SENSOR DEVELOPMENT USING BERKELEY MOTE PLATFORM

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Industrialised nations have dedicated significant investments toward the development of civil infrastructure. To preserve this investment, attention must be given to proper maintenance. Structural Health Monitoring (SHM) has emerged as a tool to support this task. Networks of smart sensors, built upon wireless communication, have the potential to significantly improve SHM. Numerous platforms for smart sensors have been developed, most of which utilise proprietary hardware/software. The Berkeley Mote, utilised in this study, was the first open hardware/software platform to be developed. However, the Berkeley Mote was designed for generic applications and therefore the available sensors are not optimised for use in civil infrastructure applications. Acceleration and strain are among the most important physical quantities to judge the health of a structure. Although commercially available sensor boards have accelerometers, their applicability towards civil infrastructure is limited. This paper presents the development of new acceleration and strain sensor boards based on the Berkely-Mote platform and provides experimental verification of their performance within civil infrastructure applications.

Keywords: Acceleration sensor; strain sensor; civil infrastructure; smart sensor; wireless sensor network.

1. Introduction

Industrialised nations dedicate considerable investment towards civil infrastructure, typically ranging between 8–15% of their gross domestic product (GDP), every year [US Census, 2004; Jensen, 2003]. Without proper maintenance, the infrastructure can deteriorate and even become a liability. For example, lack of maintenance has caused the Federal Highway Administration (FHWA) to declare 31.4% of all bridges in the USA to be structurally deficient or functionally obsolete. Turner [1999] indicated that updating these bridges and maintaining appropriate repair levels would require about $80 billion.
In recent years, SHM has emerged as a tool to support effective operation and maintenance of the civil infrastructure. Numerous SHM techniques have been developed that estimate the health of structures by monitoring their physical behaviour and associated environmental conditions [Doebling et al., 1996]. However, due to available technology, traditional approaches have been centralised in terms of collecting and analysing information. Thus drawbacks have included expensive and time-consuming sensor installation, signal degradation, and data flooding.

The development of wireless platforms based upon smart sensors has the promise of overcoming these deficiencies. This technology allows use of larger and denser arrays of sensors, which can support more effective SHM [Spencer et al., 2004]. Parallel and decentralised computing, as well as data aggregation, are some of the additional capabilities offered by a network of smart sensors [Gao et al., 2005]. New sets of potential scenarios can now be explored, such as formation of clusters of sensors around joints to detect local failure.

A diverse number of smart sensors have been developed [Lynch et al., 2002; Glaser and Min, 2004; Chung et al., 2004], nearly all of which use proprietary hardware/software. The first available open hardware/software research platform was the Berkeley Mote. Users of the Berkeley Mote can easily customise both the hardware and software for a particular application.

However, as the Berkeley Mote was designed for generic applications, the available sensors are not optimised for use in civil infrastructure applications. Acceleration and strain are among the most important physical quantities to judge the health of a structure. While acceleration measurements are essential to obtain global responses of a structure, structural strains provide an important indicator of local structural behavior. Studer and Peters [2004] demonstrated that multi-scale sensing yields better results than single-scale measurements for damage identification. However, commercially available sensor boards have only accelerometers, though their applicability to civil infrastructure is limited.

This paper investigates sensor boards for the Berkeley Mote platform from the civil engineering application perspective. The suitability of the currently available accelerometer on the Berkeley Mote sensor board is initially studied. The acceleration sensor board was determined to have both low sensitivity and high noise density. A new sensor board employing the SD-1221 accelerometer [Silicon Designs Inc., 2005], along with a 4-pole Butterworth anti-aliasing (AA) filter board, has been designed and fabricated. Additionally, a new strain sensor board is developed and its performance is experimentally verified. The new boards’ design and suitability for civil infrastructure applications are reported herein.

2. Berkeley Mote Platform

This study employs the Berkeley Mote platform as it is an open hardware/software, smart-sensing platform with a large user community (see http://www.tinyos.net/). This section provides an overview of the software and hardware characteristics of
the Berkeley Mote platform as well as a detailed assessment of its sensor board from the civil engineering applications perspective.

2.1. Overview

The Berkeley Mote platform was developed under the Networked Embedded Systems Technology (NEST) program with the quantitative target of building dependable, real-time, distributed, embedded applications comprising 100 to 100,000 simple computing nodes [DARPA, 2005]. The platform consists of four basic components: Power, sensors, computation, and communication. These motes are autonomous and connectable to other motes. The main advantages are small physical size, low cost, modest power consumption, and diversity in design and usage.

The latest versions of the Berkeley Mote include the MicaZ, Mica2, and Mica2dot processor boards (Fig. 1). The Motes have improvements in memory and radio over predecessors and specifications are summarised in Table 1. In this

![Berkeley Mote processor boards: (a) MicaZ, (b) Mica2, and (c) Mica2dot.](image)
Table 1. Characteristics of the MicaZ, Mica2, and Mica2dot processor boards.

<table>
<thead>
<tr>
<th></th>
<th>MicaZ</th>
<th>Mica2</th>
<th>Mica2dot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash memory</td>
<td>128 K bytes</td>
<td>128 K bytes</td>
<td>128 K bytes</td>
</tr>
<tr>
<td>Measurement memory</td>
<td>512 K bytes</td>
<td>512 K bytes</td>
<td>512 K bytes</td>
</tr>
<tr>
<td>EEPROM</td>
<td>4 K bytes</td>
<td>4 K bytes</td>
<td>4 K bytes</td>
</tr>
<tr>
<td>A/D (Channels)</td>
<td>10 bits (8)</td>
<td>10 bits (8)</td>
<td>10 bits (6)</td>
</tr>
<tr>
<td>Frequency</td>
<td>1400 MHz–2483.5 MHz</td>
<td>433/868/916 MHz</td>
<td>433/868/916 MHz</td>
</tr>
<tr>
<td>Data rate</td>
<td>250 K bps</td>
<td>19.2 K bps</td>
<td>19.2 K bps</td>
</tr>
<tr>
<td>Outdoor range</td>
<td>100 m</td>
<td>300 m</td>
<td>300 m</td>
</tr>
<tr>
<td>Size</td>
<td>6×3×1 cm</td>
<td>6×3×1 cm</td>
<td>2.5×0.6 cm</td>
</tr>
</tbody>
</table>

Table 2. Description of the available sensor boards.

<table>
<thead>
<tr>
<th>Name</th>
<th>Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTS101CA</td>
<td>Photo resistor and thermistor.</td>
</tr>
<tr>
<td>MTS300CA</td>
<td>Photo resistor, thermistor, acoustic sensor and acoustic actuator.</td>
</tr>
<tr>
<td>MTS310CA</td>
<td>Photo resistor, thermistor, acoustic sensor, acoustic actuator, biaxial accelerometer and magnetometer.</td>
</tr>
<tr>
<td>MTS400/420CA</td>
<td>Thermistor, hygrometer, barometer, Photo resister, accelerometer, GPS(only on MTS420CA)</td>
</tr>
</tbody>
</table>

The Berkeley Mote utilises an operating system, TinyOS, to eliminate the gap between raw hardware capabilities and a useful system. The work presented by Hill [2000] and Hill et al. [2000] describes the design of this tiny event-driven operating system that provides support for efficient modularity, and concurrency-intensive (i.e. multiple tasks running concurrently) operation. Furthermore, the 178 bytes of memory is sufficient for TinyOS.

2.2. Accelerometer on MTS310CA sensor board

One of the available sensor boards, MTS310CA, which has an accelerometer, ADXL202E (see Fig. 2), is experimentally evaluated from a civil engineering perspective. This commercially available sensor board has been developed for generic purposes. Therefore, the applicability of the board for structural health monitoring needs to be assessed.

The ADXL202E is a low-cost, low-power, 2-axis capacitive accelerometer with analog and digital output housed on a single monolithic integrated circuit. The
ADXL202E is capable of acceleration measurements up to 2 g. The measurements can be both dynamic (e.g. vibration) and static acceleration (e.g. gravity). The outputs are analogue voltages or digital signals whose duty cycles (ratio of pulse width to period) are proportionate to acceleration. The MTS310CA sensor board uses the 2 analogue outputs for this accelerometer. Table 3 presents the main electronic characteristics of the ADXL202E.

To assess the efficiency of the ADXL202E accelerometer, performance was compared with a PCB model 393B04 high sensitivity piezoelectric seismic accelerometer (see Fig. 3 and Table 4). Wired data acquisition systems were employed to compare accelerometers’ performance separately from inaccuracy due to wireless communication. The 393B04 reference accelerometer has been recently calibrated by the manufacturer, so its performance is well known.

Both the ADXL202E sensor board and the 393B04 were mounted on a shake table [University Consortium on Instructional Shake Tables, 2005; see Fig. 4] for comparison of the two sensor signals under dynamic excitations. The table is capable of providing a peak acceleration of ±2.5 g with a maximum stroke of ±3 in. A DSPT SigLab 20–42 spectrum analyser [Spectral Dynamics Inc., 2005] was used to drive the shaking table and to acquire data from PCB 393B04. The Siglab spectrum analyser has a 20-bit sigma-delta analogue to digital (A/D) converter with an eight-pole elliptic 90 dB AA filter. The Berkeley Mote platform employs a 10-bit A/D

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**Table 3. Characteristics of the ADXL202E accelerometer.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input range</td>
<td>±2 g</td>
<td></td>
<td></td>
<td>Hz</td>
</tr>
<tr>
<td>Frequency response</td>
<td>0–6kHz</td>
<td></td>
<td></td>
<td>Hz</td>
</tr>
<tr>
<td>Operating Voltage ($V_{dd}$)</td>
<td>3</td>
<td>5.25</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Operating current</td>
<td>0.6</td>
<td>1.0</td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>Sensitivity ($V_{dd} = 3V$)</td>
<td>140</td>
<td>167</td>
<td>195</td>
<td>mV/g</td>
</tr>
<tr>
<td>Output noise (RMS)</td>
<td>200</td>
<td></td>
<td></td>
<td>μg/√Hz</td>
</tr>
</tbody>
</table>

Fig. 2. Accelerometer ADXL202E [Analog Devices Inc., 2005].
Fig. 3. Accelerometer PCB 393B04 [PCB Piezotronics Inc., 2005].

Table 4. Characteristics of the 393B04 accelerometer.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typ</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input range</td>
<td>±5</td>
<td>G</td>
</tr>
<tr>
<td>Frequency response (nominal, 3 dB)</td>
<td>0.02-2000</td>
<td>Hz</td>
</tr>
<tr>
<td>Sensitivity (±10%)</td>
<td>1032</td>
<td>mV/g</td>
</tr>
<tr>
<td>Output noise (RMS)</td>
<td>0.04</td>
<td>µg/√Hz</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>18-30</td>
<td>V</td>
</tr>
<tr>
<td>Operating current</td>
<td>2-10</td>
<td>mA</td>
</tr>
</tbody>
</table>

Fig. 4. UCIST shake table [Quanser Consulting Inc., 2005].
converter without an AA filter. The AA filter must be included on the sensor boards according to the specific application. The MTS310CA has a one-pole AA filter with a cutoff frequency of 50 Hz.

The Mica2 and the MTS310CA were placed on the MIB510 programming board, which in turn was connected to the serial port of a PC. The oscilloscope application within TinyOS was downloaded to the Mica2. The application acquires data from the analog input and forwards it to the PC through a serial port. On the PC side, the Java interface, “SerialForwarder”, and “Oscope” retrieved and stored data. Both acquisition systems (i.e. SigLab and Berkeley Mote platform) were set to sample at 256 Hz. Figures 5 and 6 provide a comparison of the accelerometers in the time and the frequency domain when subject to a relatively large amplitude random acceleration of 24.6 mg (RMS).

As shown in Fig. 5, the response in time domain of the ADXL202E sensor board, compared with that of 393B04 is resonable. In the frequency domain (see Fig. 6), the response of the two accelerometers is in good agreement above 1.5 Hz. However, the noise floor for the ADXL202E is greater than the signal level below 1.5 Hz.

The performance of the ADXL202E for low amplitude random acceleration signals was also investigated. Figures 7 and 8 show a comparison in the time and frequency domains when the accelerometers were subject to a RMS acceleration of 5.8 mg.

![Fig. 5. Acceleration record for large amplitude random excitation.](image)

![Fig. 6. Power spectral density of the acceleration for large amplitude random excitation.](image)
As shown in Fig. 7, the response of the MTS310CA sensor board compared with that of the reference accelerometer is quite poor in the time domain. In the frequency domain (see Fig. 8), the responses of the two accelerometers also do not correlate well. The noise floor for the MTS310CA is higher than the signal level below 5 Hz. This limitation is primarily due to the low sensitivity of ADXL202E accelerometer, as well as the lower resolution of Mica2's 10-bit A/D converter. For civil engineering applications in which natural frequencies are typically from 0.2 to 2 Hz, the small acceleration signal at low frequencies is important. Thus, the poor resolution needs to be improved.

3. Acceleration Sensor Board Development

In this section, new sensor boards are designed by adopting a high sensitivity, low noise level, accelerometer. Experimental results in the previous section showed that currently available accelerometer for the Berkeley Mote platform has low sensitivity, which can be particularly problematic at low frequencies. Therefore, its suitability for civil engineering applications is limited. A new sensor board, named “Tadeo”, overcomes many of the deficiencies of the existing sensor. To address concerns with aliasing of measured acceleration signals, the design of a modular four-pole Butterworth filter board is also presented.
3.1. High sensitivity acceleration sensor board

A high sensitivity accelerometer with low noise density was sought. The SD-1221 accelerometer [Silicon Designs Inc., 2005] meshes well with these needs. The main characteristic of this accelerometer is its low noise floor, $2 \mu g/\sqrt{\text{Hz}}$, which is 100 times lower than that of the ADXL202E. In addition, the sensitivity of the SD-1221 is $1000 \text{mV/g}$, which is approximately 6 times greater than that of the ADXL202E (see Table 5).

However, SD-1221’s power requirement of 5 V, which is beyond the 3 V capabilities of the Mica2 platform, required consideration. The supplied power voltage from the Mica2 was boosted to the required level. The MAX-1682 [Maxim Integrated Products Inc., 2005], a switched-capacitor voltage doubler, was used to increase the voltage from 3 V to 6 V. Then, a voltage regulator, LT1761ES5-5 [Linear Technology Corporation, 2005], was implemented to reduce the voltage to 5.0 V and eliminate the noise induced by the voltage doubler. The LT1761ES5-5 is a low-noise, low-dropout, linear regulator with an output ranging from 4.935 to 5.065 V. With these modifications, the output of the linear regulator was provided to the SD-1221 accelerometer.

Following a proof-of-concept demonstration using a prototype board with only the acceleration sensor (Fig. 9), a final sensor board was designed. The sensor board layout was based on the MTS310CA. The SD-1221 high sensitivity accelerometer

Table 5. Characteristics of SD-1221 accelerometer.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input range</td>
<td>±2</td>
<td></td>
<td></td>
<td>g</td>
</tr>
<tr>
<td>Frequency response (nominal, 3 dB)</td>
<td>0–200</td>
<td>0–400</td>
<td></td>
<td>Hz</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>1000</td>
<td></td>
<td></td>
<td>mV/g</td>
</tr>
<tr>
<td>Output noise (RMS)</td>
<td>2.0</td>
<td></td>
<td></td>
<td>µg/√Hz</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>4.75</td>
<td>5.0</td>
<td>5.25</td>
<td>V</td>
</tr>
<tr>
<td>Operating current</td>
<td>10</td>
<td>14</td>
<td></td>
<td>mA</td>
</tr>
</tbody>
</table>

Fig. 9. Prototype of the high sensitivity accelerometer.
was implemented on a PCB in addition to light, temperature, and acoustic sensors. The PCB was designed using the Protel DXP program [Altium Limited, 2005] and manufactured at Fineline Circuits & Technology [2005]. The sensor board, named “Tadeo,” is shown in Fig. 10.

### 3.2. Four-pole Butterworth anti-alias filter board

To address concerns with aliasing of measured acceleration signals, a modular four-pole Butterworth filter was designed. The Sallen-Key topology [Sallen and Key, 1955] was used for the design of the Butterworth filter. This topology employs an active approach, which uses operational amplifiers. Rail to rail input/output amplifiers, MAX4132 [Maxim Integrated Products Inc., 2005], give the filter a rail to rail input/output property, which results in efficient use of the input/output voltage range. The cutoff frequency was set as 50 Hz. This cutoff frequency allows verification of the acceleration sensor board over wide frequency range. It should be noted that, depending on application requirements, filters with other cutoff frequencies can be easily constructed by changing resistors and capacitors.

The final PCB (see Fig. 11) was manufactured at the Electronics Services Shop [ESS, 2005] based on the cascaded two second-order filter design (see Fig. 12). The filter’s transfer function was verified as shown in Fig. 13. The difference between the design value and the measured value of the transfer function is within the expected range of error due to finite precision of the capacitors on the board.

### 3.3. Experiment

To test the performance of the new acceleration sensor boards, i.e. the “Tadeo” sensor board and the AA filter board, they have been compared with the 393B04 reference sensor, as well as the MTS310CA sensor board. Four sets of sensors were mounted on the shake table: (i) ADXL202E accelerometer on MTS310CA sensor board, (ii) SD1221 accelerometer on the “Tadeo” sensor board, (iii) SD1221 accelerometer on the “Tadeo” sensor board including the AA board, and (iv) 393B04 reference accelerometer. Sensor boards 1 to 3 were each connected to Mica2s mounted on programming boards and then wired to a PC. The oscilloscope
application within TinyOS was downloaded to the Mica2s. On the PC side, a java interface, “Listen”, was modified to retrieve and save data from the three Mica2s. The reference accelerometer was connected to a DSPT SigLab 20–42 spectrum analyser [Spectral Dynamics Inc., 2005]. The sensors were subjected to a displacement
white noise excitation with a 5 Hz bandwidth. The RMS of the acceleration signal, sampled at 256 Hz, is 9.2 mg.

Figures 14 and 15 show the measured acceleration time history and the power spectral density, respectively. The 10-bit A/D converter on the Mica2 limits the resolution of its signals. The higher sensitivity of the accelerometer on the “Tadeo” sensor board allows for smaller acceleration to be detected when compared to the MTS310CA. The Tadeo sensor board signal fluctuation shown in Fig. 14, and high noise floor observed in Fig. 15 are considered to be a result of aliasing. High frequency components of broadband noise are folded back to the frequency range of interest. This phenomenon is actually quite common. For example, a 98 Hz signal sampled at 50 Hz will appear as an aliased 2 Hz signal. Due to the significant aliasing in the signal, the “Tadeo” sensor board’s resolution can be further improved with the addition of an AA filter. The combination of the “Tadeo” sensor board and the filter board yields a signal which is close to the reference, though a slight discrepancy was observed. Further improvement in resolution, by using an even higher sensitivity accelerometer or higher resolution ADC for example, is expected to eliminate this discrepancy.

To further investigate the sensor board’s characteristics, transfer functions and coherence functions were calculated from the recorded signals. Figure 16 shows the measured transfer functions from the reference accelerometer to the accelerometers...

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Fig. 14. Acceleration record for band limited white noise excitation.

Fig. 15. Power spectral density of the acceleration for band limited white noise excitation.
on the three sensor boards. The transfer functions should have a unit magnitude (or 0 dB) if the two compared signals are the same. The combination of the “Tadeo” sensor board and the filter board gives transfer function magnitude close to 0 dB and performs much better than the MTS310CA sensor board or the “Tadeo” sensor board without the AA filter. Figure 17 presents the corresponding coherence functions. The coherence function indicates the degree of correlation, or linear relationship, between two signals as a function of frequency [de Silva, 2000]. Perfectly correlated signals yield a coherence function equal to 1. The advantage of the combination of the “Tadeo” sensor board and filter sensor board is evident in Fig. 17.

The performance of all the sensor boards is difficult to judge in the frequency range very close to 0 Hz. The problem arises from a number of causes, including the reference sensor’s inability to measure constant component and extremely small shake table excitation at the frequencies, due to the shake table’s limited stroke of ±3 in. Nevertheless, system resolution of the order of mg, accomplished by the “Tadeo” sensor board and the filter board, is considered sufficient for structural vibration measurement.

To obtain the transfer function for the “Tadeo” sensor board and the filter sensor board under a reasonably large input acceleration over a wide frequency range, the sensor boards were subjected to a velocity white noise excitation with a 100 Hz bandwidth. The RMS of the acceleration signal sampled at 256 Hz is 300 mg. Figure 18 shows the transfer functions from the reference signal to the three sensor boards.
board signals. Transfer function of the Tadeo sensor board and filter board agree with the transfer function of the filter board in Fig. 13, demonstrating that the signal from the developed boards is close to the reference signal over a wide frequency range. Also, Fig. 18 exhibits that the sensitivity of the MTS310CA sensor board decreases as frequency increases. The sensitivity drop is due to the one pole analog filter on the MTS310CA. A 3 dB drop is expected at the filter’s cutoff frequency, 50 Hz, which approximately agrees with Fig. 18. Also, this sensitivity drop was reproduced with a computer simulation model of the accelerometer [Analog Devices Inc., 2005].

Through these experiments, the “Tadeo” sensor board and the filter sensor board were found to possess characteristics which overcome the deficiencies of the MTS310CA sensor board. The higher resolution and low noise level of the newly developed sensor boards allows monitoring of civil infrastructure’s low frequency/low amplitude accelerations. Further improvement in accuracy is thought to be achievable using a higher resolution A/D converter.

4. Strain Sensor Board Development

In addition to acceleration, structural strain is also an important physical quantity for civil engineering applications. Strain measurement, which indicates local structural behaviour, is expected to provide valuable clues for SHM. Although a great variety of strain sensors exist, no sensor board has been developed for the Berkeley Mote platform. The search for, selection, and test of an appropriate strain sensor tailored to the Mote platform are presented herein. Tests demonstrate that the strain gage sensor board has good resolution, and that the output is comparable with conventional wired strain sensors.

4.1. Strain sensor board

There exist many different types of strain sensors using diverse methods for measurement, such as: Mechanical, optical, or electrical means. The mechanical strain sensor, for example a slide caliper, is simple but generally has poor resolution.
A device with levers to amplify strain to readable values can be devised, but is prohibitively large. Optical sensors are typically costly and/or too delicate to be used with the large number of Berkeley Motes expected to be deployed on civil infrastructure. Electrical sensors, which include the piezoelectric sensor, semiconductor strain gage, and the widely used foil strain gage (see Fig. 19), have high resolution and are small, sturdy, and inexpensive. Thus, they are good candidates for developing a wireless strain sensor.

Several characteristics were identified as desirable in a smart wireless strain sensor for civil infrastructure applications and are realised as indicated in the following paragraphs.

First, low frequency responses (e.g. below 1 Hz) typically found in tall and/or long civil infrastructure need to be measured and sensors with DC capability are preferable. Polyvinylidene fluoride film sensors, one type of piezoelectric sensor, are appealing as they are rugged, inexpensive, and have low power requirements. However, their sensitivity in the low frequency range is poor and researchers are working to resolve this difficulty [Satpathi et al., 1999]. As for a semiconductor strain gauge, though large sensitivity to strain is an advantage, its sensitivity to temperature variation and a tendency to drift are nontrivial disadvantages in view of its DC capability. In contrast, foil strain gages (see Fig. 19) have a wide frequency range and possess a DC capability. The gage is a metallic resistor, whose resistance varies almost linearly with its strain. A gage bonded to an object deforms with the object’s surface, and yields resistance change. A circuit with a Wheatstone bridge and amplifier converts the resistance change to a readable voltage change. For this project, foil strain gauges were chosen.

Secondly, low power consumption is an important characteristic as the wireless sensor network frequently operates on local battery power. For example, one
prototype of the Berkeley Mote can operate for up to a year on a single battery while in the power down mode. The power down mode shuts off everything except a watchdog and an asynchronous interrupt logic necessary for wake up. However it operates for only 30 hours at peak load [Hill et al., 2000]. Thus the sensor was designed using a high resistance 4500Ω strain gage, as opposed to the widely used 120/350Ω gages, in an effort to moderate power consumption. Power consumption in the sensor’s Wheatstone bridge is inversely proportional to the resistance. The measurement range was selected to be 1 με to 2000 με. The lower limit was set based on the resolution of a commercial wireless strain sensor product, the SG-Link Wireless Strain Gauge System [MicroStrain Inc., 2005]. The upper limit was set based on the yielding strain of steel. To achieve a wide measurement range despite the Mica2’s 10 bit ADC restriction, a variable gain amplifier was implemented.

Finally, a target noise level is sought that is equal to the resolution, 1 με. Significant high frequency noise was found to be present in the strain sensor board. The low-pass filter described in Sec. 3.3 was also employed in this application to remove the high frequency noise. This filter also reduces the problem of aliasing. To have a larger signal to noise ratio and to mitigate problems with power fluctuation in the Mica2’s, two AA batteries and a voltage doubler/regulator, LTC1682-5 [Linear Technology Corporation, 2005], are added which provides a constant 5 V excitation for the strain bridge. Note that an amplifier with low noise, AD623 [Analog Devices Inc., 2005], was selected for this circuit (see Fig. 20).

4.2. Experiment

The strain sensor/anti-aliasing filter boards must be calibrated before use. These boards were stacked on a Mica2, and shunt calibration was conducted to determine the sensitivity of the strain sensor. The shunt calibration simulates a resistance change in the strain gage by shunting the Wheatstone bridge with a known resistor. The output can then be calibrated for the sensor system. For convenience of calibration, the strain sensor board is equipped with switches to shunt the bridge with 4 different resistors that are wired in parallel with the strain gauge.

![Fig. 20. Wireless strain sensor circuit schematic.](image-url)
The sensor noise level must also be characterised. From the RMS of the measured signal, the resolution of the strain gauge is estimated to be 3.0\( \mu \varepsilon \), which is slightly larger than the target noise level. By using a more precise amplifier, as well as electromagnetic shielding, further reduction in the noise level of the analogue circuit is considered possible.

The onboard microprocessor was next exploited to yield better resolution of the strain sensor. A frequency domain analysis indicated that the noise of the signal consisted mainly of a 50 Hz component. The natural frequencies of the experimental structure model, described in detail in the following paragraph, are estimated to be smaller than 5 Hz. Consequently, an 8-pole Butterworth digital filter with a cutoff frequency of 25 Hz was employed to eliminate the 50 Hz noise. The shunt calibration procedure was repeated with this digital filter (see Fig. 21). The noise level of this strain sensor was thus reduced to 0.2\( \mu \varepsilon \).

The accuracy of the strain sensor/AA filter boards was experimentally verified using a 3-storey building structure model. A strain gauge was installed on the first storey wall of the structural model and connected to the strain sensor/AA filter boards on the Mote (see Fig. 22). A reference strain gauge was also attached on this structure, and the gauge was wired to a conventional strain measurement.
system. The outputs of the wireless strain sensor and the reference strain sensor were compared for the case where the structure was responding under free vibration. As shown in Fig. 23, the two measurements show good agreement.

To demonstrate the ability to acquire several physical quantities in a network, acceleration and strain measurements were simultaneously collected using two different Mica2 nodes. The Tadeo Sensor board was used as the acceleration sensor board (Fig. 24).

The strain and acceleration data measured by the Mote nodes was transmitted to a base station without data loss. Lossless transmission of the data was made possible using a new communication program [Mechitov et al., 2004]. The program stores data on the Motes memory during measurement and subsequently sends it to the base station through the sensor network. To efficiently utilise available memory on the Motes, the microprocessor downsampled the data originally sampled at 250 Hz to 62.5 Hz, after the digital filter eliminated the high frequency components.
The lossless transmission program, however, induces noise in the data. During data acquisition, the program stores the acquired data to flash memory on the Mica2 every 5 samples. This writing process draws current from the battery, causing a voltage drop to the entire Mote Platform which is also performing A/D conversion. As long as A/D conversion takes place during the voltage drop (i.e., due to the writing process), which was experimentally estimated to take 15–20ms, the acquired data fluctuates by 5–7 times the resolution of the A/D converter. Adding a capacitor and/or an extra power source parallel to the Mica2’s batteries reduced this fluctuation, though it was not eliminated completely. This problem will be addressed in future work. Since the strain sensor board has an adjustable amplifier onboard, in this experiment the gain was adjusted to provide a large signal to noise ratio.

In this section, the development of a strain sensor board was presented. A foil strain gage was chosen for its frequency range capability. A test on a three-storey model building shows that the wireless strain sensor has good resolution and that the output is comparable with conventional wired strain sensors.

5. Conclusions

In this paper, the use of smart sensor technology for SHM of civil infrastructure has been investigated. Focus was placed on developing appropriate sensor boards for the Berkeley Mote platform.

Due to its open software/hardware environment, smart sensors based on the Berkeley Mote platform were selected as the focus of this research. A description of the software and hardware characteristics of the Berkeley Mote platform was presented. Features and characteristics of this platform, including both the hardware and software, were detailed. Smart sensors based on this platform provide the impetus for the development of the next generation of SHM systems.

A new sensor board (named “Tadeo”) that implements the SD-1221 high sensitivity accelerometer was developed. The currently available MTS310CA sensor board, which includes the bi-axial accelerometer ADXL202E, was assessed through a series of experiments. The MTS310CA sensor board was shown to be deficient for civil engineering applications. Aliasing of measured acceleration signals was eliminated through the use of a modular four-pole Butterworth filter. Tests of the “Tadeo” sensor board and the filter board showed excellent performance.

A new sensor board that implements a high resistance foil strain gauge was developed. The foil strain gage was chosen because of its frequency range capability. A laboratory test with a three-storey building showed that the wireless strain sensor has good resolution, and the output is comparable with conventional wired strain sensors.

The developed sensor boards allow structural acceleration and strain measurement using the Berkeley Mote platform. The sensitivity and accuracy of the sensor boards are high enough to capture civil infrastructure’s motion. Structural response
measurement under earthquake loading, as well as wind load, traffic load, and/or experimental excitation force, is among the prospective usages.

Simultaneous measurement of both acceleration and strain were successfully demonstrated using the wireless sensor network, which is representative of future uses of the wireless sensors for advanced SHM strategies. Future research on fusion of the measurements from multi-scale physical responses is expected to provide more effective indications of structural condition.

References