An overview of wireless structural health monitoring for civil structures

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Wireless monitoring has emerged in recent years as a promising technology that could greatly impact the field of structural monitoring and infrastructure asset management. This paper is a summary of research efforts that have resulted in the design of numerous wireless sensing unit prototypes explicitly intended for implementation in civil structures. Wireless sensing units integrate wireless communications and mobile computing with sensors to deliver a relatively inexpensive sensor platform. A key design feature of wireless sensing units is the collocation of computational power and sensors; the tight integration of computing with a wireless sensing unit provides sensors with the opportunity to self-interrogate measurement data. In particular, there is strong interest in using wireless sensing units to build structural health monitoring systems that interrogate structural data for signs of damage. After the hardware and the software designs of wireless sensing units are completed, the Alamosa Canyon Bridge in New Mexico is utilized to validate their accuracy and reliability. To improve the ability of low-cost wireless sensing units to detect the onset of structural damage, the wireless sensing unit paradigm is extended to include the capability to command actuators and active sensors.

Keywords: wireless sensors; embedded computing; wireless telemetry; structural health monitoring

1. Introduction

Society’s built environment consists of complex structural systems that are large in dimension, rich in detail and expensive to construct. While structural design codes have proven to be successful in preventing catastrophic global failures, structures commonly experience varying levels of structural damage over their operational lives. Structural damage can be initiated by different load sources including extreme loads, like those experienced during earthquakes, or from a combination of live loads and poor structural maintenance. For example, the 1994 Northridge earthquake resulted in over $20 billion worth of damage in structures located within the Los Angeles metropolitan area (Celebi et al. 2003). Immediately following major seismic events, structures are often required by law to undergo detailed visual inspection by trained building officials (Celebi et al. 2004).

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Unfortunately, buildings often remain closed for many days until inspectors are available for inspection. Furthermore, post-seismic event inspections can be expensive; following the Northridge earthquake, the cost of inspecting the connections of steel moment frame buildings was between $200 and $1000 per welded connection (Hamburger 2000). Seismic loadings are not the only source of structural damage; often, structures exposed to excessive live loadings, e.g. highway bridges, are at risk. In the United States, the ageing national inventory of highway bridges (currently over 583 000 bridges) undergoes visual inspection every 2 years as part of the federal National Bridge Inspection Program (NBIP). The NBIP was initiated in 1971 after 46 people died in the catastrophic collapse of the Point Pleasant Bridge in Ohio. Today, approximately 13% of the national bridge inventory has been classified by the NBIP guidelines as structurally deficient, suggesting many bridges do not meet safety standards (FHWA 2003).

Early identification and assessment of structural damage are necessary for ensuring that structures continue to meet life-safety standards over their operational lives. Owing to the subjective and labour-intensive nature of visual inspections, structural monitoring systems can alternatively be employed. Structural monitoring systems consist of sensors installed in a structure, with response measurements communicated by coaxial cable to centralized data repositories where data are stored and processed. Direct consequences of using cables to communicate sensor measurements to a centralized data repository are high system costs and labour-intensive installations. Small systems installed in buildings that consist of 10–15 sensor channels can roughly cost $5000 per sensor channel (Celebi 2002). It is more common to find larger monitoring systems, often hundred or more sensors, in long-span bridges. As an example, the Tsing Ma Suspension Bridge in Hong Kong was constructed with over 350 sensor channels installed (Ni et al. 2001). In the United States, 61 of California’s long-span bridges have been instrumented with over 900 sensing channels (Hipley 2001). The costs of these large-scale monitoring systems are generally higher as a result of their size and the need for placing cables in weatherproof conduits.

Response data generated by structural monitoring systems have been instrumental in (i) characterizing structural vibration characteristics, (ii) validating design models, and (iii) better understanding nonlinear structural responses resulting from seismic loadings. Strong interest also exists in using structural response measurements to identify the existence of damage in civil structures. If reliable algorithms that accurately identify structural damage were available, the embedment of these algorithms within structural monitoring systems would automate the task of assessing structural health. Structural health monitoring systems offer facility managers the opportunity to adopt condition-based maintenance strategies in lieu of schedule-based maintenance approaches and to evaluate structural integrity immediately following a major seismic event.

The majority of the damage detection methods proposed for civil structures have concentrated on changes in the global vibration characteristics of a structure to identify the existence of damage. The use of global modal properties of a structure for damage detection has been hampered by their sensitivity to a structure’s environmental factors (e.g. temperature); thus, the onset of structural damage can be difficult to detect (Doebling et al. 1996). The field’s interest in global vibration characteristics historically derives from the low density of sensors encountered in most structural monitoring systems; low sensor densities
only provide insight to the low-order modal properties of the structure. With the low number of sensors poorly scaled to the large spatial dimensions of the structure, there is a need for greater monitoring fidelity that is achievable by increasing the number of sensors within the structure (Farrar et al. 2003). The use of hundreds of sensors in a single structure would allow for not only global-based damage detection, but also, more importantly, for a more detailed local investigation of the structure. However, structural monitoring systems defined by high sensor densities are only practical if the costs of structural monitoring systems are substantially reduced.

The declining cost of computing and communication technologies, coupled with growing capabilities at rates espoused by Moore’s Law, has led to the emergence of mobile computing technologies that are rapidly changing many facets of society (Moore 1968). The development of wireless sensors is an integral part of the mobile computing revolution. Integration of wireless communication with sensors has widely been proposed across a number of different engineering applications to reduce the cost and the manual efforts of installing dense sets of sensors in large-scale physical systems (Culler & Hong 2004). The limitations of current structural monitoring technologies have prompted structural engineering researchers to explore the use of wireless sensors for performing many of the tasks associated with monitoring civil structures. Straser & Kiremidjian (1998) were the first to propose the integration of wireless radios with sensors to substantially reduce the cost of structural monitoring systems. Since their seminal study, a number of researchers have begun to investigate the use of wireless sensors for structural monitoring applications (Lynch 2002; Casciati et al. 2004; Glaser 2004; Spencer et al. 2005). From these research efforts, wireless structural monitoring systems are blossoming into a viable low-cost technology that the structural engineering community can employ to acquire empirical performance data of their structures.

This paper will review the author’s experiences in designing and validating low-cost wireless sensing units for the structural health monitoring of civil structures. Wireless sensing units embody a convergence of wireless communications and mobile computing with sensors, resulting in modular building blocks from which wireless structural monitoring systems can be constructed. An enabling feature of the design of wireless sensing units is the integration of mobile computing hardware; on-board computational resources are leveraged to allow sensors to self-interrogate their measurement data in real time. The large number of engineering analyses that have been embedded in the cores of wireless sensing units will be presented in detail. In particular, embedded algorithms that automate the task of detecting damage in civil structures are elaborated in this review. To validate the ability of wireless sensing units to replace traditional tethered monitoring systems, the Alamosa Canyon Bridge in New Mexico is utilized. While wireless sensing units offer functionality not offered by traditional tethered monitoring systems, many technological challenges associated with wireless telemetry shape how wireless structural monitoring systems are deployed in real structures. In particular, the power consumption characteristics of wireless sensing units encourage the decentralization of computational authority to the sensors. As will be shown in this paper, wireless sensing units’ computational autonomy is well suited for local-based damage detection procedures as opposed to global damage detection. Towards this end, the
paper concludes with the design of a novel wireless sensing unit that includes capabilities to command actuators and active sensors. Wireless active sensing units are designed to locally excite the high-order response modes of structural components so that structural damage can be detected with greater reliability.

2. Architectural design of wireless sensing units for structural monitoring

Wireless sensing units are proposed for monitoring the behaviour and health of civil structures based on advanced embedded system technologies that are commercially available. The wireless sensing unit represents the fundamental building block from which wireless structural monitoring systems for civil structures can be constructed. Within a wireless structural monitoring system, each wireless sensing unit will be responsible for three tasks: (i) collection of structural response data, (ii) local interrogation of collected measurement data, and (iii) wireless communication of response data or analysis results to a wireless network which comprises other wireless sensing units. The complex nature and large spatial dimensions of civil structures impose demanding performance levels that are best attained by explicitly designing the wireless sensing unit for the application. To ensure that the wireless sensing units can accomplish each of the three enumerated tasks, a top-down design strategy is proposed. As shown in figure 1, the hardware design of the wireless sensing unit is first divided into three functional modules: data acquisition subsystem (also termed the sensing interface), computational core and wireless communication channel. For each functional module, commercially available off-the-shelf hardware components are selected based on an analysis of component functionality and cost. When fully assembled, the wireless sensing unit should ideally cost less than a few hundred dollars. To assist in the selection of hardware components, table 1 summarizes the performance criteria established for each of the three functional modules of the wireless sensing unit. The desirable performance features sought will be described for each functional module of the wireless sensing unit design.
In order to serve as a substitute for cable-based structural monitoring systems, the wireless structural monitoring system must be able to collect sensor data with equivalent accuracy. For example, to capture low-order global response modes of a civil structure, the wireless sensing unit sensing interface should be designed to record response data at sample rates below 100 Hz. Capturing high-order response modes of structural components might also be of interest when undertaking localized monitoring strategies. The sensing interface should therefore be capable of recording at relatively high sample rates (greater than 500 Hz). For generalization of the sensing interface functionality, it should not be designed specific to any one type of structural sensor; rather, the interface should be able to accommodate any sensor type. To convert analogue sensor outputs to a digital format, an analogue-to-digital converter (ADC) with a resolution of 16 bits or higher is needed. Recent microelectromechanical system (MEMS) sensors have been designed with measurement outputs modulated upon digital square waves. To allow for the interface of these new digital-output MEMS sensors, the sensing interface will also require a means of reading measurements data modulated upon square waves.

(a) Data acquisition subsystem

In order to serve as a substitute for cable-based structural monitoring systems, the wireless structural monitoring system must be able to collect sensor data with equivalent accuracy. For example, to capture low-order global response modes of a civil structure, the wireless sensing unit sensing interface should be designed to record response data at sample rates below 100 Hz. Capturing high-order response modes of structural components might also be of interest when undertaking localized monitoring strategies. The sensing interface should therefore be capable of recording at relatively high sample rates (greater than 500 Hz). For generalization of the sensing interface functionality, it should not be designed specific to any one type of structural sensor; rather, the interface should be able to accommodate any sensor type. To convert analogue sensor outputs to a digital format, an analogue-to-digital converter (ADC) with a resolution of 16 bits or higher is needed. Recent microelectromechanical system (MEMS) sensors have been designed with measurement outputs modulated upon digital square waves. To allow for the interface of these new digital-output MEMS sensors, the sensing interface will also require a means of reading measurements data modulated upon square waves.

(b) Computational core

The computational core is primarily responsible for the operation of the wireless sensing unit, including collection of data from the sensor interface, execution of embedded computing procedures and managing the flow of data through the wireless communication channel. The computational core will be assembled from microcontrollers with on-chip computing resources to support the embedded algorithms that interrogate the measurement data collected. For support, the computational core also requires memory where both measurement data and embedded computing software can be stored. To accommodate the storage of measurement data, rewritable random access memory (RAM) will be needed. If at least 256 KB of RAM is included in the wireless sensing unit design, then 128 000 data points (as 16 bit digital numbers) could be stored at one time.

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Similarly, static read only memory (ROM) is needed for the storage of software written for operation of the unit and for the processing of response data. Approximately 256 KB of ROM memory would provide ample space for the simultaneous embedment of multiple software modules.

\( (c) \) Wireless communication channel

In recent years, wireless communications have rapidly matured into a highly reliable substitute to wired-based communications. Civil structures pose a challenging environment in which wireless communications are to be employed for the transfer of data in the structural monitoring system. A distinct advantage of designing wireless sensing units explicitly for structural monitoring lies in the ability to select specific wireless communication systems that ensure the best level of service within the complex structural environment. This ‘form follows function’ approach is in stark contrast to the use of generic wireless sensors whose communication attributes might be poorly suited to the environment posed by a civil structure. In particular, two characteristics of the wireless communication channel must be considered when selecting an appropriate wireless technology: reliability and range. The wireless communication channel must be highly reliable with little to no data loss as a result of channel interference, multi-path reflections and path losses. Spread spectrum wireless radios are preferred because they distribute data across the full radio spectrum so that the integrity of the data can be maintained even if a single frequency is experiencing interference. Network protocols (e.g. transmit control protocol/internet protocol) that require a receiver to send an acknowledgement to the sender can also be employed to provide additional reliability to the spread spectrum wireless channel.

The large spatial dimensions of civil structures require wireless communication ranges of at least 100 m. Radio signals naturally attenuate as they propagate through structural materials, especially reinforced concrete (Seidel & Rappaport 1992). To anticipate the attenuation of radio signals within enclosed civil structures, a wireless radio with an unobstructed open space range of over 200 m is necessary for integration with the wireless sensing unit. While shorter range radios can also be used, they would require wireless sensing units to be spaced closer together and to employ repeated transmission (‘hopping’) of data through many units to arrive to a desired recipient.

\( (d) \) Prototype wireless sensing units

One of the first to propose the design of a wireless sensing unit for structural monitoring was Straser & Kiremidjian (1998). Their wireless sensing unit is designed to be used within periodic or extreme-event (seismic) monitoring strategies. Their design includes the integration of an eight-channel 16 bit ADC, a Motorola 68HC11 microcontroller core and 900 MHz Proxim ProxLink radio. When fully assembled, their unit is approximately 1950 cm$^3$ in volume and is capable of reliably communicating with ranges as far as 300 m line-of-sight. To render the wireless sensing unit suitable for extreme-event monitoring, an acceleration-based trigger circuit is also included to awaken the unit at the initiation of seismic motion.
The design of a wireless sensing unit, constructed from more advanced commercial electrical components, was recently proposed by Lynch et al. (2002). The sensing interface of their prototype wireless sensing unit includes the single-channel Texas Instruments ADS7821 ADC with a resolution of 16 bits and a maximum sampling rate of 100 kHz. Since MEMS-based sensors with digital outputs can be interfaced, the wireless sensing unit is designed to read measurement from digital square waves on two channels, bringing the total number of simultaneous sensor channels to three. The low-power 8 bit Atmel AT90S8515 AVR microcontroller is selected to serve as the unit’s computational core. The memory included in the Atmel AVR serves as the sole memory space for the wireless sensing unit design. For the storage of embedded software, 8 KB of ROM memory is available while 512 bytes is available in RAM for temporary data storage. With storage space limited in RAM memory, the wireless sensing unit is used to continuously broadcast the collected measurement data stream as it is collected. In later studies, the original wireless sensing unit design proposed by Lynch et al. (2002) is upgraded with an additional 32 KB of external static RAM (SRAM) to permit the storage of additional measurement data. For the wireless communication channel, the Proxim RangeLAN 2 radio modem is selected. The RangeLAN 2 is a 2.4 GHz radio that employs frequency hopping spread spectrum to ensure the integrity of data communicated. The radio data rate is 1.6 Mbps while its communication range is 300 m in open-space and 150 m within enclosed structural interiors.

The two wireless sensing unit designs proposed illustrate the utility of coupling wireless communications with sensors. The computational cores of both prototypes were primarily responsible for the overall operation of the unit, including the collection of data from sensors and the wireless transmission of data to a network of other wireless sensing units. Even though a fast Fourier transform (FFT) was embedded in the core of the wireless sensing unit proposed by Lynch et al. (2002), the cores included in both designs are not well suited for the computational demands that will be posed by embedded algorithms specific to the structural engineering domain. Lynch et al. (2003a) propose a redesign of the wireless sensing unit originally proposed (Lynch et al. 2002) to include greater computational resources. Two specific improvements are made in their new design; a second microcontroller with higher computational throughput is adopted while additional RAM memory is added. The functionality of the computational core is enhanced by the inclusion of the 32 bit Motorola PowerPC MPC555 microcontroller. The MPC555 contains a floating-point arithmetic and logic unit that is used to execute floating-point calculations in hardware. In addition to providing greater computational power, the microcontroller provides additional memory to the wireless sensing unit design with 448 KB of ROM and 26 KB of RAM provided on-chip. With the MPC555 included in the design of the wireless sensing unit, few limits exist on the type of data interrogation algorithms that can be embedded for real-time execution. A drawback of the MPC555 is that it draws 110 mA of current when powered at 3.3 V (as compared with the Atmel AVR that draws 8 mA when powered at 5 V). Owing to the MPC555 consuming more power than the AVR, the MPC555 is ordinarily kept off; only when engineering analyses are required for execution is the MPC555 powered on by the AVR. A dual processor core design allows the functional tasks of the core to be optimally partitioned between two microcontrollers. An additional 512 KB of

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external SRAM is added to the computational core so that measurement and temporary data created by the execution of embedded software can be stored. Figure 2 presents a schematic summarizing the architectural design of the wireless sensing unit proposed by Lynch et al. (2003a). The final wireless sensing unit prototype is also shown in the figure. The academic prototype unit is compact (300 cm$^3$ volume) and, at the time of construction, costs less than $500.

In table 2, the hardware design and performance attributes of each wireless sensing unit discussed in this section are summarized. As shown in the table, the hardware capabilities of the sensing unit designs continue to progress as a result of the rapid evolution of commercial wireless and mobile computing technologies. A reduction in the cost and form factor of wireless sensors can be observed parallel to the improvements in functionality. Evidence of this trend is a wireless sensing unit proposed by Wang et al. (in press). This academic unit is compact (240 cm$^3$) and low cost (less than $200). In the near future, wireless sensing units will be commercially manufactured to have volumes below 20 cm$^3$ and for less than $100 per sensing node.

3. Development of embedded firmware for sensor-based data interrogation

To automate the operation of wireless sensing units in the field, software is needed for embedment in the units’ computational cores. Embedded software, often termed firmware, is written to operate the underlying hardware of the units and to execute sophisticated algorithms that interrogate structural response data. Unlike a large personal computer, the computational resources of a wireless sensing unit are limited; special attention must therefore be paid to these limitations during the writing of firmware. To simplify the code development process, firmware is primarily written using C, a high-level programming language. In some instances, assembly programming is also used to optimize the code’s computational efficiency. As shown in figure 3, the firmware development process is separated upon multiple layers of software development: a low-level device driver layer and upper application layers.

The device driver layer, acting as a real-time operating system of the wireless sensing units, consists of software modules that each operates a facet of the unit’s hardware (e.g. operation of the unit’s ADC). The device drivers act as an
intermediary layer between hardware and upper software layers and are effective in hiding details specific to the operation of hardware from upper application layers of software. Each module of the device driver layer contains functions that initialize

Table 2. Summary of prototype wireless sensing units for structural monitoring.

<table>
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<tr>
<th></th>
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<tbody>
<tr>
<td>data acquisition</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>analogue channels</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>maximum sample rate</td>
<td>240 Hz</td>
<td>100 kHz</td>
<td>100 kHz</td>
<td>100 kHz</td>
</tr>
<tr>
<td>ADC resolution</td>
<td>16 bit</td>
<td>16 bit</td>
<td>16 bit</td>
<td>16 bit</td>
</tr>
<tr>
<td>digital channels</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>computational core</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>processor</td>
<td>Motorola 68HC11</td>
<td>Atmel AVR</td>
<td>Dual AVR/PowerPC</td>
<td>Atmel ATMega128</td>
</tr>
<tr>
<td>bus size</td>
<td>8 bit</td>
<td>8 bit</td>
<td>8 bit/32 bit</td>
<td>8 bit</td>
</tr>
<tr>
<td>clock speed</td>
<td>2.1 MHz</td>
<td>4 MHz</td>
<td>4 MHz/20 MHz</td>
<td>8 MHz</td>
</tr>
<tr>
<td>program memory</td>
<td>16 KB</td>
<td>8 KB</td>
<td>448 KB</td>
<td>128 KB</td>
</tr>
<tr>
<td>data memory</td>
<td>32 KB</td>
<td>32 KB</td>
<td>512 KB</td>
<td>256 bytes</td>
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<td>wireless channel</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>radio</td>
<td>Proxim ProxLink</td>
<td>Proxim Range-Lan2</td>
<td>Proxim Range-Lan2</td>
<td>Maxstream 9XCite</td>
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<tr>
<td>frequency band</td>
<td>900 MHz (ISM)</td>
<td>2.4 GHz (ISM)</td>
<td>2.4 GHz (ISM)</td>
<td>900 MHz (ISM)</td>
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<tr>
<td>spread spectrum</td>
<td>direct sequence frequency</td>
<td>hopping</td>
<td>hopping</td>
<td>hopping</td>
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<tr>
<td>line-of-sight range</td>
<td>300 m</td>
<td>300 m</td>
<td>300 m</td>
<td>300 m</td>
</tr>
<tr>
<td>enclosed range</td>
<td>150 m</td>
<td>150 m</td>
<td>150 m</td>
<td>100 m</td>
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<tr>
<td>data rate</td>
<td>19.2 kbps</td>
<td>1.6 Mbps</td>
<td>1.6 Mbps</td>
<td>38.4 kbps</td>
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<td>assembled unit</td>
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<td>dimensions</td>
<td>15X13X10 cm</td>
<td>10X10X5 cm</td>
<td>12X10X2.5 cm</td>
<td>10X6X4.5 cm</td>
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<tr>
<td>power source</td>
<td>9 V battery pack</td>
<td>9 V battery pack</td>
<td>9 V battery pack</td>
<td>7.5 V battery pack</td>
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</table>

Figure 3. Abstraction layered approach to embedded firmware development.
and operate a component of the wireless sensing unit hardware. Some of the common modules written include operation of the ADC, collection of measurement data from digital-output sensors, control of the serial port and transmit/receive operation of the wireless radio (Lynch 2002). For each wireless sensing unit design variation, the device driver layer must be modified to reflect the hardware specific to the unit’s design. Upper layers of software are given limited access to the device driver layer modules through well-defined application program interfaces (APIs). By standardizing the interface between the device driver layer and upper software layers, APIs essentially allow the same upper layers to be used across multiple wireless sensing unit platforms without modification.

After the device driver layer is completed, numerical procedures that locally interrogate measurement data can be written for the wireless sensing units. Wireless sensing units are an attractive technology owing to their capability to autonomously execute the algorithms embedded in them. While many engineering analyses can be converted to a set of numerical procedures for embedment, the structural engineering field is particularly interested in wireless sensing units that can execute damage detection procedures in real or near real time. Wireless sensing units that interrogate structural response data for signs of damage provide the system with a structural health monitoring capability. It should be emphasized that damage detection procedures are not the only type of algorithm that can be embedded in the cores of wireless sensing units; algorithms associated with system identification, model validation, among others, can also be embedded. In the following sections, algorithms that have been embedded in the core of the wireless sensing unit proposed by Lynch et al. (2003a) are presented to illustrate the wireless sensing units’ computational potential. The algorithms embedded are executed by the Motorola PowerPC microcontroller, unless noted otherwise. Table 3 also serves as a summary of the algorithms embedded and the corresponding validation studies performed to verify their accuracy.

<table>
<thead>
<tr>
<th>Algorithm / Method</th>
<th>Analysis Type</th>
<th>Validation Study</th>
</tr>
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<tbody>
<tr>
<td>fast Fourier transform (FFT)</td>
<td>system ID</td>
<td>Alamosa Canyon Bridge, Lynch et al. (2004a)</td>
</tr>
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<td></td>
<td>damage detection</td>
<td>5 d.f. shear structure, Lynch (2002)</td>
</tr>
<tr>
<td>autoregressive models (AR)</td>
<td>system ID</td>
<td>5 d.f. lab structure, Lynch (2002)</td>
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<td>AR–ARX damage detection pattern recognition method</td>
<td>damage detection</td>
<td>lump-mass structure, Lynch et al. (2004b)</td>
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<td>damage index models</td>
<td>damage detection</td>
<td>cement coupling beam, Lynch et al. (2004c)</td>
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<tr>
<td></td>
<td></td>
<td>cement bridge pier</td>
</tr>
<tr>
<td>wavelet transforms (WT)</td>
<td>damage detection</td>
<td>compression of 5 d.f. shear structure time-history data, Lynch et al. (2003b)</td>
</tr>
<tr>
<td></td>
<td>power efficiency</td>
<td>compression of 5 d.f. shear structure time-history data, Lynch et al. (2003b)</td>
</tr>
<tr>
<td>Huffman coding</td>
<td>power efficiency</td>
<td>compression of 5 d.f. shear structure time-history data, Lynch et al. (2003b)</td>
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Table 3. Engineering analyses locally executed by wireless sensing units.
(a) Fourier transform

Transformation of data from the time-domain to the frequency-domain is performed to determine the modal properties of a structure, including natural frequencies and corresponding mode shapes. Frequency response functions can be calculated from discretely sampled time-history data by using the Fourier transform. However, a more efficient algorithm can be employed to reduce the calculation of the frequency response function from an $O(N^2)$ process to an $O(N \log_2 N)$ process; the Cooley–Tukey FFT is selected for embedment in the wireless sensing unit (Press et al. 1992). The FFT has been coded to be executed by both the Motorola MPC555 and Atmel AVR microcontrollers. The FFT has been used to accurately identify the primary model frequencies of various laboratory and field structures (Lynch 2002).

(b) Autoregressive model fitting

Sohn & Farrar (2001) propose a novel approach for detecting damage in structures whose vibration characteristics exhibit sensitivity to environmental and operational variations. To separate changes in the system attributable only to damage, a statistical pattern recognition framework is proposed for damage diagnosis. As part of their detection strategy, the coefficients of autoregressive (AR) and autoregressive with exogenous inputs (ARX) time-series models fit to stationary response data are used as damage-sensitive feature vectors. Well suited for civil structures, the damage detection methodology is studied for embedment in wireless sensing units for autonomous execution (Lynch et al. 2004b). In addition to elegantly handling environmental variations, the method is a local-based damage detection method that identifies damage in the vicinity of a single measurement point. The method is relatively straightforward to implement as it does not require the wireless transfer of long time-history response records between wireless sensing units. Many computational routines can be employed to calculate the optimal set of coefficients corresponding to AR and ARX models fit to structural response data. A computationally efficient approach proposed by Burg (1968) is encoded in the core of the wireless sensing units to calculate AR model coefficients from structural response data. Least-squares can also be employed, but requires matrix inversions which can lead to numerical instabilities; in contrast, Burg’s approach is unconditionally stable. Lynch et al. (2004b) illustrate the ability of the wireless sensing unit to accurately identify damage introduced in a simple 8 d.f. laboratory lump-mass structure using the AR–ARX pattern recognition approach to damage detection.

(c) Damage index models

During seismic loading of reinforced concrete (RC) elements, a large portion of the seismic energy is dissipated through inelastic deformations resulting in minor to severe crack damage. Damage models have been proposed that correlate the observed damage in RC components to key structural response parameters including structural displacements, internal forces and dissipated hysteretic energy (Park & Ang 1985; Wang & Shah 1987). These studies have resulted in the formulization of cumulative damage index models that use component-level response parameters to calculate an estimated measure of the degree of crack
damage. Provided their success in estimating damage in seismically loaded RC structural components, coupled with their computational simplicity, damage index models are attractive for embedment in the computational core of the wireless sensing units. Immediately following an earthquake, wireless sensing units with damage index models embedded could tell facility owners instantly the severity of damage in their RC structural components.

Kratzig et al. (1989) have proposed a damage index model that employs dissipated hysteretic energy to calculate a cumulative damage index model for a cyclically loaded RC structural element. Lynch et al. (2004c) propose the use of peak component drifts within the Kratzig et al. (1989) damage index model to calculate the amount of crack damage sustained to cyclically loaded fibre-reinforced cementitious composite structural elements. Embedded firmware is written for the wireless sensing unit to allow it to autonomously execute the proposed damage index model. Once the cyclic drift response of a cementitious component is measured and recorded, the wireless sensing unit is programmed to identify all of the positive and negative response peaks for calculation of the cumulative damage index. In their study, Lynch et al. (2004c) successfully use a wireless sensing unit to calculate the damage index of a shear wall coupling beam.

4. Wireless monitoring of the Alamosa Canyon Bridge

To validate the performance of the wireless sensing units in the field, the Alamosa Canyon Bridge in southern New Mexico is selected for instrumentation (Lynch et al. 2004a). The Alamosa Canyon Bridge, as shown in figure 4, is an attractive test structure because it is located in a remote area and is seldom used by traffic. The bridge consists of seven spans each identically constructed from steel girders supporting a concrete deck. Each span is 15.2 m long, approximately 7.3 m wide and supported at both ends by concrete piers. An 18 cm concrete deck sits upon six deep steel girders (W30×116 sections) separated from one another by 1.47 m. The girder ends are attached to the concrete pier with standard rollers providing them with pin-support behaviour.

Given its easy access, the third northernmost span (an interior span) of the Alamosa Canyon Bridge is chosen for instrumentation. The goal of this study is to demonstrate the feasibility and performance of the prototype wireless sensing units in a full-scale civil structure. To achieve these goals, wireless sensing units
are installed upon the span’s girders to measure the span response to ambient and forced vibrations. A commercial cable-based monitoring system is installed in parallel with the wireless system to permit a baseline for performance comparison. The accuracy of the wireless sensing units will be assessed by comparing time histories, frequency response functions and modal frequencies with those derived using the commercial system. The mode shapes of the bridge are not calculated in this study owing to the limited number of prototype sensing units available for installation. In addition, the internal clocks of the units have not been configured to synchronize with each other during the testing of the Alamosa Canyon Bridge.

Previous system identification studies have instrumented the northernmost span of the Alamosa Canyon Bridge. The northernmost span is supported by a concrete pier on one end and the bridge abutment at the other. Doebling et al. (1997) determine the modal properties of the span from forced and ambient vibration responses measured with a tethered monitoring system. The first four modal frequencies of the instrumented span, as calculated using the eigensystem realization algorithm (ERA), are documented as 7.4, 8.0, 11.5 and 19.6 Hz. Additional studies of the Alamosa Canyon Bridge have explored changes in bridge modal properties resulting from variations in temperature. Farrar et al. (1997) have shown a 0.3 Hz rise in the bridge’s first modal frequency as a result of a 7°C temperature drop between the bridge’s night and mid-day temperature.

(a) Instrumentation strategy

A wireless modular monitoring system consisting of seven wireless sensing unit prototypes proposed by Lynch et al. (2003a) is installed. Interfaced to the wireless sensing units are Crossbow CXL01LF1 MEMS accelerometers. The CXL01LF1 is a high sensitivity MEMS accelerometer with low-noise and high-stability characteristics. The CXL01LF1 sensitivity is 2 V g\(^{-1}\) and can sense accelerations in the range of ±1 g. The 0.5 mg noise floor of the accelerometer combined with its maximum measurable acceleration provides a dynamic range of over 67 dB. The accelerometer is capable of measuring vibrations from DC to its bandwidth limit of 50 Hz. An additional feature of the accelerometer is an internal anti-aliasing filter on the analogue signal output. The wireless communication channel of the wireless sensing units is used to transfer data from the sensing units to a centralized data repository. In this study, a Linux-based laptop running a custom designed data acquisition program is employed for controlling the network of wireless sensing units and to store bridge response data received. The laptop is positioned approximately 50 m from the instrumented span with no physical obstruction between the laptop and wireless sensing units.

For performance comparison, a commercial tethered monitoring system is installed in parallel to the wireless structural monitoring system; the Dactron SPECTRABook dynamic signal analyzer is selected as the commercial system. The SPECTRABook accommodates eight simultaneous analogue input channels with sampling rates as high as 21 kHz. The internal sensing interface of the Dactron system employs a 24 bit ADC, providing a dynamic range of 120 dB. Accelerometers mounted to the bridge are interfaced directly to the data acquisition system via coaxial cable. A Windows-based laptop containing RT
Pro Signal Analysis software is interfaced to the SPECTRABook in order to control the system and to obtain response data with ease. Once data have been acquired, modal analysis tools provided by RT Pro can be used for modal identification of the instrumented test structure. Used exclusively with the cable-based monitoring system is the Piezotronics PCB336C accelerometer. The PCB336 is a piezoelectric accelerometer that is capable of recording vibrations within a 1–2000 Hz spectrum. Since the internal transduction mechanism of the accelerometer depends upon piezoelectric materials, accurate measurements at frequencies below 1 Hz are not possible. The PCB336 accelerometer has a relatively large sensitivity of \(1 \text{ V g}^{-1}\) and a high amplitude range of \(\pm 4 \text{ g}\). Combined with the accelerometer noise level of 60 \(\mu\text{g}\), the accelerometer has a broad dynamic range of 97 dB.

Accelerometers corresponding to both monitoring systems (wireless and wired) are epoxy mounted to the steel girders of the Alamosa Canyon Bridge span in the seven locations denoted in figure 5. Each location is provided with...
unique location number such as S1, S2, etc. Except for location S4, all the accelerometers are mounted at the midpoint of the girder web. The accelerometers installed at location S4 are situated 38 cm above the bottom flange surface of the girder. As shown in figure 5, the PCB336 accelerometer is installed at the girder midpoint on the left and the CXL01LF1 on the right with wireless sensing units placed upon the girder flange. A 10 m cable is used to connect the PCB336 to the Dactron SPECTRABOOK situated beneath the bridge span. The installation time for the wireless monitoring system was about half the time required for installing the cables associated with the Dactron system.

(b) Forced vibration testing

To produce a sizable vibration response of the Alamosa Canyon Bridge, two excitation inputs are applied to the instrumented span: modal hammer blows (figure 6a) and truck traffic (figure 6b). Both excitation sources will yield reasonably high acceleration responses that are measurable using the accelerometers selected. Modal hammers contain load cells in their heads so that the applied load can be recorded. In this validation study, the applied load measured by the modal hammer head is recorded by the Dactron monitoring system.

First, impulse loads are exerted to the instrumented span using the Piezotronics PCB86C50 modal hammer. The point of impact of the modal hammer is selected to be at the centre of the span with respect to both its length and width directions. The load is repeatedly applied numerous times to measure the acceleration response of the span at all sensor locations; a total of seven tests are performed resulting in 14 time-history recordings (seven from the wireless sensing units and seven generated by the Dactron system). The Dactron system measures the response at a sampling rate of 320 Hz, while the wireless sensing unit is configured to record the response at 976 Hz. The bridge responses measured by the accelerometers mounted at sensor location S3 are presented in figure 7. In comparing the acceleration response of the Alamosa Canyon Bridge recorded by both monitoring systems, strong agreement in both amplitude and time is evident. Minor discrepancies exist in the initial peak measured by the two systems, with the Dactron system measuring a peak of 0.17 g and the wireless sensing unit peak amplitude roughly 0.13 g. Subsequent peaks after the initial peak are in complete agreement with each other. For the other sensor locations,
results similar to those for sensor location S3 are obtained with strong agreement evident in the response measured by both monitoring systems. These time-history results indicate the reliability and accuracy of the prototype wireless sensing unit.

For the dynamic truck load test, the accelerometers mounted at sensor location S7 are employed. The acceleration response of the Alamosa Canyon Bridge at S7 is recorded by both the Dactron and wireless data acquisition systems. Similar to the modal hammer test, the wireless sensing unit is configured to first locally store the data and to then transmit the data upon demand after the completion of the test. Different from the modal hammer test, the wireless sensing unit is configured to sample at 244 Hz. Figure 8 presents the acceleration response of the structure measured over a 2 s interval. The truck is loading the span between the first and the second seconds of the recording. Again, good agreement exists in the two recorded time histories.

(c) **Identification of modal frequencies**

To identify the primary modal frequencies of the instrumented bridge span, the frequency response function is calculated using the response time-history recorded at sensor location S3 collected during the modal hammer excitation. Since the excitation delivered by the modal hammer is a nearly perfect impulse, the frequency response function calculated from the impulse response of the system represents the transfer function of the instrumented span. In contrast, the response time-histories recorded from the truck excitation cannot be used to determine the system transfer function because the excitation input delivered by the truck is not measured in the study.

First, the Cooley–Tukey FFT algorithm is executed by the computational core of the wireless sensing unit to calculate the frequency response function from the span response. The wireless sensing unit is configured to perform a
4096 point FFT analysis using the response data stored in memory; after the frequency response function is calculated, the wireless sensing unit transmits the complex-valued frequency response function to the laptop that is serving as the monitoring system’s data repository. The Dactron monitoring system is also used to calculate the frequency response function using data it has collected during forced vibration testing. The ANALYTICAL software package, RT Pro Signal Analysis, is installed on the laptop managing the Dactron monitoring system and is used to calculate an 8192 point FFT analysis of the response time-history data.
The frequency response function calculated by both systems from measurements obtained at sensor location S3 are presented in figure 9. Strong agreement exists in the two frequency response functions, particularly, with the peaks of the function in alignment. The first three primary response modes can be identified from the frequency response functions and are determined to be located at 6.7, 8.2 and 11.4 Hz. Some differences are also observed, e.g. the frequency response function corresponding to data obtained by the Dactron system is smoother than that obtained from the wireless sensing units. This is partly due to the resolution of the Dactron frequency response function being greater than that of the wireless system with six times more points defined in the frequency range (0–30 Hz) plotted. Second, the lower analogue-to-digital conversion resolution of the wireless sensing unit introduces more quantization noise in the lower magnitudes of the frequency response function. This additional quantization noise is most dominant below 2.4 Hz where a large discrepancy exists in the two frequency response functions.

The modal frequencies determined from all the sensor locations (S1–S7) are tabulated in table 4. The seven sensor locations yield similar modal frequencies of the instrumented span. The average of the first three modal frequencies is determined to be 6.83, 8.4 and 11.6 Hz, respectively. This is in contrast to the modal frequencies acquired for the northernmost span from past system identification studies: 7.4, 8.0 and 11.5 Hz (Doebling et al. 1997). The per cent difference between the identified modal frequencies of the two spans are 7, 5 and 1% for the first, second and third mode, respectively. Subtle structural differences that exist between the two different spans instrumented (such as differences in the boundary conditions) can be the cause for variability.

Table 4. Modal frequencies of the instrumented span of the Alamosa Canyon Bridge as determined during modal hammer forced vibration testing.

<table>
<thead>
<tr>
<th>modal frequency</th>
<th>first span past study (Hz)</th>
<th>wireless sensing unit location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S1 (Hz)</td>
<td>S2 (Hz)</td>
</tr>
<tr>
<td>1st mode</td>
<td>7.4</td>
<td>6.7</td>
</tr>
<tr>
<td>2nd mode</td>
<td>8.0</td>
<td>8.3</td>
</tr>
<tr>
<td>3rd mode</td>
<td>11.5</td>
<td>11.6</td>
</tr>
</tbody>
</table>

5. Technical challenges associated with wireless telemetry

Wireless monitoring systems have the potential to serve as low-cost substitutes for traditional tethered structural monitoring systems. However, it should be noted that differences exist between wireless and tethered monitoring systems that shape how wireless monitoring systems will be deployed in civil structures. Unlike tethered monitoring systems where electrical power is delivered to sensors through the same coaxial cable intended for communication, a wireless structural monitoring will largely depend upon battery power. With battery supplies limited in their operational life expectancy, the usage strategy of the wireless
monitoring system is strongly influenced by a desire to conserve battery power. An additional challenge with wireless telemetry is the lack of a common clock to which sensors can reference during data acquisition.

(a) Electrical power characteristics of wireless sensing units

In structures where connecting the wireless monitoring system to a structure’s native power system (e.g. wall outlets) is not practical, battery packs are a probable power source for wireless sensing units. With batteries limited in their operational life, it is necessary to assess the amount of battery energy consumed by wireless sensing units during their operation. Using the wireless sensing unit prototype proposed by Lynch et al. (2003a), the energy consumed by the unit is experimentally measured using two 7.5 V battery packs constructed from batteries of different cell chemistries. First, an alkaline (Zn/MnO$_2$) battery pack assembled from five Energizer AA E91 batteries is used to power the wireless sensing unit. Next, lithium-based (Li/FeS$_2$) batteries of high energy density are also considered by constructing a battery pack of five Energizer AA L91 battery cells. The wireless sensing unit is turned on and the electrical current drawn from the battery packs is measured using a current meter. Using the electrical currents measured, the life expectancy of the battery packs can be calculated from engineering design charts provided by the battery manufacturer. Table 5 summarizes the expected operational life of the batteries when continuously drained based on the electrical currents measured. It should be noted that values listed in table 5 are conservative because wireless sensing unit use would be duty cycled. When batteries are intermittently used, cell chemistries are provided time to re-attain equilibrium resulting in operational lives well beyond those predicted assuming continuous use.

The rationale for including a dual processor core in the wireless sensing unit prototype design is evident after observing the power consumption characteristics of the unit in its different modes of operation. To preserve battery energy, the MPC555 should remain in an off or sleep state when interrogation of response data is not required. When the MPC555 is turned off, the wireless sensing unit draws a small amount of electrical power (40 mW) providing the unit with a long-life expectancy. However, when it is appropriate to execute embedded algorithms, the MPC555 should be powered on; as soon as the data

Table 5. Anticipated operational life-expectancy of wireless sensing units powered by various battery chemistries.

<table>
<thead>
<tr>
<th>operational state</th>
<th>circuit current (mA)</th>
<th>internal voltage (V)</th>
<th>Energizer L91 Li/FeS$_2$ 7.5 V pack (h)</th>
<th>Energizer E91 Zn/MnO$_2$ 7.5 V pack (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVR only (MPC off)</td>
<td>8</td>
<td>5</td>
<td>500</td>
<td>300</td>
</tr>
<tr>
<td>AVR on + MPC sleep</td>
<td>54</td>
<td>5 + 3.3</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>AVR on + MPC on</td>
<td>160</td>
<td>5 + 3.3</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>RangeLAN active</td>
<td>190</td>
<td>5</td>
<td>13</td>
<td>4</td>
</tr>
<tr>
<td>RangeLAN sleep</td>
<td>60</td>
<td>5</td>
<td>40</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 5

Wireless structural health monitoring

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processing tasks have been completed, the MPC555 should once again be powered down. By utilizing the wireless sensing unit’s two microcontrollers in this manner, impressive computational resources are available when needed without having the high-power microcontroller continuously depleting the battery source.

The importance of including a capable computational core in the wireless sensing unit design is reinforced when observing the power demands of the wireless radio. The power required to operate the RangeLAN 2 radio is the rate of energy the radio would consume from the unit battery. When drawing 190 mA at 5 V, the power demand of the radio is 950 mW. In contrast, when drawing 110 mA at 3.3 V, the power of the MPC microcontroller is 330 mW. Clearly, the MPC555 is 2.6 times more power efficient than the wireless radio. By using the MPC555 more than the wireless radio, less battery energy is required to power the units. To determine the total amount of energy saved by the battery, the time needed to perform embedded analyses should be calculated. The time for transmission of the raw time-history record is also calculated using the radio’s serial band rate. As long as the time of execution of the analysis is faster than 2.6 times the time of transmission, battery energy will be saved and a longer battery life can be expected.

The amount of battery energy that can be conserved by locally processing data and wirelessly transmitting analysis results in lieu of wirelessly transmitting the unprocessed time-history data will be illustrated using actual structural response data collected during various validation studies (Lynch et al. 2004b). To calculate the amount of battery energy saved, the time required by the MPC555 to execute various embedded algorithms using a given time-history record is compared to the time the RangeLAN 2 would take to transmit the raw time-history data. From the time measured, the amount of battery energy consumed by the MPC555 and RangeLAN 2 radio can be calculated using the power specification for each component (330 and 950 mW for the MPC555 and radio, respectively).

The computation time of the embedded algorithms depends largely upon the computational complexity of the algorithm. For example, the computational complexity of the Cooley–Tukey FFT is of order $O(N \log N)$, where $N$ is the length of the initial time-history record. To verify this relationship, FFTs corresponding to different record lengths will be performed with modal frequencies transmitted to the network. In a similar manner, AR models are fit to stationary response data and the AR model coefficients transmitted. For the analysis of the energy consumed in fitting AR models to time-history data, the number of coefficients and the time-history lengths varied. Table 6 presents the time associated with each analysis and the amount of battery energy saved. Clearly, the computational efficiency of the embedded FFT and transmission of modal frequencies as compared to transmission of the time-history record provides a major energy saving of over 98%. The calculation of AR coefficients is more complex and requires external memory for temporary data storage resulting in longer execution times. Hence, the energy saved is not as impressive as for the FFT, but major savings of over 50% are still experienced. Clearly, end-users of wireless sensing units should be cognizant of the execution times of their analyses, but on average, significant savings will be experienced by local data interrogation in lieu of transmitting time-history data for processing by centralized data repositories.

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Lossless data compression

In many instances, the wireless transmission of raw time-history data within the wireless monitoring system will be necessary. To improve the power efficiency of the wireless monitoring system during the transmission of structural response time-histories, data compression techniques can be employed by the units. Data compression algorithms generally fall into two broad classes: lossless and lossy compression. Lossless compression, often used in medical imaging applications, guarantees the integrity of the data without distortion. In contrast, lossy compression reduces data with reasonable distortions but can generally achieve higher compression rates. For structural monitoring, there is also low tolerance for distortion in structural response data resulting in only lossless compression considered for inclusion in the wireless sensing unit.

Numerous lossless compression techniques can be considered but the computationally inexpensive compression technique, known as Huffman coding, is selected for implementation (Moffat & Turpin 2002). Lossless Huffman coding exploits statistical relationships in the data to pair short binary symbols (e.g. 011) to data values recurring with high probability while long binary symbols (e.g. 0110101) are reserved for those with low probability of occurrence. For example, if the 16 bit integer value ‘21’ was the most commonly occurring data sample, a short 1 bit symbol can be given to it, such as ‘1’. Next, if ‘227’ is the next most common value, it might be given the 2 bit symbol ‘01’. This process is repeated until a Huffman look-up table has been generated with a unique binary symbol given to each permissible data value. The Huffman look-up table can be used to convert original time-history data from a fixed length binary representation (16 bits) to a more compact binary representation of variable length. Prior to generation of a Huffman look-up table, inherent structures in data can be exploited to attain compression with higher rates. The structure in the data can be described by transformation of the initial record using a de-correlation transform. Many transforms could serve as suitable candidates,

<table>
<thead>
<tr>
<th>analysis</th>
<th>length of record (N)</th>
<th>time of MPC555 calculation (s)</th>
<th>energy consumed MPC555 (J)</th>
<th>time for wireless transmission (s)</th>
<th>energy consumed radio (J)</th>
<th>energy saved (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFT</td>
<td>1024</td>
<td>0.0418</td>
<td>0.0152</td>
<td>1.7067</td>
<td>1.6213</td>
<td>99.062</td>
</tr>
<tr>
<td>FFT</td>
<td>2048</td>
<td>0.0903</td>
<td>0.0328</td>
<td>3.4133</td>
<td>3.2426</td>
<td>98.988</td>
</tr>
<tr>
<td>FFT</td>
<td>4096</td>
<td>0.1935</td>
<td>0.0702</td>
<td>6.8267</td>
<td>6.4854</td>
<td>98.917</td>
</tr>
<tr>
<td>AR (10 coef)</td>
<td>2000</td>
<td>1.3859</td>
<td>0.5031</td>
<td>3.3333</td>
<td>3.1666</td>
<td>84.112</td>
</tr>
<tr>
<td>AR (20 coef)</td>
<td>2000</td>
<td>2.8164</td>
<td>1.0224</td>
<td>3.3333</td>
<td>3.1666</td>
<td>67.713</td>
</tr>
<tr>
<td>AR (30 coef)</td>
<td>2000</td>
<td>4.2420</td>
<td>1.5398</td>
<td>3.3333</td>
<td>3.1666</td>
<td>51.374</td>
</tr>
<tr>
<td>AR (10 coef)</td>
<td>4000</td>
<td>2.7746</td>
<td>1.0072</td>
<td>6.6667</td>
<td>6.3333</td>
<td>84.097</td>
</tr>
<tr>
<td>AR (20 coef)</td>
<td>4000</td>
<td>5.6431</td>
<td>2.0484</td>
<td>6.6667</td>
<td>6.3333</td>
<td>67.657</td>
</tr>
<tr>
<td>AR (30 coef)</td>
<td>4000</td>
<td>8.5068</td>
<td>3.0879</td>
<td>6.6667</td>
<td>6.3333</td>
<td>51.243</td>
</tr>
</tbody>
</table>

(b) Lossless data compression

In many instances, the wireless transmission of raw time-history data within the wireless monitoring system will be necessary. To improve the power efficiency of the wireless monitoring system during the transmission of structural response time-histories, data compression techniques can be employed by the units. Data compression algorithms generally fall into two broad classes: lossless and lossy compression. Lossless compression, often used in medical imaging applications, guarantees the integrity of the data without distortion. In contrast, lossy compression reduces data with reasonable distortions but can generally achieve higher compression rates. For structural monitoring, there is also low tolerance for distortion in structural response data resulting in only lossless compression considered for inclusion in the wireless sensing unit.

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but in this study, a Daubechies-4 discrete WAVELET TRANSFORM (WT) will be used for de-correlation. The WT has also been proposed as a key component of some damage detection methods (Robertson \textit{et al.} 2003); hence, a WT software module embedded in the wireless sensing unit could be used for both damage detection and data compression. Figure 10 summarizes the proposed data compression strategy implemented in the core of a wireless sensing unit. Employing the Huffman lossless compression technique on actual structural response data, the wireless sensing units have been capable of attaining compression ratios ranging from 0.6 to 0.8 (Lynch \textit{et al.} 2003\textsuperscript{b}). These compression rates translate directly into energy save by the battery supply.

\begin{figure}[ht]
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{Lossless compression using Huffman coding and wavelet de-correlation.}
\end{figure}

(c) \textit{Time synchronization}

Time synchronization between wireless sensing units is another challenge associated with wireless telemetry. Time synchronization is necessary to ensure that structural response time histories collected at different locations can be accurately aligned on a common time-scale. To distribute a common clock to a network of wireless sensing units, a global beacon signal can be employed to ping the network. Once each wireless sensing unit receives the same beacon ping, the units are programmed to set an internal clock to 0. This method has been successful in attaining relatively close synchronization between wireless sensing units; synchronization errors of less than 0.1 ms have been reported (Straser & Kiremidjian 1998). More recently, Wang \textit{et al.} (in press) have reported time synchronization errors of the order of only a few microseconds in a 900 MHz wireless structural monitoring system. Real-time clocks included in the design of the wireless sensing units will have a tendency to drift over long periods of time. As a result, a wireless monitoring system must be continuously resynchronized.
An alternative approach to synchronization between time-history records has been proposed by Lei et al. (2005). In their approach, the error of an autoregressive with moving average time-series model fit to two data streams is minimized to find perfect time alignment of the streams. An attractive feature of this approach is that it can be done by the wireless sensing units after structural responses have been recorded by the monitoring system.

6. Wireless active sensing for component-level health monitoring

A direct benefit of wireless sensing units being low cost is that wireless monitoring systems defined by high sensor densities are encouraged. Dense-sensor deployments provide greater insight to the behaviour of the structure at component-level length-scales resulting in empirical response data from which damage can be more accurately identified. Some of the challenges associated with wireless telemetry (e.g. power consumption and time synchronization) also encourage wireless sensing units to shift focus from using global response characteristics for damage detection and to perform component-level investigation of the structure. For example, the pattern recognition time-series damage detection method proposed by Sohn & Farrar (2001) requires the structure to be measured at one sensor location to detect damage in the sensor vicinity. Since time-history data do not need to be shared between wireless sensing units (a task that would consume battery energy), this local-area damage detection methodology is energy efficient.

Active sensors are emerging as a promising sensor technology well suited for local investigation of structural components. Historically, structural monitoring systems have employed passive sensors that are only responsible for recording the response behaviour of a structure. In contrast, active sensors are sensors equipped with capabilities to excite the system in which they are installed, while simultaneously recording the system’s response. Piezoelectric materials are widely used for active sensing because their unique mechanical–electrical properties allow them to behave as actuators or sensors. Piezoelectric pads surface mounted to structural elements have been employed to actively sense structural systems with the intention of diagnosing damage in the element. For example, Wu & Chang (2001) have employed piezoelectric rings mounted to steel reinforcement bars to identify de-bonding. Others, including Park et al. (2000), have shown that the electrical impedance of piezoelectric pads mounted to masonry and steel structures exhibits detectable changes when damage is present in the vicinity of the piezoelectric pad. An advantage associated with locally actuated excitations is that they are repeatable.

To take advantage of active sensors in a wireless health monitoring system, a new wireless sensing unit prototype is proposed to which active sensors can be attached and commanded. The design of the wireless active sensing unit is optimized for piezoelectric active sensors that could impart acoustic and ultrasonic waves into structural elements, but any type of actuator could be commanded. Many of the functional elements used in the design of the passive wireless sensing unit proposed by Lynch et al. (2003a) are employed in the wireless active sensing unit prototype design. To serve as the unit core, the Motorola MPC555 PowerPC microcontroller is retained for its extensive on-chip memory.
(both read only and RAM), on-board floating-point processor and quick speed (20 MHz). To collect data simultaneously from multiple passive sensors interfaced to the unit, the internal multi-channel 10 bit ADC of the MPC555 will serve as the unit’s sensing interface. For the transfer of data between the wireless active sensing unit and the wireless monitoring system, the low-power MaxStream XCite wireless modem operating on the 900 MHz unlicensed radio spectrum is chosen. The XCite modem is capable of transferring data at rates as high as 38 400 bits s$^{-1}$ and to ranges as far as 300 m in open space (90 m on the interior of concrete structures). Using frequency hopping spread spectrum techniques, the radio is highly reliable and immune to narrow band interference. Unlike the RangeLAN 2 radio previously adopted, the MaxStream modem has very low power consumption characteristics by consuming 55 mA of electrical current when transmitting. To command active sensors, an actuation interface circuit is designed using off-the-shelf integrated circuit elements. The 12 bit Texas Instrument DAC7624 digital-to-analogue converter (DAC) is the primary component of the actuation interface with additional instrumentation amplifiers included to increase the DAC range to ±5 V. The actuation interface is designed as actuator transparent and can accommodate any type of active sensor (piezoelectric, ultrasonic, impact hammers, etc.). Both the actuation and sensing interfaces are controlled in real time by the MPC555 core at sampling rates below 40 kHz. To comfortably store long command and response time-history records, 256 KB of additional RAM is included in the wireless active sensing unit core. Figure 11 illustrates the architectural design of the wireless active sensing unit.
Various validation studies have been conducted to assess the performance of the wireless active sensing unit to command active sensors (Lynch 2005). As part of the validation study, piezoelectric pads are epoxy mounted to the surface of a slender aluminium plate that is 28 cm long, 7 cm wide and 3.175 mm thick. The wireless active sensing unit commands one piezoelectric pad to generate surface acoustic waves in the aluminium plate, while a second pad is employed to record the corresponding response of the plate. The MPC555 microcontroller is utilized to interrogate the input–output time-history response of the system to successfully identify the existence of cracks introduced to the plate.

7. Discussion and conclusions

In recent years, wireless sensor technology has rapidly matured and been applied to a number of different applications. Specific to the field of structural monitoring, wireless communications coupled with traditional structural sensors can substantially reduce monitoring system costs while providing functionality not present in existing commercial structural monitoring platforms. An important ingredient in the evolution of wireless sensors is the inclusion of inexpensive mobile computing technology. Combining computing power with structural sensors allow the sensors to take ownership of the data processing tasks that are often associated with the data repositories of traditional centralized structural monitoring systems. Tremendous interest surrounds the use of a wireless structural monitoring system’s computational resources to automate the task of interrogating structural response data for signs of damage. Such a structural health monitoring system represents a major paradigm shift in the design and use of future structural monitoring systems.

The purpose of this paper was to provide a detailed overview of the author’s experience in designing wireless sensing units for the health monitoring of civil structures. The paper has reviewed the design of a number of different wireless sensing unit prototypes that have been designed explicitly for structural monitoring applications. The firmware required to operate the units and to locally interrogate structural response data has been presented. The Alamosa Canyon Bridge has served as an example of one of the many validation studies performed on the wireless sensing unit prototypes developed. Forced vibration testing of the Alamosa Canyon Bridge showcased the accuracy and reliability of the wireless structural monitoring system installed. As wireless structural health monitoring systems continue to decline in cost, field deployments will become defined by an increasing number of wireless sensing unit nodes. High densities of sensing nodes provide the monitoring system with better spatial resolution which can improve the accuracy of damage detection analyses. To further enhance the functionality of wireless sensors, a novel wireless active sensing unit design is proposed. An actuation interface is included in the design of a wireless active sensing unit for which active sensors can be commanded. Active sensing coupled with low-cost wireless sensing units produce a compelling technology for future use in structural health monitoring systems.

Even though wireless sensing technologies continue to advance in lockstep with the rapid evolution of related embedded systems technologies, in many regards, wireless structural monitoring systems are still in their infancy.
Opportunities still exist to improve the hardware and software features of existing wireless sensing unit prototypes. With power consumption still a major challenge, work is needed to produce wireless sensors whose hardware designs allow them to be employed in long-term field deployments. Power harvesting technologies, under development in academia, could offer opportunities to replenish battery energy by harvesting power from ambient structural vibrations. With computational responsibility spatially distributed throughout the wireless structural monitoring system, new approaches to interrogating structural response data for signs of damage are also needed. The development of future damage detection algorithms intended for embedment in the wireless monitoring system would greatly benefit if the architecture (e.g. a decentralized computing grid) and limitations (e.g. power constrained) of the wireless system architecture are taken into account a priori. Greater emphasis should be placed upon the use of real civil structures for validation of wireless monitoring systems. While the Alamosa Canyon Bridge has been instrumental in the validation of the performance of a prototype wireless monitoring system, validation studies employing greater numbers of sensing nodes are necessary to determine the scalability of the proposed technology.

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References


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