Design and Performance Validation of a Wireless Sensing Unit for Structural Monitoring Applications

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Abstract. There exists a clear need to monitor the performance of civil structures over their operational lives. Current commercial monitoring systems suffer from various technological and economic limitations that prevent their widespread adoption. The wires used to route measurements from system sensors to the centralized data server represent one of the greatest limitations since they are physically vulnerable and expensive from an installation and maintenance standpoint. In lieu of cables, the introduction of low-cost wireless communications is proposed. The result is the design of a prototype wireless sensing unit that can serve as the fundamental building block of wireless modular monitoring systems (WiMMS). An additional feature of the wireless sensing unit is the incorporation of computational power in the form of state-of-art microcontrollers. The prototype unit is validated with a series of laboratory and field tests. The Alamosa Canyon Bridge is employed to serve as a full-scale benchmark structure to validate the performance of the wireless sensing unit in the field. A traditional cable-based monitoring system is installed in parallel with the wireless sensing units for performance comparison.

Key words: Wireless monitoring; wireless sensing unit; structural health monitoring

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1. Introduction

The installation of structural monitoring systems in civil structures entails the spatial distribution of embedded sensors to measure structural responses to environmental loads. Historically, structural monitoring systems have been used to monitor strong ground motions and their effect on structures, leading to improvements in the design of structures in zones of high seismicity (Shakal 2001). Today,

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additional benefits are derived from installing structural monitoring systems in a variety of structures. For example, monitoring systems are extensively used to monitor top-story displacements of structures adjacent to large excavations, to track the long-term performance of a structure and to help calibrate nonlinear analytical models.

In the future, structural monitoring systems will become increasingly popular for a broader set of applications. In particular, monitoring systems will serve as the necessary infrastructure for automated structural health monitoring systems. Rapid advancements made in the field of damage detection are yielding algorithms capable of using structural response measurements to identify the existence, location and type of damage present in a structural system (Doebling et al. 1996). Methods are becoming more reliable in detecting the onset of damage, particularly in civil structures where environmental and operational variability often mask evidence of damage (Sohn et al. 1999). The coupling of a structural monitoring system and damage detection methods results in a structural health monitoring system. Many benefits are associated with an automated structural health monitoring system including cost-effective condition-based maintenance being used in lieu of the current schedule-based maintenance paradigm.

In California, hundreds of structures can be cited as examples of structural monitoring including municipal buildings, long-span bridges and dams. For example, over sixty of California's long span bridges have been instrumented with a total of more than 900 sensing channels (Hipley 2001). World-wide, structural monitoring is growing in popularity. In Asia, long-span bridges have been instrumented with monitoring systems monitoring their behavior to strong wind and seismic loads including the Tsing Ma suspension bridge in Hong Kong and the Akashi Kaikyo suspension bridge in Japan (Ni et al. 2001, Tamura 2001).

Current commercial monitoring systems employ hub-spoke system architectures with remote sensors wired directly to a centralized data acquisition server. The tasks of aggregating, storing, and interrogating the measurement data are assumed by the centralized server. The hub-spoke wire-based monitoring systems suffer many economic and technological limitations. The current cost of installing monitoring systems in civil structures is high. For example, the cost of installing a monitoring system in the Tsing Ma suspension bridge was reported over $27,000 per sensing channel (Farrar 2001). The expensive nature of structural monitoring systems is a direct result of the wires used to communicate sensor measurements to the centralized data server. Over 75% of the installation time is attributable to the laying of wires in a structure with installation costs representing up to 25% of the system total cost (Straser and Kiremidjian 1998). Installation efforts and costs can increase for structures with difficult to reach locations through which wires must be installed.

Wires also represent a fragile component of current monitoring systems. Tearing of wires and rodent nibbling are common occurrences necessitating vigilant maintenance efforts on the part of system owners. An additional limitation of centralized system architectures is the central data server. Being a single point of possible failure in the system, the central server can become overburdened as system size grows and computation demands increase. As a result, if the centralized system architecture is used for structural health monitoring applications, careful attention must be paid to the implementation of damage detection methods to ensure the computational capabilities of the server are not saturated.

In response to the identified limitations of current state-of-practice systems, a novel monitoring paradigm is proposed: wireless structural monitoring (Straser and Kiremidjian 1998, Lynch et al. 2002a). Identifying wires as a severe limitation of tethered monitoring systems, the incorporation of wireless communications is proposed for the transfer of measurement data in a wireless monitoring system. The past decade has witnessed a revolution in wireless communication technologies; wireless capabilities improve and costs continue to reduce. As a result, wireless communications can serve as reliable substitute to wires at a fraction of their associated costs. A second innovation is proposed; integrate computational power for local processing of measurement data with each sensing node of the system (Lynch et al. 2002b). By providing each sensor the means to process its own data, computational burden is removed from the centralized server in addition to many benefits associated with parallel data processing reaped.

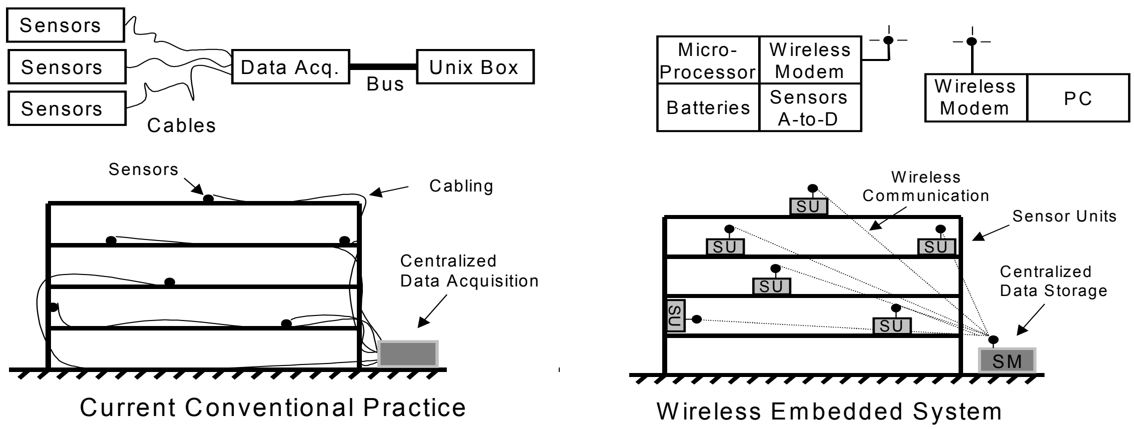

Figure 1 – Wire-based versus wireless structural monitoring systems

The innovations of the proposed wireless monitoring system are embodied by the design of a wireless sensing unit that is constructed from advanced embedded system and wireless technologies (Lynch 2002). Wireless sensing units represent the fundamental building block of wireless modular monitoring systems (WiMMSS), as illustrated in Fig. 1. The unit design is optimized for application in civil structures with a heavy emphasis placed upon keeping the total unit cost low. Damage detection methods, as they mature, will be embedded in the wireless sensing unit to deliver a low-cost automated structural health monitoring system.

This paper explores the design of a prototype wireless sensing unit for WiMMS deployment. In particular, the design process focuses upon the design of three modular subsystems: sensing interface, computational core and wireless communications. The wireless sensing unit is fabricated and validated using a series of performance tests in both the laboratory and field. The focus of the laboratory validation tests is to explore the interfacing of different sensing transducers with the wireless sensing unit. The Alamosa Canyon Bridge in New Mexico is selected to serve as a benchmark structure for field validation of the wireless sensing unit. A classical cable-based monitoring system is installed in parallel in the bridge to facilitate comparison of the wireless system's performance.

2. Hardware Design of the Wireless Sensing Unit

As the enabling building block of an automated structural health monitoring system, careful attention is paid to the design of the wireless sensing unit. A modular design with off-the-shelf components is employed to keep fabrication efforts reasonable and total unit costs low. The architectural design of the wireless sensing unit, as shown in Fig. 2, is divided into three major subsystems: sensor interface, computational core, and wireless communications.

The first subsystem, the sensing interface, is responsible for the interfacing of various sensing transducers (e.g. accelerometers, strain gages, and anemometers) that will provide measurements of environmental loads and responses of the structure. To accommodate multiple sensors simultaneously, a multiple sensing channel interface is designed. At the core of the sensing interface subsystem, is a single-channel analog-to-digital (A/D) converter that can resolve the output of any analog sensor to a 16-bit digital representation. Sampling rates as high as 100 kHz can be attained using the Texas Instruments ADS7821 16-bit A/D converter. Two additional sensing channels are provided that accept duty cycle modulated outputs from a wide class of digital sensors. Many commercial MEMS-based accelerometers provide duty cycle modulated outputs with resolutions of 14-bits (Analog Devices 1999).

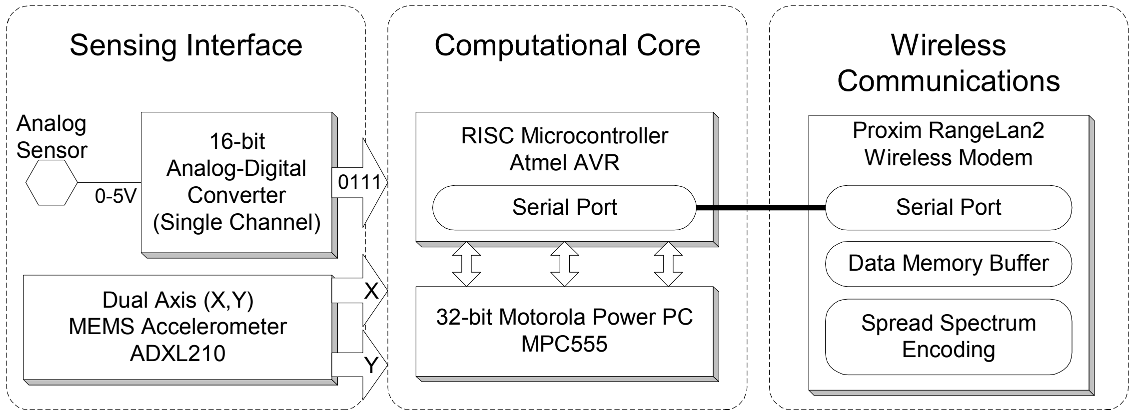

Figure 2 – Architectural design schematic of proposed wireless sensing unit

After measurement data is collected by the sensing interface, it is read by the computational core of the wireless sensing unit. At the center of the unit's architectural design, the computational core is responsible for aggregating measurement data from the sensing interface, executing data interrogation tasks, and transferring data through the wireless modem to a wireless network comprised of wireless sensing units. A two processor core design is employed with a low power 8-bit microcontroller chosen for simple unit operation and a powerful 32-bit microcontroller dedicated to performing data interrogation tasks. The Atmel AT90S8515 AVR microcontroller is selected for its capability-rich hardware design, low cost and efficient power characteristics. Some enabling features incorporated in the sensing unit design are on-board timers, pulse width modulators, universal asynchronous receiver-transmitters (UART), 8 Kbytes of flash read only memory (ROM) and 512 bytes of static random access memory (SRAM). For the execution of computationally demanding data interrogation algorithms, the 32-bit Motorola MPC555 PowerPC microcontroller is selected. With 448 Kbytes of flash ROM and 26 Kbytes of RAM, sufficient on-board memory is provided to serve as storage of measurement data. Special data registers are provided by the MPC555 to perform rapid floating-point calculations in hardware.

The use of wireless communication for data transfer gives the low cost and modular installation features of the proposed wireless sensing unit. The Proxim RangeLAN2 radio modem is chosen to serve as the reliable wireless communication technology of the wireless sensing unit. Operating on the 2.4 GHz unregulated FCC industrial, scientific and medical (ISM) band, data rates of 1.6 Mbps can be attained with communication ranges of up to 350 meters in unobstructed open space. Within structures constructed from heavy construction materials (e.g. concrete), the communication range reduces to about 160 meters. To ensure reliable wireless communication, data packets are modulated using frequency-hopping spread spectrum (FHSS) techniques.

3. Prototype Fabrication

The selected components for the wireless sensing unit are assembled into a single package. A two-layer printed circuit board is designed to house the components and the support circuitry associated with each component. Careful attention is paid during the circuit design to prevent the injection of electrical noise that can result from a poor circuit board layout (Ginsberg 1990). Roughly 10 cm by 10 cm, the printed circuit board is sufficiently compact, and is powered by a direct current (DC) 7.5 V power source. The RangeLAN2 radio modem is kept in its original packaging and is not included in the printed circuit board design. The radio is attached to the wireless sensing unit through a serial port. Fig. 3 shows a picture of the completed prototype wireless sensing unit. The printed circuit board is packaged at the top of the unit with the wireless modem housed beneath.

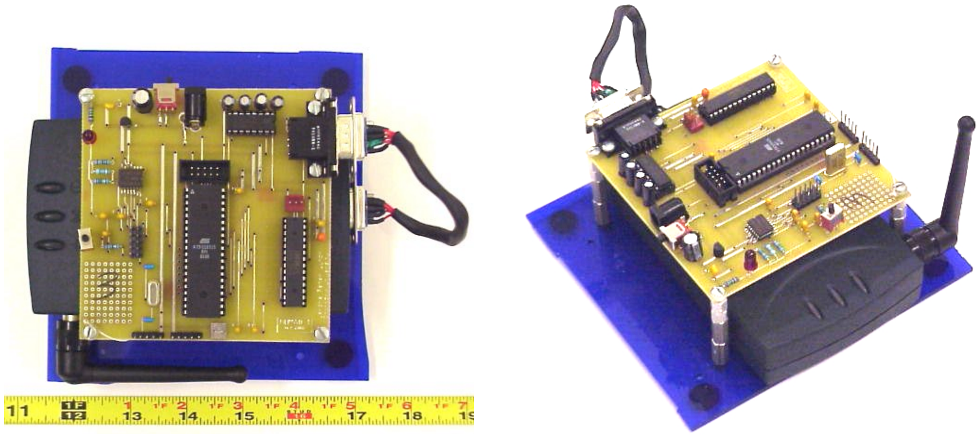

Figure 3 – Top and perspective view of prototype wireless sensing unit

A variety of power sources can be chosen to power the wireless sensing unit. If a portable power source such as a battery is selected, an effective power usage strategy is required to maximize the unit's operational life before necessitating attention. Table 1 tabulates the operating currents of the most power demanding system components. Each component is capable of being placed in sleep mode where power usage is significantly reduced.

Table 1 – Supply current demand of key sensing unit components

Operational State	Atmel AVR AT90S8515 (5V at 4 MHz)	Motorola PowerPC MPC555 (5V at 40 MHz)	Proxim RangeLAN2
Active	8 mA	110 mA	160 mA
Sleep	2.5 mA	4 mA	60 mA

Each component is maintained in sleep mode until its active operation is required. The low power Atmel microcontroller, responsible for overall unit operation, is always kept in its active mode. Once data is collected and interrogation is required, the PowerPC microcontroller is awakened from its sleep mode. The PowerPC, drawing 110 mA, is only kept awake until it has completed its computational tasks. The wireless modem represents the most power demanding component of the wireless sensing unit design. As a result, the importance of using the computational core for processing and consolidating data before transmission is underscored.

Batteries represent one potential power source with a broad variety commercially available. Two batteries packs are integrated to the wireless sensing unit; one is dedicated to powering the circuit components while the second is to power the wireless modem. Two battery cell chemistries are considered for adoption: alkaline (Zn/MnO_2) and lithium (Li/FeS_2) cells. The alkaline cell is a typical battery used in consumer electronics and is considered a low-cost solution with low energy density. The lithium cells are three times more expensive, but possess a higher energy density. To make a conservative estimate of the operational life of the two battery cells integrated with the wireless unit, design charts provided by the battery manufacture are used to calculate the continuous usage time of the battery given a known electrical current draw. The results of this study are tabulated in Table 2 for the wireless sensing unit in different operational states. The lithium battery cells are significantly longer lasting, offsetting their higher costs.

Table 2 – Operational life of the wireless sensing unit using battery power sources

Operational State	Current (mA)	5-AA L91 (Li/FeS2) Battery Pack (7.5 V)	5-AA E91 (Zn/MnO2) Battery Pack (7.5 V)
AT90S8515 Circuit with MPC555 Asleep	54	50 hours	30 hours
AT90S8515 Circuit with MPC555 Active	160	15 hours	5 hours
RangeLAN2 Asleep	60	40 hours	25 hours
RangeLAN2 Active	160	15 hours	5 hours

4. Embedded Software Design

With the prototype wireless sensing unit fabricated, software is required to manage its operation. The role of embedded hardware is to act as an intermediary between the physical hardware layer of the system and the intention of the unit end user. Software is written for embedding in the computational core's microcontrollers. Both microcontrollers employ reduced instruction set computer (RISC) architectures that have been optimized for software written in high level programming languages such as C and Java (Bogen and Wollan 1996).

Software designed for the wireless sensing unit is organized upon two layers of software abstraction. The lowest layer of software is closest to the hardware and is therefore responsible for direct operation of the different hardware subsystems of the unit. This layer serves as an abstraction layer hiding hardware implementation details from the additional software layer above. A modular approach is taken to authoring software for this layer with each software module limiting its scope to the operation of one hardware subsystem. Given the close relationship between each module and a segment of the system's hardware, the modules are also known as hardware drivers. For operation of the prototype wireless sensing unit, six modules are required. Software executing computational tasks associated with engineering applications would be written for the second software layer. Some engineering applications that are envisioned for embedding include damage detection and modal analysis methods.

Fig. 4 graphically depicts the structuring of the wireless sensing unit software development efforts. The six modules presented in the device driver layer primarily control the operation of the AVR microcontroller, while application software would be executed in the PowerPC (PPC) microcontroller. The first module is for the control of the serial communication UART required for communications with the wireless modem. The second and third modules implement the PPX and MCP communication protocols that are specific to the RangeLAN2. A fourth module is designed to control the A/D converter while a fifth module implements a special real-time data stack to hold measurement data. The last module operates two input channels for digital sensors.

To illustrate the broad computational capabilities of the prototype sensing unit, a fast Fourier transform (FFT) is encoded. The FFT is used to transform measurement data from the time-domain to the frequency domain. In modal analysis, the FFT is often employed to derive the frequency response function from time-history data. The natural periods of response and mode shapes can be determined from the frequency response functions (Ewins 1984). Historically, changes in the modal properties of a structure have been used to hypothesize the existence of structural damage (Doebling et al. 1996). Various algorithms of the FFT are available for use, but the Cooley-Tukey approach is used in this study

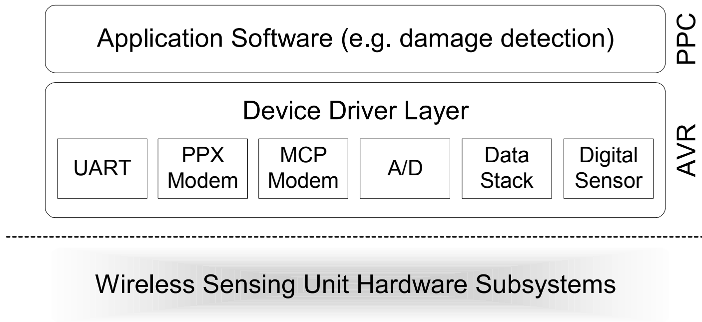

Figure 4 – Embedded software layers

(Press et al. 1992). The approach reorders the initial time-history data and performs a series of two-point Fourier transforms on adjacent data points.

5. Laboratory Data Acquisition

A variety of sensing transducers can be interfaced to the wireless sensing unit. Often, monitoring of civil structures entails the use of accelerometers to measure acceleration responses, strain gages to measure stress in structural members, linear displacement transducers to measure relative displacement, and anemometers to measure wind speeds. In this study, a micro-electro mechanical system (MEMS) accelerometer is selected. After recording measurement data from the accelerometer, the wireless sensing unit is used to produce the frequency response function of the system.

A wide variety of accelerometer types with different performance characteristics are commercially available. For structural monitoring applications, the force balance accelerometer is most popular due to its accuracy and high-level output (Kinemetrics 2002). Most recently, MEMS researchers have fabricated in silicon dies sensing transducers on the micrometer scale. The result is sensing transducers integrated with digital circuitry to yield low cost yet highly accurate sensors with small form factors. In particular, accelerometers have been beneficiaries of these developments with MEMS-based accelerometers of different internal architectures readily available.

In this study, the Analog Devices ADXL210 accelerometer is considered for integration to the wireless sensing unit. The ADXL210 is a MEMS-based accelerometer employing a differential capacitor internal architecture. Advanced photolithography and etching methods are used to release a silicon proof mass connected to its housing through linear springs. Along the proof mass's perimeter are differential capacitors that generate a square wave signal in response to the displacement of the proof mass. The amplitude of the resulting square wave is linearly proportional to acceleration of the sensor. The ADXL210 is capable of measuring an acceleration of $\pm$ 10 g, with a sensitivity of 100 mV/g. The bandwidth and noise floor of the accelerometer are adjustable with smaller bandwidths resulting in a lower noise floor. A bandwidth of 50 Hz is sufficient for structural applications, resulting in an RMS resolution (noise floor) of 4.33 mg.

To validate the performance of the wireless sensing unit with an ADXL210 accelerometer interfaced, a five degree-of-freedom test structure mounted to an 11-kip shaking table is utilized. The aluminum structure behaves as a shear structure because the structure's floors are constructed as rigid diaphragms. The ADXL210 accelerometer is mounted to the top story of the structure to measure absolute acceleration responses. The wireless sensing unit is attached to the fourth story. The dimensions of the test structure are illustrated in Fig. 5.

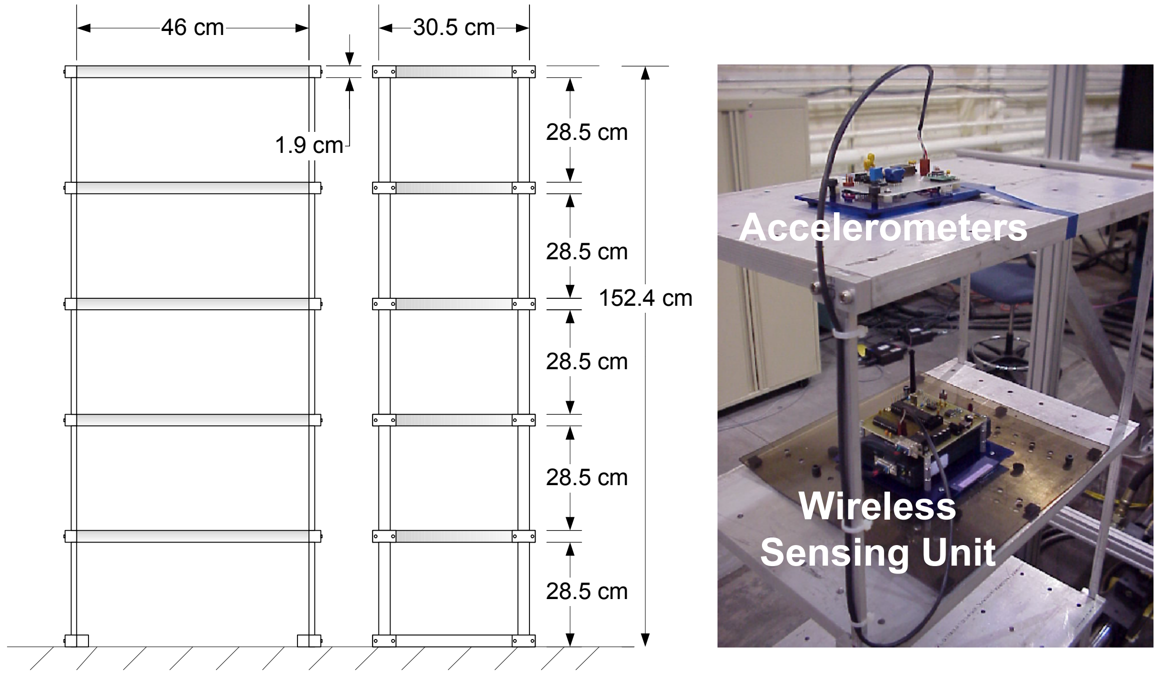

Figure 5 – Test structure for laboratory validation of the prototype wireless sensing unit

First, from log decrement calculations of the structure's free vibration response, structural damping is estimated to be 0.5% of critical damping. Next, a sweep sine signal of constant displacement amplitude (0.2 cm) and linearly varying frequency (0.25 to 3 Hz over 60 seconds) is applied by the shaking table. During the excitation, the absolute acceleration response at the top story is recorded at 30 Hz by the wireless sensing unit using the ADXL210 accelerometer. Fig. 6 presents the measured absolute acceleration response of the structure and the theoretical response determined from an analytical model of the structure. The measured absolute acceleration response is in good agreement with that obtained for the theoretical model of the test structure.

The frequency response function of the recorded time history is calculated by the wireless sensing unit using an embedded FFT algorithm. The FFT is performed on 1024 consecutive time points of the response from 10 to 44 seconds. The first three modes of response of the test structure can be visually identified from the response function of Fig. 7. The first three modes are identified at 2.87, 8.59, and 13.54 Hz. The identified modal frequencies are within 3% of those analytically calculated from the theoretical model at 2.96, 8.71 and 13.70 Hz. The frequency response function could be improved using smoothing techniques.

6. Field Deployment – Alamosa Canyon Bridge

The Alamosa Canyon Bridge located in Truth or Consequences, New Mexico, is selected to serve as the benchmark structure for field validation of the wireless sensing unit. Constructed in 1937, the bridge is comprised of seven simply supported spans, each 15.2 m in length and 7.3 m wide. Each span is comprised of six W30 x 116 steel girders, spaced 1.47 m apart, supporting an 18 cm concrete deck. A more detailed description of the Alamosa Canyon Bridge is presented in Fig. 8. The bridge and its modal properties have been documented in detail from previous benchmark studies (Farrar et al. 1997).

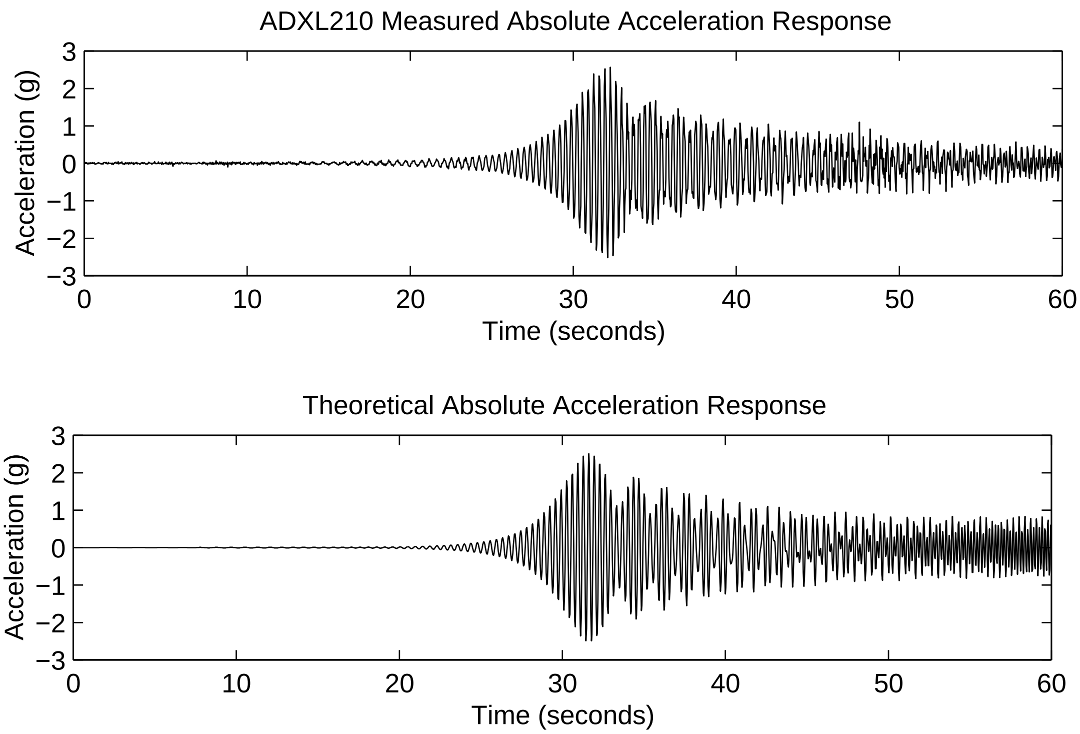

Figure 6 – Actual measured (top) and theoretical (bottom) absolute acceleration response of the test structure

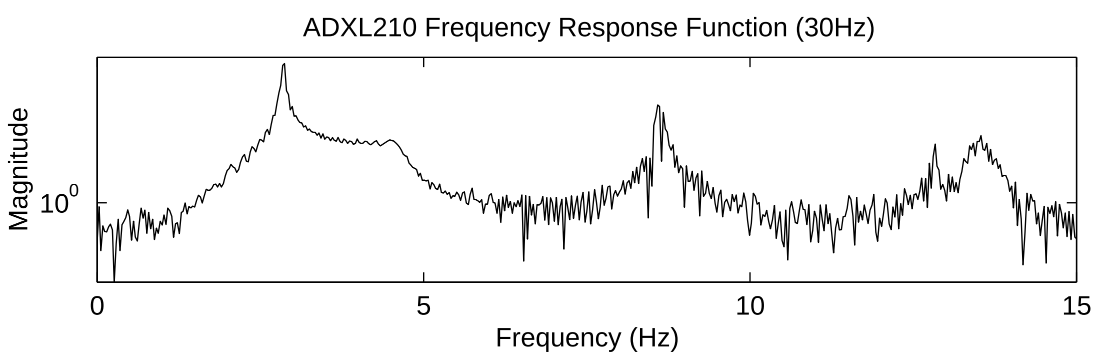

Figure 7 – Frequency response function of five-story test structure

The goal of the field validation tests is to compare the performance of the prototype wireless sensing unit to that of a commercial cable-based structural monitoring system. The commercial data acquisition system selected is the Dactron SpectraBook dynamic signal analyzer. The SpectraBook can accommodate 8 simultaneous input channels with sampling rates as high as 21 kHz. Analog sensors interfaced to the system are converted to 24-bit digital representations. A wireless monitoring system is installed adjacent to the Dactron system with wireless sensing units placed at sensor locations (marked as S1 to S7 in Fig. 8) throughout the structure.

Two different accelerometers are selected for installation in the Alamosa Canyon Bridge to measure a broad set of ambient and forced vibrations. The first accelerometer used with the Dactron system is the

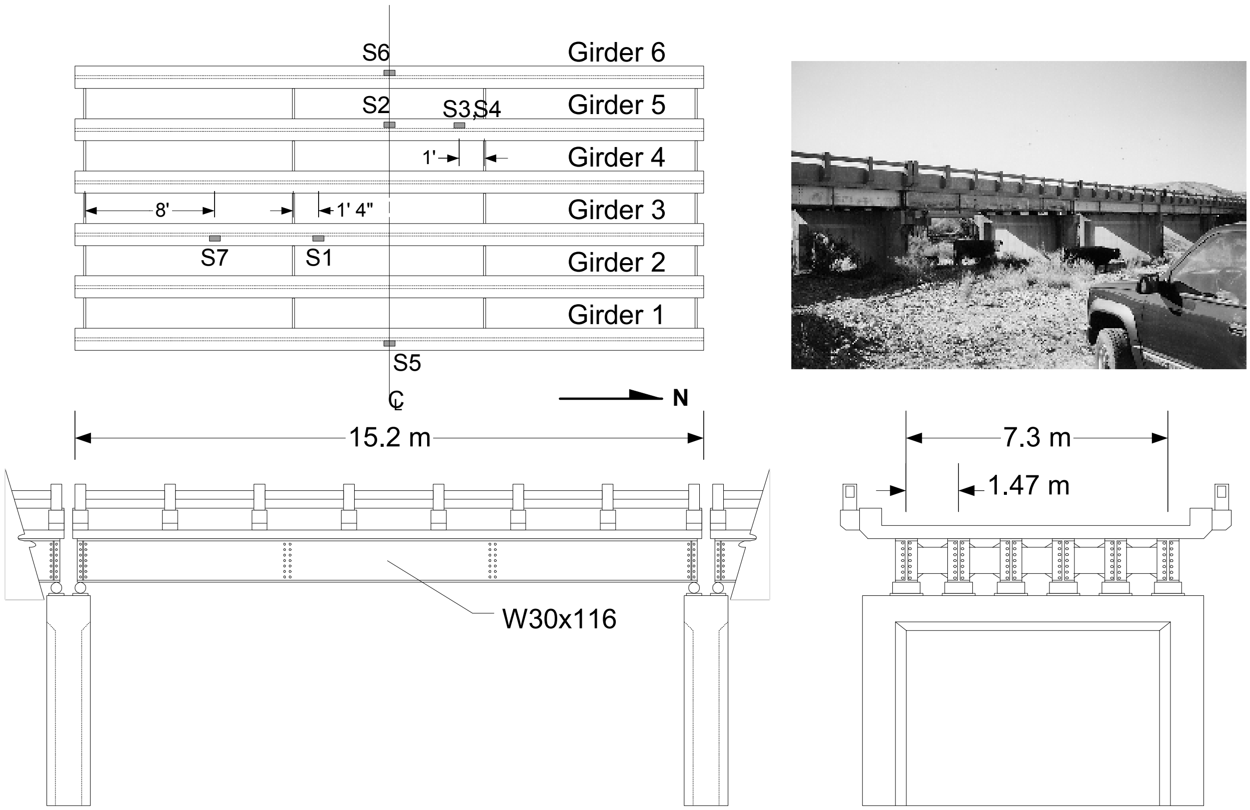

Figure 8 – Field validation structure – Alamosa Canyon Bridge, NM, USA

Piezotronics PCB336C accelerometer. The piezoelectric internal architecture of the PCB336C is capable of measuring acceleration responses in the 1 to 2000 Hz frequency range and $\pm$ 4g amplitude range. The accelerometer is well suited for measuring low acceleration response with a noise floor of 60 μg and a high sensitivity of 1 V/g. Interfaced to the wireless sensing unit is a MEMS-based capacitive accelerometer, the $\pm$ 1 g Crossbow CXL01LF1. The CXL01LF1 is also well suited for low amplitude response measurements because of its 2 V/g sensitivity and 500 μg noise floor. The noise floor of the CXL01LF1 represents a 90% reduction compared to that of the ADXL210 (4.33 mg). Both accelerometers are epoxy mounted at the girder's midpoint at the locations noted in Fig. 8 as S1, S2, etc.

To excite the structure, a modal hammer is used to deliver a nearly perfect impulse to the structure. The PCB86C50 modal hammer is used to impact the bridge at the center of the deck (in both the length and width direction). The tip of the hammer contains a load cell that is capable of recording the time-history of the delivered loading to the structure. One valuable feature of the excitation delivered by the modal hammer is that it is a nearly perfect impulse.

The structure is loaded by a modal hammer blow to the center of the bridge deck, as shown in Fig. 9. The response to the excitation is measured by the accelerometers mounted at sensor location S3 and recorded by the Dacton system and the wireless sensing unit. The acceleration response of the Alamosa Canyon Bridge is presented in Fig. 10 as measured by both data acquisition systems. The Dacton 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.

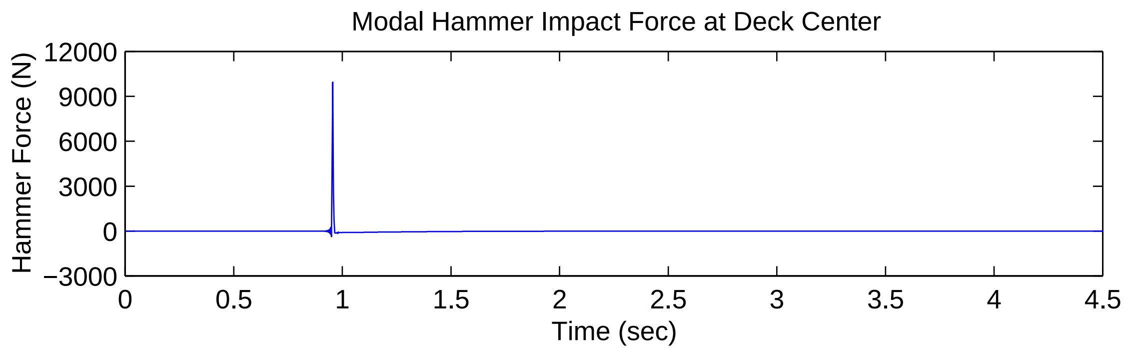

Figure 9 – Recorded impact load from modal hammer

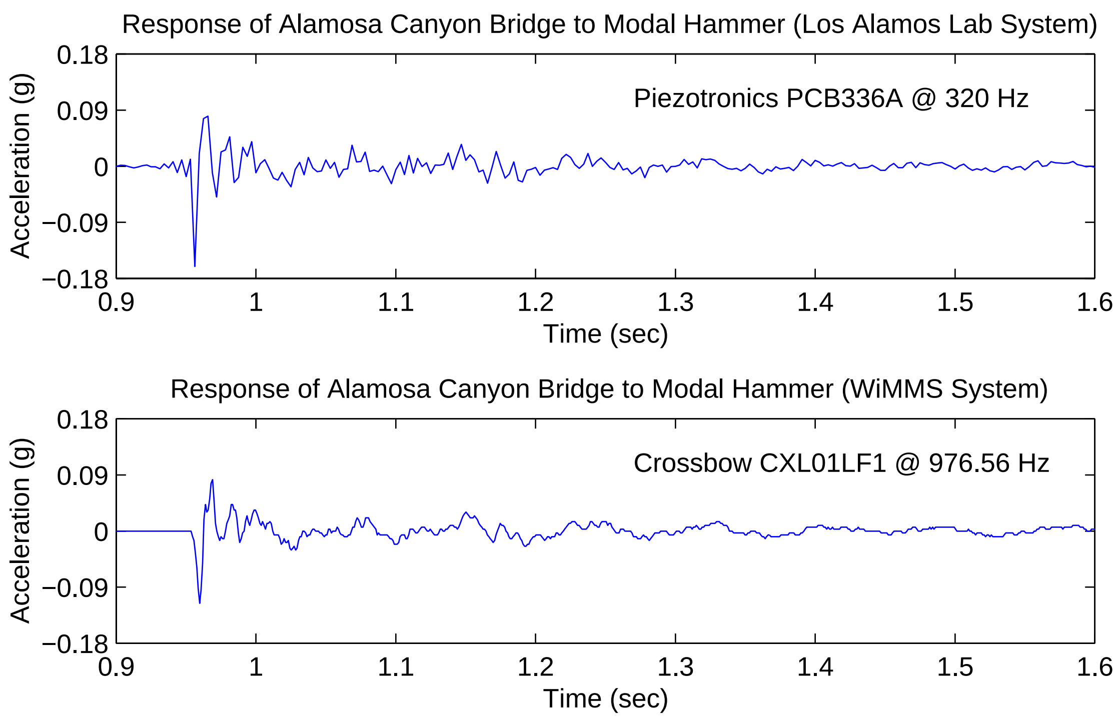

Figure 10 – Acceleration response at S3 measured by the PCB336 (top) and CXL01LF1 (bottom) accelerometers

In comparing the measured acceleration response of the Alamosa Canyon Bridge to the same modal hammer impact force, the strong agreement in both amplitude and time is evident. Minor discrepencies exist in the initial peak measured by the two systems, with the Dacton system measuring a peak of 0.17 g and the wireless sensing unit peak amplitude roughly 0.12 g. Subsequent peaks after the intial peak are in complete agreement with each other. These results indicate the reliability and accuracy of the prototype wireless sensing unit.

The modal impact test is repeated numerous times to measure acceleration at the other sensor locations indicated in Fig. 8. In total, 14 acceleration time-history records are obtained (7 from the wireless sensing units and 7 generated by the Dactron system). For the other sensor locations, results

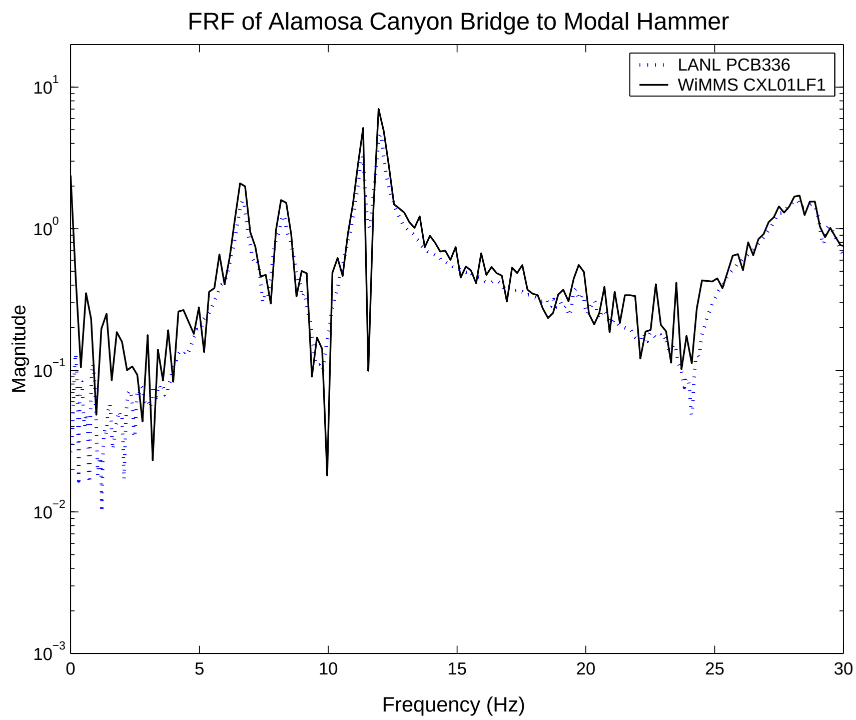

Figure 11 – Frequency response function of the measured acceleration at S3

similar to those for sensor location S3 are obtained with strong agreement in the response measured by the two systems.

6.1 Frequency Response Function

To assist in identifying the primary modal frequencies (modal analysis) of the bridge, the frequency response function of the system is determined from the hammer excitation time-history response measured at S3. The frequency response function is nearly identical to the bridge's transfer function because of the nearly perfect impulse delivered by the modal hammer.

The frequency response function is determined in two ways. First, the Dactron system employs RT Signal Pro Signal, an analytical software package for modal analysis, to automatically calculate the frequency response function from the measured time-history. For the measurement data collected by the wireless sensing unit, the computational core of the unit is used to execute the Cooley-Tukey FFT algorithm embedded. After locally executing the FFT algorithm, the calculated frequency response function is wirelessly transmitted to a laptop serving as a data repository. The frequency response function calculated by both systems from measurements obtained at sensor location S3, is presented in Fig. 11. The FFT performed from the Dactron system measurements was an 8192 point analysis. With memory limited on the wireless sensing unit, only 5000 data points could be stored. As a result, the FFT performed by the wireless unit was a 4096 point analysis.

Strong agreement exists in the two frequency response functions, particularly, with the peaks of the function in alignment. Some differences are present at the very low frequencies due to the DC limitations of the piezoelectric architecture of the PCB336C accelerometer. Three modes of response are immediately evident from the frequency response function at 6.7, 8.2 and 11.4 Hz. It is unclear if the second peak at 12 Hz actually corresponds to the fourth mode of the bridge. Previous published modal analysis results of a different span of the bridge with identical geometry indicate that the first four modes are located at 7.3, 8.0, 11.7 and 20.2 Hz (Farrar et al. 1997). The difference between the identified mode frequencies are less than 9% and can be attributed to subtle structural differences that exist between the two different spans instrumented.

The frequency response function corresponding to data obtained by the Dactron system is smoother than that obtained from the wireless sensing unit. 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 to 30 Hz) plotted. Second, the lower conversion resolution of the wireless sensing unit's A/D converter introduces more quantization noise in the lower magnitudes of the frequency response function.

6.2 Dynamic Traffic Loading

An additional forced vibration test is performed on the Alamosa Canyon Bride. A large truck is used to drive over a wood plank placed at the center of the span instrumented, as shown in Fig. 12. When the truck is driven at approximately 64 km/hr, the force exerted by the truck is greater than that of the modal hammer, thereby inducing a greater acceleration response in the structure.

For the dynamic truck loading 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. Fig. 13 presents the acceleration response of the structure measured over a 10 second interval. The truck is loading the span between the first and second seconds of the recording. Again, good agreement exists in the two recorded time-histories.

Figure 12 – Forced vibration induced by a speeding truck crossing the bridge

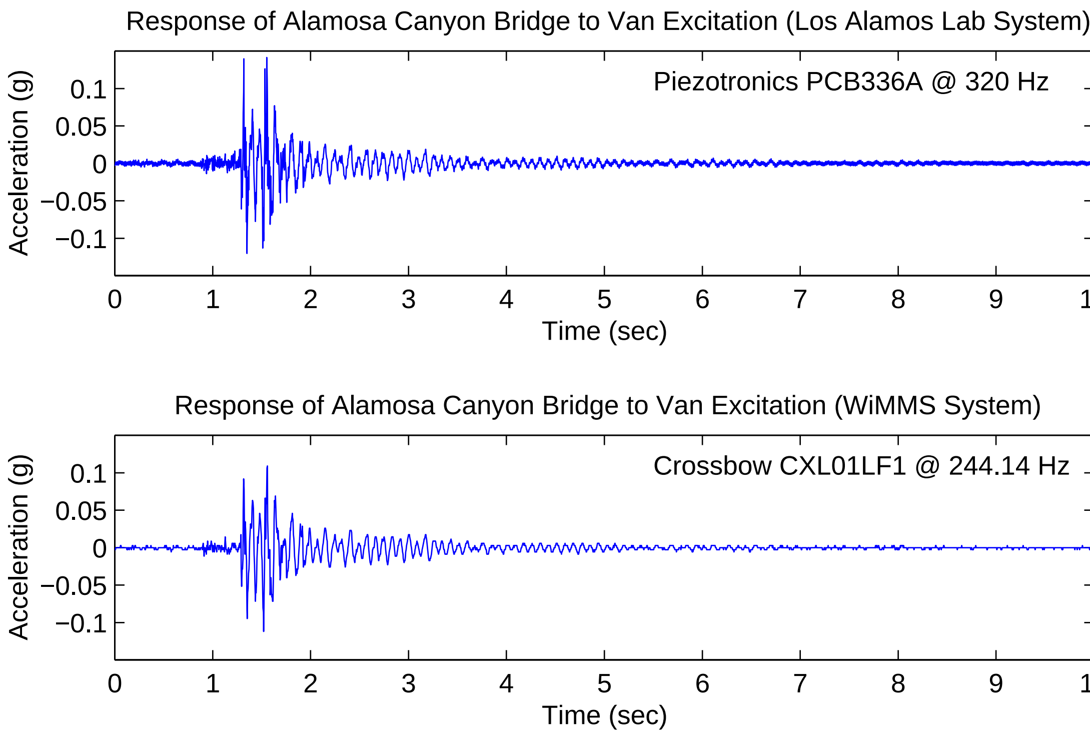

Figure 13 – Acceleration response at S7 measured by the PCB336 (top) and CXL01LF1 (bottom) accelerometers

7. Conclusion

The design of an advanced wireless sensing unit, capable of deployment in wireless modular monitoring systems (WiMMS), has been presented. With the advanced embedded system technologies integrated, a low cost yet computationally capable design has been achieved. In particular, a RangeLAN2 wireless modem was employed to accommodate reliable peer-to-peer transfer of measurement data. A dual microcontroller design was pursued with a low power 8-bit microcontroller responsible for simple data acquisition tasks and the second used only for implementation of demanding numerical algorithms.

Software was written using a modular layered approach. The lowest layer was comprised of a series of software modules used to operate a specific hardware subsystem. Upon the second layer, software was written to process and interrogate measurement data without being hampered by hardware implementation details. Specifically, the widely used fast Fourier transform was encoded for the local execution on the wireless sensing unit.

After the design was completed and prototype units fabricated, a series of validation tests were performed to ensure adequate performance was attained. First, the laboratory setting was exploited to interface MEMS-based accelerometers to the wireless sensing unit. A capacitive architecture MEMS accelerometer was used to track the absolute acceleration response of a laboratory test structure excited by a shaking table. The measured response was nearly identical to that predicted using a theoretical model of the structure. The frequency response function of the structure was derived by the wireless sensing unit from the measured data. Modes identified from the derived frequency response function were within 3% of those predicted by the analytical model of the structure.

With the wireless sensing unit validated in the laboratory, the units were taken to the field for installation in the Alamosa Canyon Bridge located in New Mexico. A traditional tethered monitoring system was installed in parallel to the wireless monitoring system comprised of wireless sensing units. Forced vibrations were induced in the structural system using a modal hammer. The absolute acceleration response of the bridge was monitored. Post-processing of the recorded response was performed using an FFT to derive the frequency response function of the structure. The Cooley-Tukey FFT algorithm is executed by the wireless sensing unit to determine the frequency response function of its measured acceleration response data. In comparison to the wire-based data acquisition system, the wireless system performed nearly as well at a fraction of the tethered system cost.

Future improvements can be made to the current design of the wireless sensing unit. Immediately evident was a need for improved A/D converter resolution and increased memory for the storage of temporary measurement data. In addition, the wireless modem represents a high power demand component. As a result, new wireless technologies should be considered with far reaching range yet possess low power demands. As the embedded system market evolves, new and innovative technologies emerging will inevitably be candidates for inclusion in the wireless sensing unit to increase capabilities, lessen costs and reduce power consumption characteristics.

With respect to embedded application software, more work is needed to explore novel data interrogation schemes for embedding. In particular, work is needed to explore data interrogation methods that can utilize the wireless sensing units to perform damage detection analysis. Preliminary implementation of time-series predictive modeling methods for damage detection has been successfully embedded in the wireless sensing unit (Lynch et al. 2002b). With robust damage detection capabilities integrated to the wireless sensing unit's core, the units would represent a first step towards the development of an automated structural health monitoring system.

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