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The Design of a Wireless Sensing Unit for Structural Health Monitoring

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ABSTRACT

Structural monitoring systems used in practice employ conventional cables to communicate sensor measurements to a centralized data acquisition unit. Cabled based systems have high installation costs and leave wires vulnerable to ambient signal noise corruption. In addressing these inherent drawbacks, a modular wireless monitoring system is proposed. Such a system promises lower capital and installation costs simultaneously ensuring reliable communication between sensing units. A proof-of-concept sensing unit has been designed and fabricated using standard integrated circuit components and wireless modem technology. Employing an enhanced RISC microcontroller, the sensing unit has powerful computational capabilities for data aggregation and processing. The sensing unit is flexible in its design by allowing any analog sensor to be used. Two MEMS based accelerometers are considered for this study.

INTRODUCTION

The structural engineering community has identified the need for a rational and economical method of monitoring the performance and safety of civil structures over their life spans. The current state of practice includes the monitoring of some key structures in areas of high seismic activity. These structures have been identified as special due to the essential role they play in society such as hospitals or due to their high everyday demand such as long span bridges. The high capital and installation costs associated with monitoring systems have made structure owners reluctant to pay

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for what they see as an unnecessary amenity. However, recordings of structures during ambient vibrations and seismic disturbances are essential in determining the demand placed upon structures. In the case of structures in high seismic zones, information provided by monitoring structural responses will inevitably lead to better scientific understanding of how structures behave in the nonlinear realm, as well as possibly assess damage during and after an earthquake. In the case of structures not located in zones of high seismicity, the monitoring of everyday ambient vibrations of the structures can potentially lead to long-term assessment of structural retrofit needs. Many notable cases of the value associated with monitoring key structures can be cited. For instance, measurements taken of the County Services building during the 1979 Imperial Valley earthquake revealed striking discontinuities of the building's time history response indicating sudden changes in structural integrity during the disturbance [1].

The origin of current commercially available structural monitoring systems is from those used regularly in the laboratory setting. Such systems typically employ a hub-spoke system architecture with a centralized data unit used for retrieving analog data signals from remote sensors such as accelerometers. Within the centralized unit, the analog signals are typically converted to digital measurements and processed. While such systems are well suited for small structures tested in the lab, they do not scale well to large system implementations such as for bridges and buildings. As a result, their implementation time and costs are high. Installation time of a moderate size monitoring system can consume over 75% of the total system testing time with installation costs approaching over 25% of the total system cost. The California Department of Transportation (Caltran) has instrumented 61 of the state's 22,000 bridges and has reported that it costs well over $300,000 per toll bridge to install a structural monitoring system of only 60 accelerometers. A large portion of the cost includes the laying of wire conduits needed to protect wires from harsh weather conditions at a cost of $10 per linear foot [2].

WIRELESS MODULAR MONITORING SYSTEM FOR STRUCTURES

Due to the reducing price and rapid advancement of key technologies such as sensors, microprocessors, wireless networks and integrated circuits, it is now possible to provide a low cost alternative to the traditional wire-based monitoring systems by using a wireless monitoring system. A wireless infrastructure provides a free infrastructure by eradicating the need for the installation of wires as well as a flexible infrastructure by accommodating different network configurations such as direct communication between sensing devices (see Figure 1). The flexibility of the wireless communication network of system sensors allows for system modularity as well as reduced dependence upon a centralized data acquisition unit to coordinate the activities of the system. The new wireless systems will be termed Wireless Modular Monitoring Systems or rather WiMMS [3].

An additional benefit of wireless communication is that it encourages functional independence of the individual sensing units. Rather than relying upon a central computer to perform analog-to-digital data conversion for each unit, the units themselves have the ability to perform the conversion prior to sending their

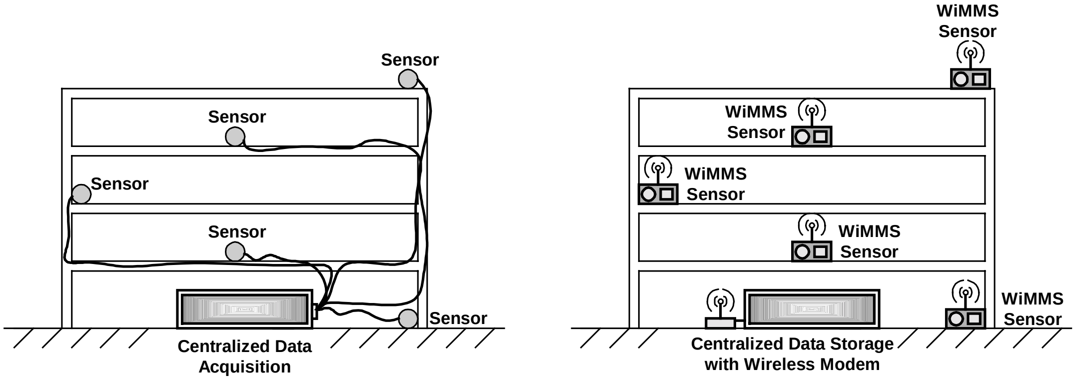

Figure 1. The Evolution of a Conventional Cable Based to a Wireless Embedded Structural Monitoring System

measurements to the sensing network. Going one step further, a primary innovation of the system is the migration of computational power from the centralized data acquisition system to the sensor units. The distributed on-board computational power of the system can potentially facilitate parallel data processing that could render applications like damage detection procedures feasible in real time.

DETAILED UNIT DESIGN

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 2. Described below is the motivation and criteria used in the selection of some of the system components as well as a detailed description of how they work.

Computational Core

Perhaps the most important choice in the development of the wireless sensing unit is the hardware chosen to act as the unit's computational core. This core will be responsible not only for aggregation of sensing data from on-board sensing transducers (i.e. accelerometers), but they will also take part in the task of cleansing and processing the data. Various suitable alternatives are available ranging from field programmable gate arrays (FPGA) to digital signal processing (DSP) chips. The final selection was based upon the criteria of efficient power consumption characteristics of the core. As a result, a microcontroller core architecture was chosen because of their low power and high performance characteristics.

In particular, an enhanced Atmel RISC microcontroller was selected from microcontrollers currently available on the market. The Atmel AVR microcontroller 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 Atmel RISC microcontroller provides a high performance solution with inherently low power consumption characteristics. The enhanced RISC (Reduced

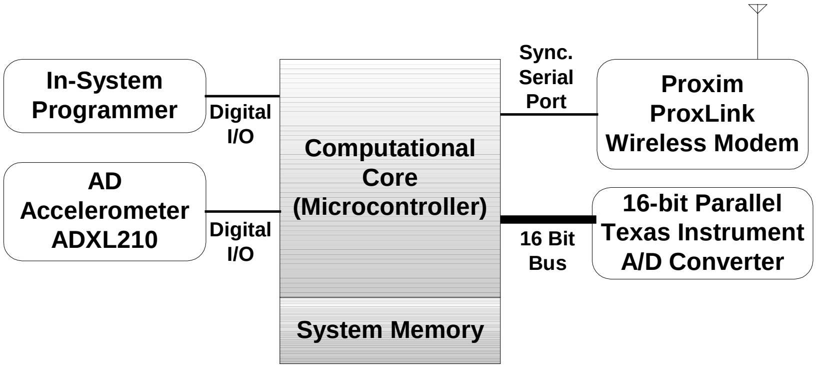

Figure 2. Functional Layout of the Proof-of-Concept Wireless Sensing Unit

Instruction Set Computer) architecture of the microcontroller provides computational speed by reducing the ordinary instruction set available to CISC (Complex Instruction Set Computer) microcontrollers thereby allowing single cycle instruction execution [4]. This means code is executed at the same rate as the microcontroller's 4 MHz oscillator clock. The Atmel RISC microcontroller is enhanced with additional instructions to allow for CISC like execution without compromising RISC performance. The Atmel AVR chip provides one of the highest MIPS (Million Instructions Per Second) per unit power consumption ratio of the market.

Although the Atmel microcontroller is an 8-bit architecture, the design of the microcontroller's architecture is optimized for using high-level languages such as C and Java for programming the microcontroller [5]. On an ordinary 8-bit microcontroller, the use of a high level language for programming adds significant overhead to the microcontroller's code execution since they are optimized with the assumption that they would be programmed using assembly. By providing 32 8-bit general purpose registers with 3 16-bit pointers included, the Atmel AVR microcontroller allows for high code density when using high-level languages for programming. The large number of general purpose registers is necessary for allowing local variable definitions while the 3 16-bit pointers are useful for allowing indirect jumps and elegant data memory accessing.

Wireless Communications

Resonating with the demands of the current end users of structural monitoring systems, a low cost but highly reliable wireless solution that allows for peer to peer (P2P) communication between sensing units and communication to a central data logging computer is sought. This task can be accomplished using wireless modem technology. The Proxim ProxLink MSU2 wireless modem was selected for the wireless sensing unit.

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 secure digital communication links between modems. The baseband data to be transmitted via direct sequence spread spectrum is multiplied by a pseudo-noise spreading sequence (also known as a chirping code).

The pseudo-noise signals appear random but can be reproduced deterministically at the receiver. Multiple users can simultaneously access the same wireless bandwidth without interference since each user employs a unique pseudo-noise sequence that is orthogonal to all other sequences [6]. The ProxLink wireless modems encode each bit of data with an 11-bit pseudo-noise chirping code.

The guarantee of a reliable digital communication channel between wireless modems is attained using spread spectrum techniques. Concentrating data upon a narrow frequency band is avoided by spreading the transmittable signal over multiple frequency channels within the available radio band. Spread spectrum communication is less sensitive to narrow band interference that is commonly associated with industrial machines and other radio devices operating within close proximity to the wireless network. For spread spectrum modems to operate properly, both the sender and receiving modems must be self synchronized and follow a prescribed sequence of frequencies. This ensures a secure communication link since it is difficult for third party wireless modems to listen in to communication occurring between devices. Specifically, the ProxLink modems divide the available 902-928 MHz band into three distinct channels each with 160 frequency bands. The modems transmit on one channel alternating between the 160 individual bands.

The range of the ProxLink modems in open space is as far as 1000 feet. The communication range of the ProxLink modems inside buildings has been shown to be as far as 100 feet [3]. Within buildings, the shielding behavior of common structural materials such as steel and concrete cause a reduction of power of the radio frequencies [7]. Empirical studies reveal that the higher the radio frequency, the better the building penetration characteristics of the signal are within heavily constructed buildings. For lighter construction such as wood framed houses, lower frequencies perform better since they can better diffract within buildings [8].

Sensing Transducer

There exist a large number of sensing transducers that can be used in the monitoring of structures. Some examples include strain gages, accelerometers, velocity meters, and displacement transducers. To ensure flexibility of the sensing unit, the overall design is sensor independent and is compatible with any type of analog sensor. A low noise single channel Texas Instrument 16-bit analog-to-digital (A/D) converter is used to measure the output voltage of the analog sensor and relay this measurement in digital form to the unit's microcontroller.

Given the wide spread use of accelerometers within the structural sensing field, accelerometers were considered in this study. In recent years, micro-electro mechanical system (MEMS) based accelerometers have become popular. By fabricating micrometer sized mechanical elements upon silicon, revolutionary sensors can be fabricated along with CMOS based circuits all on one chip. The result is accurate and sensitive sensors in form factors and unit costs not previously possible. In particular, the two MEMS accelerometers considered were the Analog Device's ADXL210 10g digital accelerometer as well as a high performance piezo-resistive planar accelerometer fabricated by Professor Thomas Kenny's group at Stanford University.

ANALOG DEVICES ADXL210

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. The MEMS accelerometer is fabricated as a surface micromachined polysilicon structure placed upon a silicon wafer that houses signal conditioning circuitry for open loop acceleration measurement. A duty cycle modulator within the signal conditioning circuitry provides an anti-aliased digital signal of acceleration for direct input to a microcontroller. The resolution of the duty cycle modulator is 14 bits, which is better than the accelerometer itself.

The performance characteristics of the accelerometer can be calibrated by judiciously selecting appropriate resistors and capacitors placed on external pins of the accelerometer. A tradeoff exists between the bandwidth and resolution of the accelerometer with greater bandwidths causing reduced resolution. 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.

HIGH PERFORMANCE PLANAR PIEZORESISTIVE ACCELEROMETER

In the high performance planar accelerometer, designed by Professor Kenny's group at Stanford University, a large proof mass is connected to a rigid base through a mass less cantilevering element. The element is very slender allowing for easy deflection only in the horizontal plane of the accelerometer (see Figure 3). Some out-of-plane response could be experienced but would have little to no effect on the resulting acceleration reading. Piezoresistors, a material that produces voltage in direct proportion to tensile and compressive strain, are implanted along the flexural sides of the cantilevering element. The strain experienced by these surfaces when the proof mass deflects is proportional to the sensor's acceleration. As a result, voltage output of the accelerometer is directly proportional to the acceleration of the accelerometer's packaging [9].

One nice attribute of the sensor is that the characteristics of the sensor can be tuned to a specific application by simply changing the dimensions of the cantilevering element. For example, to maximize sensor sensitivity, the flexural width should be minimized while the mass radial length is maximized. A tradeoff exists between the bandwidth and the resolution of the accelerometer. With increased resolution, the resonant frequency of the sensor and hence its bandwidth is reduced. Over the full dynamic range of the sensor, the Kenny/Partridge accelerometers maintain nearly constant sensitivity implying a fairly linear transfer function of the accelerometer. The maximum value of the 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 of the ADXL210. The end stops of the accelerometer also prevent the flexural element from entering the nonlinear region of response.

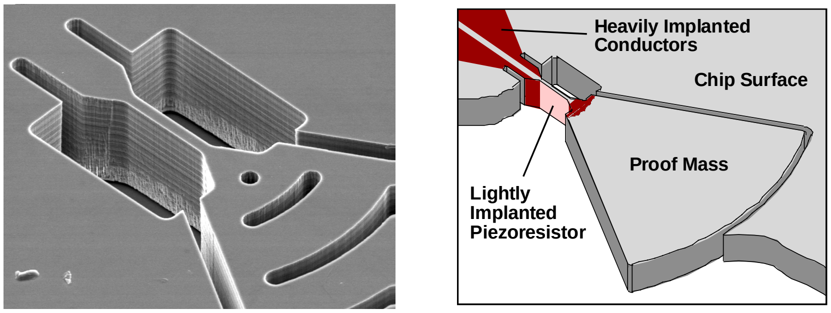

Figure 3. MEMS Based High Performance Planar Piezoresistive Accelerometer

When compared against commercially available accelerometers, the experimental results of the accelerometers produced by the Kenny group are quite impressive. One set of accelerometers were designed and fabricated for specific adoption within the wireless structural sensing unit. These specific accelerometers have a radial length of 1 mm and a flexural width of 5 μm. The full dynamic range of the accelerometers is well above 10g with a resolution of 20 μg at an acceleration bandwidth of 650 Hz.

Unit Packaging

To accommodate all of the individual components of the system, a two-layer printed circuit board has been preliminarily designed. The printed circuit board is 4” by 4” in size and provides a convenient means of packaging all of the system components in an efficient manner with low transient noise characteristics ensuring board performance as close as possible to the performance of the integrated circuits. The circuit board houses the microcontroller, the ADXL210, the 16-bit A/D as well as all the supporting circuitry. The A/D unit is used for reading acceleration measurements of the high performance planar accelerometer. The ProxLink wireless modem is externally attached to the circuit through a serial line originating from the modem’s serial port. With the accompanying 9V alkaline battery power supply, the current system can be contained within a sealed packaging unit roughly 5” by 4” by 1” in dimension (see Figure 4).

SENSOR UNIT VALIDATION

With a completed working prototype unit, the functionality of the unit was first validated through various controlled experiments in the laboratory. While such tests are sufficient for measuring the overall performance of the unit, before implementing the sensor unit in a full-scale WiMMS system, it would be prudent to perform many tests of the unit in the field.

In the first validation experiment, the sensor unit is placed upon a flat static laboratory surface and queried for acceleration data from the on-board ADXL210 accelerometer. The motivation of this experiment is to quantify the resolution of the accelerometer in a steady 0g state. As previously mentioned, the noise floor of the accelerometer’s measurements is set to have an RMS value of approximately 4 mg.

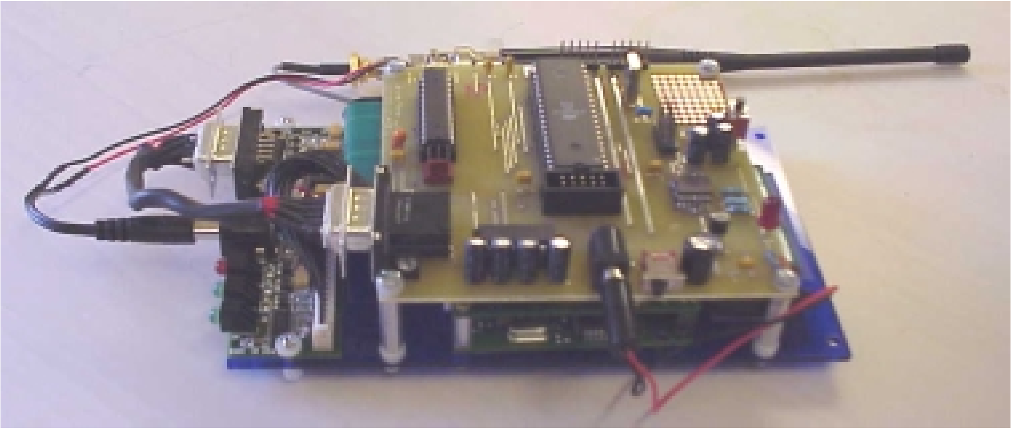

Figure 4. Complete Proof-of-Concept Wireless Sensing Unit

Steady state experiments verify that the accelerometer's noise falls within this region (see Figure 5).

In the second experiment, the sensor unit is tested for performance characteristics during sinusoidal excitations. By mounting the sensor unit upon a single-axis shaking table, sinusoidal input excitations can be generated. Using the on-board ADXL210 to measure the acceleration of the sensor unit, the acceleration data is logged. By superimposing the measured data upon the input excitation of the unit, the overall performance of the sensor unit can be obtained. For example, Figure 6 illustrates the measured test data of the sensing unit during the tracking of an input sinusoid excitation acceleration of a signal with an amplitude of 0.75g and a frequency of 2 Hz. As shown, the measured data coincides well with the input signal with some noise incorporated within the signal. However, appropriate filtering techniques can be included within the sensor unit's microprocessor or remotely in a data-logging unit to rectify the clean true signal from the noisy measured data.

CONCLUSION

The objective of this study was to design and fabricate a proof-of-concept embedded wireless sensing monitoring system. As compared to its cabled counterparts, the system enjoys the benefit of cheaper and quick installations. With computational power pushed forward from a central data acquisition system to the sensing units, they hold the promise of being capable of performing computationally intensive procedures in real time. Some potential procedures of significant value to the protection of vital civil structures would be damage detection methods that can diagnosis damage in a structure during the structure's life span.

Additional validation tests are planned for the proof-of-concept unit to ensure a high level of performance when installed in the field. Additional units are being fabricated for a full system implementation of the proposed WiMMS sensing architecture.

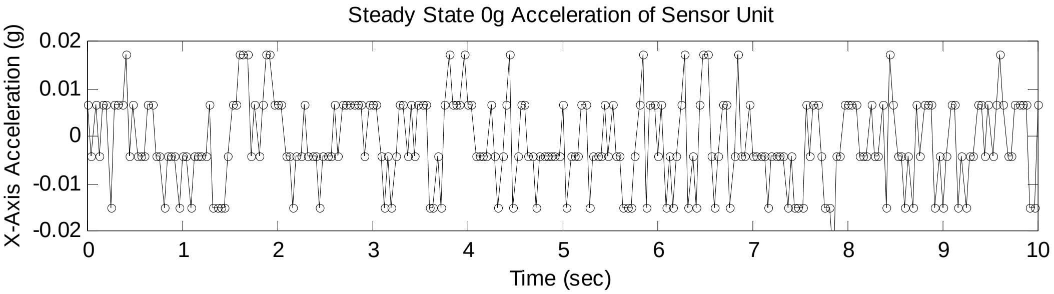

Figure 5 – Steady State Validation Experiment of the Proof-of-Concept Sensor Unit
(ADXL210 X-Axis)

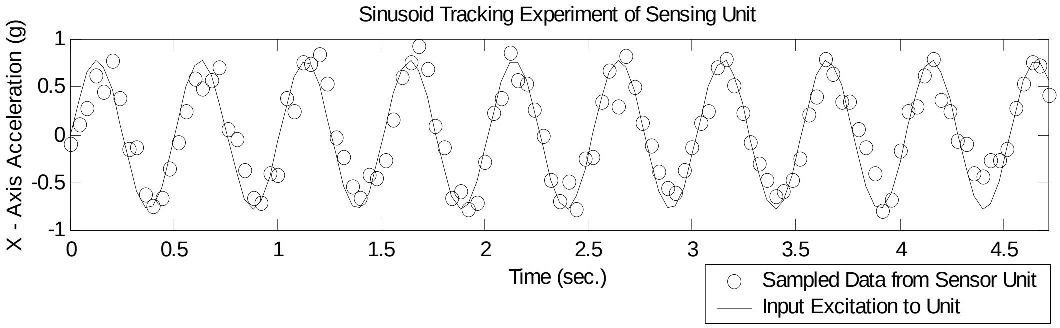

Figure 6 – Sinusoid Tracking Experiment of 2Hz, 0.75g Acceleration Signal
(ADXL210 X-Axis)

Future generation units will push the technology envelope by incorporating some new technologies just emerging on the marketplace. Efforts are already underway investigating advanced wireless devices that are more power efficient than the current ProxLink wireless modem. A Bluetooth wireless modem, supporting the ad-hoc Bluetooth wireless network protocol, is being considered as an alternative to be incorporated within the sensing unit.

ACKNOLEDGEMENTS

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