Multi-Purpose Wireless Accelerometers for Civil Infrastructure Monitoring

ABSTRACT

A new wireless MEMS accelerometer sensor board is designed to meet the specific hardware and software requirements of structural engineering applications. The board has four channels of accelerometers in two directions and one thermometer. It is compatible with Mica devices for control and communication, which in turn support TinyOS as their operating system. Hardware components are designed to detect a range of vibrations of a civil infrastructure from low-amplitude ambient to earthquake strong motions. Software components are added to the general framework of TinyOS to support aggressive sampling rates and reliable communication of the measured signals. As a preliminary prototype field test, the boards have been installed on a footbridge over highway I-80 at Berkeley, CA, to measure ambient vibrations of the bridge and wirelessly communicate the signals to a base station. The collected data is then processed and analyzed and modal properties of the bridge are computed.

1 INTRODUCTION

A new generation of small, inexpensive and efficient devices has been emerged, thanks to advances in Micro Electro Mechanical Systems (MEMS), which can sense a physical response, process it locally, and communicate it wirelessly.

A range of sensing devices is now available in MEMS technology that can measure acceleration, velocity, strain, tilt, temperature, light, sound and other physical quantities.

Software and hardware advances in networking, data management and wireless communication make it possible to create networks of hundreds or even thousands of these

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devices. Wireless Sensor Networks (WSN) can be used for monitoring applications, such as. Structural Health Monitoring (SHM). Although the instrumentation of structural systems to-date have been primarily for scientific purposes but the goal of the ongoing research is to develop software, hardware and algorithmic components for operation of a SHM sensor network. Such a network consists of a high spatial resolution of sensors throughout the critical points of the structure, which measures physical response of the system when and where needed, performs some local processing, and presents the necessary information for the human or automated operator about state of health of the structure. Such network can be used after a structural event, such as an earthquake, to provide safety information for the users, or in a continuous monitoring scheme to detect possible detioration and damage, update models of the structure and aid the engineers and owners in decision-making. These applications require a spatially dense network, with the capacity to collect and process a high volume of data, and reliable channels to communicate data and information.

In this paper, hardware and software specifications for structural engineering applications are established by the need to measure ambient vibrations as well as earthquake's strong motions in order to identify local and global damage in structural systems. A new MEMS sensor board is described and software components are defined for a software framework to create a sensor network suitable for SHM applications.

Many applications using wireless networks need only a low duty cycle and low power consumption. Habitat monitoring is, for example a leading application of WSN, which requires a very low duty cycle, low data rate, small data size and a fanatic emphasis on low power consumption; ZebraNet [7], James Reserve [4], a vineyard in British Columbia [16] and Great Duck Island [11] projects are examples of such applications. Structural engineering applications however, are on the other end of application spectrum because of the high sampling rate and large data volume. They critically depend on more aggressive application of wireless networks and require high-fidelity sensing, collection of large volume of data and more sophisticated capability of on-board signal processing. To address these issues, a specific-purpose program was created, which allows for a great deal of robustness and efficiency to control the accelerometer board for SHM applications. Software components have been developed to support these capabilities by providing necessary components for aggressive sampling, reliable data transmission and to efficiently control the board.

Structural engineering applications also need the sensor board to be sensitive in a wide range of accelerations, from ambient vibrations to the strong motion of an earthquake. For example the peak horizontal acceleration for ambient vibrations of Golden Gate Bridge were in the order of 100's of mg according to [1] while peak acceleration in a major earthquakes could be as high as 2g. The new hardware is designed to cover this range and at the same time provide the required sensitivity.

2 HARDWARE ARCHITECTURE

A sensor unit consists of a sensor board and a control/communication device to drive the board, and store and communicate data. Mica2 motes, which are used in this project, are equipped with a Micro-Controller (Atmel Atmega 128L), which has 128KB of program memory, 4KB of RAM and runs at 8MHz. The mote is also equipped with a RF tunable frequency radio chip (Chipcon CC1000) with a data rate of 38.4Kbps (see http://www.tinyos.net/scoop/special/hardware). Mica2 also has an external 512 KB of EEPROM for data storage. A newer version of the motes, MicaZ will be used in future deployments which is identical to Mica2, except than for its radio chip, which runs at 2.4GHz providing 250Kbps bandwidth. Since the generic sensor board, which is the default sensor board for mica platform (called Mica Sensorboard; see http://webs.cs.berkeley.edu/tos/hardware/sensorboard.html), is not sensitive enough for structural engineering applications, an accelerometer sensor board was designed and tested that meets the hardware requirements of SHM applications [13].

2.1 DATA ACQUISITION

Data acquisition consists of sensing the signal, sampling, and having measures to characterize the fidelity of the data and its noise level [8][13]. Sensors collect acceleration data as well as the temperature. Collected data then passes through an analog filter (anti-aliasing) and is sampled by a 16-bit Analog-to-Digital Converter. Digital data then goes through digital filtering (averaging, etc.) and a Feedback Jitter Controller checks its fidelity (Jitter is the distortion of a signal caused by poor time-synchronization).

2.2 SENSOR BOARD

The major sensors on the board are accelerometers, of which two different ones are used. Each board has a total of 4 channels in two directions; two in vertical direction and two in horizontal direction. The range of ±2g is divided between the two types of accelerometers to provide both the required range for earthquake's strong motion and accuracy of the order of 10's of μg for ambient vibrations.

Each board, as pictured in FIGURE 1, has one ADXL202 and two SiliconDesign1221 on it. ADXL202 is an accelerometer by Analog Devices. It is a low-cost, low-power complete 2-axis accelerometer with a measurement range of ±2g with a nominal resolution is 200 μg per root-square Hz, allowing signals below 2mg (at 60 Hz bandwidth) to be resolved [2]. SiliconDesign1221 is a very low-noise (2μg/(root Hz)) single-axis accelerometer, which provides the sensitivity required for ambient vibration analysis [14]. The range of SiliconDesign accelerometer is reduced to ±0.1g so that using a 16-bit A/D converter, a maximum nominal resolution of 3μg is achieved. Our tests showed that the noise floor of the accelerometer itself is controlling and the device is sensitive to within 30μg [13]. Each board is also equipped with a thermometer and the data are stamped, at a lower frequency, with the temperature.

2.3 TESTING, VERIFICATION AND CALIBRATION

A variety of tests were performed to determine the noise characteristics of the sensor board. They included tests of the board in quiet environment to estimate the noise floor, as

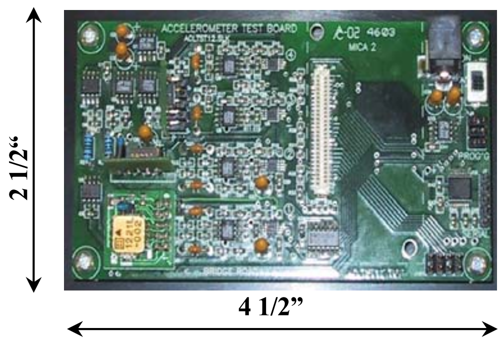

FIGURE 1. Sensor Board with 4 Accelerometer Channels

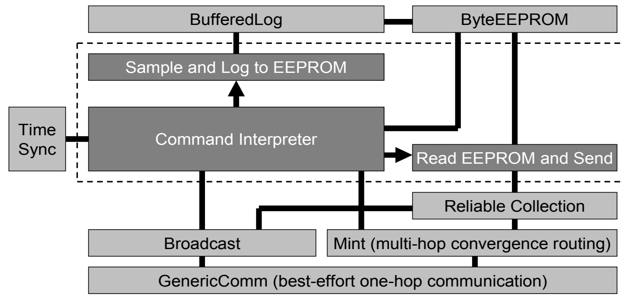

FIGURE 2, Overall Software Architecture

well as shaking table tests to investigate the performance of the board in a dynamic range and at higher frequencies.

The quiet environment tests compare the performance of SiliconDesign accelerometer with a highly sensitive BKS FBA-23 reference accelerometer, which shows the equivalent RMS acceleration noise for SiliconDesign is 312 $\mu m / Sec^2$, or 32mg.

Each sensor needs to be individually calibrated for both acceleration and temperature. The calibration process consists of a series of tilt test. The board is rotated a few degrees at a time, using a high-accuracy tilting machine in Crossbow labs [3] and the output of the A/D converter at each station is recorded. The tests provide calibration information for all of the boards and confirm that the accelerometers are very linear within their range.

3 SOFTWARE ARCHITECTURE

TinyOS [10][6], provides the software infrastructure for the sensor network. It is an operating system developed in UC Berkeley, which has become the de facto standard operating system in WSN. In this section we describe the components added to TinyOS for SHM applications.

3.1 DATA ACQUISITION

The data acquisition has been developed to address the following important issues for SHM applications:

- High-frequency sampling and low jitter, which is a variation in sampling intervals.
- Time synchronization to enable sampling to start simultaneously at all nodes.
- Large-scale Multi-hop network: Monitoring systems span over long distances, which makes it impossible to cover the entire network with single hop communication. This makes a large-scale multi-hop network necessary to provide connectivity.
- Reliable command dissemination and data collection: commands/triggers need to be disseminated and data should be flowing throughout the network reliably. SHM applications cannot afford loss of data due to transmission.

FIGURE 2 shows the overall architecture of software. Structure Monitoring Toolkit (SMT) is an application layer program, which drives all components. On top of best-effort one-hop communication, broadcast is used for command dissemination, and MintRoute [15] is used for information reply. Reliable data collection layer lies above broadcast and MintRout. SMT uses all of these components. For time synchronization, FTSP [12] is used. BufferedLog [17] is used to support high frequency sampling. These components meet all challenges except high frequency sampling and reliable data collection; the following additional components are developed to facilitate that.

3.2 HIGH FREQUENCY SAMPLING

Structure monitoring requires sampling at high frequency with uniform intervals, and jitter becomes a critical problem as sampling rate becomes higher. FIGURE 3(a) shows interaction of sampling and other jobs such as writing data from RAM to flash in CPU.

Timer event for sampling occurs regularly with a uniform interval. However, to be serviced by the CPU, the CPU should finish servicing pending atomic section. Only then, can the CPU handle timer event and sampling. The worst jitter is determined by the longest atomic section, which can be running when the timer event occurs. This implies that no chance should be given to unnecessary components' atomic section to run on CPU. Therefore, every component is turned off except EEPROM during sampling.

Figure 3(b) is the histogram of jitter values. A peak occurs at 625ns, which is the wakeup time. Except this peak, the frequency of jitter is largest near 0s, and gradually decreases as jitter value increases. Jitter values are capped within 10μs.

3.3 LARGE-SCALE DATA TRANSFER

Significant loading events on a structure, such as earthquake, happen rarely and with a relatively short period of time, which makes it unacceptable for the WSN to lose data due to transmission. The goal is to achieve reliable data transmission with the minimal expense of channel capacity and bandwidth. It is also necessary to design a protocol for data collection that scales over a multi-hop network. In applications like SHM, sampling cycle is determined by data collection time; since sampling is fast, data collection takes most of time. Resource usage should hence be minimized, because wireless sensor nodes are limited in computational power, memory space and energy.

Straw (Scalable Thin and Rapid Amassment Without loss) is a reliable data collection to provide these properties. At the high level view, the sender sends the entire data once, and the receiver asks for retransmission of missing data.

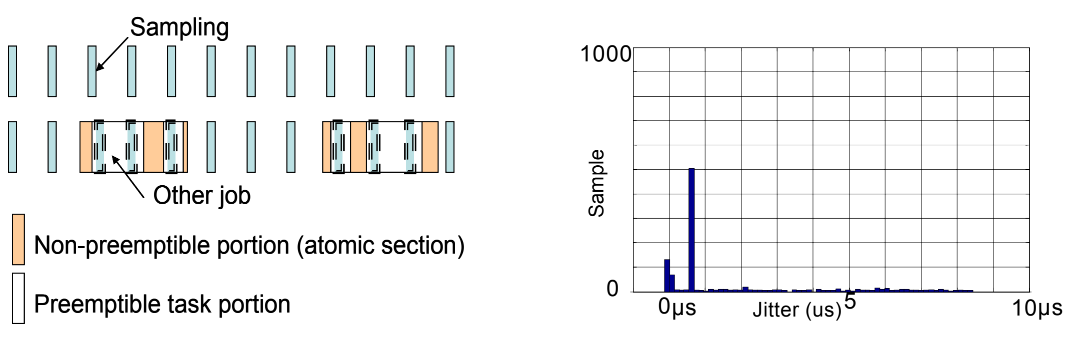

FIGURE 3: (a) Occurrence of Jitter, (b) Histogram of Jitter at 5KHz

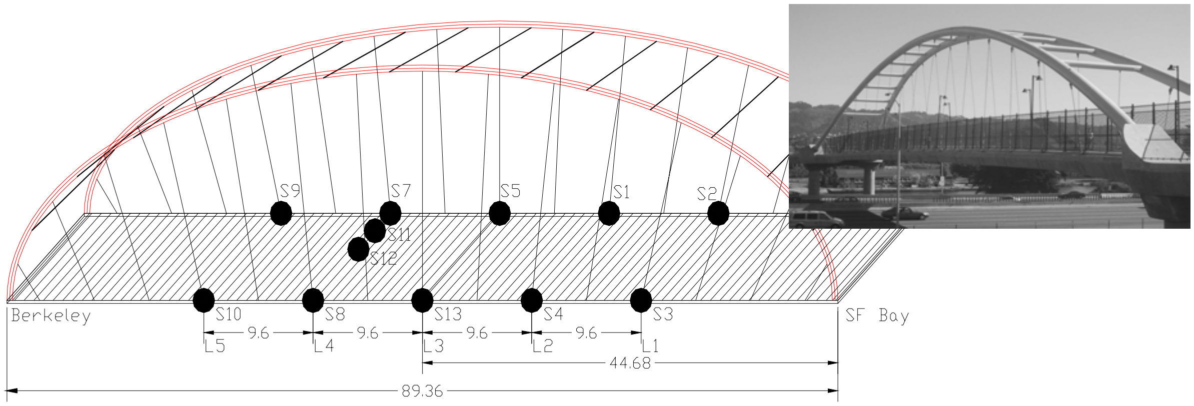

FIGURE 4, I-80 Pedestrian Overpass and the locations of the sensors boards

4 TESTBED SHM APPLICATION

In order to test the board a testbed experiment was designed to assess the performance of the hardware in a hostile environment, test the robustness of the software, and measure vibrations of a large structure under ambient vibrations and characterize the noise.

A pedestrian bridge over passing I-80 at Berkeley, CA, was chosen for the testbed SHM application, see FIGURE 4. It is a tied-arch bridge with a span of 89.36 m. The arches consist of two semi-parabolic 762 mm diameter steel arch tubes, connected by 14 transverse 408 mm diameter struts every 4.8 m. The deck is suspended from the arch by 38 mm diameter hangers every 4.8 m.

4.1 DEPLOYMENT PLAN

12 motes were used in the test-bed experiment. The boards were placed on both sides of the main span at 5 different locations; see FIGURE 5. The network collected data for 4 minutes, with a sampling frequency of 200Hz, resulting in 48000 samples per channel. A total of 3 channels per board were used: 2 channels of high resolution SiliconDesign and one

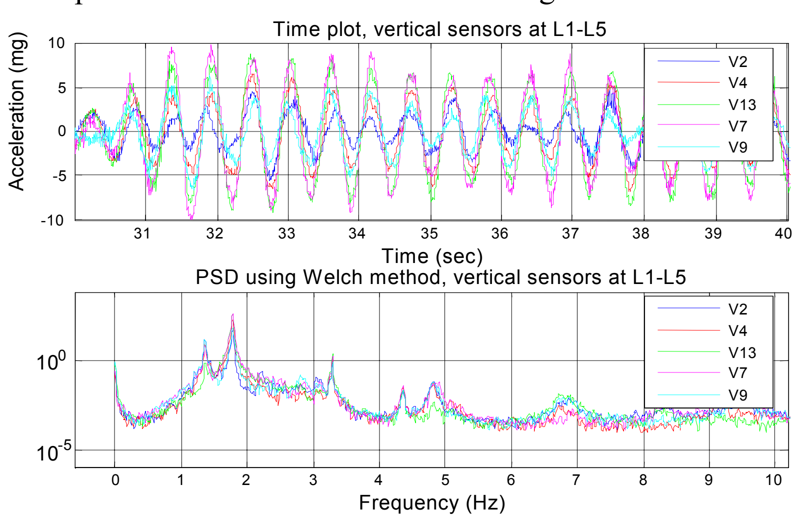

FIGURE 5, Time- and frequency-domain plots of 5 high-resolution vertical sensors

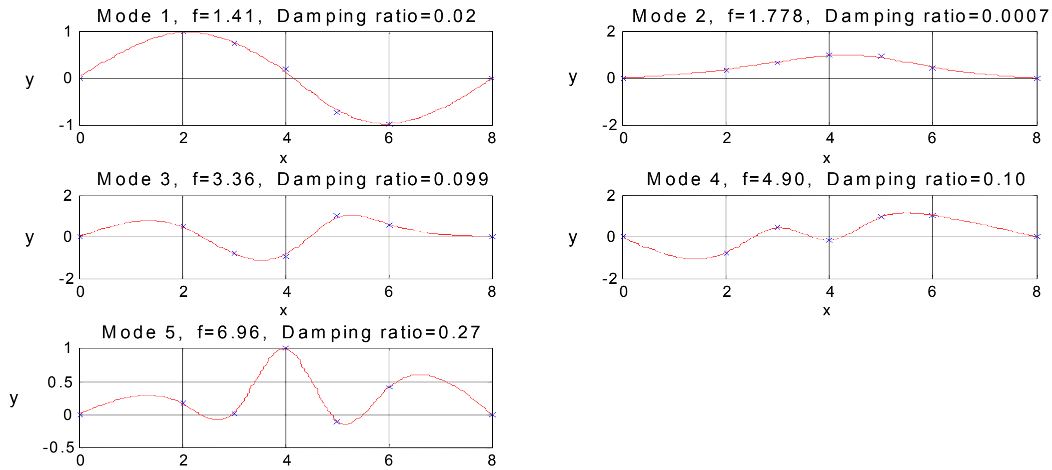

FIGURE 6, Estimated vertical frequencies, damping ratios and mode shapes

channel of the on-board thermal sensor for temperature calibration. Five vertical signals from high-resolution sensors on boards S2, S4, S13, S7 and S9 are then selected for system identification, one from each of the five locations shown in FIGURE 4. A 10 second calibrated segment as well as the low 10Hz of these signals are shown in FIGURE 5.

4.2 SYSTEM IDENTIFICATION

A second-degree differential equation results in a second-degree difference equation. The discritized data fits a second-degree ARX model of the form:

$$\sum_{i=0}^{p} A_i u(n-i) = \sum_{i=0}^{q} B_i x(n-i) + \varepsilon(n)$$

Here u is the vector of output signals, x is the vector of input signals, and A_i and B_i are Auto-Regressive and eXplanatory parameters. The eigenproperties of this discrete system are a transformation of eigenproperties of the original continuous system.

Estimated modal properties of the first five vertical modes are shown in FIGURE 6. Note that in the following graph x-axis represents the length of the bridge, where $x=0$ is the east-support of the bridge at bent-3, $x=4$ represents the mid-span and $x=8$ is the west-support at bent-2. The estimated modal properties are consistence with the structural properties of an arch structure [5]. The first mode is an anti-symmetric mode, with a node at the mid-span, which is expected in an arch structure [9]. The second mode, which is the dominant mode, is symmetric with no node and a maximum at the mid-span. Third, fourth and fifth modes are also consistent with the expected mode shapes, although the higher levels of damping ratios suggest that the signals are noisy at these modes, and hence the estimates might not be as accurate as the first two modes.

CONCLUSION

A new accelerometer sensor board is developed that meets the requirements of SHM applications. The board is equipped with very sensitive devices to measure ambient vibrations as well as inexpensive accelerometers to sense earthquake strong motion.

Dynamic and tilt testing shows that the board is able to sense vibrations in ±2g range with a sensitivity of 30µg. Software components provide capability of high frequency sampling, time synchronization, multi-hop networking and reliable transformation of data and commands throughout the network. A network of 12 boards was used on the I-80 pedestrian overpass as a preliminary testbed structure. Ambient vibrations of the bridge were recorded and vertical modal properties of the bridge were estimated.

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