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Issues in Wireless Structural Damage Monitoring Technologies

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ABSTRACT

A second-generation wireless sensing unit for real-time structural response measurements has been designed and fabricated. Drawing upon advanced technological developments in the areas of wireless communications, low-power microprocessors and micro-electro mechanical system (MEMS) sensing transducers, the wireless sensing unit represents a high-performance yet low-cost solution to monitoring the short-term and long-term performance of structures. A sophisticated reduced instruction set computer (RISC) microcontroller is placed at the core of the unit to accommodate on-board computations, measurement filtering and data interrogation algorithms. As a result, the computational burden of the centralized data logger is placed on the individual sensing units. A wide array of different sensors can be interfaced to the unit delivering a sensor transparent module. The wireless infrastructure lowers overall system installation costs by eliminating laborious cabling tasks. Initial validation of the system is performed with the use of a small-scale two-story model structure instrumented with our sensors and excited with a portable shaking table.

1. INTRODUCTION

There is a clear need for a rational and economical method of monitoring the performance and safety of civil structures throughout their life spans. Recordings of structures during ambient vibrations and seismic disturbances are essential in determining the demand placed upon those structures. For structures in high seismic areas, information provided by monitoring structural responses will inevitably lead to better scientific understanding of how structures behave in the nonlinear realm. Many notable cases can be cited that prove the value associated with monitoring key structures. For instance, measurements taken of the County Services building during the 1979 Imperial Valley earthquake revealed deficiencies in the conceptual design of the structure resulting in the catastrophic performance of the structure (Bolt, 2001).

Within the structural health monitoring research community, a significant amount of research is focused upon developing ways of detecting damage in structures (Doebling et al., 1996). An integral component of a health monitoring system is a network of sensors that will provide the damage detection algorithms with time history response measurements of the structure. Damage detection strategies that can hypothesize potential locations of damage will need dense arrays of sensors located throughout a structure. Key to future implementation of damage detection systems is the development of low cost monitoring that can assist in the long-term assessment of structural retrofit needs.

2. WIRELESS MODULAR MONITORING SYSTEMS

A low cost alternative to the widely used traditional wire-based monitoring system is proposed for application in civil structures. Such a system is now possible due to the reducing price and rapid advancement of key technologies such as sensors, microprocessors, wireless networks and integrated circuits. The important innovations are the inclusion of wireless communication and on-board computing capabilities into the sensing units. Wireless communication eliminates the need for wires and therefore represents a significant cost reduction over a wire-based counterpart. Furthermore, the wireless infrastructure provides system design flexibility for different network configurations and peer-to-peer (P2P) architecture. The new wireless systems are termed Wireless Modular Monitoring Systems, WiMMS, (Straser, and Kiremidjian, 1998). The migration of computational power from the centralized data acquisition system to the sensor units provides further flexibility to the system. The on-board computational power of the system can facilitate parallel data processing that can make applications like damage detection procedures feasible in real time.

3. DESIGN OF THE WIRELESS SENSING UNIT

A fully functional proof-of-concept sensing unit to be used in the proposed WiMMS system has been designed and fabricated from commercially available components. An overview diagram of the sensing unit is shown in Figure 1.

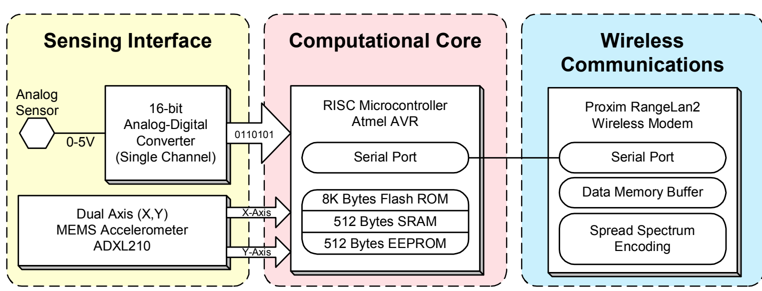

Figure 1. – Functional Layout of the Proof-of-Concept Wireless Sensing System

3.1. Computational Core

One of the most important choices in the development of the wireless sensing unit is the design of the computational core. This core is responsible for aggregation of sensing data from on-board sensing transducers (i.e. accelerometers), and the task of cleansing and processing the data. Various alternatives are available ranging from field programmable gate arrays (FPGA) to digital signal processing (DSP) chips. The final selection is based on efficient power and high performance specifications.

An enhanced Atmel RISC microcontroller was selected for its high performance solution with inherently low power consumption characteristics. This is an 8-bit microcontroller with a full suite of on-board services such as internal oscillators, serial communication UARTS, timers, pulse width modulators (PWM), and four 8-bit input/output ports. The enhanced RISC (reduced instruction set computer) architecture of the microcontroller provides computational speed and enables code to be executed at the same rate as the microcontroller's 4 MHz clock. The Amtel RISC microcontroller is enhanced with additional instructions to allow for CISC like execution without compromising RISC performance. The design of the microcontroller's architecture is optimized for using high-level languages such as C and Java (Bogen and Wollan, 1999).

3.2. Wireless Communications

Current monitoring system end-users are seeking a low cost but highly reliable wireless solution that allows for peer-to-peer (P2P) communication as well as communication with a central data logging unit. This task is accomplished using a wireless modem. The Proxim ProxLink MSU2 wireless modem was selected for this purpose. Operating in the unlicensed 902-928 MHz Industrial, Scientific, Medical (ISM) radio band, the radio modem employs direct sequence spread spectrum communication techniques to ensure a secure digital communication link between modems. Data are transmitted using direct sequence spread spectrum and can be simultaneously accessed by multiple users without interference (Rappaport, 1996). Data encoding is with an 11-bit pseudo-noise chirping code.

A reliable digital communication channel between wireless modems is attained using the spread spectrum techniques, which is less sensitive to narrow band interference generated by ordinary industrial machines and radio devices located near the wireless network. Specifically, the ProxLink modems divide the available 902-928 MHz band into three distinct channels each with 160 frequency bands. The range of the ProxLink modems in open space is 1000 feet and inside buildings has been shown to be 100 feet (Straser and Kiremidjian, 1998). Empirical studies reveal that the higher the radio frequency, the better the building penetration characteristics of the signal.

3.3. Sensing Transducers

The sensing transducers that can be used in the monitoring of structures include strain gages, accelerometers, velocity meters, and displacement transducers. The overall design is sensor independent and is compatible with all analog sensors. A low noise, single channel, Texas Instrument 16-bit analog-to-digital (A/D) converter is used.

Accelerometers were considered in this study because of their widespread use. The two micro-electro mechanical system (MEMS) accelerometers considered are the Analog Device's ADXL210 10g digital accelerometer and the high performance piezoresistive planar accelerometer fabricated by Professor Thomas Kenny's group at Stanford University.

Analog Device's ADXL210 accelerometer is a low cost, low power accelerometer that can measure acceleration on two axes. The internal architecture of the accelerometer uses balanced differential capacitors to measure acceleration. A 14 bits duty cycle modulator within the signal conditioning circuitry provides an anti-aliased digital signal for direct input to a microcontroller. For application in structural monitoring systems, the bandwidth of both axes of the ADXL210 is set to 50 Hz providing an RMS resolution of 4 mg.

In the high performance planar accelerometer, a large proof mass is connected to a rigid base with a cantilevering element (Partridge et al, 2000). An advantage of the sensor is that its performance can be tuned for a specific application by simply changing the dimensions of the cantilevering element. Over the full dynamic range of the sensor, the Kenny/Partridge accelerometers maintain nearly constant sensitivity implying a linear transfer function of the accelerometer. The maximum dynamic range of the accelerometer is a direct result of the proof mass being arrested by its wafer housing. This stopping mechanism allows the accelerometer to experience very high accelerations without breaking, as could be the case with the ADXL210. The dynamic range of the accelerometers is well above 10g with a resolution of 20 μg at an acceleration bandwidth of 650 Hz.

To accommodate all of the individual components of the system, a two-layer 4" by 4" printed circuit board is designed to provide a efficient packaging all system components. Low transient noise characteristics are ensured in the board design. The circuit board houses the microcontroller, the ADXL210, the 16-bit A/D and all the supporting circuitry. The ProxLink wireless modem is externally attached to the circuit through a serial port. The demonstration system can be contained within a packaging unit 5" by 4" by 1" in dimension as shown in Figure 2.

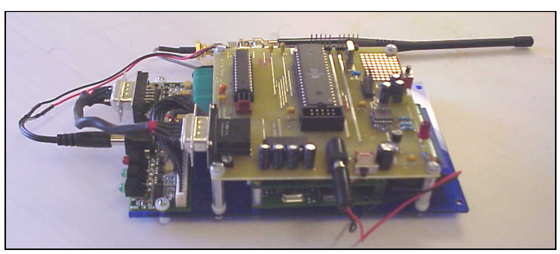

Figure 2. – Proof-of-Concept Wireless Sensing Unit

4. SYSTEM VALIDATION

In order to validate the prototype units, numerous validation tests were performed ranging from signal tracking by the on-board ADXL210 accelerometer to actual instrumentation within laboratory test structures. For this study, the instrumentation of a small-scale test structure is considered. Two units are attached to each floor of a two-story shear model structure. The floors of the structure are rigid and sustain no deformation relative to the flexible columns. The structure, mounted upon the surface of a 700 N shaking table, is excited and the response at each floor is measured by the sensing unit with on-board accelerometer sampling data at 20 Hz. The data are transmitted from both sensing units to a central data-logging computer.

The purpose of the experiment is to identify the natural frequency of the structure's two modes. As shown in Figure 3, an input sine sweep motion with 0.2 cm constant displacement amplitude and a linearly varying frequency of 1 to 15 Hz over the duration of 10 seconds is used to excite the modes of the structure. The measured response of each floor of the structure is shown in Figure 3. The frequency response is calculated using recordings from the first and second floors (see Figure 4), providing visually identified modes at 1.9 Hz and 5.0 Hz. Similar results (1.95 Hz and 5.05 Hz) are obtained using DAIMOND (Doebling et al., 1997). These results are found to be compatible with the calculated natural frequency of the structure (1.86 Hz and 5.10 Hz).

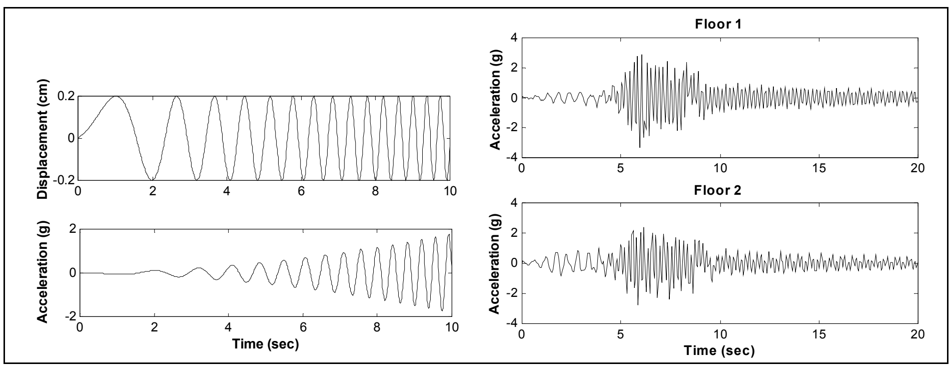

Figure 3. – Input Sine Sweep Disturbance and Response at each System Degree of Freedom

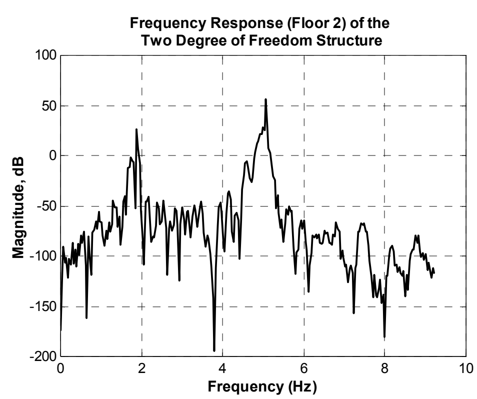

Figure 3. – Frequency Response at Second Floor

5. CONCLUSION

A wireless sensing unit has been designed, fabricated and validated. As compared to its wired counterparts, the proposed wireless modular monitoring system delivers a compelling cost-benefit advantage as well as the guarantee of a quick yet flexible installation. With computational power included within the wireless units, it can be harnessed to perform computationally intensive procedures in real time. Through wireless collaboration, the units have the potential of solving complex problems characterized by high dimensionality in parallel.

The proof-of-concept embeddable wireless monitoring system has been used in a series of validation tests. As shown in this paper the modal properties of a laboratory test structure were identified correctly with the current system. Alternate validation tests are planned to ensure a high level of performance when installed in the field. Additional WiMMS sensing units are currently being designed and fabricated for *validation* in a full-scale structure.

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