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REAL TIME VISUALIZATION OF STRUCTURAL RESPONSE WITH WIRELESS MEMS SENSORS

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SUMMARY

This study develops and investigates reliability and accuracy of wireless MEMS (Micro Electro Mechanical Systems)-type sensors for real-time seismic monitoring of bridges. The wireless capability added to the developed MEMS Sensors makes it possible to avoid the use of lengthy multiple cables for the bridge monitoring. This study introduces two types of MEMS accelerometers: the ADXL 202E and the Silicon Design SD1221. To demonstrate the efficacy of this system for monitoring, acceleration of a pedestrian steel bridge under excitation at the span center was measured. The result is compared with that from traditional cabled sensor, PCB 393C. The MEMS-based wireless sensors are shown to be cost-effective for carrying out real-time monitoring missions.

INTRODUCTION

For the purpose of vibration monitoring of large-scale structures, Chung et al., 2003a developed MEMS (Micro Electro Mechanical Systems)-type accelerometers. These have wireless remote transmission capability, which makes it easy to achieve real-time visualization of structural response during earthquake and such other events. Difficulties associated with traditional sensors in installing and keeping their cables in proper working condition thus can be alleviated. Currently, MEMS-based acceleration devices utilizing Analog Devices' ADXL series are popular for health monitoring with wireless communication capability. These devices appear to have relatively high noise levels and lack real-time visualization capability. As an alternative, MEMS-based accelerometer devices are built around Silicon Design's chip, which result in a much lower level of noise. The devices are low-cost and capable for wireless communication equipped with transmitter chip. Receiver unit for data acquisition is connected to a laptop computer by serial cable allowing real-time visualization. Traditional sensors have to be cabled giving rise to a cumbersome task for wiring and exposing the sensor system to electro-magnetic interference. The devices developed here

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based on both Analogue and Silicon Design chips can replace traditional sensors providing a low-cost modular type alternative with portable transceivers for wireless communication.

This study demonstrated first, through laboratory test, the accuracy of the MEMS-type accelerometers and associated instrumentation with the use of wireless communication. Second, field vibration test of a steel bridge is carried out with a cable-based traditional accelerometer together with the MEMS devices in order to assess the performance of wireless device and data acquisition systems (see Figures 1 to 10). Agreement was excellent between visualization of the record transmitted in real time by wireless from the MEMS sensors (Fig.7) and that obtained off-line from a traditional sensor used as a reference (piezoelectric based, Fig. 8). Figure 9 shows the corresponding Fourier amplitudes of these time histories. We are currently validating these results from 3D analytical methods.

THE SENSORS

Three acceleration sensors used in this study are (1) the ADXL202E, (2) the SD1221 and, (3) PCB-393C. The MEMS accelerometers, Sensors (1) and (2), feature low-power consumption, low-cost manufacturing and easy installation in comparison with Sensor (3).

ADXL 202E

The ADXL 200 series [1], manufactured by Analog Devices, are the most popular and inexpensive MEMS accelerometers used by industrial sector. They have been investigated by Lynch et al (2003) [3, 4]. The first prototype device in this study implemented ADXL202E chip, Micro-controller, A/D converter and serial driver integrated in circuit design within a case, connected with commercial wireless transceiver that contains the transmitter and receiver in one unit. Figure 1 shows these sensor unit and commercial transceivers. The ADXL202E can measure acceleration with a full-scale range of ±2g in two axis. The main board of the sensor device, consisting of a micro-controller, A/D converter and ADXL 202E accelerometer chip, is powered by a 9V battery. Output signals from the main board is sent to these portable transceivers by the RS232—serial communication port connections. The receiving unit acquires the signal from one or many transceivers, and delivers the data to a laptop computer using a customized visualization window panel programmed in C++ and visual basic languages.

In order to estimate the performance of wireless sensor units, prototypes of sensors made of ADXL202E chips were tested on a laboratory shake table applying sinusoidal movement at 10 mg 2 Hz. Figure 2 shows the data that was acquired by a laptop computer with a receiver. According to the result of shake test, although clear sinusoidal excitation was given to the sensor unit, it includes relatively high noise, because of the static noise from ADXL202E and its associated instrumentation (such as A/D converter and transmitter). The Root Mean Square (RMS) value of static noise is approximately 3.0 mg in this case. Generally, the excitation of a concrete bridge or large-scale structure by ambient vibration is expected to measure acceleration under 5 mg or less. Therefore it appears that the ADXL202E is not sensitive enough for detecting the structural acceleration in real civil infrastructure monitoring projects.

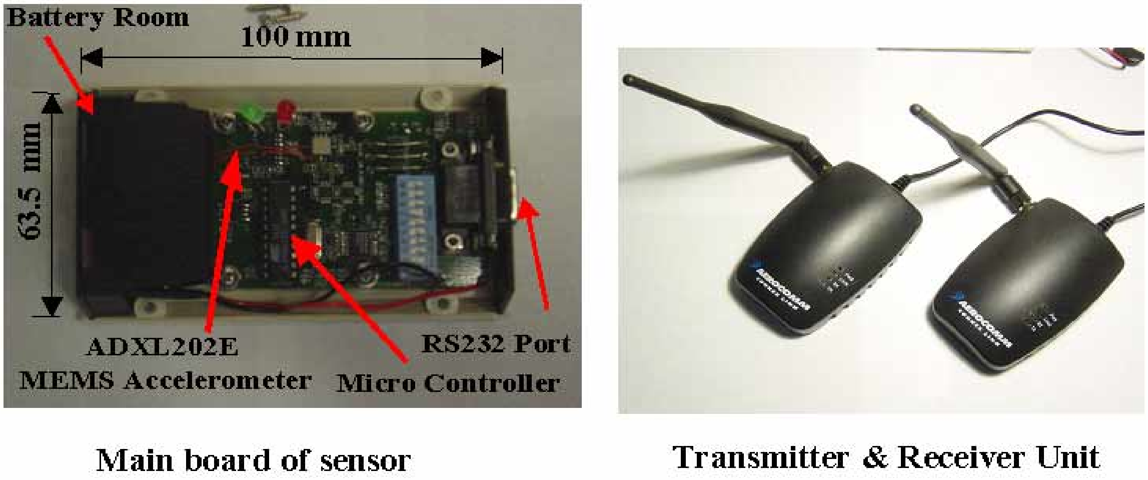
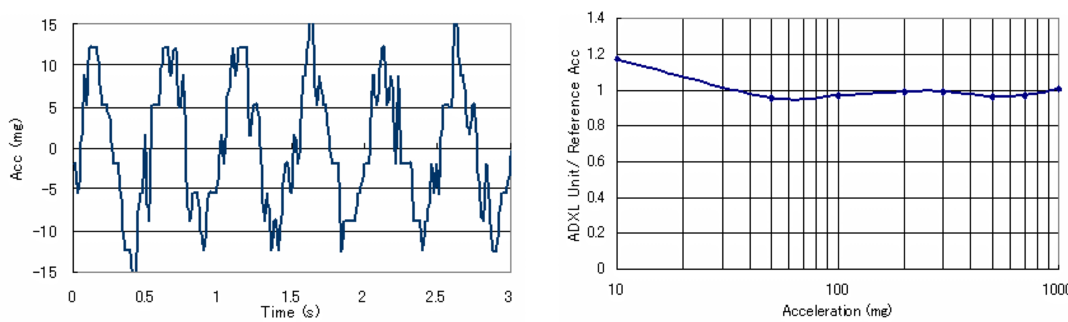


Figure 1. Interior and exterior diagrams of the ADXL202E wireless MEMS accelerometer device.



(a) Shaking test at 2 Hz & 10 mg. (b) Linearity curve.

Figure 2. Linearity test of ADXL 202E sensor

SD1221

For better performance in measuring a small excitation, a MEMS accelerometer device built around Silicon Design's (SD chips) was introduced [2], which results in a much smaller level of noise and a much higher sampling rate. In this case, the FM transmitter was integrated and housed in the same box as the SD accelerometer and micro controller. Powered by a 9V battery, the wireless communication could range up to 250m in an open area. The receiving unit is also powered by a 9V battery and is connected to a laptop computer for field data acquisition. There is no AC power requirement for either the sensing unit or data acquisition devices. This significantly reduces installation issues such as cost, time and human labor for the monitoring of bridges or structures. Figure 3 shows the wireless sensor unit comprising of the Silicon Design accelerometer SD1221, and integrated with FM transmitting and receiving units.

Performance of the wireless sensor unit with SD1221 chips was also tested using a shake table. Figure 4 shows the data that was recorded by the laptop computer associated. The shake table results suggest that thus model performs better at low g's, because the static noise from SD1221 and its associated instrumentation approximate 1.0 mg. Therefore, with the confidence of SD1221 sensitivity, it can be considered more effective than ADXL202 chips for detecting structural acceleration in health monitoring projects.

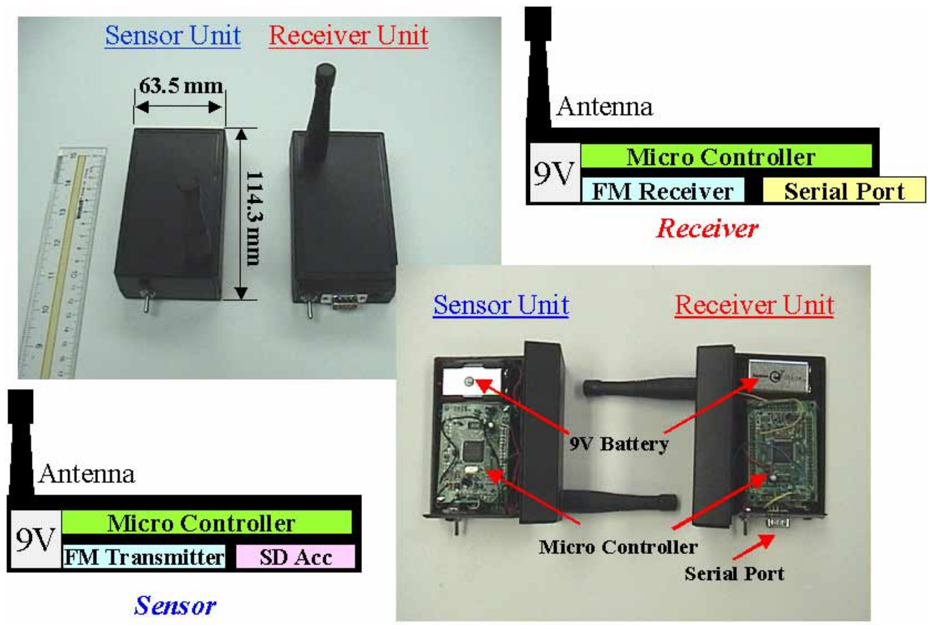
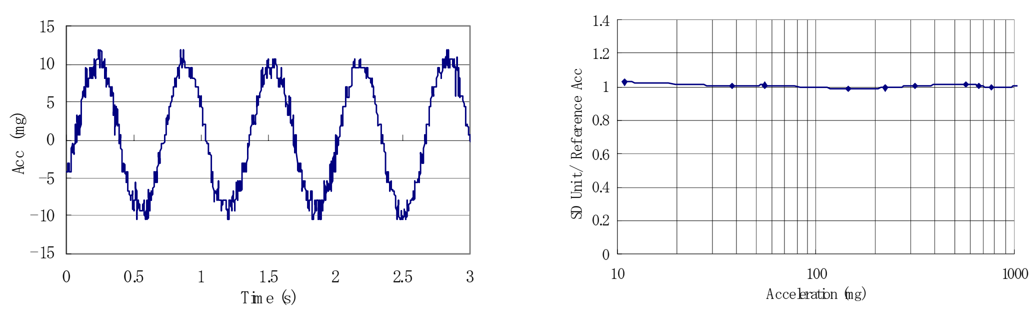


Figure 3. Wireless sensor using Silicon Design SD1221



(a) Shaking test at 2 Hz & 10 mg.

(b) Linearity curve.

Figure 4. Linearity test of SD 2210 sensor

PCB 393C

PCB 393C are widely used in the structural monitoring case studies by investigators. To assess the reliability of ADXL202E and SD1221 sensors, PCB 393C was instrumented on bridge as a control. In this study, limitation of the PCB sensor was seen, because it required long cables connected in order to carry out a simple measurement of bridge vibration test.

FIELD EXPERIMENT

The pedestrian bridge which was tested locates in Peltason Street on the University of California, Irvine campus (Figure 5). This bridge is a steel truss bridge, approximately 30m (100ft) long and 3.0m (10ft) wide. Concrete decks are apparent on the structure as well as steel tubular elements for the truss. The bridge was subjected to an excitation load simulated on the middle span. The bridge was excited accordingly and generated vibrations measured by the three different sensors, ADXL202E, SD1221, and PCB 393C.

As shown in Figure 6, the sensors were positioned in the middle of the bridge, located close to one side. Placing the sensors in the middle of the span, the maximum vertical excited displacement and acceleration were recorded as well as the lateral movements. It has to be noted that our primary interest in this field experiment is to measure the vertical (up and down) motion of bridge, the torsional and lateral movement were not discussed in depth in this paper. However, the effect of wind forces was observed in the data acquired from all of the sensors.

Figure 5. UCI steel truss pedestrian bridge tested with wireless MEMS sensors

Figure 6. Going from top to bottom: ADXL 202E, traditional PCB 393C and, SD1221 sensor.

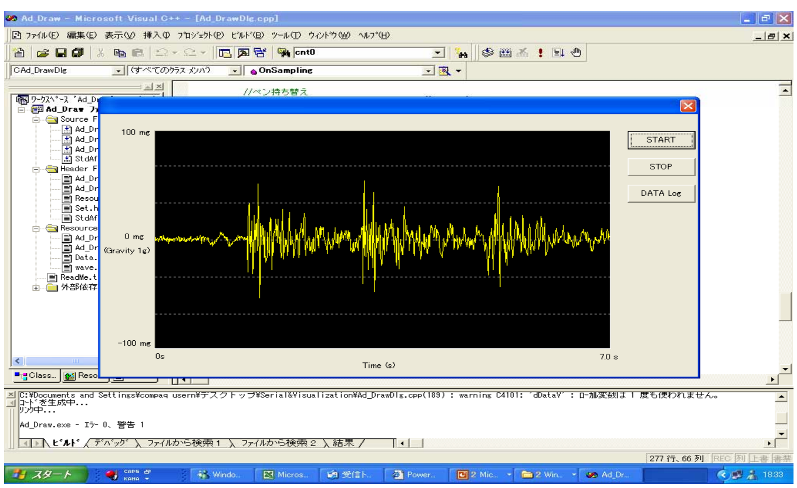


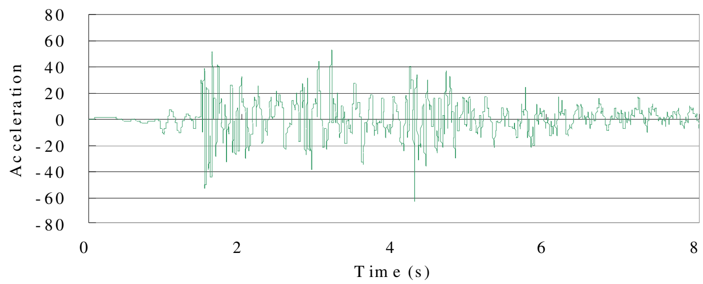
Figure 7. Real-time visualization (Wireless)

Data acquisition for this experiment was successful in wireless communication. Receiving station from wireless receiver delivered the signal to the connected laptop computer. The transmission distance was validated up to a 150m (400ft) linear distance. The goal has been achieved to demonstrate the implemented wireless technology, yet to be satisfied in communicational distance mattered in real structural monitoring mission.

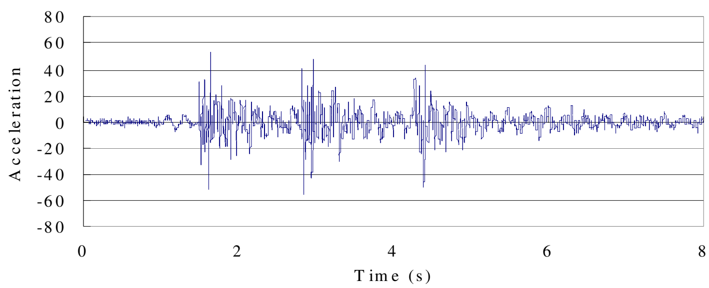
Vertical acceleration was sensed by our devices and being recorded by laptop computers. The time history acceleration curves are graphed as shown in Figure 8. In further exploring the frequency functions of acquired acceleration time-histories, fast Fourier transform (FFT) method was used to alter the bridge responses (acceleration time histories) to the function in frequency domain (see Figure 9). Figure 9 shows that all three sensors recorded field test frequency peaks 1, 2, and 3, which occur at approximately 4 Hz, 6 Hz, and 13 Hz. This suggests that the wireless MEMS sensors have performed well compared with the traditional type of cabled sensor.

COMPUTER MODEL AND NUMERICAL ANALYSIS

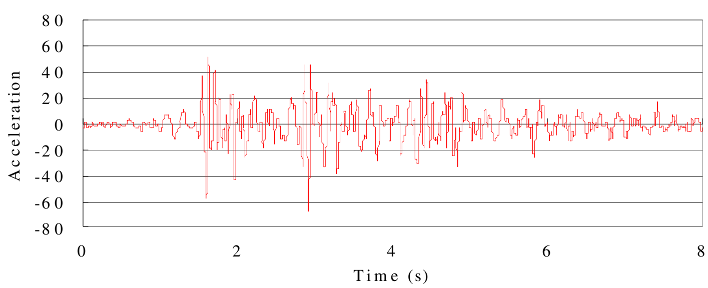
A computer model of the bridge was created using SAP 2000, a professional bridge design and analysis software package, to perform dynamic analysis of bridge structure for verifying results from the field experiment. To generate the bridge model, original detail blueprints form the bridge design companies were obtained, for material properties and structural dimensions set up in the computer modeling. These blueprints comprised of engineering graphs such as shown in Figure 10. The specifications and boundary conditions were carefully verified in SAP2000 under an assumption of 3-D frame elements analysis (see Figure 11).



(a) Experimental results of vertical acceleration vs. time of the seismic traditional PCB 393C cabled sensor.



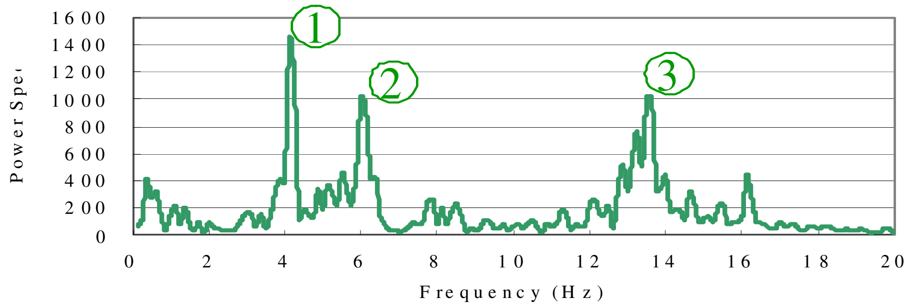
(b) Experimental results of vertical acceleration vs. time of the Silicon Design unit.



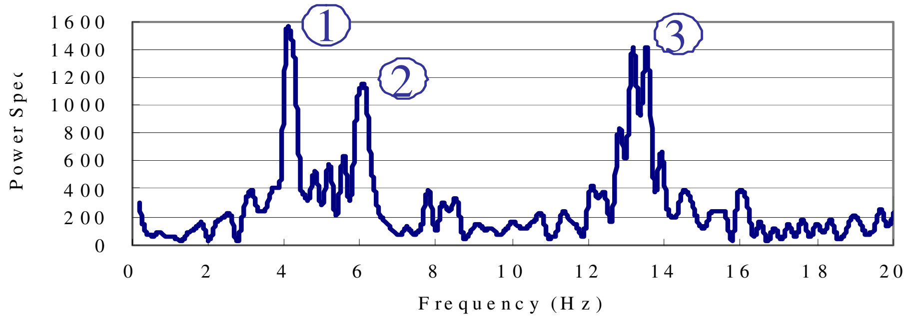
(c) Experimental results of vertical acceleration vs. time of the ADXL 202E unit.

Figure 8. Time history of structural acceleration due to excitations

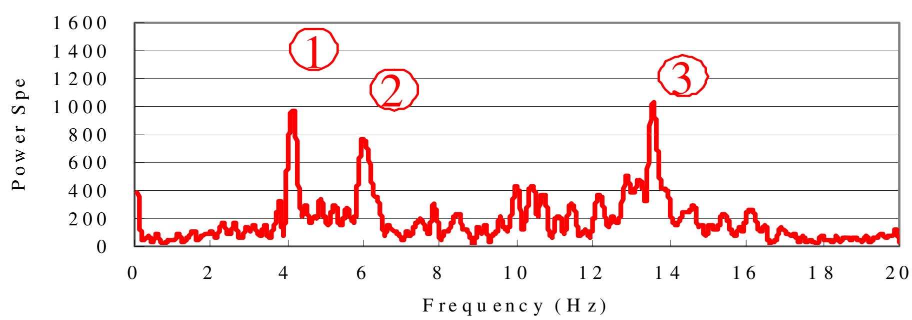
In the dynamic analysis, the impulse force function was modeled by triangular functions with a total time interval of 0.06 sec. Overall, there were three main runs computed through SAP 2000 for the bridge model: (1) static analysis; (2) time-history analysis; and (3) modal analysis. Static analysis achieves reaction forces at supports and in members of the bridge. Time history analysis incorporates the live excitation loads (triangular function is assumed) for determining the time history of response functions. The result from time history analysis was then engaged for modal analysis to determine the frequency of each mode.



(a) PCB 393C – Mode 1: 4.12 Hz, Mode 2: 6.00 Hz, Mode 3: 13.63 Hz



(b) SD1221 – Mode 1: 4.08 Hz, Mode 2: 6.12 Hz, Mode 3: 13.17 Hz



(c) ADXL202E – Mode 1: 4.20 Hz, Mode 2: 5.96 Hz, Mode 3: 13.57 Hz

Figure 9. FFT of vertical acceleration

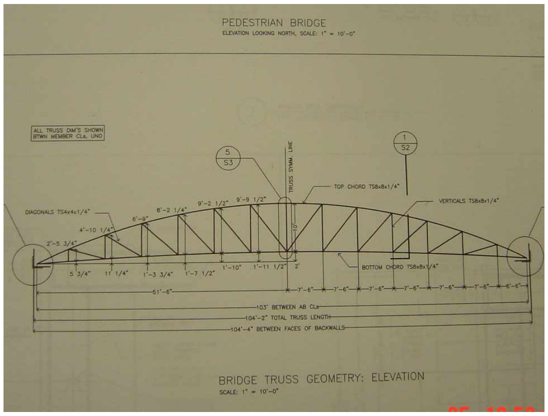


Figure 10. UC, Irvine pedestrian bridge steel truss bridge design layout provided by construction company

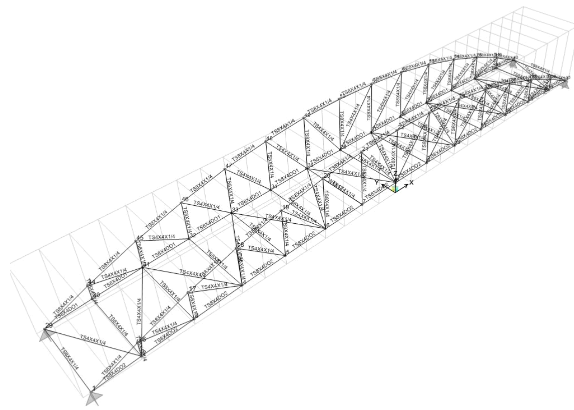


Figure 11. Three-dimensional model of bridge produced on SAP-2000 indicating all member properties and support conditions.

SUMMARY AND RECOMMENDATIONS

As determined by comparison with the traditional PCB-393C sensor both ADXL202E and the SD1221 MEMS accelerometers with the wireless communication proved satisfactory for measuring acceleration on the UCI's bridge. Despite differences between the sensors, such as noise level and band width, etc., both offer low cost for installation and re-production, low power consumption, and are small and light weight. In the near future, it is hoped that these wireless MEMS accelerometers will be applied to CalTrans' highway system in Southern California. Ambient vibration experiments can be conducted, which real-time data acquisition can speed up the process of performing such experiments on this intricate highway network.

The sensors are durable to reprogram their detection functions. By further developing the embedded micro-computer units and functions such as detecting frequency responses, possible damage of bridge structures can be detected to give early warning to citizens and prevent suffering the loss of life or property damage. The sensors can have numerous other uses and offer great potential for carrying out structural monitoring missions in harsh environments.

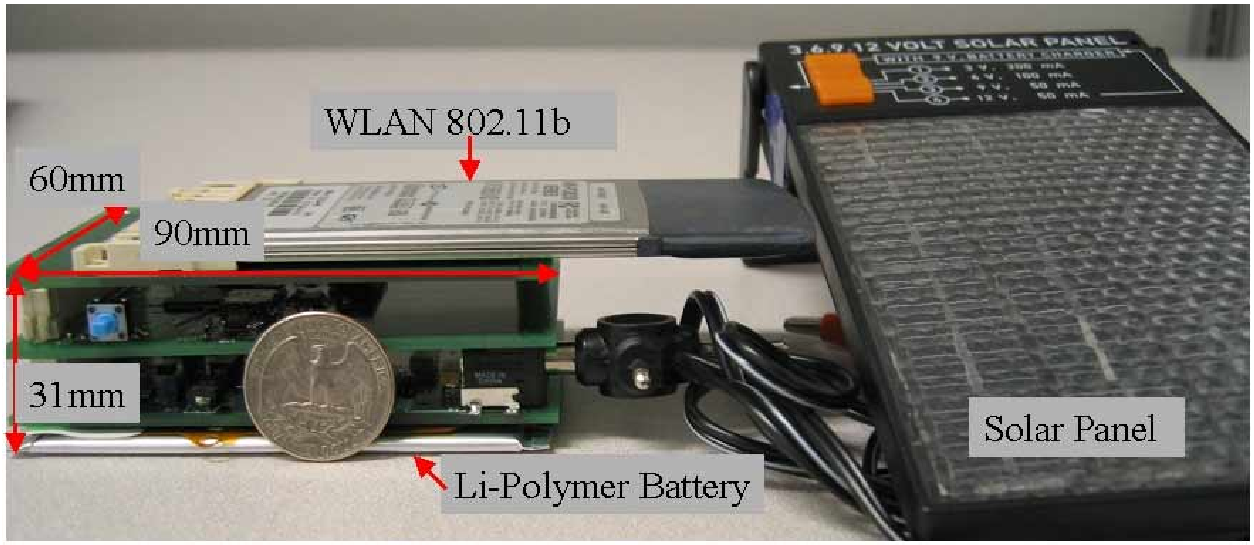


Figure 12. Wireless Sensor Node : DuraNode

However, several challenges remain to be solved, including power and communication distance. Power consumption on the units is fairly high. A 9V battery in the Silicon Design unit can only run for approximately five hours. The main problem is with the radio module, which consumes most of the power while communicating point-to-point. In a joint effort between the electrical and civil engineers at UCI, the sensor node is being prototyped with greatly improved power efficiency and wireless interface, as shown in Figure 12. This new sensor node includes extended power management circuitry to support a high-capacity, 2000mAh, rechargeable battery whose energy can be replenished with a solar panel, a wind generator, or any other power source. Also, by replacing the FM radio with a digital radio interface such as Bluetooth or 802.11b, it will be able to improve the energy efficiency of wireless communication by several orders of magnitude. Together, we expect these features to enable the sensor nodes to eventually be able to operate for years without maintenance. Moreover, these sensor nodes will be able to form a network, not just communicating directly with the base station. Ultimately, this work will provide comprehensive communication and network solutions, with seamless design, for carrying out structural monitoring missions.

ACKNOWLEDGEMENT

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