The 6th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
Hong Kong | 9-11 December 2013

VIBRATION-POWERED WIRELESS SENSOR FOR STRUCTURAL MONITORING DURING EARTHQUAKES

Daniel Tomicek, Y.H. Tham, Winston K.G. Seah and Ramesh K. Rayudu
School of Engineering and Computer Science, Victoria University of Wellington,
P.O. Box 600, Wellington 6140, New Zealand. Email: winston.seah@ecs.vuw.ac.nz

ABSTRACT

During rare catastrophic events, like earthquakes that last only for a short time, buildings and critical infrastructure are subjected to different levels of stress that can result in severe structural damages rendering a building and its surrounding areas unsafe. After the event, engineers are called upon to assess the damage and structural integrity of the building at short notice and typically can only rely on visual inspection together with their years of professional experience to make critical decisions which often have major influence on the post-disaster recovery process. Data on the level of stress sustained by buildings and other critical infrastructure acquired during the event can significantly help in post-disaster recovery and assessment of buildings' structural integrity. Structural engineers can benefit from a sensing system that monitors the vibrations experienced by different parts of a building to help them in their assessment of the potential damage suffered by the building, and focus on areas that experienced the highest level of vibrations and stress. While installing sensors to acquire such data is not difficult, ensuring that there is power to drive the sensors at the critical moment of the event is a challenge. One approach is to connect the sensors to a constant power source using wires, which may be damaged or severed during the earthquake leaving the sensors without power at the most critical moments. Using portable sources, like batteries, requires regular maintenance to replace them which can be infeasible when these sensors are deployed at inaccessible locations. We present a novel design of a self-powered wireless sensor for monitoring the levels of vibration and stress that buildings suffered during an earthquake. Energy is harvested from vibrations of the buildings during earthquakes and sensor data are transmitted wirelessly to collection/access points, for further analysis by structural engineers.

KEYWORDS

Structural health monitoring, vibration energy harvesting, wireless sensor, experimental prototype.

INTRODUCTION

The ability to monitor infrastructure during an earthquake using sensor network nodes could prove to be beneficial for engineers. The structural vibration characteristics of an earthquake obtained from these nodes can be used in identifying the location and the extent of the damage caused to a specific area of a building, which may not have easily been seen from visual inspections. Whilst a number of techniques already exist to monitor these events, a spatially distributed wireless sensor network (WSN) could prove to be beneficial. Installing sensors to acquire such data is not difficult, but ensuring that there is power to drive the sensors at the critical moment of the event is a challenge. One approach is to connect the sensors to a constant power source using wires, but can damage or severe during the earthquake leaving the sensors without powerrendering them useless. To date, the primary way to power these wireless sensor networks have been with batteries. Whilst this form of energy is adequate to power the node, batteries can last anywhere from 10 days to 10 years depending on the type and use. For a WSN which could have up to thousands of remote nodes, it would not be ideal to replace the batteries periodically when they run out of energy. Practically, a node should have an expected lifespan equal to or greater than the infrastructure it is monitoring (Elvin *et al.* 2006).

The impracticality of changing batteries in WSNs has motivated the research and development into alternative energy sources to power the nodes in such networks. Energy harvesting, or scavenging, is a process in which energy is collected from an external source such as wind, solar, heat or vibrations, and stored (Vieira *et al.* 2003). The energy collected from harvesting in general is very small, and therefore is usually only enough to power a node for a short time span. The node must use this energy efficiently to power up, initialise itself, take readings from a sensor and then transmit the data to a gateway node that is connected (via the Internet or other communication means) to a remote data acquisition centre. We refer to a WSN powered by ambient energy harvesting (WSN-HEAP) as a WSN that solely relies on energy harvested from its surrounding environment to operate. For structural monitoring in earthquakes, this would be from the vibrations caused by the earthquake itself. Whilst solar power would be an ideal source of renewable energy as it has been successfully utilized in many applications, it would be impractical to do so as these WSN nodes could be embedded in concrete structures, or installed in places where there is no light source, such as, in a wall or between floors. Thus a vibration-based transducer is used to harvest energy from vibrations from the shaking structure during an earthquake to power the WSN nodes.

In this paper, we present a novel design of a self-powered wireless sensor for monitoring the levels of vibration sustained by buildings during an earthquake. We briefly discuss related work on WSNs for structural monitoring, and the use of energy harvesting. We then describe the design of our system and the series of tests carried out using a realistic simulation of an earthquake to demonstrate the efficacy of our solution, before concluding.

BACKGROUND AND RELATED WORK

Earthquakes and Structures

When information about an earthquake is released in newspapers, news accounts, articles etc. the public is told the magnitude of the earthquake (e.g. from a Richter scale). Whilst this is an accurate measure of the energy released from the tremor, it does not give an accurate measure of the acceleration felt on the ground (Wald *et al.* 1999). This is critical as there is a distinct correlation between the earthquakes acceleration and the damage caused to buildings (Elenas *et al.* 2001). Thus, the peak ground acceleration (PGA) is a more practical measurement for an earthquake when determining the structural damage sustained on the surface, as it is the maximum acceleration felt on the ground in the place of interest. The peak ground velocity and distance can be determined from the acceleration, and is sometimes considered instead of PGA when evaluating structural damage in extreme earthquakes; when large tremors above 1.2*g* strike earthquake-flexible buildings, damage is proportional to velocity not acceleration (Wald *et al.* 1999). An Overall Structural Damage Index (OSDI) is a numbering system used to give an indication of the extent of the damage to a structure caused by an earthquake. This index gives a single value between 0 and 1 that summarises all existing damages on columns and beams in a structure, to give a representation of the significance of the earthquake. The destruction extent of the earthquake is considered *low* if OSDI < 0.3, *medium* if 0.3 < OSDI < 0.6, *great* if 0.6 < OSDI <0.8, and *total* if OSDI > 0.8. A list of notable earthquakes with their corresponding OSDI and PGA values are shown in Table 1, are plotted in Figure 1 to show the positive correlation between structural damage and the peak ground acceleration. It is seen that earthquakes classified as “low destruction” on the OSDI index have a PGA of 0.6*g* to 1*g* with higher OSDI earthquakes having PGA of up to 1.4*g*. Therefore, a good acceleration rate to target for structural health monitoring caused by earthquake tremors is at least 0.6*g*.

Earthquake	OSDI	PGA Max
Alkion (L)	0.081	0.603
Alkion (T)	0.082	0.575
Big Bear (270°)	0.071	0.702
Big Bear (360°)	0.103	0.799
Erzincan (N-S)	0.397	0.991
Erzincan (E-W)	0.169	0.834
Izmir (NS)	0	0.309
Izmir (E-W)	0	0.14
Hyogo-Ken Nanbu	0.55	1.149
Kalamata	0.094	0.582
Montenegro	0.198	1.049
Landers (0°)	0.129	0.622
Landers (90°)	0.151	0.714
Cape Mendocino (0°)	0.222	1.476
Cape Mendocino (90°)	0.098	0.757
Naghloo	0.15	0.963
San Salvador (0°)	0.106	0.794
San Salvador (90°)	0.096	0.889
Strazhitsa	0	0.298
Whittier	0.116	0.945

Table 1. OSDI/PGA of notable earthquakes

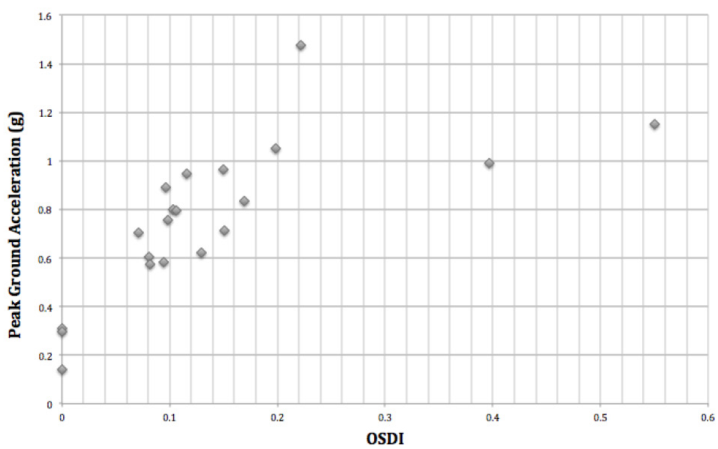


Figure 1. OSDI and corresponding PGA values

Vibration-Based Energy Harvesters

A transducer is used to transform the energy from movements, into usable energy in the form of an electric current in order to power the WSN nodes. Vibration energy is normally generated by a mechanical component attached to an inertial frame acting as a fixed reference. The inertial frame transmits the vibrations to a suspended inertial mass that produces a relative displacement between them (Beeby *et al*. 2006). These types of systems have a resonant frequency that needs be matched with the characteristic frequency of the application environment, which in this case are the frequencies found in earthquakes. Several mechanisms have been investigated in the past in creating vibration based energy harvesters. The mechanisms mainly used are piezoelectric, electromagnetic and electrostatic (Roundy *et al.* 2003). Piezoelectric energy harvesters rely on the piezoelectric effect in which charge is generated on an active material when mechanically stressed. Electromagnetic harvesting utilises Faraday's law of induction to induce an electric field from a changing magnetic field caused by the vibrations. An electrostatic generator utilises the relative movement between electrically isolated charged capacitor plates to generate energy, where the work done against the electrostatic force between the plates provides the harvested energy (Beeby *et al*. 2006). A measurement study to select a vibration-based transducer for low frequencies of less than 10*Hz* has found that piezoelectric-based harvesters give the best power output at these frequencies (Raj 2012).

Wireless Sensors in Structural Health Monitoring and Application of Vibration Energy Harvesting

Since the mid 1990's, research in industry and academia has proposed numerous WSN-based Structural Health Monitoring (SHM) systems (Lynch and Koh 2006). These systems are intended to detect and localise damages in buildings, bridges, aircraft etc. by measuring structural responses to earthquakes, wind or vehicles. These are advantageous over traditional SHM systems as, aside from a more accurate reading, structures can be monitored remotely without the need for potentially costly site visits. There is also a saving in power cabling and LAN infrastructure costs when deploying nodes wirelessly (Chintalapudi *et al.* 2006). During normal operation, a WSN used for SHM periodically updates the health condition of a structure, assessing anomalies and damages, the location and severity of the anomalies and a prediction of its life expectancy. The WSN can also provide real time assessments of extreme events such as from earthquakes and explosions (Ling *et al.* 2009). The data obtained can be used to aid direct damage assessments such as visual inspections and X-ray scans.

Vibration-based energy harvesting has been utilised to power wireless sensors in industrial automation applications as well as structural health monitoring of aircrafts. Torah *et al.* (2008) propose an autonomous wireless sensor node powered by vibration energy harvesting targeted for condition monitoring applications. They implemented and tested their sensor on an industrial air compressor and an office air conditioning unit to continuously monitor the vibration levels. MicroStrain, Inc. produces various sensors that utilize energy harvesting for power, among which is an integrated structural health monitoring and reporting (SHMR) system for use on military aircraft (Arms *et al.* 2008). The piezoelectric materials used for energy harvesting are bonded to the structure of the aircraft and used to harvest vibration and strain energy to power the wireless sensors. The vibration frequencies of all these applications fall in the 50*Hz* and higher range.

DESIGN OF VIBRATION-POWERED WIRELESS SENSOR

Piezoelectric Harvesting for Structural Monitoring during Earthquakes

The problem with using a piezoelectric transducer to provide energy is that the duration of the quake needs to be long enough to generate adequate power to operate the wireless sensor node. For example, the earthquake that struck Christchurch, New Zealand on February 2011 had only 12*s* worth of intense shaking (Clifton 2011). An earlier design using only a single energy harvester requires a minimum of 18.9*s* of shaking at 0.6*g* to power the node (Yek 2012), which in terms of usability in an earthquake, is not viable. In the case of the vibrations produced by earthquakes, the waves occur at very low frequencies such as 0.5*Hz* to 10*Hz* (Elvin *et al.* 2006). Most commercially available vibration-based energy harvesters have been designed to work on industrial machinery which typically vibrates at much higher frequencies such as 50*Hz* to 300*Hz* (Arms *et al.* 2007; Torah *et al.* 2008; Park 2010). Since the amount of energy harvested depends on the frequency of oscillations, the amplitude (PGA) and the duration, gathering energy from building motion during earthquakes proves to be a difficult task.

For successful energy harvesting, the harvester must be tuned to the natural frequency of the environment. For a cantilevered beam configuration, the most significant parameters influencing the natural frequency of the system are the length and thickness of the wafer along with the weight of the point mass (Ahmad and Alshareef 2011). In general, the longer and thicker the wafer and the larger the point mass, the lower the resonant frequency of the system will be. For energy harvesting in low frequencies such as those in earthquakes, the resonant frequency of the system must be tuned to a frequency between 0.5*Hz* and 10*Hz*. As the frequency of the earthquake cannot be predicted, the system must be able to respond to an earthquake at the resonant frequency of the structure it is monitoring. One way to increase the amount of energy that can be harvested is to put several piezoelectric harvesters in parallel. Xue *et al.* (2008) have demonstrated that by having several harvesters in parallel, the frequency band can be widened and shifted to dominant frequencies such as those existing in earthquakes, along with increasing the total obtainable raw power. We adopted this approach of using multiple harvesters connected in parallel to achieve the necessary power output that can charge and operate the wireless sensor node in less than 8 seconds, which based on historical data of earthquakes would make the node ready for taking measurements during the more severe periods of the quake.

Wireless Sensor Node Design

The design of the system was split into two main sections – the design of the microcontroller circuitry (referred to as microcontroller board or MCB) and the design of the power management circuitry (referred to power management board or PMB), each on its own circuit board. The aim was to keep the design modular and easier to manage, since creating two separate boards created clear goals to aim for and easier debugging.

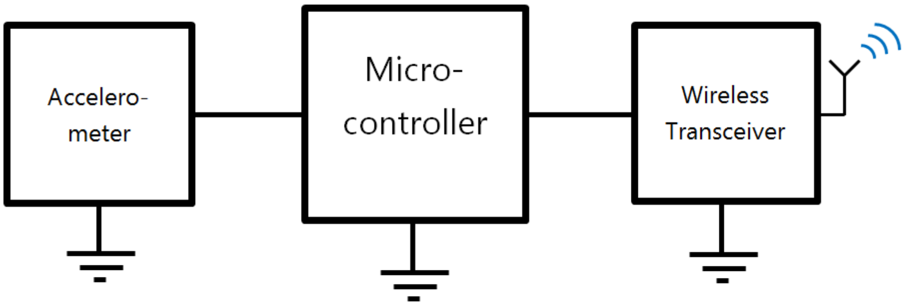


Figure 2. Microcontroller Board (MCB) Overview

Microcontroller Board (MCB)

The main features of the MCB, as shown in Figure 2, include the processor unit “Micro-controller” needed to initialise other components and create the packet of data, the wireless transceiver which sends the packets (via an antenna) and an accelerometer to read the acceleration of the building during an earthquake. With low power being the most important consideration in the design of our WSN node, we chose the Texas Instrument MSP430F2619 microcontroller (TI 2013b) for the processor unit as it is able to meet the following requirements of our WSN:

- Have ultra low power consumption;
- Have an input voltage that the PMB can produce;
- Have at least two communication ports, to connect to the transceiver and the accelerometer; and
- Have at least 10 *kB* of flash memory.

The choice of accelerometers is a compromise between accuracy and power consumption; the range and sensitivity (related to accuracy), along with the number of axes were also considered in the accelerometer selection. There are three ways of the interfacing an accelerometer chip with a microcontroller: using the inter-chip serial communication protocols, viz., Serial Peripheral Interface (SPI) and Inter-integrated Circuit (I^2C), and by sampling an analogue output of the accelerometer. Sampling an analogue output and passing the signal to an analogue-to-digital converter (ADC) is the simplest approach but commercially available accelerometers that output analogue signals are designed to be highly accurate and consequently have high power consumption. Between SPI and I^2C, an accelerometer that supported SPI is preferred since I^2C requires pull-up resistors for operation that would consume more power than using SPI (Oudjida *et al.* 2009). The LIS331HH accelerometer (ST 2013) was chosen for its low power consumption (as low as $10\mu W$ at $1.8V$), and a suitable range and sensitivity of $\pm 6g$ and $3mg$ respectively. This was deemed adequate since the earthquakes being measured would be unlikely to exceed $6g$; the highest ground acceleration measured during any earthquake that hit New Zealand was in Christchurch in 2011, which had a rate of $2.2g$ (Bradley and Cubrinovski 2011). This chip is designed to work with both I^2C and SPI buses. The other major component of the MCB is the wireless transceiver. The Texas Instrument CC2520 was selected because it is a low power transceiver using IEEE802.15.4 technology that transmit on the $2.4GHz$ unlicensed band. Furthermore, it has been designed to work with the MSP430F2619, interfacing via SPI.

As the main design goal of the current prototype is to achieve lowest possible energy usage, the accelerometer has been programmed to update its values in the registers once every $200ms$, which is the lowest usable energy consuming state. Using this configuration, the IEEE 802.15.4 packets sent are 19 bytes in length, comprising the preamble header, timestamp and the payload data (6 bytes in length). Each payload contains three accelerometer values (x, y and z) in raw format from the LIS331HH. Considering the IEEE 802.15.4 packet has a maximum payload size of 127 bytes, there remains space for up to 20 more sets of raw accelerometer data; more data can be sent if data compression is utilized. The accelerometer also uses significantly less energy than other components, like the wireless transceiver, and this enables the sampling rate to be increased easily to acquire more acceleration data to the level that is required for structural health monitoring. A cluster-based medium access control protocol has also been developed for a network of such sensing devices to transmit their data (Cheng, *et al.* 2013).

Power Management Board (PMB)

The basic components of the PMB are shown in Figure 3. It comprises of an energy transducer (in this case the piezoelectric-harvester which in its raw form is high voltage, low current AC signal) being converted into DC form for energy storage on a capacitor. This is then converted into a usable low voltage, high current signal by a voltage regulator to be used by the MCB. As our aim was to build a low-cost wireless sensor node that can be deployed in large numbers, we picked the Midé V25W for our prototype implementation. It provided the flexibility to tune the resonant frequency below 10HZ that we needed, at a cost of less than US$100 each as compared to customized solutions that have been quoted at over US$5000.

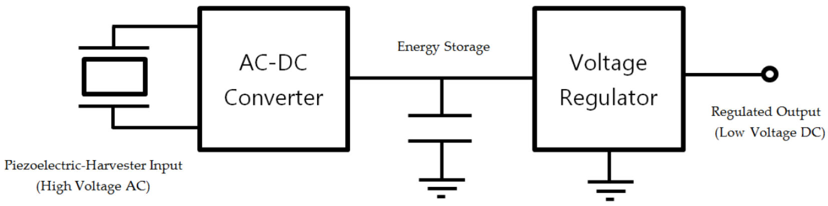
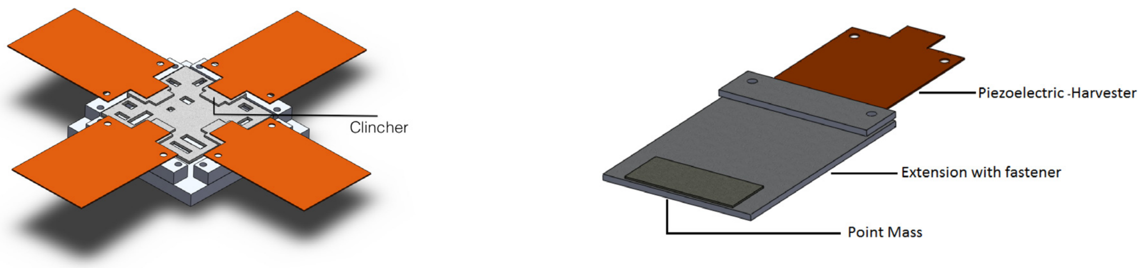


Figure 3. Power Management Board (PMB) Overview

Building on the findings of Xue *et al.* (2008), we determined that four harvesters connected in parallel are needed to produce enough energy to power up the WSN by 5 seconds. To accommodate the PMB printed circuit board (PCB) layout, we built the base platform to secure the four harvesters with the PMB in the middle, as shown in Figure 4(a). To lower the resonant frequency of the harvester, we added an extension with a point mass. As this was only a proof-of-concept prototype, we have adopted this crude approach to lower the resonant frequency to match those measured during earthquakes. Custom-built vibration energy harvesters with low resonant frequencies in the range of 0.5*Hz* to 10*Hz* can be used later when the system is refined for actual deployment purposes.



(a) Base platform (b) Extension and point mass

Figure 4. Piezoelectric harvesters mounted on base platform, and extension for lowering resonant frequency

After harvesting the energy, it is critical that as little as possible of the energy is lost through the process of converting it into a form usable by the MCB. Firstly, a high efficiency design is required for the conversion of AC from the piezoelectric-harvester to DC. Typically, a diode bridge rectification circuit is used for this process; however, the problem associated with using a rectifier in energy saving devices is that voltage is lost across the diodes in the rectification process. Using Schottky diodes in place of normal diodes in the bridge are ideal as an energy saving technique, as they have low voltage drop (0.2V compared to 0.6V). A full wave rectification is selected as it gives a smoother voltage on the output, although the signal has to go through twice as many diodes. Using Schottky diodes compensates the increased voltage drop due to more diodes. Following rectification, the energy is stored in capacitors. Capacitors are used as they offer a fast discharge compared to batteries; capacitors store energy without the need for chemical reactions to take place. Among the different types of capacitors, niobium oxide capacitors were chosen for their low leakage currents (from a low equivalent series resistance (ESR)) and better protection against failures that may result in a short circuit and damage rest of the system (Faltus 2008). Finally, the voltage regulator is needed to ensure that the output voltage meets the requirements of the MCB. A switch mode buck converter was selected as other options like linear voltage or shunt regulators are highly inefficient, losing substantial amounts of energy as heat or other causes (Sedra and Smith 2007).

SYSTEM TEST AND EVALUATION

The time needed to charge the capacitors on the PMB is the most critical element in the design of the system; due to the momentary nature of earthquakes, the charge time must be as short as possible. This addresses the (energy) supply side of the problem. However, we also need to know the demand side, which is how much energy the MCB requires to start operating and continuing operating until the earthquake has passed. While datasheets provide information on the power consumption of the various components used to implement the system, many other aspects of the system cannot be easily determined, except through careful measurements. Most importantly, we need to evaluate how the system performs in an actual earthquake, which is a very challenging task. In the following, we will discuss the procedures undertaken to measure the power consumption of the system, the amount of energy generated and stored by the PMB under different acceleration rates, and lastly, the performance evaluation of the system at a realistic earthquake simulation site.

Energy required to send a packet and Charging Times for varying acceleration rates

We set up the system in the laboratory and used a digital multimeter to sample the voltage on the input to the MCB with a sampling period of $100\mu s$. A packet sniffer (SmartRF board from Texas Instruments) is used to receive all packets sent by the MCB. The results of the test, as shown in Figure 5, indicated that the MCU consumes a small amount of power in the first $12ms$ for initialisation and powering up, where the majority of power is consumed by the transceiver in order to send packets. In this test, the number of packets observed by the packet sniffer was three. Three distinct peaks can be seen which corresponds to the three separate packets sent. From this, we computed the energy required to send a single packet as $0.30mJ$ which is the minimum needed to be available before the system can operate. Further experimentation and optimization of the system showed that the optimal capacitance of the PMB is $94\mu F$, which could yield 0.49 mJ of energy. With the system mounted on a mechanical oscillator that can be tuned to shake at a specified frequency and constant acceleration, we measured the charging times over varying acceleration rates at a set frequency of $7Hz$ to obtain the results shown in Figure 6. The charging time indicates the time taken for the buck converter (voltage regulator) to turn on and provide energy to the MCB. Various other tests that were conducted showed that with an acceleration rate of $0.6g$, we are able to send the first packet after $0.8s$ from the onset of shaking.

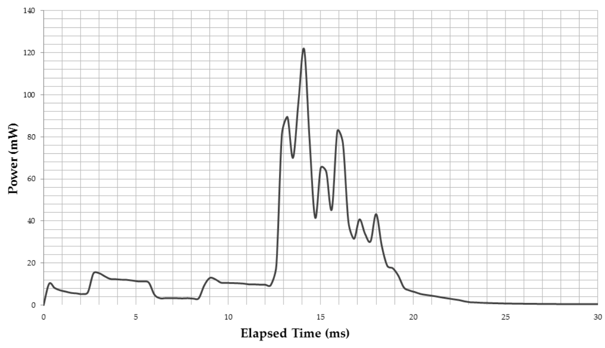


Figure 5. Power consumed by MCB

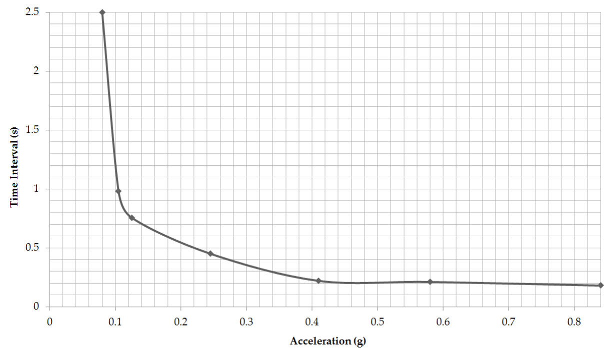


Figure 6. Charge times over acceleration rates

Earthquake Simulator in Museum of New Zealand "Te Papa"

The "Awesome Forces: Earthquake House" is a permanent exhibition at the Museum of New Zealand "Te Papa" that simulates the horizontal movement of the 1987 Edgecumbe Earthquake (Te Papa 2013). This place was chosen for more realistic testing of the system as the frequencies and accelerations are modelled more closely to a real earthquake, compared with testing on the mechanical oscillator which has a single frequency and keeps the same acceleration over time. The earthquake that struck Edgecumbe just after noon on the 2nd of March was reported to be of magnitude 6.5 with an average acceleration rate of $0.261g$ (Dowrick 1988). The completed wireless sensor node, comprising the PMB with four vibration energy harvesters plus extensions, MCB and antenna, mounted in an enclosure for protection is shown in Figure 7; when deployed, the enclosure is fully covered to protect the wireless sensor node from any damage due to environmental causes or tampering. The system was configured to send as many packets (containing acceleration rates measured by the accelerometer) as possible for as long as it has power. After the system was mounted in an unobtrusive location above the exit

(Figure 8), a receiving station comprising a SmartRF packet sniffer connected to a laptop computer was located nearby to receive and log the transmitted packets.

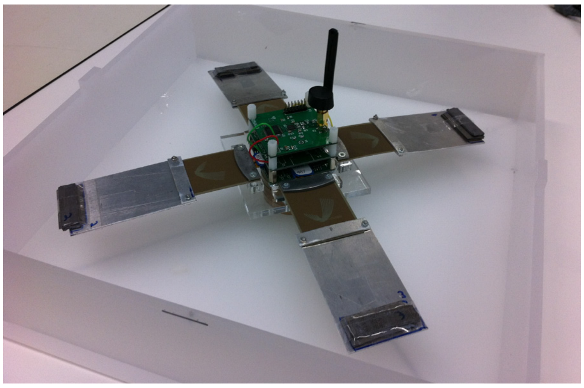


Figure 7. Assembled wireless sensor node inside enclosure (patent pending)

Figure 8. Assembled system being installed by Te Papa technicians on Earthquake House

To validate the charge timings and further tune the harvesters (if necessary), an analysis of the shaking that occurs in the Earthquake House was required. This involved an analysis of the frequency spectrum of the shake. Figure 9 shows the actual acceleration rate of the Edgecumbe quake of 1987 (McVerry *et al.* 1989). A portable accelerometer (Midé Slam Stick) was attached to the Earthquake House in Te Papa to sample the acceleration at 3.2*kHz* for the duration of three shakes, and the result of this test is shown in Figure 10. As expected, the resulting acceleration is not at a constant frequency, but consisting of several sharp jolts (in this case, 10 for each quake) which ran for 25*s*. The 3-minute gap between each quake is the time for the exhibition to give information, giving a chance for the visitors to come and go before the next one would start, following this same pattern for the remainder of the day. Applying a Fast Fourier Transform on the acceleration data produced the frequency spectrum as shown in Figure 11.

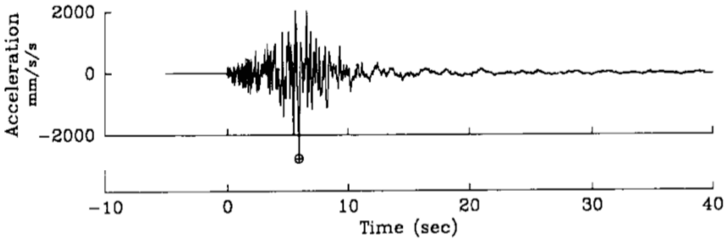


Figure 9. Acceleration rate during Edgecumbe Earthquake 1987 (McVerry *et al.* 1987)

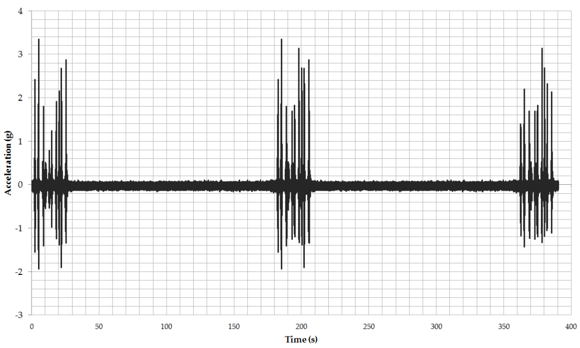


Figure 10. Acceleration rate of Earthquake House over 3 "quakes"

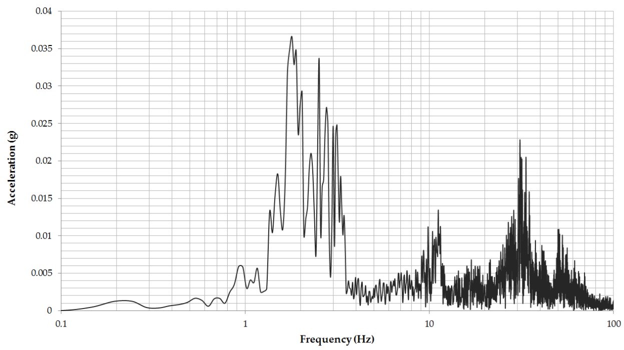


Figure 11. Frequency spectrum of Earthquake House for an arbitrary "quake"

The most contributing frequencies were in the 1.5*Hz* to 3.5*Hz* range with another major contribution at the 31*Hz* point. From this data, the mass points were shifted as far down as possible in order to harvest from as low frequencies as possible (as these frequencies contained the most movement). For practical reasons, although the Te Papa Earthquake house does not exactly model the real quake, it provides a sufficiently adequate model of key components.

Test Results

With the harvesters tuned and receiving station set up, the system was left to run everyday during the opening hours of the museum, from 10:00hrs to 18:00hrs, for a period of one week. A sample of the results that were collected during a random period of the testing is shown in Figure 12. Four quake events can be observed to have occurred where the vertical red lines indicate the times when packets were sent; in this figure, we have not indicated the dimensions of the y-axis as the focus is on the times when packets were transmitted, corresponding to the jolts (cf: Figure 10.)

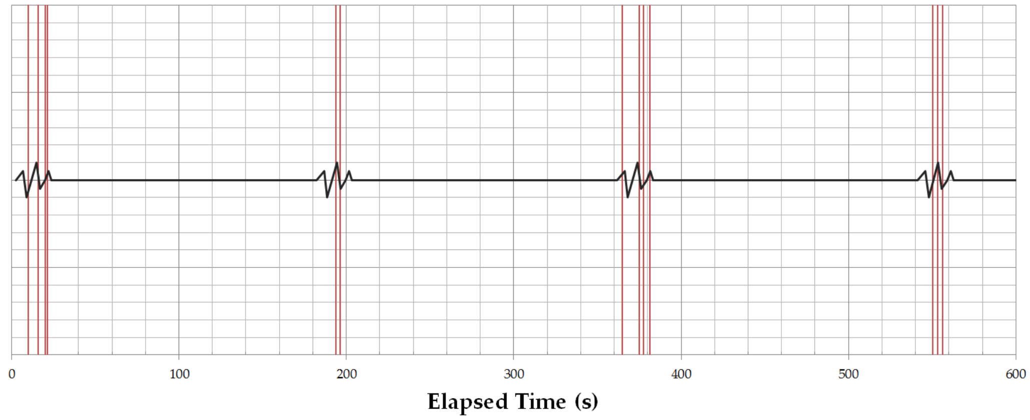


Figure 12. Times when packets were sent during a 10-minute period

If we zoom into one of the quakes, we can observe the series of jolts and the time instances when a packet was generated and sent, denoted by a vertical line as shown in Figure 13. From a cold start (i.e. empty capacitors) it took 8*s* for enough energy to be harvested before the first packet was sent. The second packet was sent about 6*s* later, which implied that there was some remaining charge in the capacitors. The next two jolts, which appeared to be stronger, were able to produce enough energy to send the next packet, and another soon after; this is possible because our capacitors are able to hold enough charge to send *one* extra packet. Averaging over all the data collected, we noted that the time needed to send the first packet from the instance shaking started is 7.2*s*.

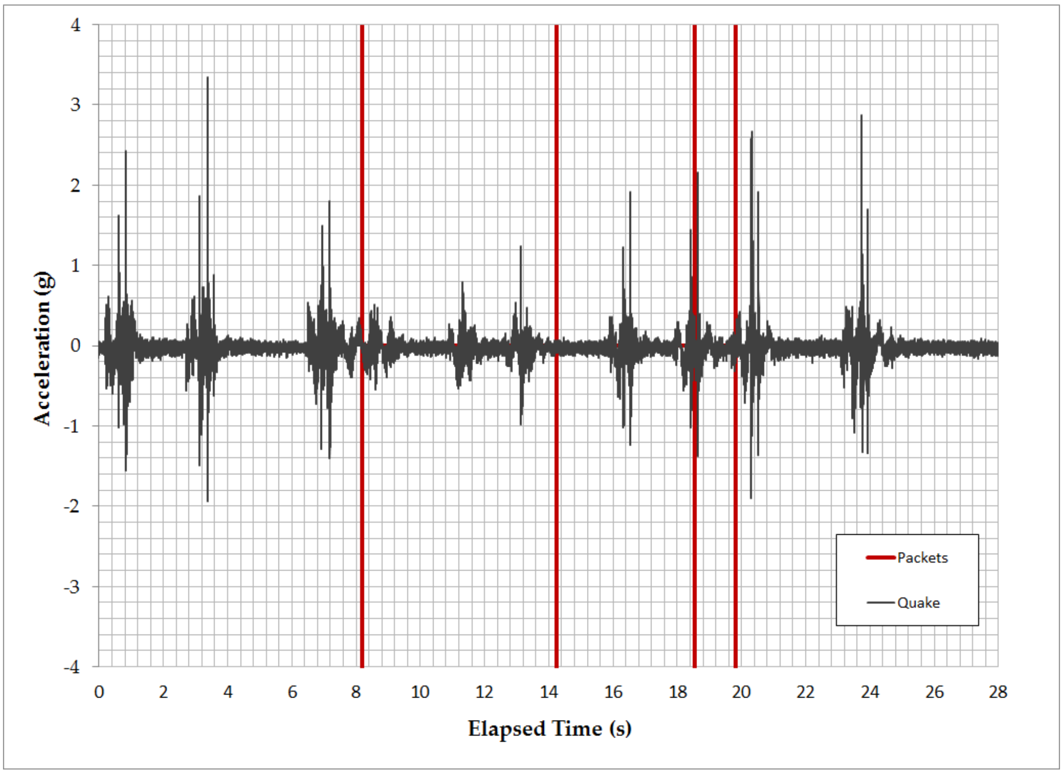


Figure 13. Acceleration over time showing when each packet was sent

This proves our hypothesis that powering a wireless sensor node using just the kinetic energy from an earthquake is possible. While the acceleration rates have been measured by the accelerometer, the system can still provide an approximate estimation of the shaking severity by simply noting the time instances when consecutive packets are generated, and then work out the amounts of energy needed to produce those packets. That is, measuring how fast the packets are generated and sent can give an indication of the shaking severity.

CONCLUSIONS

A rare catastrophic event like an earthquake can cause substantial damage to buildings and other critical infrastructure in a very short span of time. In the ensuing disaster recovery effort, any information on the level of stress sustained by the buildings resulting from the shaking can provide valuable information to engineers assessing the damage and buildings' structural integrity. We have presented a novel design of a self-powered wireless sensor that harvests energy from the buildings' movement to power itself. It does not require any other power source (e.g. batteries) and uses the movements caused by an earthquake to gather its energy. Once adequate energy has been accumulated, the system takes measurements and transmits the data wirelessly to (remote) collection/access points, for further analysis by structural engineers. The system operates only when needed, i.e. during an earthquake, and there is no need to ensure that adequate power is provided from a fixed supply or batteries. A prototype of the wireless sensor has been implemented and tested successfully at the Awesome Forces Earthquake House in the Museum of New Zealand "Te Papa"; the Earthquake House simulates 1987 Edgecumbe Earthquake and provided a good testbed for our prototype. The results demonstrated that our system is able to send its first packet within 8*s* from the onset of an earthquake and continue to send sensed data until the earthquake is over. Moving forward, a few key areas for further research include reducing the footprint of the system, shortening the time needed to send the first packet, increasing the accelerometer sampling rate, efficient data acquisition and compression, and a multiple access control scheme to prevent nodes from sending packets simultaneously, resulting in lost packets due to interference and collisions.

ACKNOWLEDGMENTS

The authors acknowledge the financial support provided by VicLink and KiwiNet through a TechJumpStart grant. The authors also gratefully acknowledge the Museum of New Zealand "Te Papa" for their permission to test the wireless sensor prototype at their "Awesome Forces: Earthquake House" exhibit, and the strong support from their staff – Steve Crombie, Eleanor Laban, John Manning and Dan Ruck, without which this work would not have progressed so quickly.

REFERENCES

Ahmad, M. and Alshareef, H. (2011). "Modeling the power output of piezoelectric energy harvesters", *Journal of Electronic* Materials, 40, 1477–1484.

Arms, S.W., Townsend, C.P., Churchill, D.L., Galbreath, J.H., Corneau, B., Ketcham, R.P. and Phan, N. (2007). "Energy Harvesting, Wireless, Structural Health Monitoring And Reporting System", *Proceedings of the 2nd Asia-Pacific Workshop on Structural Health Monitoring*, Melbourne, Australia, 2-4 December 2007.

Beeby, S., Tudor, M. and White, N. (2006). "Energy harvesting vibration sources for microsystems applications", *Measurement Science and Technology*, 17, 175 – 195.

Bradley, B. and Cubrinovski, M. (2011). "Near-source strong ground motions observed in the 22 February 2011 Christchurch earthquake", *Seismological Research Letters*, 82(6), 853–865.

Cheng, M.Y., Chen, Y.B., Wei, H.Y. and Seah, W.K.G. (2013). "Event-Driven Energy-Harvesting Wireless Sensor Network for Structural Health Monitoring", *Proceedings of 38th Annual IEEE Conference on Local Computer Networks*, Sydney, Australia, 21-24 October 2013.

Chintalapudi, K., Fu, T., Paek, J., Kothari, N., Rangwala, S., Caffrey, J., Govindan, R., Johnson, E. and Masri, S. (2006). "Monitoring civil structures with a wireless sensor network", *IEEE Internet Computing*, 10(2), March-April, 26 – 34.

Clifton, C. (2011). "Christchurch Feb 22nd Earthquake: A Personal Report", NZ Heavy Engineering Research Association (HERA). Available from: http://www.hera.org.nz/Story?Action=View&Story_id=1398. Accessed on June 1, 2013.

Dowrick, D. (1988). "Edgecumbe earthquake: some notes on its source, ground motions, and damage in relation to safety", *Bulletin of the New Zealand National Society for Earthquake Engineering*, 21(3), 198–203.

Elenas, A. and Meskouris, K. (2001). "Correlation study between seismic acceleration parameters and damage indices of structures", *Engineering Structures*, 23(6), 698 – 704.

Elvin, N.G., Lajnef, N. and Elvin, A.A. (2006). "Feasibility of structural monitoring with vibration powered sensors", *Smart Materials and Structures*, 15(4), 977 – 986.

Faltus, R. (2008). *Tantalum And Niobium Oxide Capacitors Deliver Enhanced Reliability, Wide Temperature Range and Low Leakage For Automotive Applications*, *AVX Technical Paper*. Available from: http://www.avx.com/docs/techinfo/TA_NBO_CAPSAUTO.pdf. Accessed on June 1, 2013.

Ling, Q., Tian, Z., Yin, Y. and Li, Y. (2009). "Localized structural health monitoring using energy-efficient wireless sensor networks", *IEEE Sensors Journal*, 9(11), 1596 –1604.

Lynch, J. and Loh, K. (2006). "A summary review of wireless sensors and sensor networks for structural health monitoring", *Shock and Vibration Digest*, 38(2), 91 – 130.

McVerry, G.H., Cousins, W.J. and Herford, R.T. (1989). "Ground-motion accelerograph records from the 1987 Edgecumbe earthquake, Bay of Plenty, New Zealand", *New Zealand Journal of Geology and Geophysics*, 32 (1), 155–166.

Midé Technology. Piezoelectric Vibration Energy Harvester, http://www.mide.com/products/volture/v25w.php. Accessed on June 1, 2013.

Oudjida, A.K., Berrandjia, M.L., Tiar, R., Liacha, A. and Tahraoui, K. (2009). "FPGA implementation of I^2C & SPI protocols: A comparative study", *Proceedings of the 16th IEEE International Conference on Electronics, Circuits, and Systems* (ICECS), 13 – 16 December 2009, 507 – 510.

Park, G., Rosing, T., Todd, M., Farrar, C. and Hodgkiss, W. (2008). "Energy Harvesting for Structural Health Monitoring Sensor Networks", *Journal of Infrastructure Systems*, 14(1), SPECIAL ISSUE: New Sensors, Instrumentation, and Signal Interpretation, 64 – 79.

Park, J.H. (2010). *Development of MEMS Piezoelectric Energy Harvesters*, PhD Thesis, Auburn University, Auburn, Alabama, USA.

Raj, P. S. (2012). *Vibration Energy Harvesting using PEH25W*, Technical Report, ECSTR12-05, School of Engineering and Computer Science, Victoria University of Wellington, New Zealand, Available from: http://ecs.victoria.ac.nz/Main/TechnicalReportSeries.

Roundy, S., Wright, P.K. and Rabaey, J. (2003). "A study of low level vibrations as a power source for wireless sensor nodes", *Computer Communications*, 26(11), 1131 – 1144.

Sedra, A.S. and Smith, K.C. (2007). *Microelectronic Circuits Revised Edition*, 5th ed., Oxford University Press, Inc., New York, NY, USA.

ST (2013). ST Microelectronics, LIS331HH – MEMS digital output motion sensor ultra low-power high full-scale 3-axes "nano" accelerometer, http://www.st.com/web/catalog/sense_power/FM89/SC444/PF247976. Last accessed on June 1, 2013.

Te Papa (2013). Museum of New Zealand, Awesome Forces (Te Papa exhibition) – Earthquake House. http://collections.tepapa.govt.nz/theme.aspx?irn=1364. Accessed on June 1, 2013.

TI (2013a). Texas Instruments, CC2520 -- Second generation 2.4 GHz ZigBee/IEEE 802.15.4 RF transceiver, http://www.ti.com/product/cc2520. Last accessed on June 1, 2013.

TI (2013b). Texas Instruments, MSP430F2619 – 16-Bit Ultra-Low-Power Micro-controller unit (MCU), http://www.ti.com/product/msp430f2619. Last assessed on June 1, 2013.

Torah, R., Glynne-Jones, P., Tudor, M., O'Donnell, T., Roy, S. and Beeby, S. (2008). "Self-powered autonomous wireless sensor node using vibration energy harvesting", *Measurement Science and Technology*, 19, 8pp.

Vieira, M., Coelho, C.N., Jr., da Silva, D.C., Jr., and da Mata, J.M., (2003). "Survey on wireless sensor network devices", *Proceedings of the IEEE Conference on Emerging Technologies and Factory Automation* (ETFA), Lisbon, Portugal, 16-19 September 2003, vol. 1, 537 – 544.

Wald, D., Quitoriano, V., Heaton, T. and Kanamori, H. (1999). "Relationships between peak ground acceleration, peak ground velocity, and modified Mercalli intensity in California", *Earthquake Spectra*, 15, 557–564.

Xue, H., Hu, Y., and Wang, Q.M. (2008). "Broadband piezoelectric energy harvesting devices using multiple bimorphs with different operating frequencies", *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, 55(9), September 2008, 2104 – 2108.

Yek, H.T. (2012). "Design and Experimentation of a Wireless Sensor Network Node Powered by Vibration Energy", *Technical Report*, ECSTR12-15, School of Engineering and Computer Science, Victoria University of Wellington, New Zealand. Available from: *see above* Raj, P.S. (2012).