage on the large resistor. And with a proper selection of an Op-Amp, this circuit works much better than the integration circuit, as demonstrated by experiments. The tradeoff in this design is that a high-value resistor can produce a larger signal and small noises can be easily amplified through high-value resistors. Our experimental result shows that a 1M resistor is the best choice for our case. An Op-Amp circuit is used to scale and offset the signal to a valid voltage range for A/D sampling by the controller. The signal conditioning circuit is shown in Fig. 6. As shown in Fig. 6, the 1M ohm resistor (R4) and the first op-amp are used to convert the charge signal to a voltage signal. The second op-amp circuit offsets the bipolar voltage signal to a unipolar positive voltage signal. It also amplifies the signal so that the signal fits the range of the A/D converter. The third op-amp circuit is an anti-aliasing low pass filter for the A/D converter.
4.3 Swept sine module

A swept sine module is needed for the active sensing of the structure (Song et al. 2008). During active sensing, one SA is used as an actuator to generate the vibration that will propagate through the structure and the other SAs are used as sensors to detect the induced vibration. Damage on the wave propagation path will alter the signal strength for the sensing SAs. A swept sine wave is used as the excitation signal as its bandwidth can be set to the specified frequency range. The frequency response in a wide frequency range will be obtained by using a swept sine excitation. This is important to evaluate the damage development. Different frequency corresponds to different wave length which correlates with different resolution for the crack detection. A high frequency signal has a less wave length and it has higher resolution and sensitivity in crack detection.

The default swept sine is generated in the range from 500 Hz to 3k Hz over 1.2 seconds. The value of the swept sine is computed by the microcontroller and output to a D/A (digital to analog) converter, and a low pass filter is applied to smooth the swept sine signal after the D/A converter. Since the frequency of the swept sine signal is up to 3K Hz and the signal lasts for 1.2 seconds, it is impractical to store all the output sample points in a table and output upon request. On the other hand, computing the output values in real time is also problematic since most embedded processors have limited computational power and are not efficient with floating point arithmetic. A simple method is designed to approximate the swept sine signal. The table look up method is used to facilitate the generation of the swept sine signal. A 5000-point sine table is pre-stored in the system’s flash memory, and a fixed point calculation is used to determine which value should be output from the sine table. The output value is updated every 14.4 microseconds. Although the swept sine signal generated using this method is not a perfect one, it is sufficient for the use as an excitation source for structural health monitoring.

The swept sine module is controlled by the wireless controller. Usually it is in a sleep mode to save system power. When there is a need for swept sine actuation, the wireless controller will generate an interrupt to the swept sine module through general purpose input/output (GPIO). If no parameter is changed, the swept sine will start to generate the default 500 Hz to 3 KHz swept sine signal. Optional hand shaking between the swept sine module and the wireless controller can be established through a serial communication.

4.4 Power amplifier

The signal from the D/A converter output from the swept sine module is -10V to +10 V, and it is
then sent to a power amplifier before it can be applied to the SA actuator. The power amplifier will generate a voltage in the range of -180 to 180 V. This voltage will enable the piezoceramic-based SA to generate stress waves strong enough to propagate through the concrete structure and detectable by other SAs. An EMCO switching power supply is used to convert the 12 Volts power supply to a +/-180 Volts high voltage power supply, which is capable to deliver 25 mA maximum current. Cirrus Logic PA15FLA operational amplifier, which is designed to drive a wide range of capacitive loads, is adopted to accomplish the amplification work. Fig. 7 shows the structure for the design of the power amplifier. A single, fully charged, 12 Volts 1.2 A/h battery is capable of powering on the circuitry and guaranteeing a bandwidth of around 8k Hz for as long as one hour of continuous use. Detailed description of this design can be found in Olmi et al. (2009).

4.5 Wireless controller

The wireless controller is the core component of the overall system. The network coordinator has an external power supply, and gathers and transmits the overall structural health information to a PC. The coordinator is connected to a PC via an RS232 connection. Higher level decisions can be made on the PC and sent to the network through the coordinator. The PC can also retrieve all the sensor data from the network. Offline data processing can then be carried out on the PC to determine the detailed health status of the structure.

A number of wireless sensor nodes have been built by several research institutes. Two commonly used architecture for wireless sensor nodes are ATMEG AVR processor plus TinyOS (Hill et al. 2000) and MPS430 plus TinyOS (Dubois-Ferriere et al. 2006). A low-power 32-bit embedded platform based on the Jennic JN5139 was selected as the wireless controller for the network in our work. The JN5139 is a low power, low cost wireless microcontroller which is suitable for IEEE802.15.4 and ZigBee applications. It integrates a 32-bit RISC processor, with a fully compliant 2.4 GHz IEEE802.15.4 transceiver, 192 kB of ROM, 96 kB of RAM, and assorted analogue and digital peripherals. It also includes hardware MAC (medium access control) accelerators, power saving and timed sleep modes, and mechanisms for security key and program code encryption. These features all make it suitable for a highly efficient, low power, single chip wireless microcontroller for battery-powered applications. Fig. 8 is a system block diagram of the JN5139.

The piezoceramic-based wireless sensor network is different from other wireless sensor networks as it requires relatively high sampling rate and computation for frequency analysis. Furthermore, the battery based wireless system requires power efficient hardware and software design. Our study shows
that JN5139 microcontrollers are suitable to address these problems. A JN5139 microcontroller can run at 32 MHz and delivers about 32 million instructions per second (MIPS). Three operating modes are provided in the JN513x microcontrollers that enable the system power consumption to be controlled efficiently to maximize the battery life. The wireless transceiver in the Jennic JN5139 comprises a 2.45 GHz radio, an O-QPSK modem, a baseband processor, a security coprocessor and a PHY controller. The transceiver can operate in the unlicensed 2.4 GHz band. IEEE802.15.4 wireless functionality is used with the transceiver and the protocol software.

4.6 Power

The wireless sensors require 3 Volts power supply only. The wireless MCU works under 3.3 Volts. A charge pump voltage regulator is used to convert the 3 Volts to -3 Volts, which provide bipolar power supply to the signal conditioning circuit. Since the wireless sensor consumes very little energy, two AA batteries are used to power the wireless sensor. The actuator system requires multiple power supply with different voltage rating. 3.3 Volts is needed by the wireless MCU, 5 Volts is needed by the D/A in the swept sine module, 12 Volts is required by the power amplifier, and +/-12 Volts is needed by the signal conditioning circuit from the swept sine module. Switching power regulators are used to reduce the power dissipation during the voltage regulating. 12 Volts lead-acid battery (1.3AH) is used to power the wireless actuator. The reason to use such kind of battery is its rechargeability. For active
sensing, although the voltage is large (180 Volts), the actuation period is short (only a few seconds) and the driving current is small (less than 10 mA). Therefore, the total power consumption is small. A lead acid battery is completely suitable for this task.

A photo of the wireless controller is shown in Fig. 9. Fig. 9(a) offers a top view, while Fig. 9(b) provides a bottom view.

5. Software system design

With the hardware system described in the previous section, proper software needs to be designed to carry out the wireless structural health monitoring and impact detection tasks. The software system is composed of two major parts, the embedded software design and the signal processing algorithm design.

5.1 Embedded software design

Since the embedded system has limited computational power, no operating system (OS) is used and all the programming is done using C language.

The software for the network coordinator is composed of five parts: the drivers for all peripherals, an interrupt driven shell, various interrupt service routines (ISRs), the network programming part, and the event driven state machine. The software architecture is illustrated in Fig. 10.

In Fig. 10, the right bottom blocks inside the border are provided as libraries by Jennic. The rest of the software has to be designed to realize the structural health monitoring and impact detection tasks. Since there is no OS, drivers are the most fundamental components in the software system. UART (Universal asynchronous receiver/transmitter) driver provides interfaces from basic functions as sending and receiving character to and from the PC to complex functions as printf to the upper level software. One important function of the UART is to print debug information to the PC, which is a very fundamental and useful method for debugging. A simple shell is designed and built on one of the UART in the system. The shell retrieves the input character from the serial register, and then either appends it to a buffer or performs a “backspace”, “delete” or “tab” operation to the end of the buffer,
depending on the character input. “Enter” is an indicator for the finishing of a command input, therefore a flag is set upon an “enter” input. Since all the system events are updated in ISRs, time spent in ISRs has to be kept to the minimum. The parsing of the shell input is performed in the system loop, where the “enter” input flag is checked. The shell input parsing layer is invoked if the “enter” input flag is set. The parser analyzes the input and finds out the entrance address of the command if this is a valid command input. A valid command input reaches the shell command layer, where the command function is actually executed. The shell implemented on the UART provides a means for a user to manage the network. All the tasks can be programmed as one of the shell commands and activated from the PC using any serial communication software, such as HyperTerminal or Putty.

Since the nodes are battery powered, the system software for the nodes is designed to minimize the power consumption over the network while realizing the function of impact detection and continuous health monitoring for the concrete structure (Avancha et al. 2004). Star topology is adopted to form the network. Normally all nodes are in sleep mode to save power. Three events can wake up a node, namely, when there is an impact to the structure, when its “heart beat” time is due, and when it receives commands from the network coordinator.

In presence of an impact to the structure, if the impact is above the threshold, the impact detection circuit will generate an interrupt to wake up the relevant nodes (nodes that are close to the impacted location) through their GPIO. These awakened nodes will start to record the impact immediately. The impact data is stored in RAM and analysis can be performed later. An impact message is transmitted to the network coordinator immediately. The network coordinator sends an acknowledgement to the node when it receives this message. If a node does not receive an acknowledgement, it will mark the impact as an unfinished event and transmit this event to the coordinator when its “heart beat” time is due. The node returns to sleep after this event. When the coordinator receives the impact message from the node, it will determine whether to retrieve the recorded impact data. The coordinator can send a command to the node in the acknowledgement, so that the node stays awake to send the data back to the coordinator.

Each node will also wake up when its “heart beat” time is due. This is the time for nodes to update events and to synchronize with the network coordinator. When the coordinator receives the “heart beat” from the nodes, it will update the system clock to the nodes and send out a preparation command to the nodes if a swept sine actuation is to be generated. The coordinator can also determine if there is any pending data stored in the nodes based on the nodes’ heart beat messages. If there is an unfinished impact reported by some of the nodes, the coordinator will decide whether to retrieve the pending data wirelessly. If a swept sine actuation is needed, the coordinator will send a command in the acknowledgement to the nodes to keep the nodes to stay alive. The nodes will stay awake to capture the vibration from the swept sine and store all the data in its RAM. The data will be retrieved by the network coordinator afterwards. The coordinator can send commands to the nodes to request the sensing data stored by the node. The command is sent after the coordinator receives the node’s “heart beat”. An acknowledgement is sent by the coordinator after it receives the “heart beat”. The coordinator will denote if it wants to send a command to the sensor node in the acknowledgement while time synchronization is performed at the same time. A sensor node will stay awake if it determines there is a command coming from the acknowledgement. Then the coordinator can send out the command and the sensor will return to sleep mode after it finishes the command. The software system is event driven. All interrupts will be processed, registered as an event and then return. The system will poll the event queues for updated events.

A flow chart for the main loop and the serial interrupt of the software system is shown in Fig. 11.
5.2 Signal processing algorithm

In the proposed active sensing approach, wavelet packet analysis is utilized for signal analysis after data is retrieved from SAs wirelessly. Wavelet analysis can be viewed as an extension of the traditional Fourier transform. Fourier analysis consists of breaking up a signal into sine waves of various frequencies and phases. Similarly, wavelet analysis consists of a breaking up of a signal into shifted and scaled versions of the original (or mother) wavelet.
A wavelet is a waveform of effectively limited duration that has an average value of zero.

\[ \int_{-\infty}^{+\infty} \Psi(t) dt = 0 \]  

(2)

Using a selected analyzing or mother wavelet function \( \Psi(t) \), the continuous wavelet transform (CWT) of a function \( f(t) \) is defined as

\[ W_f(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(t) \Psi\left(\frac{t-b}{a}\right) dt \]  

(3)

where \( a > 0 \) and \( b \in R \) are the dilation and translation parameters, respectively. The bar over \( \Psi(t) \) indicates its complex conjugate.

In wavelet analysis, a signal is split into an approximation and a detail. The approximation is then itself split into a second-level approximation and detail, and the process is repeated. The decomposition tree for wavelet analysis is shown in Fig. 12.

In wavelet packet analysis, the details as well as the approximations can be split. The decomposition tree of wavelet packet analysis is shown in Fig. 13. In this paper, the Daubechies wavelet base (db2) is used as the mother wavelet. The frequency band is not overlapped because of the orthogonality of the Daubechies wavelet base.

The wavelet packet analysis is an effective signal processing tool for damage feature extraction since it enables the inspection of relatively narrow frequency bands over a relatively short time window. In the proposed approach, the sensor signal \( S \) is decomposed by an \( n \)-level wavelet packet decomposition into \( 2^n \) signal sets \( \{X_1, X_2, \ldots, X_{2^n}\} \). The energy of the decomposed signal is represented by \( E_{ij} \), where \( i \) is the time index and \( j \) is the frequency band \((j=1\ldots2^n)\). \( E_{ij} \) can be expressed as

\[ E_{ij} = \|X_j\|^2 = x_{j,1}^2 + x_{j,2}^2 + \cdots + x_{j,m}^2 \]  

(4)

![Fig. 12 The decomposition tree for wavelet analysis](image-url)

![Fig. 13 The decomposition tree for wavelet packet analysis](image-url)
where $X_j$ is the decomposed signal in time domain using wavelet packet analysis at $j$th frequency band. $X_j$ can be expressed as

$$X_j = [x_{j,1}, x_{j,2}, \cdots, x_{j,m}]$$

(5)

where $m$ is the amount of sampling data. Additionally, the energy vector at time index $i$ can be given as

$$E_i = [E_{i,1}, E_{i,2}, \cdots, E_{i,n}]$$

(6)

This energy vector is used in the experiment to analyze the health status of the structure in the experiment.

6. Experiment

The experiment was carried out on a two-story concrete frame with embedded piezoceramic-based smart aggregates. The dimension for PZT patch in SA is $10 \times 10 \times 0.267$ mm$^3$, and its average capacitance is 5.07 nF. Sixteen SAs are embedded in different locations in the concrete frame and BNC connecters are left outside of the structure for connection to the wireless coordinator or nodes. The diagram of the structure is shown in Fig. 14, and the fabricated frame is shown in Fig. 15. The base of the structure is of $288 \times 150 \times 50$ cm, and the two-story frame is of $218 \times 18 \times 194$ cm. Fig. 14 also shows the locations of the PZT based SAs.

The two-story concrete frame was damaged by an early loading procedure (Song et al 2008). There are many cracks on the frame, especially near the beam-column connections and the two roots of the supporting columns. Only the base is intact. Each smart aggregate (SA) is designed as PZTi, where $i$ is from 1 to 16.

Fig. 14 Two-story concrete frame with embedded smart aggregates

Fig. 15 Photo of the two-story concrete frame
6.1 Structure health monitoring with swept-sine excitation

The network coordinator generates swept-sine waves, and sends the amplified signal to one SA, which is in an actuation mode. This swept-sine actuation will generate stress wave that will propagate in the structure and wake up other nodes. The nodes will then collect the vibration data from the SAs and record it in RAM. A command is sent from the serial console to the coordinator to collect data wirelessly and retransmit to the PC. Data analysis can be carried out later to diagnose the health status of the structure.

Several actuator and sensor pairs are chosen to perform the structural health monitoring. Since the base is intact, the signal from PZT15 and PZT13 can be referenced as the data for a healthy structure. The structure segment between PZT 2 and PZT3 is damaged. PZT3 is used as an actuator and PZT2 as a sensor to capture the damage information. A portion of the actuator data is shown in Fig. 16; in which the swept-sine is from 500 Hz to 3 K Hz and lasts for 1.2 seconds.

The sensor signal is shown in Fig. 17. Power spectrum density for the sensor signal is computed and shown in Fig. 18.

It can be seen that the signal strength from PZT15 as an actuator to PZT13 as a sensor is much larger than that from PZT3 as an actuator to PZT2 as a sensor. This is because cracks between PZT3 and PZT2 absorb and attenuate the stress wave vibration. The frequency response comparison also shows that signals from PZT15 and PZT13 have much larger energy than that of the data from PZT3 and PZT2.

Wavelet packet analysis is used as the signal processing tool to evaluate the damage status of the concrete frame. The wavelet packet based energy vector described in section III is used to detect the existence of the damage and evaluate its severe degree. The comparison of the energy vector of a15s13 (PZT15 is used as an actuator and PZT13 is used as a sensor) and a3s2 (PZT3 is used as an actuator and PZT2 is used as a sensor) is shown in Fig. 19. From the visual inspection of the failed concrete frame, as shown in Fig. 15, there are severe cracks between PZT2 and PZT3. Since PZT13 and PZT15 are located in the base, there are almost no cracks between the propagation path between PZT13 and PZT15. The wave propagation distance between PZT2 and PZT3 is approximately the same as that of PZT13 and PZT15. From the energy vectors comparisons of these two actuator-sensor pairs (a15s13 and a3s2), it can be seen that the energy values at different frequency bands for the
actuator-sensor pair a3s2 are much lower than those of the actuator-sensor pair a15s13. This experimental result has demonstrated that the existence of the damages in the propagation path has significantly attenuated the wave transmission energy and the drop value of transmission energy is correlated with the severe degree of damage. Therefore, the proposed energy vector can be used to detect the existence of the damage and evaluate the damage severity. From the energy vector comparison of actuator sensor pairs of a16s13, a15s12, a15s13 and a3s2 as shown in Fig. 20, it can be seen that the energy values at different frequency bands are much lower than those of a16s13, a15s12 and a15s13. The experimental results shown in Fig. 20 have further demonstrated that the damage status between PZT2 and PZT3 are much more severe than the damage status between actuatorsensors pairs of a16s13, a15s12 and a15s13. It is clear from the above analysis that structural health monitoring results based on the wireless smart aggregate is in consistence with results from visual inspection of the damage concrete structure.

### 6.2 Impact detection

Sensor nodes are in sleep modes most of the time. Nodes that are near to the impact will wake up and record the vibration upon an impact on the structure. Fig. 21 shows two sets of impact data...
Concrete structural health monitoring using piezoceramic-based wireless sensor networks

7. Conclusions

In this paper, a wireless embedded system for piezoceramic-based structural health monitoring has been designed and implemented on a two-story concrete frame with embedded SAs to perform impact detection and structural health monitoring. The damage status of the concrete frame is evaluated using the wavelet packet analysis method. The designed embedded system balanced the high sampling speed and high computational power requirement from the piezoceramic-based SHM and the low power consumption requirement from the battery powered wireless sensor network. The proposed piezoceramic-based WSN simplified the wiring and maintenance of the SHM system and can be used for large scale in-field applications. The experiment results show that the system presented in this paper achieves the necessary system performance while maintaining low power consumption by performing offline data processing and minimizing wireless communication.

Future work would include optimization of the network topology and routing algorithm so that the wireless sensor networks can maximize its performance for minimum power consumption. Early age strength monitoring of concrete structures using wireless smart aggregates will also be conducted.

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A wireless guided wave excitation technique based on laser and optoelectronics

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Abstract. There are on-going efforts to utilize guided waves for structural damage detection. Active sensing devices such as lead zirconate titanate (PZT) have been widely used for guided wave generation and sensing. In addition, there has been increasing interest in adopting wireless sensing to structural health monitoring (SHM) applications. One of major challenges in wireless SHM is to secure power necessary to operate the wireless sensors. However, because active sensing devices demand relatively high electric power compared to conventional passive sensors such as accelerometers and strain gauges, existing battery technologies may not be suitable for long-term operation of the active sensing devices. To tackle this problem, a new wireless power transmission paradigm has been developed in this study. The proposed technique wirelessly transmits power necessary for PZT-based guided wave generation using laser and optoelectronic devices. First, a desired waveform is generated and the intensity of the laser source is modulated accordingly using an electro-optic modulator (EOM). Next, the modulated laser is wirelessly transmitted to a photodiode connected to a PZT. Then, the photodiode converts the transmitted light into an electric signal and excites the PZT to generate guided waves on the structure where the PZT is attached to. Finally, the corresponding response from the sensing PZT is measured. The feasibility of the proposed method for wireless guided wave generation has been experimentally demonstrated.

Keywords: wireless power transmission; laser; optoelectronics; active sensing; guided wave generation.

1. Introduction

In recent years, guided wave based structural health monitoring (SHM) techniques have attracted much attentions, because they are not only sensitive to small defects but also capable to propagate over a long distance in plate and pipe like structures. A number of studies have demonstrated the potential of guided wave based SHM (Moulin et al. 1997, Sohn 2003, Sohn et al. 2004, Kim and Sohn 2007, Raghavan and Cesnik 2007, Wang and Yuan 2007, Giurgiutiu 2008).

Guided waves can be generated in a structure using various devices such as ultrasonic probes, piezoelectric elements and lasers. Ultrasonic probes include wedge-coupled (Guo and Cawley 1994), air-coupled (Castaings and Hosten 2001), fluid-coupled (Ghosh et al. 1998), and electro-magnetic

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acoustic transducers (EMATs) (Guo et al. 1997). However, these probes can have low sensitivity due to the acoustic impedance mismatch between air/fluid couplants and the objects. EMATs have restrictions on the applicable frequency range, and they require electrical conductivity of the objects (Achenbach 2000).

Piezoelectric lead zirconate titanate (PZT) elements could be a good candidate for such online applications due to its small size, easy installation, low cost, noninvasive nature, and wide frequency response range. PZT transducers typically require wires to supply the power necessary for generation of guided waves and to transmit the sensed data, but the installation of wires in real structures can be expensive and labor-intensive (Çelebi 2002). To overcome these problems, there are on-going efforts to integrate a PZT transducer with a wireless sensor unit (Lynch and Loh 2006, Mascarenas et al. 2007, Grisso and Inman 2008, Lu et al. 2008). One of major challenges in such wireless systems is to secure power necessary to operate the wireless sensors. However, because guided wave based active sensing devices demand relatively high electric power compared to conventional passive sensors such as accelerometers and strain gauges (Yeatman 2009), existing battery technologies may not be suitable for long-term operation of active sensing devices.

Laser-based excitation techniques can be an alternative. Electromagnetic radiation from a laser is absorbed in the surface region of a structure, causing heating. The heated region undergoes thermal expansion, and non-contact guided waves are generated (Scruby and Drain 1990). However, in the current laser technique, it is difficult controlling the excitation source to generate desired arbitrary waveforms. Other researchers attempted to generate narrow-band guided waves using a laser (Clark et al. 1998) but were able to control only the frequency content of the generated waves not the actual waveform.

The ultimate goal of our research is to develop an optical system for guided wave generation and sensing. This paper mainly focuses on the excitation aspect of the overall system. The proposed wireless technique transmits power necessary for PZT excitation using laser and optoelectronic devices. Because power is remotely transmitted to the PZT transducer, no complex electronic components are necessary at the PZT node, making it possible to develop a self-contained, rugged, and non-intrusive PZT node. The transducer itself can be entirely passive and consequently will have a long lifetime when it has rugged packaging. In addition, any arbitrary waveform can be generated by a laser using an electro-optic modulator (EOM). This wireless power transmission scheme also can be expanded to transmit power through optical fibers and generate guided waves (Lee et al. 2009). A further research for wireless guided wave sensing is currently being developed by the authors using other optoelectronic devices, such as photovoltaic panels and laser diodes (Park et al. 2010). Finally, as shown in Fig. 1, it is envisioned that the develop technology can be integrated with autonomous

![Fig. 1 Integration optics-based active sensing technology and remote platforms based on unmanned autonomous inspection robot for civil application](image_url)
moving agents such as robots to remotely inspect the integrity and performance of large distributed infrastructure systems such as bridges.

This paper is organized as follows. First, the operational principle of the proposed system is described. Electrical circuit analysis and experimental tests are then executed to investigate the feasibility of the proposed technique, and the results are discussed. Finally, the paper concludes with a summary and future work.

2. Principle of operation

Fig. 2 shows an overall schematic of the proposed wireless guided wave excitation and sensing system. It takes advantage of optical techniques for both guided wave generation and sensing. First, a laser wirelessly transmits a generated waveform to a PZT transducer node that consists of a photodiode, a transformer and a PZT transducer. Then, the photodiode converts the light into an electric signal, and the transformer increases the voltage level of the created electric signal. The electric input signal excites the PZT attached on a structure, and the excited PZT consequently creates guided waves within the structure. Next, the corresponding reflected waves are measured by the identical PZT and re-converted into a laser and transmitted back to another photodiode located in the data acquisition unit for diagnosis. This paper mainly focuses on the wireless guided wave generation aspect of the overall system.

There are critical components necessary for wireless excitation of a PZT transducer in the proposed system; a laser as a power source, an electro-optic modulator for modulation of the laser intensity, an arbitrary waveform generator for generating a waveform such as a toneburst signal, an optical amplifier for optical power amplification, a photodiode for conversion of light into an electric signal, a transformer for voltage amplification, and a PZT transducer for guided wave generation. In the following subsections, the operational principle for each component will be briefly discussed.

2.1 Laser as a wireless power transmission source

Lasers can be characterized by a number of key optical properties, and these properties dictate
which lasers are suitable for wireless power transmission. The most unique property of the laser is its directionality. The laser emits highly directional and collimated radiation with a low angle of divergence (Svelto 1982). This is essential for wireless power transmission because the energy carried by the laser beam can be transmitted for a long distance and focused onto a small area. On the other hand, the radiation of conventional lights spreads out in all directions. Although conventional lights can be focused onto a small area using a focal lens, the energy density is very low. It is because that the conventional lights have numerous wavelength components and each component has its own refraction ratio. Therefore, only a small portion of the conventional lights can be focused onto a target area and efficiency of energy transmission drastically decreases. One final concern when using a laser is laser safety. Generally, a laser with over 10 mW is required for wireless power transmission. In this case, the laser source is classified as Class 3B based on standards such as BS4803 in Europe or ANSI Z136 in US. Accordingly direct beam viewing could be hazardous, and the use of the laser requires caution for user safety.

2.2 Generation of an arbitrary waveform using an electro-optic modulator

To remotely excite a PZT transducer with an arbitrary waveform, the modulation of the laser intensity is necessary. This modulation can be achieved using an EOM. The EOM is an optical device in which the electro-optic effect is used to modulate the intensity of light. When an external electric field is applied to a crystal, such as lithium niobate (LiNbO$_3$), in the EOM, the polarizability and the refractive index of the crystal change in response to the applied electric field (Smith 1995). This results in the transmission rate change of light intensity passing through the EOM as

$$Tr(\%) = \sin^2\left(\frac{\pi V}{2V_s}\right)$$  \hspace{1cm} (1)

Here $Tr$, $V$ and $V_s$ are the transmission rate, the applied electric voltage, and the voltage required for maximum transmission of the laser intensity, respectively.

Considering the relationship between the transmitted intensity (amplitude) of the laser versus the applied voltage, it is obvious that the transmitted intensity is a nonlinear function of the applied voltage ($Tr \sim \sin^2 V$). Local linear modulation can be performed by modulating the light intensity.

![Fig. 3 Local linear modulation of the laser intensity near the 50% transmission point (Q) of the EOM](image)
near the 50% transmission point, Q in Fig. 3, of the modulator rather than the origin. To achieve this, a quarter-wave plate (Khare 2004) is added to the EOM. This plate introduces a phase shift of \( \pi/2 \) and forces the null voltage to be aligned with Q point as illustrated in Fig. 3. When the electric voltage, which has an arbitrary waveform such as a toneburst signal as shown in Fig. 3, is applied to an EOM, the laser intensity is proportionally modulated to the shape of the input electric voltage. Thus, an arbitrary light waveform can be produced to remotely excite a PZT transducer.

2.3 **Conversion to electric signals using a photodiode**

In order to excite a PZT transducer via a laser, it is necessary to convert the modulated optical power (intensity) into an electric signal. In this study, a photodiode made of a \( pn \) junction is used for this conversion due to its small size, high conversion speed, and good sensitivity. The photodiode generates a current flow (photocurrent) in an external circuit. The greater the light intensity is, the higher and larger the photogeneration rate and the photocurrent (\( I_{ph} \)) become. The photocurrent, \( I_{ph} \) is linearly proportional to the incident optical intensity, \( P \) (Kasap 2001)

\[
I_{ph} = kP
\]  

where \( k \) is a device-dependent constant.

An equivalent circuit of the photodiode is shown in Fig. 4 (Wilson and Hawkes 1998). In the figure, \( I_{ph} \), \( I_D \), \( R_P \), \( R_S \), and \( R_L \) are the photocurrent, the diode current, the parallel resistance current, the parallel resistance, the series resistance and the external load, respectively. From the equivalent circuit analysis, the total current, \( I_L \), becomes

\[
I_L = -I_{ph} + I_D + I_P
\]  

In the above relationship, \( I_D \) is produced by the \( pn \) junction diode, and its behavior is governed by a typical diode characteristic

\[
I_D = I_o \left[ \exp \left( \frac{eV_L}{nk_BT} \right) - 1 \right]
\]  

where \( I_o \) is the reverse saturation current, \( e \) is an electron charge (-1.60 \( \times \) 10\(^{-19} \) C), \( k_B \) is Boltzmann’s constant (8.61 \( \mu \) eV/K), \( T \) is the absolute temperature of the photodiode and \( n \) is the ideality factor that depends on the semiconductor material and fabrication characteristics (\( n = 1-2 \)) (Kasap 2001). \( R_S \) and \( R_P \) are typically a few ohms (or lower) and higher than \( 10^6 \) ohm, respectively. Therefore, \( I_P \) becomes negligible.

Typical \( I_L - V_L \) characteristic of a photodiode is shown in Fig. 5, where \( I_{ph}, k_B, n \) and \( T \) are set to be 40 \( \mu \)A, 8.61 \( \mu \)eV/K, 1.48 and 300 K, respectively. It can be shown that the \( I_L - V_L \) characteristic is identical to the normal \( pn \) junction diode characteristic except that the \( I_L - V_L \) curve is shifted down.
by $I_{ph}$, which is linearly proportional to the light intensity. The open circuit output voltage, $V_{oc}$, of the photodiode is given by the point where the $I_L$-$V_L$ curve intersects the $V_L$-axis ($I_L=0$) as

$$V_{oc} = \frac{n k_B T}{e} \ln \left( \frac{I_{ph}}{I_o} + 1 \right)$$  \hspace{1cm} (5)

Fig. 6 shows the relationship between $I_{ph}$ and $V_{oc}$ in the range of 0 to 1000 mA. It is apparent that the value of $V_{oc}$ remains below 0.4 V even with a large photocurrent value of 1000 mA. Because this level of $V_{oc}$ is not high enough to excite a typical PZT transducer used for guided wave generation, an additional step described in the next subsection is necessary before being able to excite the PZT properly.

### 2.4 Voltage amplification using a transformer

In the test configuration later described in the experiment, the PZT requires an input voltage of at least 1-2 V to generate measurable guided wave in the sensing PZT. However, because the photodiode in the previous step produces a voltage output below 0.4 V, a transformer is necessary for stepping up the voltage level of the converted electric signal. The transformer is an electromagnetic device designed to transfer electric energy with an increase or a decrease in voltage as shown in Fig. 7.
The ratio of the secondary induced voltage, $V_2$, to the primary voltage, $V_1$, is proportional to the ratio of the square root of inductances of their corresponding coils (Eq. (6)). Thus, the secondary induced voltage level can be adjusted by controlling the inductances ratio of these two coils.

$$\frac{V_2}{V_1} = \frac{\sqrt{L_2}}{\sqrt{L_1}}, \text{ if coupling coefficient} = 1 \text{ (an ideal transformer)} \quad (6)$$

3. Electrical circuit analysis

Electrical circuit analysis using PSPICE circuit analysis program (http://www.cadence.com) is conducted to verify the effect of a photodiode and a transformer on the input waveform applied to the PZT transducer. Fig. 7 shows the equivalent circuits of a photodiode, a transformer and a PZT transducer. The equivalent circuit model for the photodiode is previously presented in Fig. 4. An ideal transformer is assumed, resulting in a coupling coefficient of one. As for the PZT transducer, its impedance is modeled as RC circuit that predominantly has a capacitive behavior with a parallel resistive component (Georgiou and Mrad 2004).

For the circuit analysis of the PZT transducer node, the PZT has been modeled with the capacitance value, $C_{PZT}$ of 4.7 nF and the resistance value, $R_{PZT}$ of 450 Ω. Other parameters in Fig. 7 are $R_p = 1 \text{ MΩ}$, $R_s = 1 \text{ Ω}$, $L_1 = 0.075 \text{ mH}$ and $L_2 = 1.07 \text{ mH}$. To model the pn junction diode, $I_o$, $k_B$, $n$ and $T$ are set to same parameters values used in Fig. 5. Those parameters were measured using a conventional digital multimeter (F87-5, Fluke. Inc.). $I_{ph}$ generated by the laser source has a toneburst waveform in Eq. (7) with a mean value of 29.19 mA, an amplitude of ±12.08 mA, and a driving frequency of 150 kHz as shown in Fig. 8. Note that these values of design parameters are chosen in accordance with the experiments presented in section 4.

$$I_{ph}(t) = e^{-\frac{(2\pi f)^2}{1}} \cos(2\pi ft)$$

Fig. 7 An equivalent circuit of a PZT transducer node for wireless guided wave generation

Fig. 8 A toneburst input photocurrent ($I_{ph}$) based on Eq. (7)
where $f$ is a driving frequency.

Fig. 9 shows the output voltages generated from the photodiode and applied to the exciting PZT with or without going through the transformer. The voltage without the transformer (a dashed line) has about 255 mV offset, and the peak-to-peak amplitude of the toneburst component is only 27 mV. As expected, the voltage level is not high enough to excite the PZT transducer. On the other hand, the output voltage with the transformer (a solid line) is amplified up to the peak-to-peak amplitude of 1.5 V and this voltage level is enough to excite the PZT transducer. Note that the transformer also acts as a high pass filter and removes the unnecessary DC component.

Besides the voltage level, other issues of concern are phase distortion and time delay of the output voltage. As shown in Fig. 10, both output toneburst waveforms generated with or without passing through the transformer are distorted compared to the waveform of $I_{ph}(t)$. Also, output voltage is delayed 0.61 $\mu$s during conversion to electric signal at the photodiode. It is speculated that the delay is mainly attributed to the diode characteristics because it takes time for electrons and holes to drift

$$I_{ph}(t) = e^{-\left(\frac{(2\pi f)^2}{7}\right)} \cos(2\pi ft)$$

Fig. 9 Output voltage generated from a photodiode and applied to the exciting PZT with or without passing through the transformer

Fig. 10 Phase distortion and time delay of the output voltages with or without passing through the transformer
A wireless guided wave excitation technique based on laser and optoelectronics

in opposite directions to generate a photocurrent (Wilson and Hawkes 1998). In addition, output voltage is delayed 0.33 $\mu$s during voltage amplification at the transformer. For a better comparison, each signal is normalized with respect to its maximum value. It is speculated that the characteristics of a photodiode and a transformer contribute to the distortion and delay of the waveform. Fig. 11 shows the relationship between $I_{ph}$ and $V_{oc}$ of the photodiode in the operational range of 10 mA to 50 mA. As described in Eq. (5), the photodiode has a typical nonlinear relation between $I_{ph}$ and $V_{oc}$. In addition, the transformer, which amplifies the voltage level through inductive coupling between two coils, intrinsically has resistance and capacitance components. These also contribute to the delay and phase distortion of the input signal. Those effects are explored experimentally in the following section.

Fig. 12 shows the amplitude of the output voltage generated from the photodiode with the transformer as a function of the driving frequency and the level of $I_{ph}$. The interaction between the inductance ($L_2$) of the transformer and the capacitance ($C_{PZT}$) of the PZT results in a resonance phenomenon. Here, the resonance frequency can be approximated as follows (Greve et al. 2007)

$$f = \frac{1}{2\pi\sqrt{L_2C_{PZT}}}(\text{Hz})$$

(8)

![Fig. 11 A nonlinear relationship between $I_{ph}$ and $V_{oc}$ in the range of 10 mA to 50 mA based on Eq. (5)](image1)

![Fig. 12 The relationship of the output voltage at the PZT transducer node with the driving frequency and the level of $I_{ph}$](image2)
From the circuit model in Fig. 7, the theoretical resonance frequency is calculated to be 70.97 kHz ($L_2 = 1.07 \text{ mH}$, $C_{PZT} = 4.7 \text{ nF}$). As expected, the analysis result shows a good agreement with theoretical one. Next, three different amplitudes (12 mA, 24 mA and 48 mA) of $I_{ph}$ are applied to the circuit to verify the relationship between $I_{ph}$ and the output voltage. The output voltage increases in proportion to the input $I_{ph}$. Note that, from a mechanical point of view, the actual amplitude of the guided waves generated at the exciting PZT is also influenced by the interaction between the size and shape of a PZT transducer and the driving frequency (Sohn et al. 2010). For instance, when the wavelength of a specific guided wave mode becomes twice of a PZT transducer size, the amplitude of that particular mode is amplified. Therefore, not only parameters of electronic components such as $L_1$, $L_2$, $I_{ph}$ and $C_{PZT}$ but also the driving frequency and the PZT configuration have to be optimized to maximize the magnitude of the output voltage and guided waves.

4. Experimental characterization

4.1 Experimental setup

To examine the proposed optical technique for wireless guided wave generation, experimental tests were conducted. The overall test configuration and the test specimen are shown in Fig. 13. The system was composed of a laser diode as a power source, an EOM and an arbitrary waveform generator (AWG) for intensity modulation of the laser, an optical amplifier, a collimator, a photodiode, a transformer and PZT transducers attached on an aluminum specimen.

The dimensions of the specimen and the PZT transducer node are shown in Fig. 14. The dimensions of the aluminum plate used in this study were 610 mm × 400 mm × 6 mm and two PSI-5AE type capsulated PZT wafer transducers (PZTs A and B) were mounted on the aluminum plate. The radius of each PZT was 9 mm and its thickness was 0.508 mm. The excitation PZT node (PZT A) consists of a PZT transducer and an integrated photodiode and transformer component connected through an SMA (SubMiniature version A, 1979) connector. PZT B was placed 0.290 m apart from PZT A. Note that PZTs A and B were both connected to the oscilloscope using BNC cables to record the guided wave response signals.

Fig. 13 An overall experimental setup of the proposed wireless guided wave excitation system
Fig. 15 shows a specific design of a self-sufficient PZT transducer node combined with a photodiode and a transformer. A commercial photodiode (FDG1010, Thorlab Inc.) was used, and the internal parameters of each component were same as those used in the previous electrical circuit analysis. The rubber pads were used to prevent electrical interference between the photodiode and the transformer and to protect them, and the integrated photodiode and transformer was connected to a PZT transducer through an SMA connector. When the laser is focused on the photodiode, the node converts the light into an electric signal, amplifies the voltage, and generates guided waves on a structure by exciting the PZT. Thus, it does not need any power source or a signal generator at the PZT transducer node.

The output power of the laser diode used in this experiment was 10 mW and controlled by the laser driver. Using the AWG, a toneburst signal with 2 V peak-to-peak voltage was generated at a driving frequency of 150 kHz and exerted to the EOM for intensity modulation of the laser. This modulated laser power was amplified up to 80 mW by the optical amplifier and transmitted by
optical fiber to the collimator. The collimated laser was emitted into air and aimed at the integrated photodiode and transformer for conversion to an electric signal and amplification of voltage level. Then, PZT A generated guided waves, and the responses were measured at both PZTs A and B. PZT A was also excited by using conventional wire connection to the AWG, and the corresponding responses were measured at PZTs A and B. The response data were collected using a conventional oscilloscope (WaveRunner44Xi, LeCroy. Inc.). The sampling rate and resolution of the oscilloscope were 100 MHz and 8 bits, respectively. In order to improve the signal-to-noise ratio, the responses were measured 20 times and averaged in the time domain.

Several aspects of the proposed wireless power transmission system were investigated. First, the waveform of the generated electric signal at the PZT transducer node was compared to the original input signal by checking phase distortion and time delay as well as amplitude and frequency. Then, the power transmission efficiencies at each device were evaluated quantitatively. Also, the distance between the laser and the PZT transducer node was gradually increased up to 5 m to examine the change of the energy transmission efficiency. Finally, the guided waves measured from wired and wireless systems were compared for verification of the performance of the proposed system. Detailed test results are presented in the next sub-sections.

4.2 Verification of the input waveform

Fig. 16 compares the toneburst waveforms generated by a laser and an AWG. In Fig. 16(a), the input toneburst signals are measured at two points: Signal AA is a toneburst signal generated by the AWG and measured at A-A point, and signal BB is the one measured at B-B point after the toneburst input goes through the photodiode and the transformer.

Signal AA is shown as a dotted line in Fig. 16(b). Its peak-to-peak voltage and the driving frequency were 2 V and 150 kHz, respectively. Subsequently signal BB was delineated by a solid line, and the peak-to-peak voltage and the driving frequency of the output signal were 1.41 V and 150 kHz, respectively. There was about 1.59 \( \mu \text{s} \) time delay between these two toneburst signals.

To compare only the shapes of these two signals, each signal was normalized with respect to its maximum value, and signal BB was shifted in time to be aligned with signal AA as shown in Fig. 16(c). Fig. 16(c) shows a fairly good agreement of these signals’ waveforms. However, there was a small distortion of signal BB’s waveform with respect to signal AA. The finding here is consistent with the electrical circuit analysis shown in Fig. 10. Note that both the photodiode and the transformer have intrinsic nonlinear characteristics and the transfer function of the EOM in the range of 0-\( V_p \) is not exactly linear as Eq. (1). It is speculated that these nonlinear characteristics contributed to the signal distortion. The development of a calibration technique is underway by the authors to compensate the signal distortion using the empirical transfer function of the system (Lee et al. 2009).

4.3 Investigation of the power transmission efficiency

Here, the power transmission efficiencies at each device were evaluated quantitatively. Fig. 17 shows optical and electric power measured at each device level. The optical power and the electric power were measured using a conventional optical power meter (PM100D, Thorlab.Inc.) and an oscilloscope (WaveRunner44Xi, LeCroy. Inc.), respectively. As mentioned in the previous section, a 10 mW laser diode was used as a power source. The power level was decreased to 3.42 mW during
the modulation process and then amplified about 20 times using the optical amplifier. Consequently the optical power measured at the PZT transducer node was 56.7 mW and it was converted into 7.30 mW of electrical power. From the results, it has been found that the power transmission efficiency in the wireless power transmission was 12.87% on average. The transformer stepped up the voltage level of the converted 7.30 mW electric power and 1.41 V of output voltage was produced.
4.4 Investigation of the wireless power transmission distance

The distance between the laser and the PZT transducer node was then gradually increased up to 5 m to examine the change of the energy transmission rate with the distance. The maximum wireless power transmission distance here was limited by the size of the available optical table. At least up to the maximum distance investigated here, the power transmission efficiency was not affected by the distance between the laser source system and the PZT transducer node. Using the collimator, the divergence of the laser was minimized and the spot size of the laser beam focused on the photodiode was controlled to be about 0.12 mm$^2$ for all transmission distances investigated here. However, the actual power transmission efficiency might be reduced in field due to varying environmental and operational conditions such as foggy weather and misalignment of the laser beam. A further study is underway to develop a control system that can precisely aim the laser source to the target PZT even when the target is moving.

4.5 Comparison of the guided waves generated by wired & wireless systems

Fig. 18 shows the guided waves measured at PZTs A and B when PZT A was excited with wired and wireless systems, respectively. As for the wireless system, the modulated laser remotely excited PZT A, and the corresponding guided wave responses were measured at PZTs A and B, respectively.
In the wired system, PZT A was excited this time by using a conventional wire connection to the AWG and the responses were measured in the same way as the wireless system. Each signal was divided by its standard deviation value before comparison. Fig. 18(a) shows that the guided waves generated by the wireless system and measured at PZT A were very similar to the corresponding responses created by the wired system. A similar result was found for the responses measured at PZT B in Fig. 18(b). This comparison with the conventional wired generation method confirms that the laser-based technique can properly generate guided waves.

5. Conclusions

A new wireless guided wave system based on laser and optoelectronic technology is proposed so that power as well as data for PZT excitation and sensing can be transmitted via a laser. The present work focuses mainly on the excitation aspect of the system. First, a laser is used as a power source and an arbitrary waveform such as a toneburst signal is generated using an electro-optic modulator (EOM). The modulated laser is amplified by an optical amplifier and emitted to a photodiode. The
photodiode converts the light into an electric signal, and a transformer increases the voltage level of the converted electric signal. Finally, this electric voltage is used to excite a PZT transducer and guided waves are generated in the structure where the PZT is attached. The feasibility of the power transmission aspect of the proposed wireless scheme has been experimentally demonstrated in a laboratory setup. The experimental results demonstrated that the laser-based guided wave generation technique can wirelessly excite a PZT transducer and produce measurable guided waves in a thin aluminum plate with an overall power transmission efficient of 12.87%. Using the proposed technology, a PZT transducer can be permanently attached to a structure without requiring complex electronic components, wired power supply or onboard batteries, making it possible to develop a self-contained, rugged and non-intrusive PZT node. A further research for wireless guided wave sensing is currently being developed by the authors using other optoelectronic devices, such as photovoltaic panels and laser diodes (Park et al. 2010). Finally, it is envisioned that the develop technology can be integrated with autonomous moving agents such as robots to remotely inspect the integrity and performance of large distributed infrastructure systems such as bridges.

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