DESIGN AND DEVELOPMENT OF POWER-EFFICIENT WIRELESS SENSING UNITS FOR STRUCTURAL HEALTH MONITORING APPLICATIONS

J.P. Lynch[1], Y. Wang[2], A. Sundararajan[2], K.H. Law[2] and A.S. Kiremidjian[2]

[1]Department of Civil and Environmental Engineering, University of Michigan,
Ann Arbor, MI, USA
[2]Department of Civil and Environmental Engineering, Stanford University,
Stanford, CA, USA

ABSTRACT

Structural health monitoring is a broad field that encompasses a number of synergetic technologies brought together to provide a system that can potentially identify and characterize the performance and/or possible damage in a structural system. Such a system would include a data acquisition subsystem capable of recording a structure's response to ambient and external loads and computational hardware embedded with numerical procedures to rapidly process the recorded response data to predict possible damage. This paper describes the design of a low-cost wireless sensing unit for installation in structural monitoring systems. The prototype wireless sensing unit is intended to 1) collect measurement data from the sensors installed on a structure, 2) store, manage and locally process the measurement data collected, and 3) communicate the data and results to a wireless sensing network comprised of other wireless sensing/actuation agents upon demand. The wireless sensing unit is designed not only for reliable communication of response measurements but also for power efficiency. The performance of the sensing unit is validated in the field using the Alamosa Canyon Bridge in southern New Mexico. With wireless radios consuming large amounts of power, energy preservation can be achieved by limiting the use of the wireless channel. This study explores two approaches to reduce the power demands of the wireless sensing unit. First, embedded engineering analyses are embedded and carried out by the sensing unit's computational core to avoid transmission of long time-history records. Second, lossless data compression is employed to reduce the size of data packets wirelessly transmitted.

INTRODUCTION

The broad field of structural health monitoring encompasses many advanced technologies that when integrated provides a system that can potentially identify and characterize the performance and/or possible damages of a structural system. For a structural health monitoring system, a data acquisition subsystem is required to record a structure's response to ambient and external loads. Novel technologies such as wireless radio modems have been used to reduce monitoring system costs while simultaneously broadening functional capabilities. The second necessary component for structural health monitoring is a package of numerical procedures that rapidly process the recorded response data to predict possible damages. To be of true value for the end users, the structural health monitoring system must also be low-cost, fully autonomous and highly reliable.

During recent years, as new conduits for technology transfer between disciplines take hold, the structural engineering community has begun experimenting with advanced technologies such as micro-processing and embedded computing, wireless communications, micro-mechanical solid-state sensors, and mobile computing. Adoption of these technologies can potentially improve the performance features and cost attributes of current structural engineering practices. Straser and Kiremidjian (1996,1998) have explored the potential of wireless communications in structural monitoring systems to reduce installation and maintenance costs. By eradicating the need to install coaxial cables for data communication, their work demonstrated the feasibility and the cost effectiveness of a wireless structural monitoring system. Lynch (2002) has extended this work to include embedded microcontrollers within a wireless sensing unit prototype; embedded microcontrollers can be loaded with numerical algorithms to locally process and interrogate measurement data. Wireless monitoring systems that are assembled from computationally self-sufficient wireless sensors differ significantly from traditional cable-based monitoring systems whose centralized data servers assume responsibility for all data processing tasks. Some advantages associated with computational decentralization include distributive and parallel processing of measurement data and eliminating the vulnerabilities due to single, centralized point-of-failure. A wireless sensor network of distributed computing power also provides opportunities to manage and process measurement data in new ways. For example, wireless communications consume large amounts of power and are often constrained by range and bandwidth limitations. To attain optimal usage of power, a wireless monitoring system needs to place greater emphasis on processing measurement data locally at the sensor in lieu of wirelessly transmitting long time-history records in real-time to centralized data servers (Lynch *et al.* 2003a, 2003b).

This paper describes the design of a low-power wireless sensing unit intended for installation in structural monitoring systems. Fabricated from off-the-shelf components, the units are low-cost and rich in functional features. The performance and utility of the wireless sensing unit has been illustrated on the Alamosa Canyon Bridge, located in southern New Mexico, during forced vibration testing of the bridge (Lynch *et al.* 2002). To minimize the power consumption on the wireless sensing unit, two power saving measures are considered. First, because the wireless modem requires large amounts of power for its operation, transmission of time-histories is avoided and embedded engineering analyses are locally executed by the unit's computational core. Various analyses are considered including determination of primary modal frequencies and computational components of a two-tiered statistical time-series damage detection method. Second, when wireless transmission of time-histories is required, lossless data compression using Huffman coding is considered to reduce wireless radio usage.

DESIGN OF A WIRELESS SENSING AND ACTUATION 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. As such, the capabilities of the wireless monitoring system depend on the functionality of the unit design. As shown in Figure 1, the unit consists of four functional subsystems: sensor interface, computational core, wireless communications, and actuation interface.

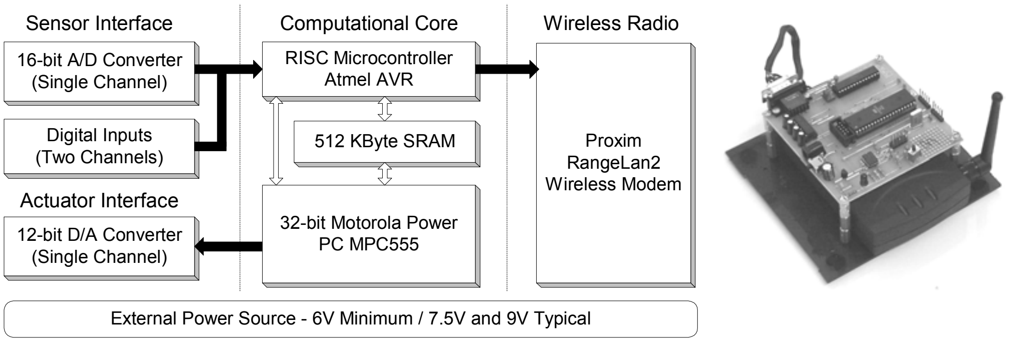


Figure 1. Design of the proposed wireless sensing and actuation unit

Data can be collected simultaneously from multiple sensors attached to the sensing interface. Current interface of the prototyped unit provides three sensing channels with one channel dedicated to the collection of data from analog sensors and two additional channels for digital sensors. With the continuing advances in microelectromechanical system (MEMS) fabrication, digital sensors that modulate their readings on square-wave signals are becoming increasingly popular. For the conversion of analog sensor readings to digital forms, a single-channel 16-bit analog-to-digital converter (A/D) is included in the interface. The interface can sample sensor data as high as 100 kHz.

The core of the wireless sensing unit contains the computational power necessary for unit operation and for execution of embedded analyses. To create a core that is both low-power and capable of executing data interrogation algorithms, a two-microcontroller design is pursued. General operation of the wireless sensing unit, such as acquisition and storage of sensor data and packaging of information for wireless transmission, is the primary role of the Atmel AVR AT90S8515 low-power microcontroller. The AVR microcontroller is an 8-bit architecture processor that draws 8 mA of current when powered by a 5 V source. With internal memory limited, sophisticated data interrogation tasks would be difficult to embed in the AVR microcontroller. As a result, a second microcontroller, the Motorola MPC555 PowerPC, is selected solely for execution of embedded engineering analyses. The 32-bit MPC555 is chosen because it has ample internal program memory and floating-point calculations are internally performed by hardware. A drawback of the MPC555 is that it draws 110 mA of current when powered at 3.3 V. Due to MPC555 consuming more power than the AVR, the MPC555 is ordinarily kept off. When engineering analyses are required for execution, the MPC555 is powered on by the AVR and turned off after their completion. By partitioning the functional tasks of the core between two microcontrollers, each has been chosen to best fit their respective roles.

A low-power wireless radio is sought with communication ranges capable of accommodating sensor nodal distances of over 300 ft. The Proxim RangeLAN2 7911 wireless modem, operating on the 2.4 GHz FCC unlicensed radio band, is chosen. Using a 1 dBi omni-directional antenna, open space ranges of 300 m can be obtained. When installed in the interior of heavily constructed buildings, the range of the radio is reduced to approximately 150 m. To sustain such long communication range, the wireless radio consumes a large amount of power. When internally powered by 5 V, the wireless modem draws 190 mA of current during transmission and reception of data; when idle, the modem draws 60 mA of current.

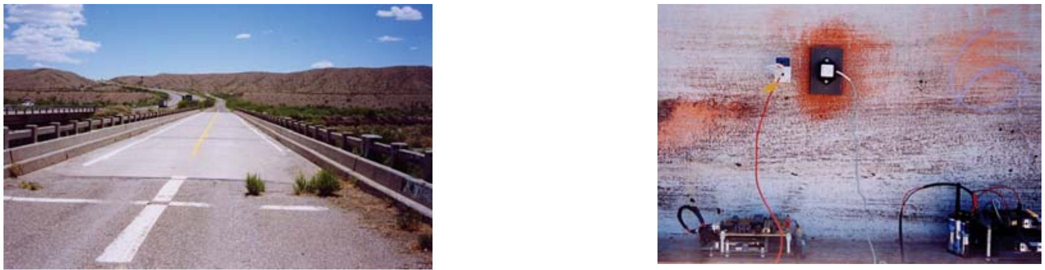
To support active sensing for damage detection in structures, the current prototype has also been designed to include an actuation interface in the wireless sensing unit design (Lynch et al. 2004). Through the actuation interface, actuators such as piezoelectric pads embedded in or mounted upon structural members, can be commanded using a 12-bit digital-to-analog converter (D/A). A Texas Instruments DAC7624 is chosen for integration with the wireless sensing unit as a single channel actuation interface. The DAC7624 can output voltage signals between ± 2.5 V and can be driven at 2 MHz. Additional circuitry is provided in the actuation interface to extend the voltage range of the output from -5 to 5 V.

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 (Lynch et al. 2002). The wireless sensing units were instrumented on the Alamosa Canyon Bridge located in southern New Mexico as shown in Figure 2. 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 was instrumented with a network of wireless sensing units. In addition, a commercial structural monitoring system using conventional cables were installed in parallel to the wireless monitoring system. The commercial monitoring system employed was the Dactron SpectraBook dynamic signal analyzer capable of accommodating 8 simultaneous input channels each with a 24-bit analog-to-digital conversion resolution. The Dactron monitoring system provided a performance baseline to which the wireless monitoring system can be compared. Figure 3 summarizes the structural details of the instrumented span. The bridge serves as a convenient structure for instrumentation because it has been used in previous system identification studies and its modal properties have been documented (Farrar et al. 1997).

In this field validation study, accelerometers were the primary sensing transducer for measuring structural responses due to impulse and traffic loads. Two different accelerometers were 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 cable-based monitoring system used the Piezotronics PCB336 accelerometer which 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 Hz to 2 kHz bandwidth can be measured. As shown in Figure 3, the span was instrumented in seven locations noted as S1 through S7 with each accelerometer attached by epoxy to the vertical midpoint of the girder web. At each location, the CXL01LF1 and PCB336 accelerometers were mounted adjacent to one another (see Figure 2(b)).

To determine the primary modal frequencies of the span, a modal hammer was employed to impose impulsive loads delivered to the bridge deck. After delivering an impact blow to the deck, the wireless and conventional cable monitoring systems simultaneously recorded the response of the structure. Figure 4(a) shows 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 agreements can be seen in the acceleration responses with amplitude peaks aligned along a shared time-axis. Similar findings were obtained 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.



(a) Alamosa Canyon Bridge (b) Accelerometers mounted

Figure 2. Field validation tests with accelerometers mounted with wireless sensor units on girder

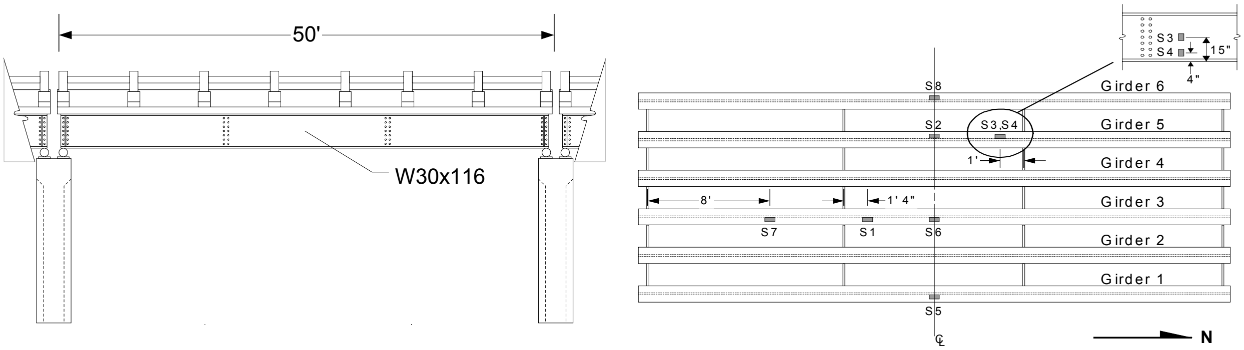
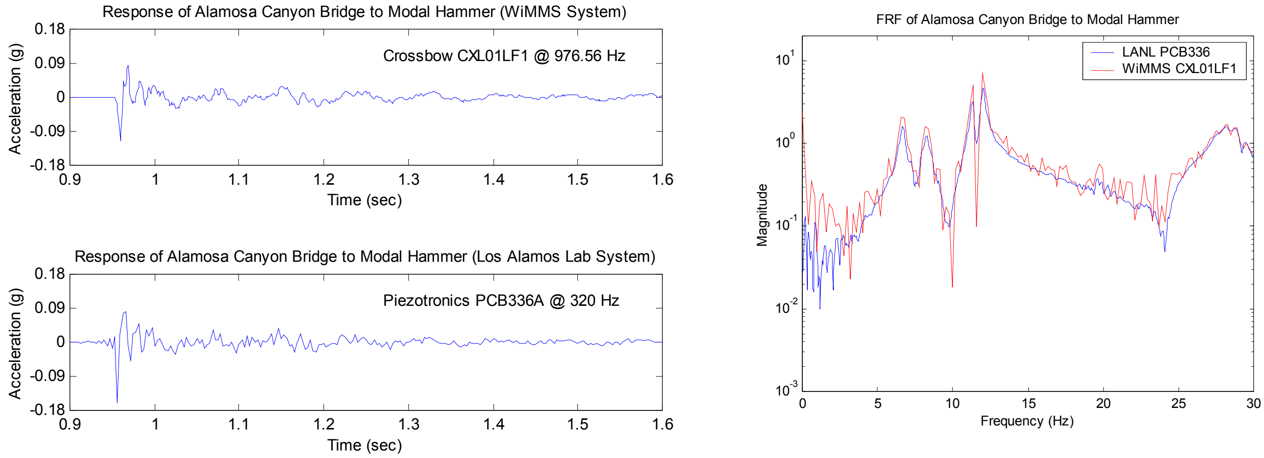


Figure 3. Structural details of the Alamosa Canyon Bridge



(a) Time-history response for a modal hammer test (b) Derived frequency response functions

Figure 4. Impulsive load responses at sensor location S3 of the Alamosa Canyon Bridge

Having obtained the time-history records of the same structural response at sensor location S3, frequency response functions were calculated from the recorded data. Figure 4(b) 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 was calculated using the unit's computational core with an embedded FFT algorithm.

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 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 data recorded by the wireless sensing unit. This can be attributed to two observations. First, over the 0-30 Hz frequency region, the density of points collected 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 shown in Figure 4(b). Table 1 summarizes the modal frequencies determined from the 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).

Table 1.
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 have also been considered during the validation tests, including a speeding truck driven across the bridge and ambient vibrations originating from an adjacent highway bridge carrying interstate traffic. The vibration tests conducted on the Alamosa Canyon Bridge have revealed a number of important findings (Lynch *et al.* 2002): 1) wireless sensing prototypes were capable of collecting sensor data with high precision, 2) modal frequencies were accurately determined using a fast Fourier transform (FFT) procedure embedded in and executed by the wireless sensing unit core, and 3) the wireless monitoring system was installed in less than half the time required by the tethered cable-based system that was installed in parallel with the wireless monitoring units.

EMBEDDED ENGINEERING ANALYSES FOR POWER-EFFECIENCY

It is important to assess the energy consumption by the wireless sensing unit which is powered using portable batteries. The energy consumed by the unit was experimentally measured using two 7.5 V battery sources. First, an alkaline battery pack constructed from Energizer AA E91 battery cells was considered. Second, lithium-based battery cells of high energy density were considered by constructing a battery pack from Energizer AA L91 battery cells. The wireless sensing unit was turned on and the electrical current drawn from the battery packs measured using a current meter. Based on the measured current draws, the life expectancy of the battery packs can be calculated from engineering design charts provided by the battery manufacturer. Table 2 summarizes the expected operational life of the batteries when continuously drained based on the currents measured. It should be noted that the values listed in Table 2 are conservative because when installed in a structure use of the unit would be duty-cycled. If batteries are intermittently used, cell chemistries are provided time to re-attain equilibrium thus resulting in extended lives.

The findings indicate that the wireless modem consumes the largest amount of battery energy. To preserve battery life, use of the modem should be minimized by limiting the amount of data wirelessly transmitted. The computational core of the wireless sensing unit is thus incorporated with an MPC555 microcontroller to process time-history data with pertinent results transmitted in lieu of time-history records. When drawing 110 mA at 3.3 V, the power of the MPC555 is 363 mW. Similarly, the RangeLAN2 radio consumes 190 mA at 5 V which is 950 mW of power. The MPC555 is about 2.6 times more power efficient than the wireless radio. To determine the total amount of energy saved, the time needed to perform embedded analyses needs to be calculated. The time for transmitting the raw time-history record can be calculated based on the radio serial baud rate (19,200 bit per second). Therefore, as long as the time of execution of the analysis is faster than the time of data transmission by more than 2.6 times, battery energy can be considered to be saved and a longer battery life can be expected.

Table 2.
Duration of battery sources for various operational states

Operational State	Circuit (mA)	Internal (V)	Energizer L91 (hours)	Energizer E91 7.5 (hours)
AVR On/MPC Off	8	5	500	300
AVR On/MPC On	160	5/3.3	15	5
RangeLAN Active	190	5	13	4
RangeLAN Sleep	60	5	40	25

Illustration of Local Data Interrogation

A large assortment of embedded analyses can be encoded in the wireless sensing unit core. In particular, algorithms pertaining to system identification and damage detection seem attractive for evaluation purposes. To assess the energy saved by the sensing unit by locally processing data, two algorithms are tested; a Fast Fourier transform (FFT) and an algorithm for fitting auto-regressive time-series models. Structural modal properties are often determined by performing a Fourier Transform on the measured response data. In this study, the FFT algorithm of Cooley and Turkey has been implemented to transform the time history response data into frequency domain (Press et al. 1992).

Many researchers are exploring the development of algorithms for detection of damage in structural systems. One promising approach uses the coefficients of auto-regressive (AR) and auto-regressive with exogenous inputs (ARX) models as feature vectors for classification (damage or undamaged) (Sohn and Farrar 2001). A database of AR-ARX model pairs is populated using models fit to ambient response data corresponding to the structure in an undamaged state. Future AR-ARX models obtained from the structure in an unknown state (damaged or undamaged) are compared to this database. Feature vectors that represent statistical outliers to the database indicate potential damage in the structure. Assuming the structural response to be stationary, an auto-regressive (AR) process model fits discrete measurement data to a set of linear coefficients weighing past time-history observations:

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

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. Weights on the previous

Table 3.
Energy Analysis of Data Interrogation versus Tranmission

Analysis	Length of Record *N*	Time of MPC555 Calculation *(sec)*	Energy Consumed MPC555 *(J)*	Time for Wireless Transmission *(sec)*	Energy Consumed Radio *(J)*	**Energy Saved** ***(%)***
FFT	1024	0.0418	0.0152	1.7067	1.6213	**99.062**
FFT	2048	0.0903	0.0328	3.4133	3.2426	**98.988**
FFT	4096	0.1935	0.0702	6.8267	6.4854	**98.917**
AR (10 Coef)	2000	1.3859	0.5031	3.3333	3.1666	**84.112**
AR (20 Coef)	2000	2.8164	1.0224	3.3333	3.1666	**67.713**
AR (30 Coef)	2000	4.2420	1.5398	3.3333	3.1666	**51.374**
AR (10 Coef)	4000	2.7746	1.0072	6.6667	6.3333	**84.097**
AR (20 Coef)	4000	5.6431	2.0484	6.6667	6.3333	**67.657**
AR (30 Coef)	4000	8.5068	3.0879	6.6667	6.3333	**51.243**

observations of y_{k-i} are denoted by the b_i coefficients. For the calculation of the coefficients by the wireless sensing unit, Burg's approach, which is more stable compared to least-squares by avoiding matrix inversions to solve the Yule-Walker equations, has been implemented (Press et al. 1992).

Response data collected during the validation tests at the Alamosa Canyon Bridge in New Mexico was used to determine the amount of energy saved by the local processing of data. The times necessary for the MPC555 to fully calculate the modal frequencies and AR coefficients are measured. Based on the measured execution times, the energy consumed by the MPC555 and the amount of energy estimated to wirelessly transmit the initial raw time-history records are compared. Table 3 presents the time associated with each analysis and the energy saved. The computational efficiency of the embedded FFT and transmission of modal frequencies as compared to transmission of the time-history record can provide major energy savings of over 98%. 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 savings of over 50% can still be obtained. This exercise illustrates that significant savings could result by local data interrogation.

Lossless Data Compression – Huffman Coding

Compression methods can be used to reduce the data size by exploiting the structures of the data. Compression algorithms generally fall in 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 achieve higher compression rates. The results presented here are based on lossless compression.

The computationally inexpensive compression technique, known as Huffman coding, was employed in the experimentation (Sayood 1996). Lossless Huffman coding exploits statistical relationships in the data to pair short symbols to data values with high probability and long symbols to those with low probability of occurrence. For example, if the 16-bit integer value "2342" was the most commonly occurring data sample, a short 1-bit symbol can be given to it, such as "0". Next, if "2455" is the next most common symbol, it might be given the 2-bit symbol "10". Hence, provided the probability mass density of the data, a compact binary representation of variable length can be used for compressed coding. Prior to the generation of a Huffman lookup table, inherent structures in the data can further be exploited to increase the compression rates. The structure in the data can be described by the transformation of the initial record using a de-correlation transform. Although many transforms could serve as suitable candidates, Wavelet Transforms (WT) was employed in this study. The complete compression process, including decompression, is presented in Figure 5.

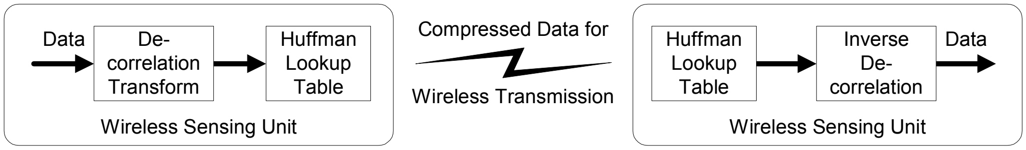


Figure 5. Huffman compression of sensor data using wireless sensing units

Structural response data acquired from shake table tests on a 5 degree-of-freedom laboratory test structure is considered in this study (Lynch et al. 2002). The top-story acceleration response of the structure to sweeping sinusoidal and white noise inputs are recorded by the wireless sensing unit using the A/D converter (with effective resolution of 12 bits). The sweeping sinusoidal input has a constant displacement amplitude envelope of 0.075 in. and a linearly varying frequency of 0.25 to 3 Hz over 60 sec. The white noise input record has zero mean and a displacement standard deviation of 0.05 in. Table 4 summarizes the performance of lossless compression and the estimated amount of energy saved having compressed data using the MPC555 and wirelessly transmitting the compressed record. In all cases considered, compression rates better than 80% (of the original record size) have been achieved. For the case of the sweep excitation input, compression rates of 61% and 71% were obtained respectively with and without applying WT for de-corrleation of the initial record. For white noise excitation, the response lacks an inherent structure that the de-correlation transform can leverage for compression and negligible reductions in the compression rate are experienced using WT.

Table 4.
Compression of Structural response data using Huffman Coding

Excitation Type	De-correlation	A/D Resolution *(bits)*	Total Record Size *(bytes)*	Compressed Record Size *(bytes)*	Compress Rate *(%)*	**Energy Saved *(%)***
Sweep	None	12	1024	733	71.58	**71.58**
Sweep	Wavelets	12	1024	626	61.17	**61.17**
White	None	12	1024	795	77.60	**77.60**
White	Wavelets	12	1024	791	77.25	**77.25**

SUMMARY AND DISCUSSIONS

A wireless sensing unit for structural monitoring has been presented. The wireless sensing unit includes the computational capabilities as its core. The core's microcontrollers facilitate localized processing of raw time-history data prior to transmission in the wireless network. Distributing computational power throughout the sensor network in this manner attains high energy efficiency thereby preserving portable battery operational lives. The study has illustrated that energy-efficiencies can potentially be gained by performing local data interrogation tasks. Furthermore, data compression can be employed to reduce the size of time-history records prior to transmission. Re-design effort is currently underway to further minimize the power consumption of the wireless sensing unit (Wang et al. 2005).

ACKNOWLEDGEMENTS

Collaboration with Drs. Chuck Farrar and Hoon Sohn of Los Alamos National Lab has been invaluable to the progress of this study. This research is partially funded by the National Science Foundation under grants CMS-9988909 and CMS-0121842.

REFERENCES

Farrar, C. R., Doebling, S. W., Cornwell, P. J., & Straser, E. G. (1997). “Variability of Modal Parameters Measured on the Alamosa Canyon Bridge,” *International Modal Analysis Conference, Proc., Orlando, 3-6 February 1997.*

Lynch, J. P. (2002). *Decentralization of Wireless Monitoring and Control Technologies for Smart Civil Structures.* PhD Thesis, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA.

Lynch, J. P., Law, K. H., Kiremidjian, A. S. Carryer, E., Farrar, C. R., Sohn, H., Allen, D., Nadler, B. Nadler and Wait, J. (2002). "Laboratory and Field Validation of a Wireless Sensing Unit Design for Structural Monitoring," *Proceedings of US-Korea Workshop on Smart Structural Systems,* Pusan, Korea, August 24-25, 2002.

Lynch, J. P., Sundararajan, A., Law, K. H., Kiremidjian, A. S. and Carryer, E. (2003a). “Design of Wireless Sensor Units with Embedded Statistical Time-Series Damage Detection Algorithms for Structural Health Monitoring,” *Caltrans/UCSD Workshop on Structural Health Monitoring and Diagnostics of Bridge Infrastructure*, *San Diego*, 7*-8 March 2003*. San Diego: CA.

Lynch, J. P., Sundararajan, A., Law, K. H., Kiremidjian, A. S., Kenny, T., and Carryer, E. (2003b). Embedment of Structural Monitoring Algorithms in a Wireless Sensing Unit. *Structural Engineering and Mechanics* 15(3): 285-297.

Lynch, J.P., Sundararjan, A., Law, K.H., Sohn, H, Park, G., and Farrar, C.R. Lynch, J.P., (2004) “Embedding Actuation Functionalities in a Wireless Structural Health Monitoring System,” *International Workshop on Advanced Smart Materials and Smart Structures Technology*, Hawaii, USA, January 12-14.

Press, W. H., Teukolsky, S. A., Vetterling, W. T. and Flannery, B. P.. (1992). Numerical Recipes in C: The Art of Scientific Computing. Cambridge: Cambridge University Press.

Sayood, K. (1996). Introduction to Data Compression. San Francisco: Morgan Kaufman Publishers.

Sohn, H. and Farrar, C. R. (2001). “Damage Diagnosis Using Time Series Analysis of Vibration Signals,” *Smart Materials and Structures*, 10(3): 446-451

Straser, E. and Kiremidjian, A.S. (1996) “A Modular, Visual Approach to Damage Monitoring for Civil Structures,” *Proc. 2nd International Workshop on Structural Control*, Hong Kong, 1996.

Straser, E. G., & Kiremidjian, A. S. 1998. *A Modular, Wireless Damage Monitoring System for Structures.* Report No. 128, John A. Blume Earthquake Engineering Center, Stanford University. Stanford: CA.

Wang, Y., Lynch, J. P. and Law, K. H. (2005). “Wireless Structural Sensors using Peer-to-Peer Communication Protocols for Computationally-Efficient Damage Detection,” (under preparation) Proceedings of the 23rd International Modal Analysis Conference (IMAC XXIII), Orlando, FL.