Power-efficient wireless structural monitoring with local data processing

J. P. Lynch, A. Sundararajan, K. H. Law, A. S. Kiremidjian & E. Carryer
The John Blume Earthquake Engineering Center, Stanford University, Stanford, CA, 94305

ABSTRACT: Conventional structural monitoring systems are centralized, employ cables for measurement transfer, and perform all data processing at the centralized server. A major drawback of these systems is their high installation and maintenance costs. To eradicate the need for expensive cable installations, wireless communications is proposed for the transfer of measurements between sensors. In addition, system functionality is improved by coupling embedded microcontrollers with the sensor for localized interrogation of raw measurements. The design of a wireless sensing unit that has been optimized for structural monitoring is proposed. The performance of the sensing unit is validated in the field using the Alamosa Canyon Bridge in southern New Mexico. A statistical time-series damage detection procedure has been embedded in the sensing unit to illustrate the energy saved by local data interrogation compared to communication of time-history response records.

1 INTRODUCTION

Civil structures require a substantial investment of money and effort for their design and construction. As a result, the structural engineering profession holds a strong interest in advancing the understanding of structural behavior under external loads to render designs more economical and resilient. Towards that end, structural monitoring systems can provide measurement of the response of structures under normal operational loads and extreme disturbances such as earthquakes. Commercial structural monitoring systems have been installed in a large number of structures in the United States, particularly those located in zones of high seismic activity. For example, the 2001 California Building Code, modeled after the 1997 Uniform Building Code (UBC), mandates the installation of at least three accelerometers in structures greater than ten stories or 5,574 meter square in aggregate floor area (ICBO 2002).

Many benefits can be reaped from embedding structural monitoring systems within civil structures. Response measurements can populate databases that would prove valuable to researchers advancing performance-based design principles. Response measurements can also be employed as input to damage detection methods that identify and locate potential damage in structural systems. In structures controlled by actuators, real-time response measurements are required by controllers to calculate control forces.

Current conventional structural monitoring systems possess three defining characteristics. First, systems employ hub-spoke architectures where sensors are connected directly to centralized data servers. Second, processing of raw sensor data is conducted at the data server and not at the sensor node. Third, for reliable communication between sensors and the data server, shielded coaxial cables are widely used.

Commercial structural monitoring systems possess some inherent limitations that have hindered their adoption. One such limitation of current designs is the saturation limit on the total number of sensing channels permissible. As a result, installations often only employ a handful of sensing channels on the order of 10 to 15 sensors (Celebi 2002). Furthermore, the installation of cables in a structure is laborious and costly and drives the total cost of monitoring systems high (Straser & Kiremidjian 1998). For instance, monitoring systems installed by the United States Geological Survey (USGS) have cost upwards of thousands of dollars on a per channel basis (Celebi 2002).

The recent advances in the electronics and computer industries have produced a large number of embedded system and information technologies that can be readily adopted for structural monitoring. One technology that should be considered is wireless communications. Wireless communications have

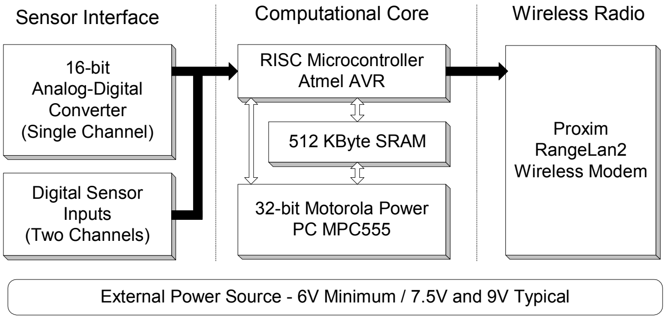

Figure 1. Design overview of the wireless sensing unit

revolutionized mobile computing by eradicating computers' dependence on wires for internet connectivity. Likewise, wireless modems are proposed for use in structural monitoring to eliminate the need for expensive cable installations. Wireless communications will simplify sensor installations and reduce system costs, thus making the technology more attractive to facility owners.

Embedded microcontrollers that consume little power for operation are also attractive for adoption. The coupling of computational power with each sensor node is proposed as a major paradigm shift in the design of structural monitoring systems. This computational power can be harnessed to locally interrogate raw time-history measurements with analysis results communicated in lieu of time-histories. An additional advantage of the parallel processing of data is that it can potentially provide gains in the overall power efficiency of the entire wireless monitoring system. This is an important concern when considering batteries as the sole power source of sensor nodes (Wang & Chandrakasan 2002).

The design of a wireless sensing unit for structural monitoring applications was first proposed by Straser & Kiremidjian (1998). Subsequent research has extended their work to include sophisticated computational cores that are capable of performing computational tasks associated with system identification and damage detection (Lynch et al. 2003b).

This paper reviews the recent developments in the design of a wireless monitoring system intended for installation in structural systems. First, the design of a low-cost wireless sensing unit capable of autonomous operation is discussed with key functional components presented. A series of field validation tests are performed on the wireless sensing unit using the Alamosa Canyon Bridge in New Mexico. During these tests, the computational capabilities of the wireless sensing unit are illustrated by the local processing of response measurements for determination of the structural frequency response function. The paper concludes with an analysis of the energy efficiency associated with the local interrogation of time-history data. A statistical time-series damage detection procedure is executed by the wireless sensing unit using data derived from a laboratory test structure to illustrate the energy efficient performance of the unit design.

2 HARDWARE DESIGN OF A WIRELESS SENSING UNIT

The design of a wireless sensing unit for structural monitoring requires a low-cost solution using minimal power. Low-power demands is an especially important design constraint since portable batteries are a likely power source for units installed in remote structures such as bridges. In addition, a design comprised of off-the-shelf electrical components is pursued to keep unit costs low (below $500 per unit) and to provide the luxury of easy hardware upgrades as technology improvements occur.

The design of the wireless sensing unit, as presented in Figure 1, can be divided into three functional components: sensing interface, computational core, and wireless communication channel. The flow of data in the wireless sensing unit begins at the sensor interface where measurements can be taken from various sensing transducers connected to the unit (including accelerometers, strain gages, and anemometers, just to name a few). After collection, the computational core takes control of the data for storage in memory. Based upon the demands of the wireless sensing unit end user, the core is capable of packaging the data for communication or can execute embedded algorithms using the raw measurements.

2.1 Sensor interface

The sensor interface is designed to accept the output of both analog and digital sensors regardless of the sensor type. This sensor transparent interface permits the use of both traditional structural sensors such as accelerometers but also for novel sensors as they become available in the future. In total, three channels are provided by the sensor interface to allow for the simultaneous acquisition of data from multiple sensors. One channel is intended for the collection of data from analog sensor outputs. This channel is serviced by a 16-bit analog-to-digital converter (Texas Instruments ADS7821) whose maximum sampling rate is 100 kHz. The two remaining channels are for digital sensors that internally modulate their output upon square-wave signals. Micromachined (MEMS) sensors, such as the Analog Devices ADXL210 accelerometer, can provide digital outputs with resolutions of 14-bits and higher (Analog Devices 1999).

2.2 Energy-efficient computational core

The computational core, responsible for the management of unit services and for executing embedded engineering analyses, is an important component of the wireless sensing unit design. A large number of microcontrollers that can be used in the core are already commercially available. In choosing an appropriate microcontroller, careful attention must be paid to energy consumption characteristics with low power microcontrollers more attractive. A low-power core with sufficient computational capabilities can be attained by employing two microcontrollers. One microcontroller is chosen for the overall operation of the wireless unit while another is chosen to execute embedded engineering analyses. By partitioning the functional tasks of the core between two microcontrollers, each can be chosen to better fit their intended roles.

The 8-bit Atmel AVR (AT90S8515) microcontroller is chosen to manage the operation of the wireless sensing unit. Some of the tasks that the AVR microcontroller will be responsible for include the collection of data from the sensing interface, management of data stored in on-board memory, and the transmission of data through the wireless modem. The Atmel AVR is chosen because it has adequate on-chip resources required to carry out these functional tasks and draws little electrical current when active (8 mA at 5 V).

The 32-bit Motorola MPC555 microcontroller is selected as the second microcontroller and will be responsible for the execution of embedded algorithms. An attractive feature of the MPC555 is that it performs floating point calculations in hardware thereby rendering the microcontroller faster and more power-efficient. Plenty of on-chip memory is available for the storage of executable programs with 448 Kbytes of read only memory (ROM) and 26 Kbytes of random access memory (RAM). When turned on, the MPC555 draws 110 mA at 3.3 V.

With the MPC555 consuming more power than the Atmel AVR, the former is normally kept off. Only when the execution of an embedded analysis is required will it be powered by the Atmel AVR. With the Atmel AVR consuming little power and the MPC555 available for performing computationally-intensive tasks, an overall low-power and computationally capable core is attained.

To collect long time-history measurement records, an additional 512 Kbytes of external static random access memory (SRAM) is provided. The external SRAM can be read and written by both microcontrollers.

2.3 *Wireless communication channel*

The cables of conventional structural monitoring systems will be replaced by low-cost wireless radios that are integrated with each wireless sensing unit. Besides reducing the overall installation costs, wireless communications facilitate decentralized communication architectures such as peer-to-peer communication between sensor nodes. For installation in civil structures, the wireless technology chosen must address the needs of a structural monitoring system. In particular, radios must provide node to node ranges of over 150 m and employ spread spectrum techniques to ensure reliability in the face of channel interference, multi-path reflection, and path loss. Furthermore, wireless communications require adequate penetration characteristics through typical civil engineering materials such as heavily reinforced concrete (Davidson & Hill 1997).

The Proxim RangeLAN2 7911 radio modem is chosen for inclusion with the wireless sensing unit design. Operating on the 2.4 GHz unregulated FCC industrial, scientific and medical (ISM) band, the RangeLAN2 accommodates data rates of 1.6 Mbps. Open space communication ranges of over 300 m can be attained by employing a 1 dBi omni-directional antenna. However, the shielding behavior of heavy construction (e.g. concrete) could reduce the range to approximately 150 m when used on the interior of structures.

The power consumption characteristics of the wireless modem are quite high. The RangeLAN2 modem draws 190 mA at 5 V when actively communicating to the wireless network. When the modem is not needed, its current draw can be reduced to 60 mA by placing it in sleep mode. In contrast to the power requirements of the computational core, the radio represents the greatest demand. This encourages the use of the computational core for data interrogation in lieu of transmitting raw time-histories

2.4 *Unit fabrication*

After choosing hardware components for the wireless sensing unit design, they are assembled into a single unit. To achieve compactness of the unit, a two-layer printed circuit board is designed for mounting integrated circuit chips, such as the microcontrollers and their supporting circuitry. Careful attention is made in the design of the printed circuit board to limit the electrical noise of the circuit. The RangeLAN2 modem is placed below the circuit board and is attached directly to the Atmel AVR microcontroller through a serial port connection. When fully assembled, the wireless sensing unit is only 10

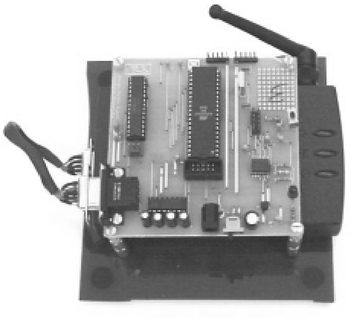

Figure 2. Complete wireless sensing unit prototype

cm by 10 cm by 3.5 cm. A picture of the completed wireless sensing unit prototype is presented in Figure 2.

A number of different power sources, including batteries and building outlets, can be used for powering the wireless sensing unit. To date, portable battery packs have been used; various battery types have been tested to assess the expected operational life of the wireless sensing unit. Table 1 summarizes the operational life expectancy of two different 7.5 V battery packs that have been used with the wireless sensing unit. The first is a standard alkaline (Zn/MnO_2) battery and the second is a long duration lithium (Li/FeS_2) battery. The operational times tabulated in Table 1 are estimates based on the engineering design charts provided by the battery manufacturer (Energizer 2003a, b). They represent the expected life of the battery when used continuously until the battery has been fully depleted and do not take into account potential life extensions when the battery is used occasionally. Therefore, longer battery lives are expected when the use of the wireless sensing unit is duty cycled for intermittent collection of ambient structural response measurements.

Table 1. Operational life expectancies of battery sources

Operational State	Current	Internal Voltage	Energizer L91 7.5V Li/FeS_2	Energizer E91 7.5V Zn/MnO_2
	(mA)	(V)	(hours)	(hours)
AVR Sleep/ MPC Sleep	8	5	500	300
AVR On/ MPC Sleep	54	5	50	30
AVR On/ MPC On	160	5	15	5
RangeLAN Active	190	5	13	4
RangeLAN Sleep	60	5	40	25

3 EMBEDDED FIRMWARE DEVELOPMENT

Embedded software, termed firmware, is required for the operation of the wireless sensing unit. Careful is attention is paid to the design of the unit's software with development efforts divided between two layers of software abstraction. The first layer of abstraction represents software required for operation of the wireless sensing unit's hardware features including operation of the sensor interface, accessing internal and external memory for data storage, and receiving and transmitting data using the wireless modem. This software will be embedded directly within the Atmel AVR microcontroller.

The second software layer is intended for engineering algorithms that can interrogate measurement data stored in memory. The functionality of this layer does not require direct access to the sensing unit's hardware and is stored in the Motorola MPC555 microcontroller. However, indirect control of hardware can be gained by the second software layer by invoking code residing in the first layer.

A large number of engineering analyses can be embedded in the proposed wireless sensing units. In particular, analyses widely used in system identification and damage detection have been explored. For example, previous work has investigated embedding fast Fourier transforms (FFT) in the wireless sensing units to derive the frequency response function from raw time-history data. The frequency response function calculated by the wireless sensing unit has been used to estimate the modal frequencies of a laboratory test structure (Lynch et al. 2002). A damage detection algorithm using two-tiered time-series models, as proposed by Sohn et al. (2001), has also been implemented. The wireless sensing unit has successfully identified damage in structural models using this approach (Lynch et al. 2003a).

Current research efforts have explored the embedding of compression algorithms for the size reduction of data prior to transmission by the wireless modem. Smaller data packets result in less power consumed by the wireless modem. Both lossless (data integrity guaranteed) and lossy (minor data distortion incurred) data compression algorithms are being considered.

4 FIELD VALIDATION ON THE ALAMOSA CANYON BRIDGE

In order to validate the fabricated prototype wireless sensing units, numerous validation tests have been performed including instrumentation within laboratory and field structures. For this study, the wireless sensing units are instrumented within the Alamosa Canyon Bridge located in southern New Mexico. The bridge serves as a convenient structure for instrumentation because it is located in a sparsely populated area of the state with almost no traffic crossing it daily. In addition, the bridge has been used in previous system identification studies and its modal properties are well documented (Farrar et al. 1997).

Constructed in 1937, the Alamosa Canyon Bridge consists of seven simply supported spans each 15.24 m long and 7.32 m wide. Each span is constructed from six W30x116 steel girders supporting a 17 cm concrete deck. The girders transfer traffic loads to concrete piers located at both ends of the span with standard rollers serving at the girder-pier interface. A single section of the bridge will be instrumented with a network of wireless sensing units. In addition, a commercial structural monitoring system using conventional cables will be installed in parallel to the wireless monitoring system. The commercial monitoring system chosen is the Dactron Spectra-Book dynamic signal analyzer capable of accommo-

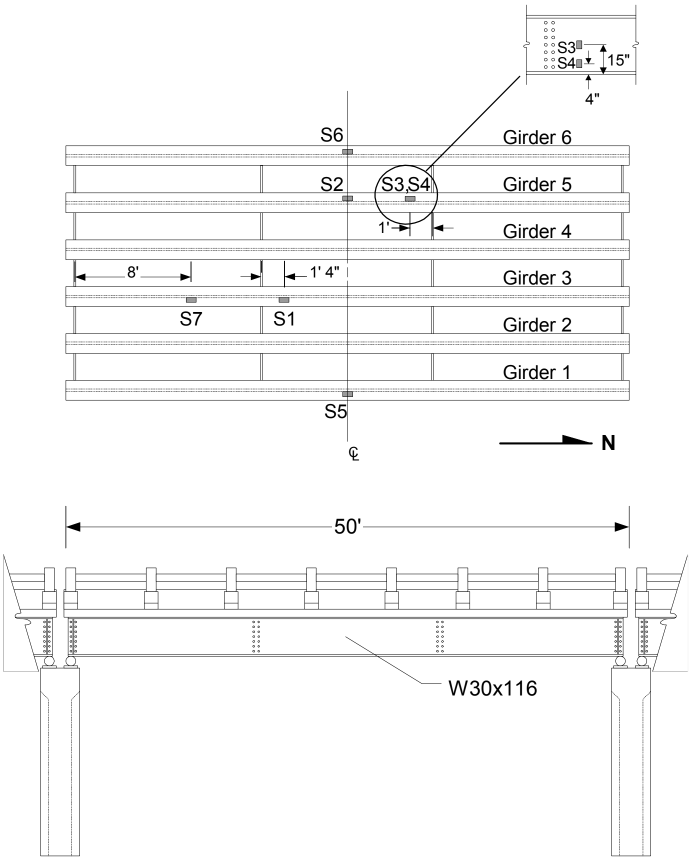

Figure 3. Structural details of the Alamosa Canyon Bridge

dating 8 simultaneous input channels each with a 24-bit analog-to-digital conversion resolution. The Dactron monitoring system will provide a performance baseline to which the wireless monitoring system can be compared. Figure 3 summarizes the structural details of the instrumented span with sensor locations noted as S1 through S7.

In this study, accelerometers are chosen as the primary sensing transducer for measurement of structural responses to impulse and traffic loads. Two different accelerometers will be employed with one type used exclusively with the wireless sensing unit and the other with the cable-based monitoring system. The wireless sensing unit has the Crossbow CXL01LF1 accelerometer interfaced. The CXL01LF1 is MEMS-based accelerometer capable of measuring accelerations in a range of 0 to ± 1 g with a root mean square noise floor of 0.5 mg and a bandwidth of 50 Hz. The Piezotronics PCB336 accelerometer is used with the cable-based monitoring system and can measure accelerations from 0 to ± 4 g with a noise floor of 60 μg. Because the PCB336 is based on an internal piezoelectric element, the accelerometer is not capable of sensing steady state accelerations; only accelerations in a 1 to 2 kHz bandwidth can be measured. As shown in Figure 3, the span is instrumented in seven locations with each accelerometer attached by epoxy to the vertical midpoint of the girder web. At each location, the CXL01LF1 and PCB336 accelerometers are mounted adjacent to one another.

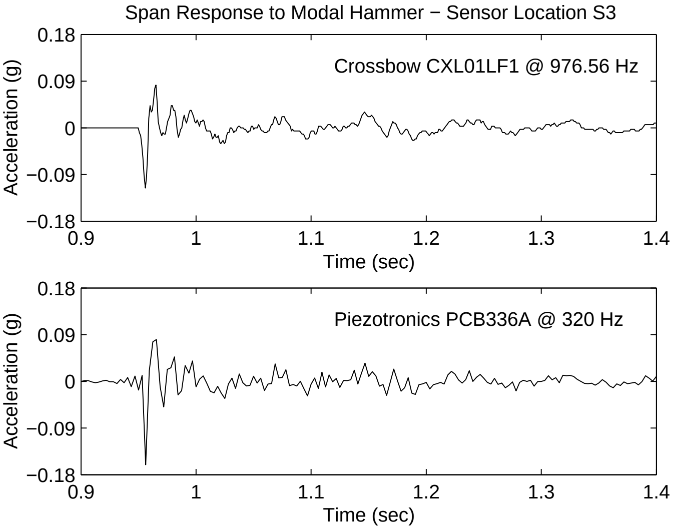

Figure 4. Time-history response at sensor location S3 of the Alamosa Canyon Bridge to modal hammer blows

The objective of the study is to determine the primary modal frequencies of the span. To attain a frequency response function representative of the structural transfer function, impulsive loads are delivered to the bridge deck by a modal hammer. After delivering an impact blow to the deck, the wireless and conventional cable monitoring systems simultaneously record the response of the structure.

Figure 4 presents the absolute acceleration time-history response of the span to a modal hammer blow located at the center of the span. The time-history response is acquired by the two systems using accelerometers mounted to the span at sensor location S3. The wireless sensing unit is commanded to collect data at a sampling rate of 976 Hz while the Dactron system collects data at 320 Hz. In comparing the recorded time-history records, strong agreement exists in the acceleration responses with amplitude peaks aligned along a shared time-axis. Similar findings are found in the time-history records recorded at different sensor locations to various modal hammer blows. These findings indicate the performance of the wireless sensing unit is reliable and accurate when compared to a conventional cable-based monitoring system.

Having obtained two time-history records of the same structural response at sensor location S3, frequency response functions are calculated from the recorded data. Figure 5 depicts the 0-30 Hz region of frequency response functions (FRF) derived from data recorded by the wireless and Dactron monitoring systems. The FRF function corresponding to the response measured by the wireless sensing unit has been calculated using the unit's computational core where an FFT algorithm has been embedded.

In comparing the two frequency response functions, strong agreement exists, particularly in the shape and location of their peaks and valleys. There exists a lack of agreement of the frequency response functions at frequencies less than 2 Hz. This is due to the limitations of the PCB336 accelerometer

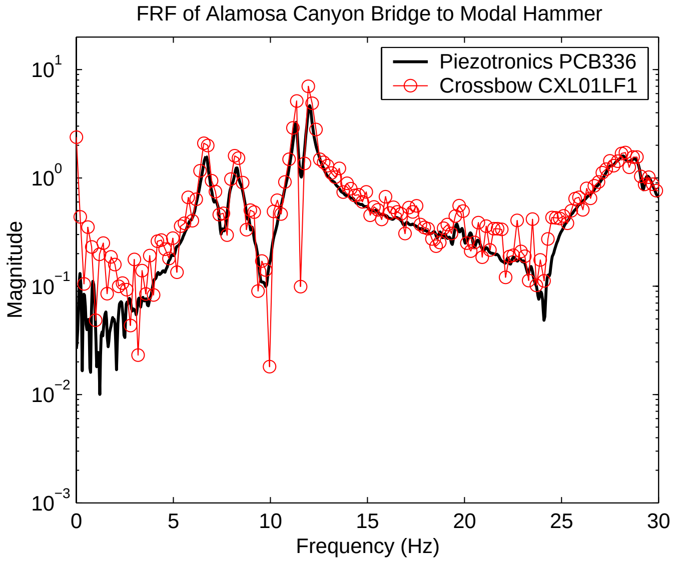

Figure 5. Frequency response function derived from time-history response data at sensor location S3

whose piezoelectric transduction mechanism is not capable of capturing steady state and low-frequency accelerations. Furthermore the FRF derived from the Dactron system is smoother compared to the one derived from the WiMMS measured data. This can be attributed to two observations. First, over the 0-30 Hz frequency region, the density of points used to define the frequency response functions is six times greater for the Dactron measured data. Second, the lower analog-to-digital conversion resolution of the wireless sensing unit introduces quantization noise that is not introduced by the Dactron data acquisition system.

The first three modal frequencies of the instrumented span of the Alamosa Canyon Bridge can be calculated from the frequency response functions of Figure 5. Table 2 summarizes the modal frequencies determined from data collected by the wireless sensing unit at the different sensor locations of the structure. Also tabulated are the modal frequencies calculated during a previous system identification study of a different span of the bridge whose structural geometries were nearly the same (Farrar et al. 1997). Variations in the modal frequencies reflect the drastic changes in the temperature of the bridge during the testing of the structure.

Table 2. Modal frequencies determined by the wireless monitoring system

Sensor Location	Mode 1 (Hz)	Mode 2 (Hz)	Mode 3 (Hz)
Past Study	7.4	8.0	11.5
S1	6.7	8.3	11.6
S2	6.8	8.5	11.3
S3	6.7	8.2	11.4
S4	6.7	8.4	11.7
S5	6.9	8.3	11.5
S6	7.0	8.4	11.8
S7	7.0	8.7	11.9

Other vibration sources are considered during testing of the bridge including a speeding truck driven across the bridge and ambient vibrations originating from an adjacent highway bridge carrying interstate traffic.

5 ILLUSTRATION OF POWER EFFECIENCY WITH EMBEDDED ALGORITHMS

With the wireless modem consuming large amounts of energy, it is only used when necessary. As a result, for preservation of battery life, the transmission of raw time-history records should be avoided. Rather, the computational core is used to locally execute embedded algorithms that interrogate time-history records with analysis results transmitted in lieu of the time-histories. With computational responsibility assumed by the distributed nodes of the wireless structural monitoring system and unnecessary use of the wireless channel avoided, tremendous gains are made in the monitoring system's overall power efficiency.

To illustrate, this study will focus upon the implementation of a promising damage detection algorithm to assess the amount of power saved by the wireless sensing unit in locally processing raw time-history records in lieu of transmitting those records to a centralized data server. It should be noted that other embedded analyses could have easily been used to draw similar conclusions.

5.1 Statistical time-series damage detection

Sohn et al. (2001) have proposed applying pattern recognition theory to the problem of structural damage detection. The success in applying pattern recognition lies in choosing appropriate performance indicators that exhibit change to damage. Their approach uses the coefficients of time-series models that have been fit to time-history records as potential indicators of damage. Previous studies have implemented their damage detection method within the wireless sensing unit for the successful identification of damage in laboratory test structures (Lynch et al. 2003a).

Assuming the response of a structure to be stationary, an auto-regressive (AR) process model is used to fit discrete response measurements to a set of linear coefficients weighing past time-history observations:

$$y_k = \sum_{i=1}^{p} b_i^y y_{k-i} + r_k^y \qquad (1)$$

The response of the structure at sample index, k, as denoted by y_k, is a function of p previous observations of the system response, plus, a residual error term, r_k^y. Weights on the previous observations of y_{k-i} are denoted by the b_i coefficients. It is assumed that the residual error of the AR model is influenced by the unknown excitation input to the system. As a result, a second time-series model is chosen to model the relationship between the residual error and the measured response of the system. For this second model, an auto-regressive with exogenous inputs (ARX) model is chosen:

$$y_k = \sum_{i=1}^{a} \alpha_i^{\ y} y_{k-i} + \sum_{j=1}^{b} \beta_j r_{k-j}^{\ \ y} + \varepsilon_k^{\ j} \tag{2}$$

A large number of AR-ARX model pairs can be derived for an undamaged structure under a variety of operational conditions to populate a database consisting of model coefficients (b_i^{DB}, α_i^{DB}, and β_j^{DB}). This database is important since it provides a statistical basis for judging if future models represent statistical outliers that would suggest potential damage.

When a time-history response of the structure in an unknown structural state (damaged or undamaged) is collected, an AR time-series fitting algorithm is executed to determine AR coefficients. These coefficients are then used to find the closest AR model match within the database. If the structure is damaged, an AR model fit to time-history data would not be in agreement with the database models corresponding to the undamaged structure. Model agreement, D, can be calculated by determining the Euclidian distance between coefficient vectors of the calculated and database AR models.

$$D = \sum_{i=1}^{p} \left(b_i^{DB} - b_i^{\ y}\right)^2 \tag{3}$$

After acquiring the closest AR-ARX model pair from the database, the ARX residual error of Equation 2 is determined by the wireless sensing unit using the unknown structural response. If the structure is in a state of damage, the statistics of the ARX model residual, ε_k^y, will vary from the residual error of the ARX model corresponding to the undamaged structure. In particular, damage can be identified when the ratio of the standard deviation of the model residual error exceeds a threshold value established from good engineering judgment (Sohn et al. 2001):

$$\sigma\left(\varepsilon^{y}\right) / \sigma\left(\varepsilon^{DB}\right) \ \geq \ h \tag{4}$$

Establishing a threshold, h, that minimizes the number of false-positive and false-negative identifications of damage is necessary for robust damage detection.

5.2 *Energy efficiencies gained by local damage detection*

For illustration of the energy efficiencies gained by performing the damage detection procedure locally, the energy consumed by the wireless sensing unit to derive the AR model coefficients, as compared to the energy needed to transmit the raw time-history record, will be calculated. The amount of energy consumed by the unit is a function of the time required by the MPC555 microcontroller to calculate the coefficients. To observe the dependency of the energy consumed upon the complexity of the algorithm, the number of data points in the time-history record, N, and the number of AR coefficients, p, will be varied.

Calculation of an AR model can be done using a number of different numerical tools. In this study, the Yule-Walker equations are solved using Burg's method (Press et al. 1992). Burg's method requires more computational resources compared to other solution alternatives such as least-square methods, but exhibits better stability because it avoids matrix inversions.

After calculating the time required by the wireless sensing unit to calculate the AR coefficients, the times are used to calculate the total energy consumed. Equation 5 presents how the energy consumed, E, by the MPC555 microcontroller is calculated using a time-history record of 4,000 points to determine 30 AR coefficients. For this record, the time taken, t, by the MPC555 to calculate coefficients is approximately 8.35 sec.

$$E = V_{REG} \cdot i \cdot t = (3.3 \ V)\ (0.11 \ A)\ (8.351 \ sec) = 3.031 \ J \tag{5}$$

In this experiment, the data stored in memory is in floating point form using 4 bytes per data point. As a result, a 4,000 point time-history record represents 16,000 bytes of stored data. To transmit this data using the RangeLAN2 modem, 11 packets are used each with an overhead of 14 bytes. In total, 16,154 bytes are sent to the wireless channel using the serial interface between the computational core and the modem. This transfer of data takes 6.73 sec using the modem's 19,200 bits per second transfer rate. Therefore, the energy consumed by the wireless modem can be determined:

$$E = V_{REG} \cdot i \cdot t = (5 \ V)\ (0.190 \ A)\ (6.73 \ sec) = 6.400 \ J \tag{6}$$

The energy required by the PowerPC to determine the AR coefficients is approximately 47% of that required to wirelessly transmit the raw time history data. This serves as illustration of the energy efficiencies associated with the local processing of raw time-history data in lieu of its wireless transmission. For this case, a 53% savings in energy is observed.

In a similar manner, the time required for records of different lengths and models of varying numbers of coefficients are determined by empirical experimentation. Figure 6 presents a summary of the energy consumed by the MPC555 to determine AR coefficients as a percentage of the energy required for transmission of the data using the wireless modem. As shown, significant gains in energy efficiency of the wireless structural health monitoring system are gained by local processing of measurement data. It should be noted that a discontinuity exists in the re-

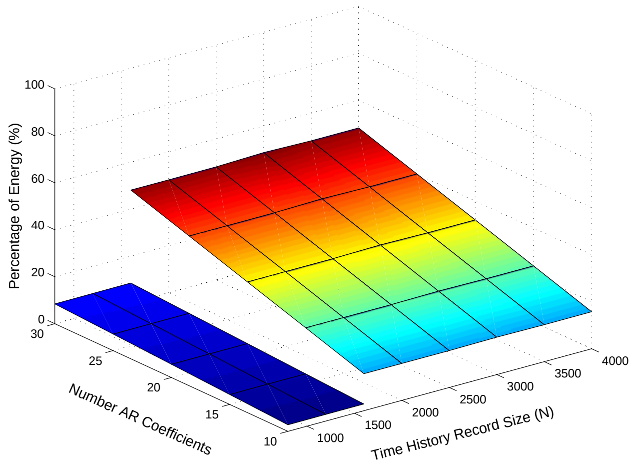

Figure 6. Energy consumed to determine AR coefficients as a percentage of energy for transmission of time-history

sults at record lengths of 1,600 points. This is due to the use of external memory for time-history records larger than 1,600 points. The read and write times to external memory are slower compared to internal memory causing an increase in the computation time of the AR coefficients.

6 CONCLUSIONS

This paper has explored the design of a novel wireless sensing unit for structural monitoring. As a low cost alternative to conventional cable-based monitoring systems, the design of the wireless sensing units have the additional advantage of a rich computational core. For validation of the wireless sensing unit, it has been instrumented within the Alamosa Canyon Bridge for a comparison of its performance to a conventional monitoring system. Results from modal hammer excitation of the bridge indicate the wireless sensing unit is accurate and reliable. Furthermore, to illustrate the core's capabilities, the transfer function of the structure was calculated using the wireless sensing unit. The installation time of the two monitoring systems varied with the laying of the Dactron system's cables, requiring greater amounts of time compared to the time needed for placement of the wireless sensing units.

This study has focused upon illustrating the performance of the wireless sensing unit computational core by embedding a promising approach to the damage detection problem: statistical pattern recognition damage detection using AR and ARX time-series. Utilizing the computational core for determination of AR coefficients has provided the monitoring system with overall operational power efficiencies.

Additional work can further improve the power consumption characteristics of the hardware design. Even lower power microcontrollers can be explored for future integration. Additional algorithm can be considered for embedding in the wireless sensing unit for local data interrogation. As the field of damage detection matures, additional damage detection methods can be considered for embedding as they arise.

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