IDEA

**Innovations Deserving
Exploratory Analysis Programs**

Highway IDEA Program

Self-powered Sensors and Actuators for Bridges

Final Report for Highway IDEA Project 117

Prepared by:
Edward Sazonov
Clarkson University
Potsdam, NY

December 2007

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)

This NCHRP-IDEA investigation by Clarkson University was completed as part of the National Cooperative Highway Research Program (NCHRP). The NCHRP-IDEA program is one of the three IDEA programs managed by the Transportation Research Board (TRB) to foster innovations in highway and intermodal surface transportation systems. The other two IDEA program areas are TRANSIT-IDEA, which focuses on products and results for transit practice, in support of the Transit Cooperative Research Program (TCRP), and ITS-IDEA, which focuses on products and results for the development and deployment of intelligent transportation systems (ITS), in support of the U.S. Department of Transportation's national ITS program plan. The three IDEA program areas are integrated to achieve the development and testing of nontraditional and innovative concepts, methods, and technologies, including conversion technologies from the defense, aerospace, computer, and communication sectors that are new to highway, transit, intelligent, and intermodal surface transportation systems.

For information on the IDEA Program contact IDEA Program, Transportation Research Board, 500 5th Street, N.W., Washington, D.C. 20001 (phone: 202/334-1461, fax: 202/334-3471, http://www.nationalacademies.org/trb/idea).

Self-powered Sensors and Actuators for Bridges

Final Report for Project 117

Edward Sazonov
Pragasen Pillay
Department of Electrical and Computer Engineering
Clarkson University
Potsdam, NY

December 31, 2007

TABLE OF CONTENTS

1. EXECUTIVE SUMMARY

Maintaining and improving the condition of bridges is critical to the structural integrity and cost effectiveness of the transportation system. Researchers and practitioners worldwide are working on technologies to ensure secure and reliable operation of bridges.

Recent advances in wireless technologies resulted in numerous attempts to utilize wireless systems for bridge monitoring. The most significant drawback of such wireless systems is the necessity to supply either wired, electromagnetically coupled (RFID) or battery power to the wireless unit. For example, the cost of battery replacements for hundreds of thousands of bridge in operation only in US becomes prohibitively expensive.

In this project we developed a prototype system that uses bridge vibration created by passing traffic to power a monitoring device. Self-powered devices have numerous advantages over RFID and battery powered devices, including no need to external power source; proactive mode of monitoring; and ability to be completely embedded into the structure.

The developed self-powered platform is based on three main components:

1. Electromagnetic energy harvester for converting vibration energy of a bridge into electrical energy
2. Energy conversion and storage circuitry designed to maximize energy delivery from the harvester into the storage
3. Wireless ultra-low power sensor platform that can reliably operate in conditions of varying energy supply

The electromagnetic harvester is based on air-core design and a spring-mass approach. Vibration of the bridge components under passing traffic excites the generator which is tuned to a fundamental frequency. The resonant vibration of the generator's core is converted into electrical energy by a matched coil.

The energy harvester is connected to the energy conversion circuitry which uses a microcontroller to perform rectification and conditioning. This circuitry allows for up to

400% increase in the amount of stored energy, thus enabling to perform more energy demanding operations or to increase frequency of measurements.

The energy-aware wireless sensor platform has a variety of digital and analog sensor interfaces. The sensor platform operates under an intelligent power management algorithm, ensuring that the sensor has enough energy to complete an atomic operation. The high-speed wireless interface delivers the acquired data.

The designed systems has been tested and validated in field conditions, remaining on RT11 bridge in Potsdam, NY for as long as a week. The results of experiments show that while energy availability varies by the hours and day of the week, on average the sensor was capable of performing 24hrs monitoring of the bridge. The results validate the proposed approach to energy harvesting and suggest that continuous monitoring of bridge infrastructure can be performed by self-powered sensors.

The technology designed in this project has been submitted to USPTO for patenting. A provisional patent application was filed in January, 2007 and a full patent will be submitted in January, 2008. The technology has been licensed from Clarkson University to a startup company AmbioSystems LLC, which currently offers self-powered electronic devices on the market. We propose further development of self-powered bridge monitoring technologies in a Phase II project that will target creation of a commercially available device.

2. INTRODUCTION

Life cycle monitoring of civil infrastructure such as bridges is critical to the long-term operational cost and safety of aging structures. Maintaining and improving the condition of bridges is critical to the structural integrity and cost effectiveness of the transportation system. An out-of-service bridge creates economic losses both for the bridge users (in terms of traffic delays and detours) and for the bridge and road operators[1]. At the end of 2001, the Federal Highway Administration (FHWA) listed nearly 25.8% of nation's 596,842 bridges as structurally deficient or functionally obsolete, in terms of dimensions, load or other characteristics[2]. Half of the bridges in the federal interstate system are over 33 years old[3]. Aging infrastructure and increased traffic levels put more pressure on the issues of bridge maintenance and operational safety.

The issues of structural health monitoring of bridges has caught the attention of many researchers and practioners[7-11].An objective evaluation of the bridge status can significantly reduce maintenance, repair and replacement costs of the structurally deficient components. An autonomous system of continuous health monitoring of bridges could generate considerable cost savings (for example, NY State inspects all bridges once every two years at $35-40 million/ per year[6]).

Monitoring of transportation infrastructure includes collecting a variety of data such as vibration and strain data, temperature and humidity, pavement salinity, etc. Localized monitoring of bridge structural elements may require placement of a dense sensor array on the structure. Many of such locations may be on elements where access to the sensors is not easy. As any practitioner knows, placing sensors on a structure requires a way to collect data from the sensors and a way of providing power to the sensors. This project addresses the issue of providing self-sustaining, autonomous power to the sensors and actuators.

To be fully autonomous, a bridge sensor would need a reliable source of power. Even the lowest power electric circuits would need battery replacements at least once every few years. Given the hard-to-access locations on a bridge, battery replacements can become a very costly operation. Hardwiring the power sources has a high price tag on installation and maintenance of wiring, plus it involves safety issues with the distribution of electric power.

Self-powered sensor and actuator networks can replace traditional, wired sensors at a tremendous reduction in cost. Self-powered sensors will also allow fully autonomous, virtually maintenance-free monitoring of structures and roadways.

Finally, when utilized nationwide self-powered sensors will eliminate the need of millions of batteries and battery replacements. This would result in a significant positive environmental impact. The self-powered generator does not contain toxic parts and can be easily recycled, which is not the case with batteries of which many contain toxic substances (cadmium, lithium, etc.) and are usually not recyclable.

3. IDEA PRODUCT

The principle deliverable of this project is a prototype self-powered platform for monitoring of bridges and overpasses. The self-powered platform consists of the following essential components:

1. Linear electromagnetic generator for harvesting vibration energy of the bridge.
2. Energy conversion circuitry for `conditioning and storage of harvested electrical energy
3. Energy-aware wireless sensors that can operate with a time-varying energy supply

The linear electromagnetic generator converts vibration of the bridge components excited by the passing traffic into usable electrical energy. The electromechanical design is durable and maintenance-free if hermetically sealed, provides for easy installation and generates power, comparable to a battery power available for sensors and actuators.

The energy conversion circuitry maximizes energy delivery from the harvester. Vibration created by passing traffic is highly non-stationary and sporadic. Without special energy conversion solutions, large amounts of harvested energy would be wasted. A microcontroller-driven circuitry senses and adapts energy conversion parameters to the current level of excitation.

The energy-aware wireless sensors operate in the conditions of varying energy availability due to transient nature of bridge traffic. The sensors employ sophisticated power management technique that minimizes overall power consumption of the sensor node. The microcontroller also oversees data acquisition and wireless transmission of the acquired data.

4. INVESTIGATION

4.1. Bridge vibration as a source of energy

In December 2005 we conducted a field test on the RT11 bridge in Potsdam, NY (Fig. 1.1). One of the goals of the field testing was objective measurement of the vibration levels on various locations on the bridge and acquisition of the actual waveforms of bridge vibrations. Such waveforms can be used in laboratory testing by supplying the signal to a shaker and thus imitating bridge vibration.

Fig. 1.1. RT11 bridge over Raquette river in Potsdam, NY.

Bridge vibration was sampled by 4 wireless accelerometers (Fig. 1.2). Each wireless accelerometer consisted of a low-noise MEMS accelerometer, gain and offset correction circuitry, 4th order anti-aliasing filter with cutoff frequency of 30Hz and a WISAN sensor node. The whole assembly was packaged into an ABS plastic box. The battery pack was attached to the lid. A key switch allows turning the power on/off without opening the box. The box is mounted to the bridge by the means of Neodymium Iron Boron (NdFeB) magnets.

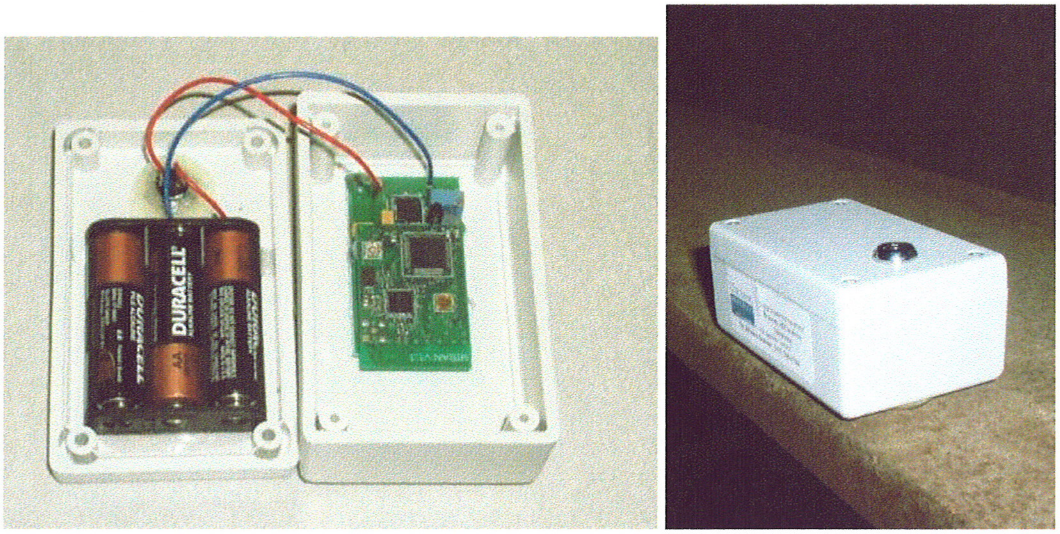

Fig. 1.2. Wireless accelerometer; attachment of the accelerometer to the bridge.

Data from the sensors were wirelessly sent to the coordinator modules attached to a notebook PC via USB interface. The Labview interface allowed visualization of the sensor data and storage on the hard drive. Responsibilities of the coordinator node include control over the network, including ensuring reliable data delivery, issuing command to the sensor nodes and receiving data from the sensor nodes, and maintaining global time synchronization in the nodes. The coordinator node was powered off the USB interface.

Acquisition of vibration data was performed in two basic configurations:

1. Test 1. Four sensors were placed on girder with approximately 12 ft between the sensors (Fig. 1.3). The closest to the support is identified by number 1000 in the following Figures. The sensor closest to the mid span of the girder had the number 1003.
2. Test 2. Two sensors were placed side-by-side at two different locations on the girder. Sensors 1003 and 1002 were placed together at the previous location of sensor 1002, sensors 1000 and 1001 were placed at the previous location of sensor 1001.

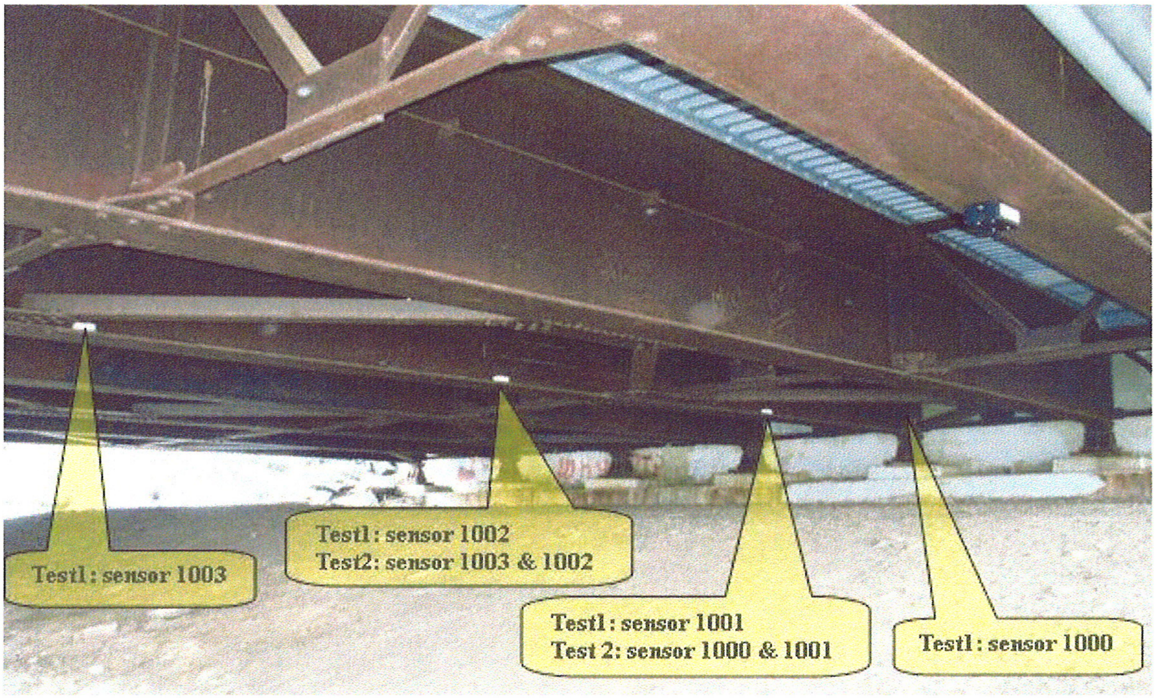

Fig. 1.3. Location of sensors on the bridge

During acquisition of vibration data the sensitivity of the accelerometer was set to be ±35mg by the adjustable gain circuitry. The constant offset generated by gravity was compensated the same circuit.

One of the goals was to establish vibration levels available at different locations of the bridge, and specifically look at the difference between vibration levels at supports vs. vibration levels close to the mid span. The vibration levels are important indicator of how much energy can potentially be harvested from the bridge at various locations.

Another goal of the experiment was to establish natural frequencies of the bridge which is important for future damage detection experiments as well as for design of energy harvesting devices that will target the frequencies with the highest energy content.

After initial installation of sensors the data collection procedure consisted of the following steps:

- the coordinator node and the sensors were powered up
- the offset compensation circuit on the sensor was adjusted to produce a steady state reading around the midrange, compensating for slanted surface of the girder's flange
- the sensors were configured via the wireless interface to acquired data at 100Hz

- vibration data was acquired several times for the period of time between 1 and 5 minutes

The following Figures illustrate the data from one of the experiments. Fig. 1.4 shows the time series from each of the sensors. As it can be seen from the Fig., the location at support is experiencing little excitation by passing traffic and amplitude of vibration decays approaching the supports. Fig. 1.5 shows frequency spectra of the girder vibration. All sensors except the support-mounted device show the same major harmonics reflecting the natural frequencies of the bridge.

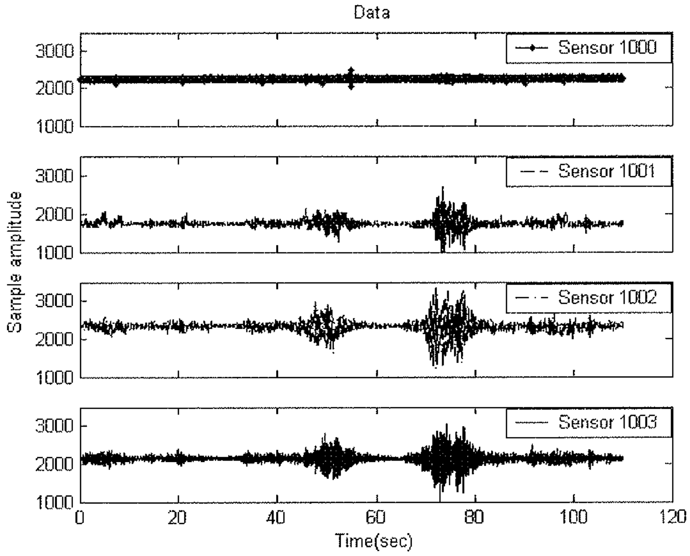

Fig. 1.4. Time series from 4 sensor locations.

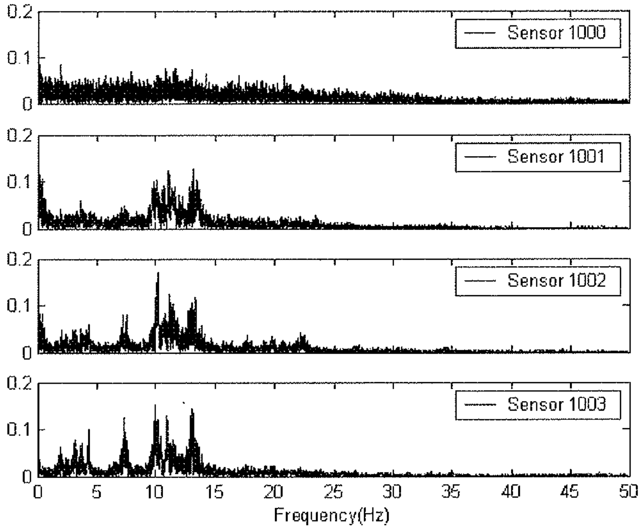

Fig. 1.5. Frequency spectra of the sensor signals.

Conclusions of the first test: there are significant levels of energy in vibration harmonics up to 15Hz. Locations around support columns experience less excitation than midspan locations, though the issue needs additional investigation. Support locations experience significant impact loading from the passing traffic. Such impact loading may have higher frequency content then data captured during this experiment.

4.2. The linear generator

As the previous Section 4.1 shows, the test bridge experiences substantial levels of low-frequency vibration. Our design is based on a linear generator which captures vibration of the bridge and converts it into useful electrical energy. The harvested parameter here is displacement of bridge girders using resonant tuning.

4.2.1. Construction of a Simple Tubular Linear Generator

The generator is designed to be single phase, high voltage and low current. The generator consists of the spring, magnets, winding and additional mass as shown in Fig. 2.1. The magnet and winding are round making for a tubular shape of the generator. The air core is adopted for decreasing the mechanical damping of the vibration. A wire with small diameter is used to make the coil link more flux. The generator's base is mounted to the bottom of a girder and vibrates together with the bridge. When the natural frequency of the generator is close the primary vibration's frequency of the bridge, the

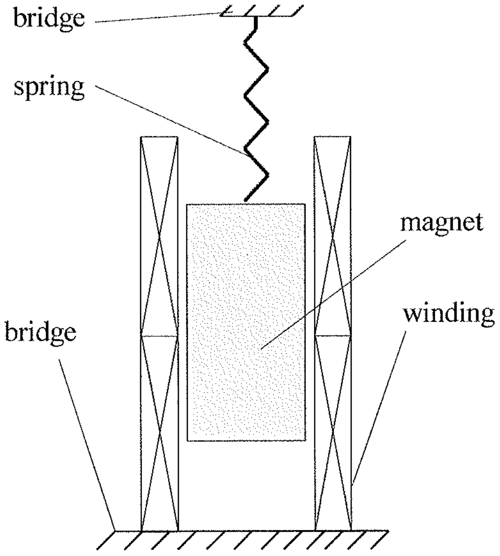

Fig. 2.1 simple tubular linear generator

resonance effect allows the magnets to move with a higher displacement than displacement of the base. The resonance allows attaining a higher voltage and harvesting more vibration energy.

To fully utilize the benefits of resonant vibration, the natural frequency of the generator must match the target natural frequency of the bridge. The frequency of the generator is set by controlling by setting the suitable mass of the magnets and stiffness of the spring. Thus, for primary frequency 3Hz of the bridge, the spring stiffness k can be set to 34N/m when the total mass of the magnets is 0.09kg. The natural frequency of the simple linear generator is 3.1Hz from the equation (4-1).

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{34}{0.09}} = 3.1Hz \tag{4-1}$$

Where f is the natural frequency; k is spring stiffness; m is the total mass.

4.2.2. Transient Analysis of the Linear Generator

The process of building the transient model is convenient and easy by using the FLUX. First, a basic drawing of the generator's construction is built by using AUTOCAD and imported into the FLUX, and then the infinite region is made around the model. Fig. 2.2 is the axial symmetry model of the outside mover linear generator. There are magnet, coil

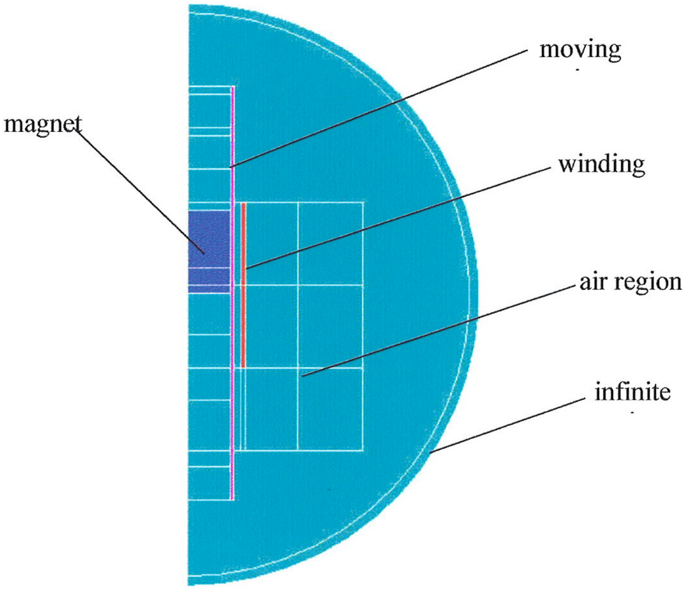

Fig. 2.2 model of generator

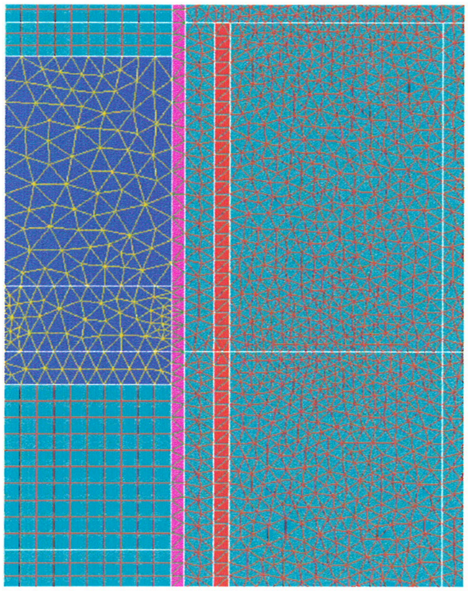

Fig. 2.3 Meshing element of

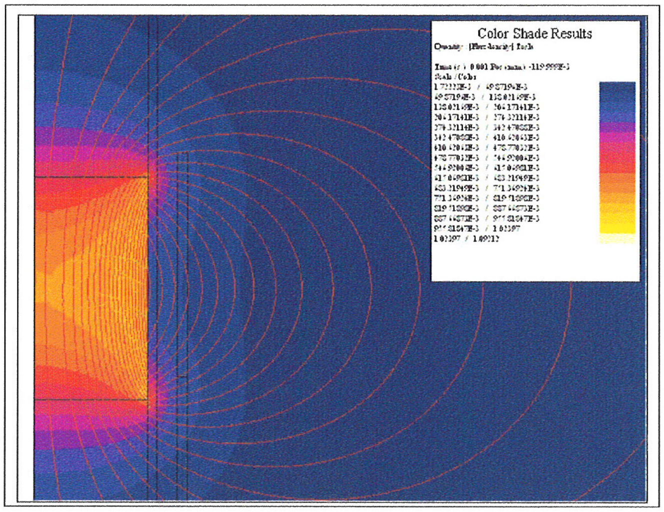

Fig. 2.4 Flux density of generator

and moving regions in the model. The second step of the analysis include meshing the regions, defining the characteristics of the materials in the different regions, assigning the mechanical parameters into the regions and coupling the electrical circuit with the magnetic field. Fig. 2.3 shows the meshing elements of the generator. The results of transient analysis are obtained after transient solving the magnetic field and then changing the meshing element until the results are similar, so the results can be considered a relative corrected solution. The Fig. 2.4 shows obtained flux density of the generator.

The circuit with a loaded generator is analyzed to obtain power curves. The internal resistor is 67kΩ and inductance is 34 H. The output peak voltage is shown in Fig. 2.5 and the output power is shown in Fig. 2.6. The results presented on Fig. 2.6 show that voltage can be above 12.7V and the output power is 1.1mW when the displacement is above 3mm and current is 0.128mA. Such voltage can supply enough power to charge the capacitor of the wireless sensor. When the displacement is 10mm, the output power is above 12.24mW and output voltage is 40.58V while the current is above 0.43mA. Thus, the output power and voltage are enough to provide the energy to the wireless sensor. The efficiency of the generator is shown in Fig. 2.7.

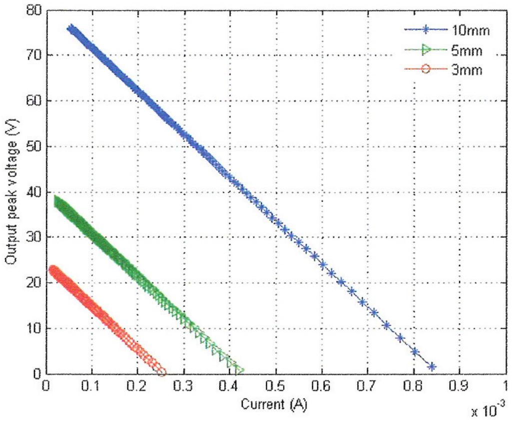

Fig. 2.5 Output voltage of generator vs. current for various sinusoidal

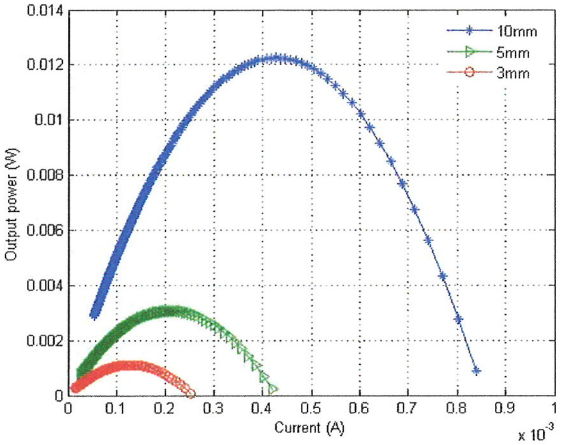

Fig. 2.6 Output power of generator vs. current

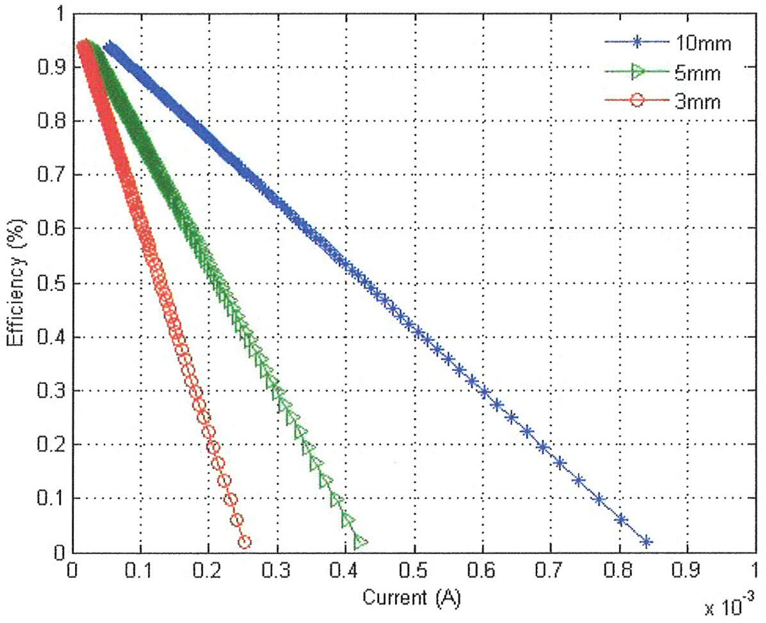

Fig. 2.7 Efficiency of generator

4.3. Self-powered Sensors

4.3.1. Software and Hardware Design for Self-powered Sensors

Introduction of IEEE802.15.4 and Zigbee standards is fuelling the boom in wireless monitoring applications by promising extensive network functionality for low-duty monitoring applications, low cost of the wireless nodes, and long battery life. Current applications of the technology range from industrial monitoring to embedding wireless sensors into household appliances. Low energy consumption results in battery life of several years for very low duty applications, normally delivering a single sensor reading a few times per day. Long battery life is a major feature that allows stand-alone sensors to be placed in the environments without wired energy sources. However, looking at the projected sales of millions of wireless sensors in the next decade, one can forecast that replacement of the millions of batteries, or the entire sensor units themselves, will present a major expense, especially for embedded sensors and sensors that are not easily accessible.

Utilization of ambient energy sources such as light, vibration, strain, or temperature gradients may eliminate the need for batteries in many applications, extend useful life and significantly cut the lifetime costs for sensors. Vibration is one of the most prominent energy sources present in industrial environments. Vibration is created by industrial machinery, electrical motors, HVAC systems, etc. Sensors powered by vibration can easily be embedded inside structures and machines, or placed in harsh environments that normally inhibit battery replacement. Vibration energy harvested from low-cost, piezoelectric fibers, may substitute for battery power in multiple monitoring applications, though the amount of available energy varies.

The creation of a self-powered wireless sensor requires attention to two major issues:

1. Energy conversion and storage of harvested energy
2. Wireless delivery of the data on extremely tight energy budget.

The following sections describe the self-powered sensor platform.

4.3.2. Linear generator as a source of energy

To understand behavior of the linear generator as a source of electrical energy a number of laboratory tests were conducted. These experiments included determination of optimal operating characteristics (load, frequency).

The setup used to conduct these experiments consisted of the generator which was attached to the shaker. The shaker power supply was then connected to a function generator which controls the frequency and displacement of the shaker. The outputs of the generator could then be connected to the test circuits.

The pencil attached to the generator as seem in Fig. 3.1 was used to draw a line on a piece of paper as the generator moved up and down. This line could then be measured with a ruler to determine the displacement of the generator

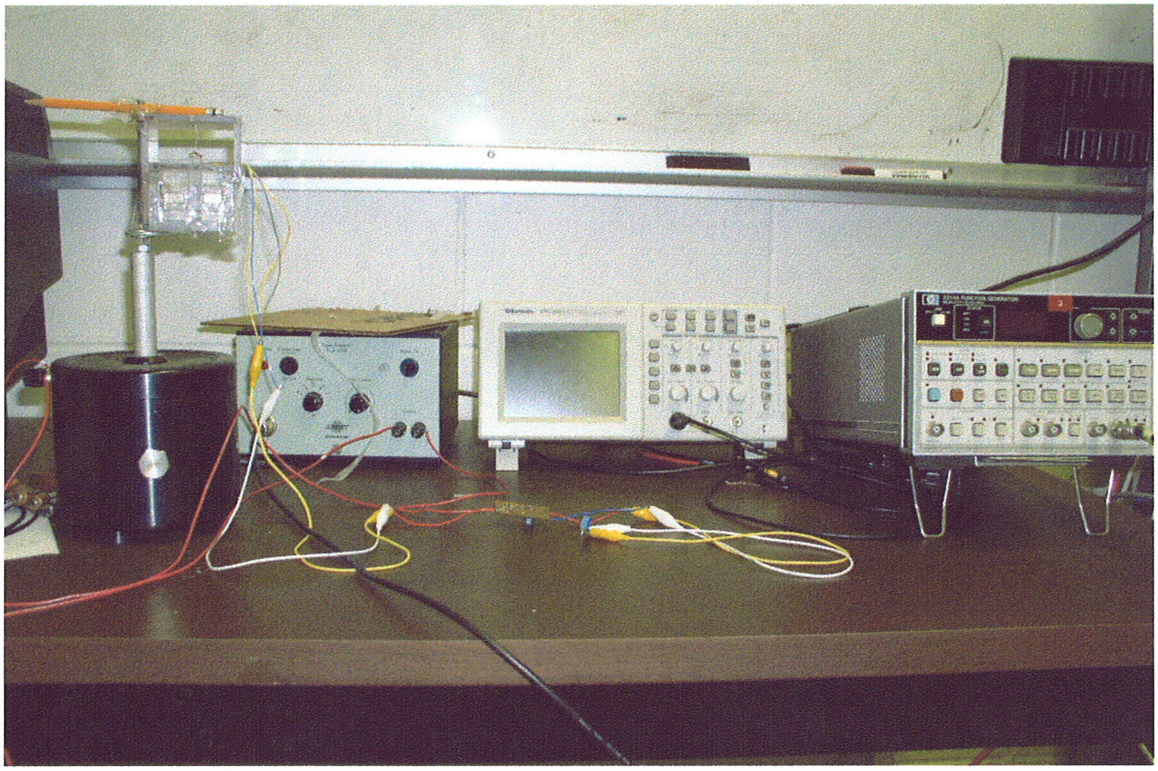

Fig. 3.1 Experimental Setup

The circuit shown in Fig 3.2 was used to find the optimal load which maximizes energy transfer from the generator into the load (Fig 3.3). This was accomplished by varying the load resistor value using a potentiometer and measuring the voltage across C1 and the current through the load.

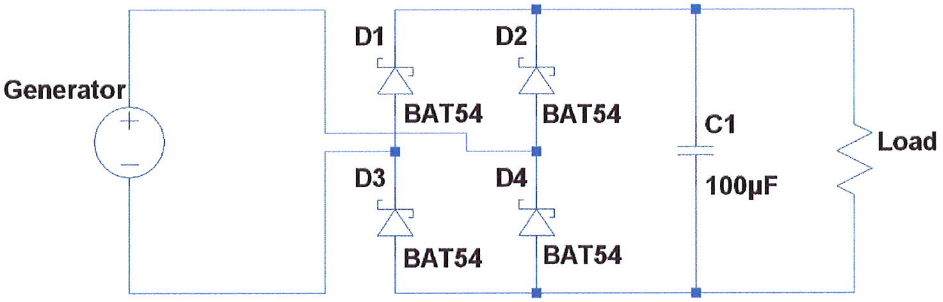

Fig. 3.2 Optimal Load Test Circuit

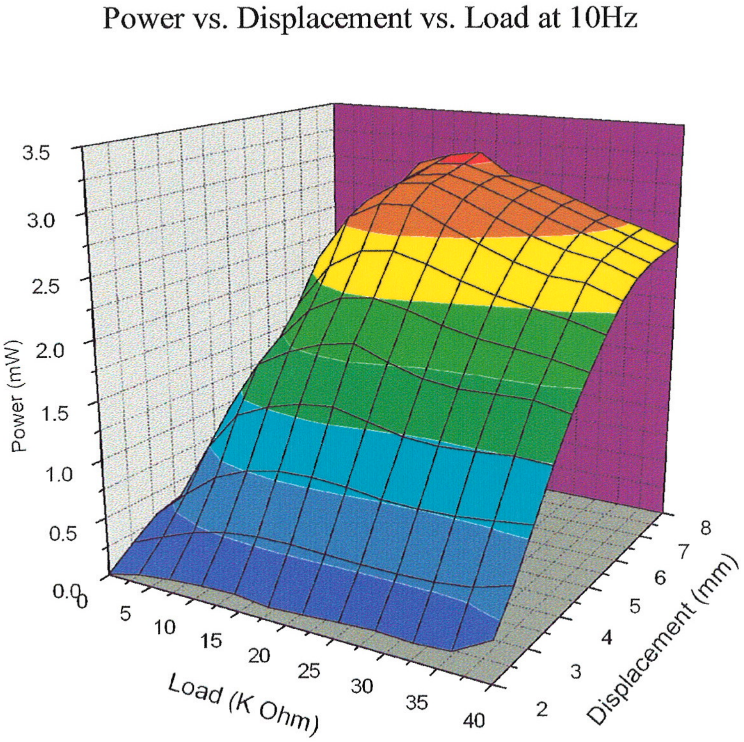

Fig. 3.3 Optimal Load Surface Plot

From the surface plot shown in Fig 3.3 it can be seen that there is an optimal load that results in the highest power. Also changing the Displacement of the generator does not change the optimal load significantly.

The key conclusion of these tests is that the generator will produce substantially higher power when the load matches the impedance of the generator and excitation provided by traffic. However, the traffic excitation is not stable and the optimal harvesting point changes in time.

4.3.3. Custom Switching Power supply design and analysis

Our tests showed that commercial circuits are not very efficient in energy harvesting applications because they consumed too much power and had low efficiency. To resolve this problem we designed a custom switching circuit.

The DC-DC Buck converter converts a Higher Voltage to a lower voltage. Its basic components are a switch, Diode, Inductor and filter capacitor and are shown in Fig. 3.4.

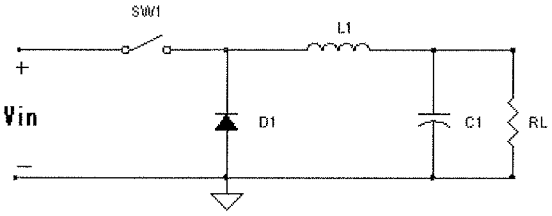

Fig 3.4 Buck Converter

Using this buck converter by varying the time SW1 is on will allow the Maximum energy to be harvested by being able to control the voltage on the rectifier capacitor which is the input to the buck converter.

In order to make the converter as efficient as possible the power loss must be minimized for each component in the converter. To do this Spice was used to analyze the power loses with different components and different situations to determine the optimal combination.

We tested several possible circuits and finally set our choice on a circuit shown in Fig. 3.5. This circuit provides the best efficiency. Table 3.1 shows power loss in each component and overall efficiency of the circuit. The efficiency achieved by this circuit is substantially higher that commercially available devices.

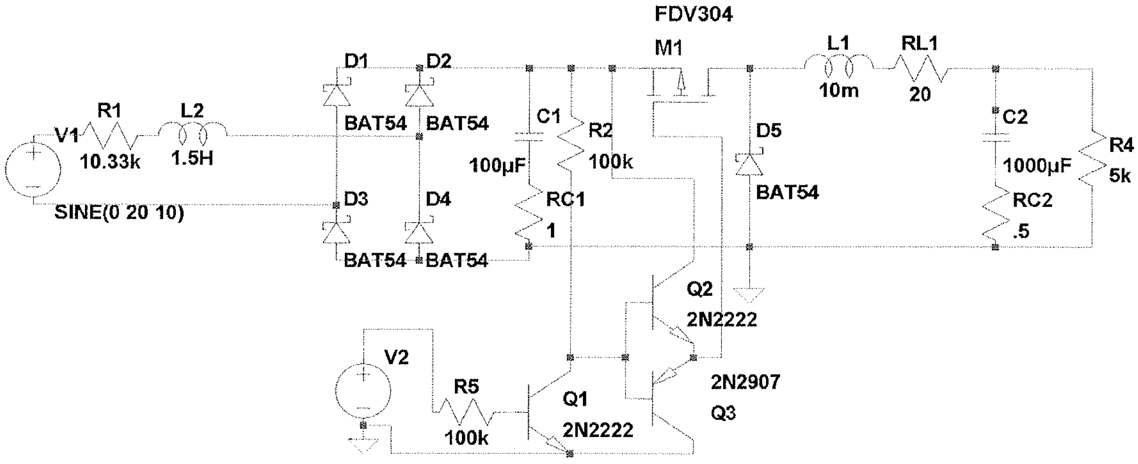

Fig. 3.5 BJT MOSFET Driver Schematic

Component	Power Loss (uW)
PMOS Switching Loss(includes BJTs)	41
PMOS Conduction Loss	50
Freewheeling Diode	112.1
Input Capacitor ESR	6.5
Output Capacitor ESR	5.3
Inductor DCR	216.8
Total	431.7

Input Power(mW)	4.15
Output Power(mW)	3.76
Efficiency	91%

Table 3.1 BJT MOSFET Driver

4.3.4. Laboratory prototype of a self-powered vibration sensor

As a result of the development, a prototype system composed of a linear generator, energy conversion circuitry and a wireless vibration sensor has been assembled and tested. Fig. 3.6 depicts the experimental setup.

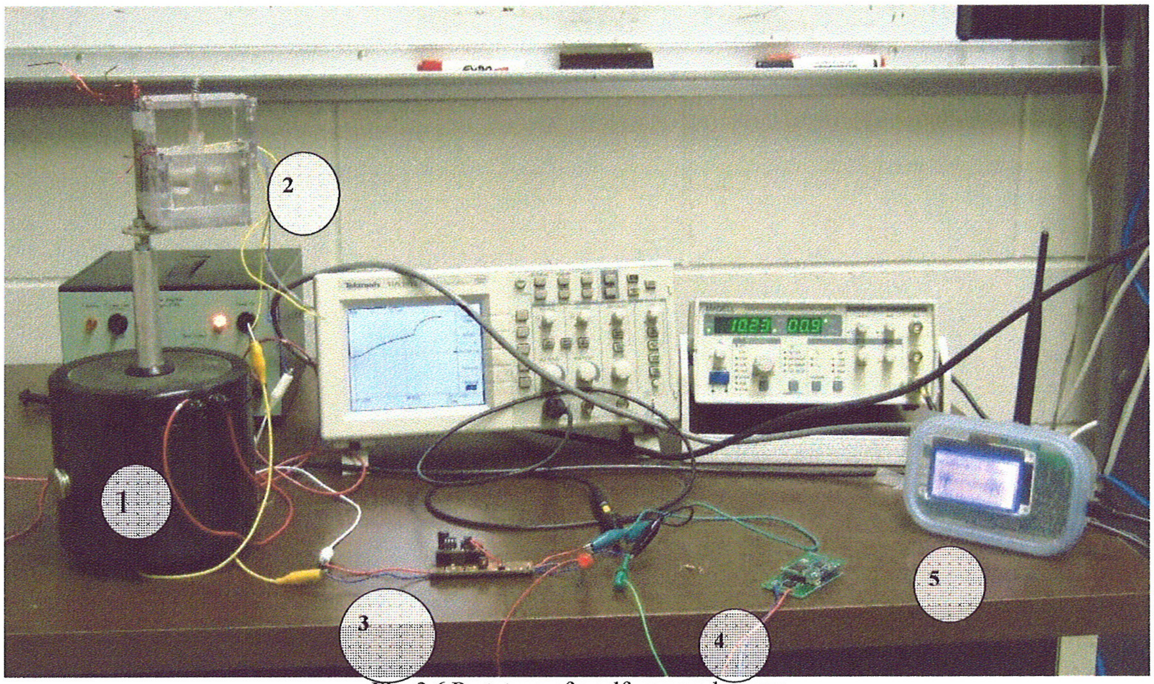

Fig. 3.6 Prototype of a self-powered sensor

A shaker (1) drives the linear generator (2) with stator displacement of 2mm at a frequency of 10Hz. An energy conversion and storage circuit (3) is powering a wireless acceleration sensor (4) that is continuously sensing vibration at the sampling frequency of 64Hz and sending the data over a wireless link to the coordinator node (5).

The linear generator was able to supply about 3mW of continuous energy to the energy conversion circuitry of which approximately 1.5mW was delivered to the wireless node. The wireless node was interfaced to a 3D low-power MEMS accelerometer capturing data in the Z direction. The data was sampled with resolution of 12bits and at sampling frequency of 64Hz. The acquired data points were downsampled to 8bit of resolution and transmitted as a packet with 100 data points. Wireless data were delivered a personal computer with Labview interface designed for visualization and storage of data.

Under continuous excitation the sensor performed reliably over a long period of time.

4.3.5. Ultra Low Power Maximum Power Point Tracking Circuit

The ability to harvest energy at the optimal point significantly improves the amount of energy harvested. The problem with continuously harvesting at the optimal point or maximum power point (MPP) is that it depends on the excitation of the energy harvesting generator. Since the MPP is continuously changing under changing traffic, an adaptive tracking mechanism is needed which can be implemented in a low power microcontroller (Fig. 3.7).

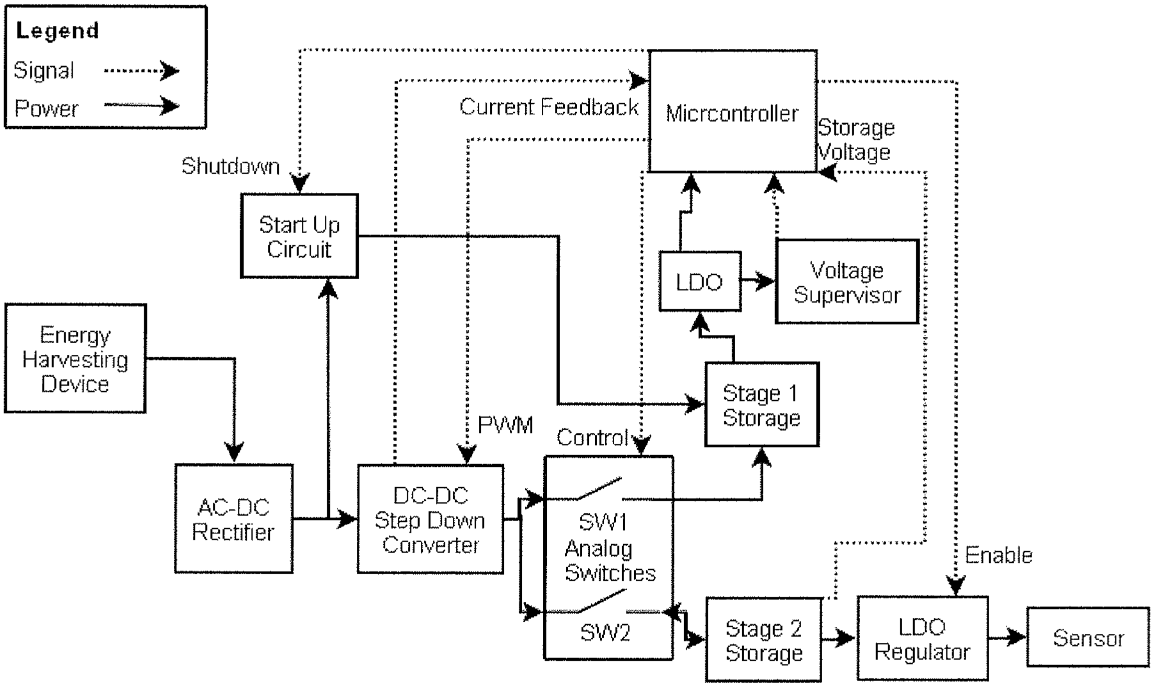

Fig. 3.7 Energy Harvesting Circuit Block Diagram

The energy harvesting circuit functions by first charging the Stage 1 Storage which powers the microcontroller. Once the microcontroller is powered, the start up circuit is shutdown and SW2 is closed. The microcontroller generates a PWM signal which allows power to flow through the DC-DC converter and start charging the Stage 2 storage. In the mean time the energy stored in the Stage 1 storage is being consumed by the microcontroller. Once the voltage on stage 1 drops below the threshold of the voltage supervisor it interrupts the microcontroller and SW2 is opened and SW1 is closed to recharge stage 1. Once stage 1 is recharged SW1 is opened and SW2 is closed and stage is continued to be charged. Once stage 2 is fully charged both SW1 and SW2 are closed and the LDO powering the sensor is enabled.

The tracking algorithm uses three variables, one to hold the value of the peak current, one to hold the old value of the peak current and one for the direction which can be either incrementing or decrementing. The initial new current and old currents are zero and the direction is incrementing the duty cycle. Next an analog to digital conversion is made and a value for the new current is obtained. This value is then compared to the old current and if it is greater and direction is equal to increment the duty cycle can be incremented. If duty cycle was previously decremented then it is decremented again. Then old current is set to the value of the new current and processor waits until the voltage across the rectifier capacitor has stabilized and then repeats the process.

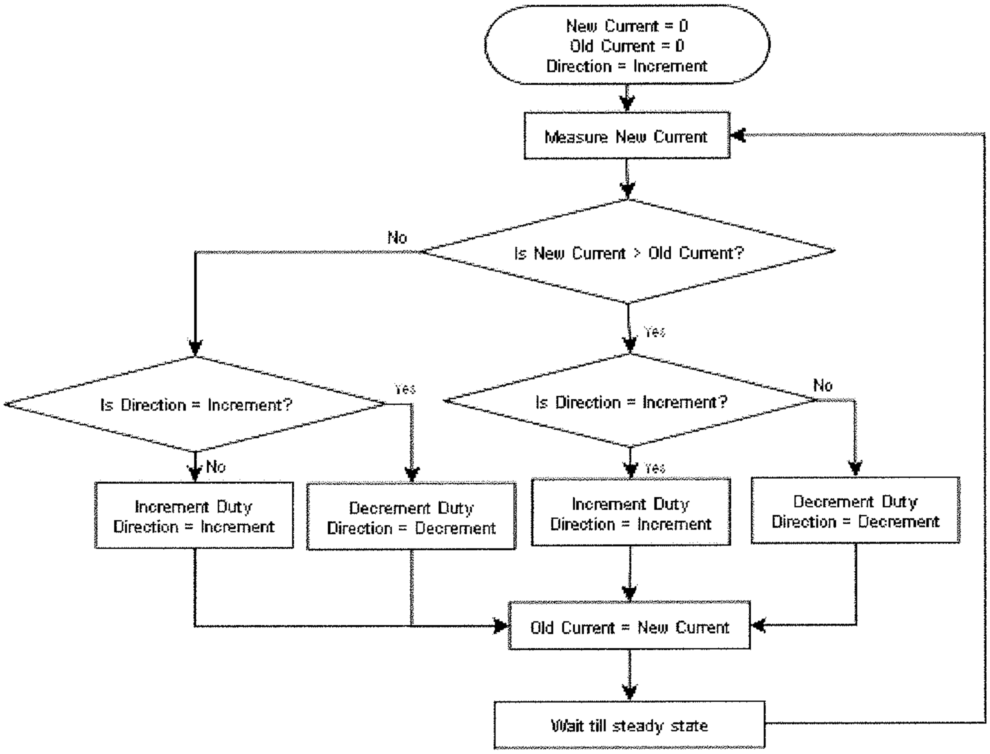

Fig. 3.8 Tracking Algorithm Flow Chart

The tests results shown in Fig. 3.9 and 3.10 were conducted by calculating the times to charge a .1F capacitor from 0 volts to 3 volts. The electromagnetic generator was under the same excitation for both tests. The first charging time was conducted while using a non adaptive approach by setting the duty cycle to a constant value which was the optimal duty cycle for an output voltage of 1.5 volts. The second test was conducted using the adaptive tracking algorithm.

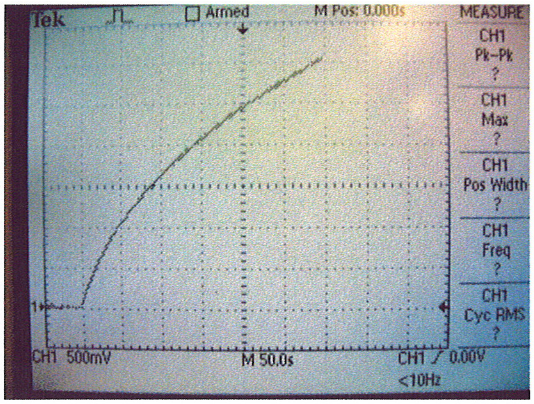

Fig. 3.9 Constant Duty Cycle Charging

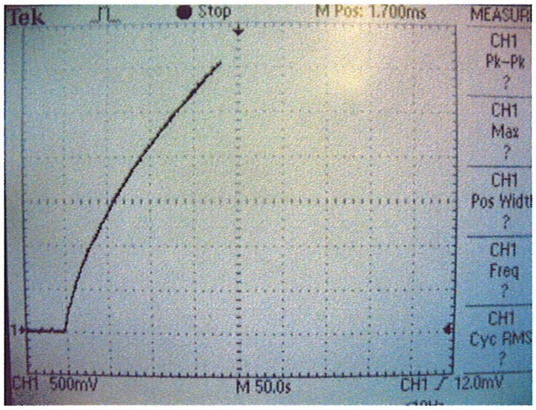

Fig. 3.10 Adaptive Algorithm Charging

From the two charging time traces the adaptive algorithm charges the capacitor about 125 seconds faster than the constant duty cycle implementation. This corresponds to about a 42% increase in efficiency by using the adaptive approach. The tracking algorithm is much more efficient because the duty cycle can be adjusted to reflect the changing output voltage of the converter as the capacitor charges. This allows the energy harvesting circuit to always operate close to the MPP.

4.3.6. Integrating Energy Harvesting with Wireless Sensors

Combining the energy harvesting electronics into the same design as the wireless sensor components has many advantages over keeping them as two separate entities (Fig. 3.11). The first advantage is that the size and price of the design can be reduced because components can be eliminated. The second advantage of combination is that the wireless sensor part can be aware of how much energy is at its disposal and make intelligent decisions on how to use that energy. However these benefits come with a price of more complexity in the code to control the system. This is because the microcontroller has to deal with both controlling the energy harvesting hardware and the wireless components.

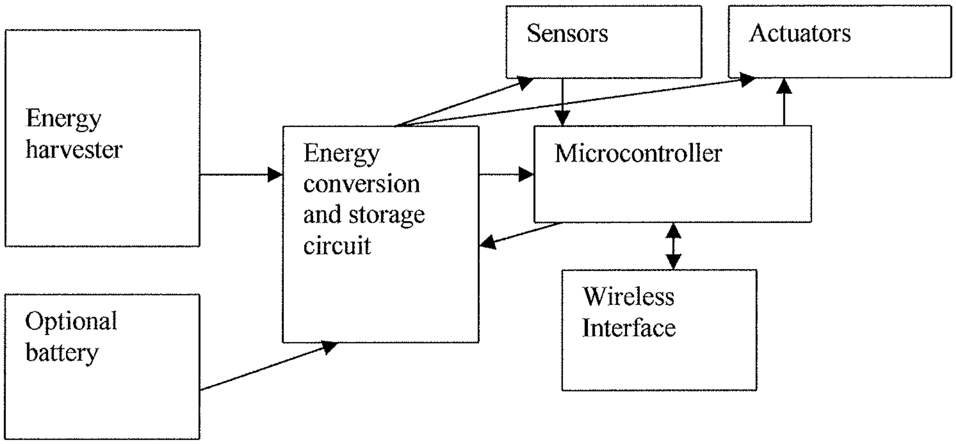

Fig. 3.11 System Block Diagram

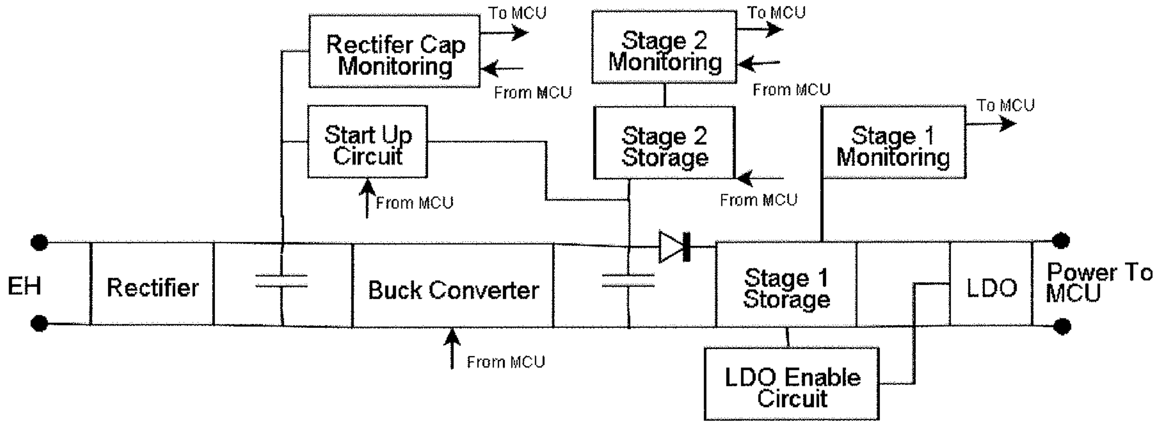

Fig. 3.12 Energy Harvesting Circuit Block Diagram

Fig 3.12 illustrates the microcontroller signals required to control energy conversion and storage. These signals give information to the microcontroller so that it can make intelligent decisions on controlling the energy harvesting circuitry. Also from these signals the microcontroller can determine when there is enough energy stored to perform a sensor reading and wireless transmission. The control signal inputs from the microcontroller allow it to put the circuit into different modes of operation to efficiently harvest the incoming energy. Also it allows it to enable circuit parts such as the Stage1 and Stage2 monitoring only when an analog to digital conversion is being performed to save power.

Operation of wireless sensor powered by ambient energy requires power-aware operation that has distinct states and modes of operation.

1. Start Up and low excitation energy accumulation – The circuit is initially in this mode. This mode of operation allows the microcontroller to be powered when its energy storage is empty. Current flows through the start up circuit and into Stage 1 Storage. Once Stage 1 is fully charged the LDO Regulator enable circuit enables the LDO which then powers on the microcontroller. The microcontroller can then make a decision on which of the following modes to enter.
2. Buck Converter Enabled – If the microcontroller believes there is sufficient incoming energy to perform active energy harvesting it will harvest energy using the buck converter. In this mode the Start Up circuitry is disabled and the buck converter is used to harvest energy by impedance matching of the energy harvesting device to the load. The input to the buck converter is a PWM signal that can be varied to accomplish maximum power point tracking.
3. Buck Converter Disabled - If the microcontroller believes incoming energy is low it can opt to harvest energy without using the buck converter by harvesting through the start up circuit. This mode is equivalent to harvesting with a rectifier and capacitor configuration and hence does not perform maximum power point harvesting but allows very low excitation levels to be accumulated and stored.

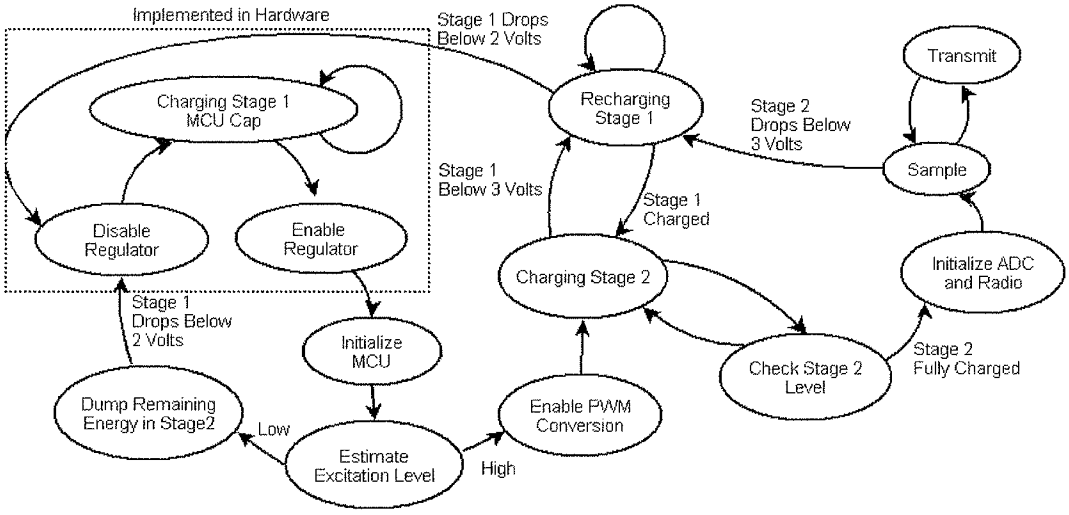

Fig 3.13 System State Diagram

As shown in Fig. 3.13, energy storage is organized in two (or more) stages that allow for storing various amounts of energy.

4.3.7. Wireless sensor

The wireless sensor integrates the energy conversion circuitry, sensor interfaces and wireless circuitry. The sensor uses TI's latest generation of microcontrollers the MSP430F2xxx series. This processor has low power consumption but more importantly has a very low power RC oscillator that has fast start up time. This allows this design to start harvesting energy right away. Fig 3.14 shows implementation of a wireless sensor combining the circuitry described in this report.

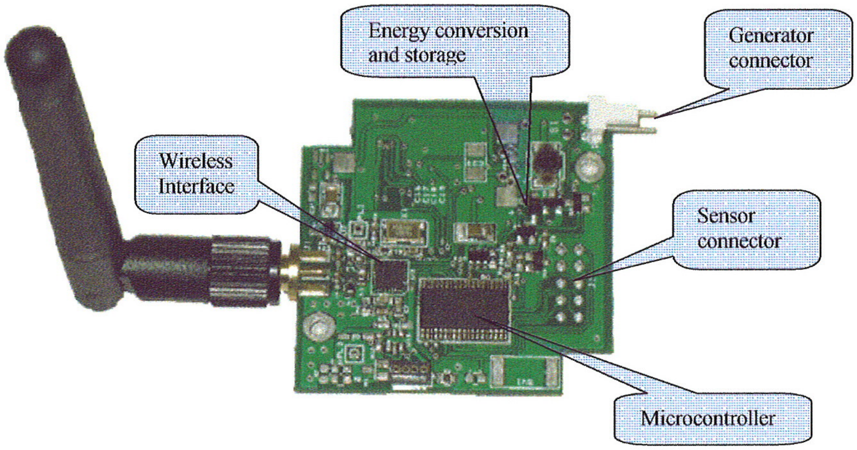

Fig 3.14 Wireless self-powered sensor

4.4. *Field testing of the self-powered platform*

Multiple field tests were performed on a prototype self-powered platform during May-November 2007. The tests were conducted on RT11 bridge in Potsdam, NY. The sensor location on the bridge is illustrated in Fig. 4.1.

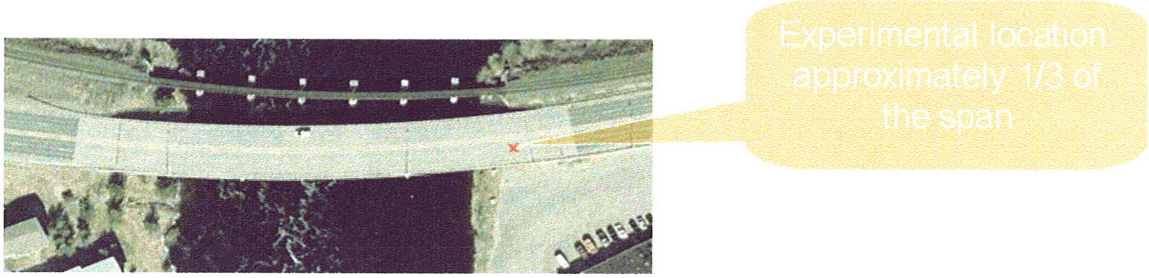

Fig. 4.1 Experimental location on RT11 bridge

The tests were conducted using an analog temperature sensor. Temperature dynamics of the bridge vibration may potentially impact performance of self-powered sensors therefore it is of interest to observe operation of the self-powered device through a range of temperatures. A working prototype of a self-powered temperature sensor is shown in Fig. 4.2. Vibration of the bridge drives the tubular linear generator at a frequency of 3.1 Hz. The spring is mounted to the vibrating mass that can transfer the vibration energy into the electrical energy. The output of the linear generator is connected to a self-powered wireless temperature sensor package which includes the energy conversion, storage and the wireless sensor. The radio transmitter of the wireless sensor sends temperature data to a notebook PC.

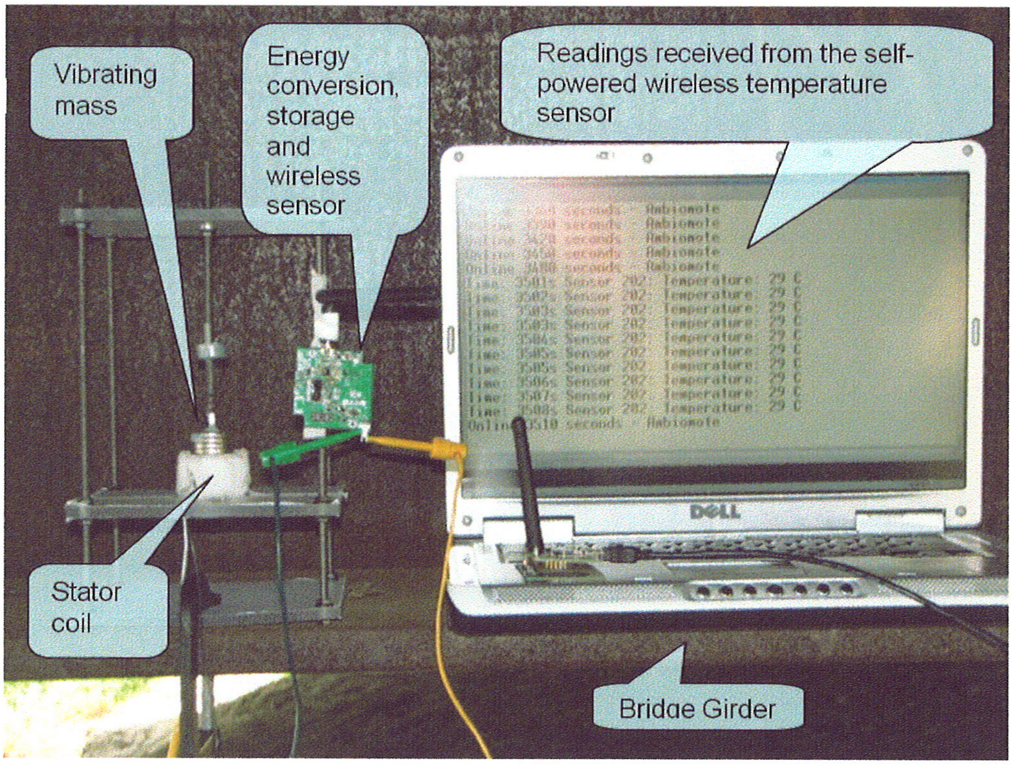

Fig. 4.2. Prototype of the self-powered wireless sensor

Initial tests were conducted using unpackaged device: this ensured easy access to the components of the self-powered sensor and convenient observation of their behavior under a variety of excitations, loads and selected operating parameters. Once parameters of reliable operation were established, the device was packaged for long-term testing.

4.4.1. 24hrs monitoring experiment

The device was installed on RT11 bridge in Postdam, NY. The generator, wireless sensor and a data logger were packaged inside a small safe which sat on the bottom flange of a girder (Fig. 4.3). The safe was chained to the girder to prevent vandalism. When harvested energy levels were sufficient the wireless sensor transmitted a temperature reading to the data logger which recorded the transmission and time of the transmission recording the time history of the operation.

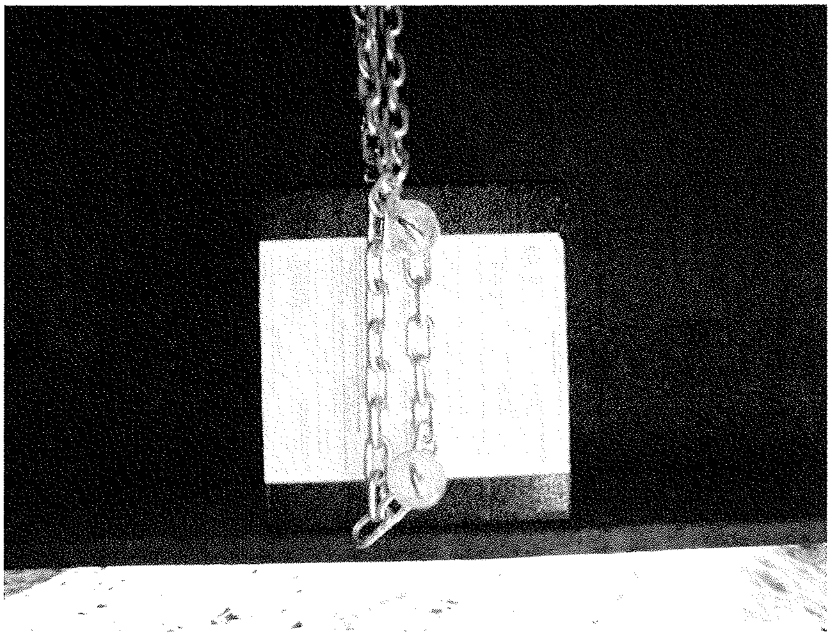

Fig. 4.3 Bridge installation

The number of transmission obtained over a 24 hour test are shown in Fig. 4.4. These results indicate that sufficient energy for bridge monitoring is available throughout the day. It should be noted that RT11 bridge is a rural bridge with relatively low traffic volume. The number of measurement/transmissions would be higher on a high-traffic bridge. Figure 4.5 shows the history of temperature readings over the test period.

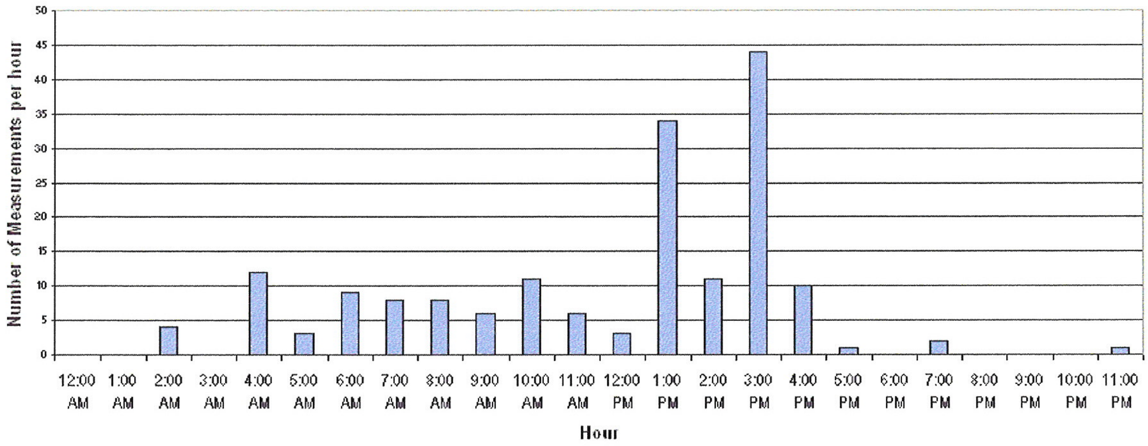

Fig 4.4 Number of transmission over 24 hours

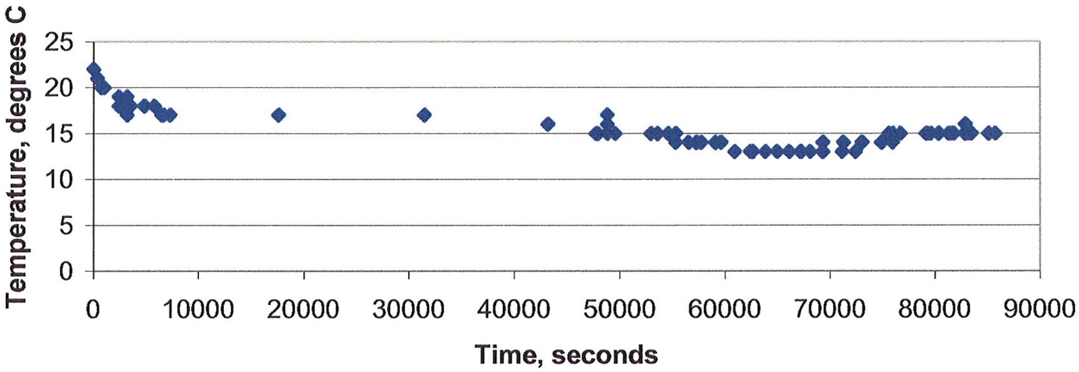

Fig 4.5 Average temperature per hour

4.4.2. Week Long Test

The test was conducted in October of 2007 to verify sensor performance on a longer time scale. Specifically, behavior of the energy harvested as a function of bridge temperature was of interest. The sensor was left unattended for a period of one week. All of the transmissions generated by the sensor were recorded by the data logger.

Fig. 4.6 shows the number of total transmissions per day. From the data it appears that the highest amount of traffic occurs during the middle of the week. Fig 4.7 shows the average number of transmission per hour over the week long period.

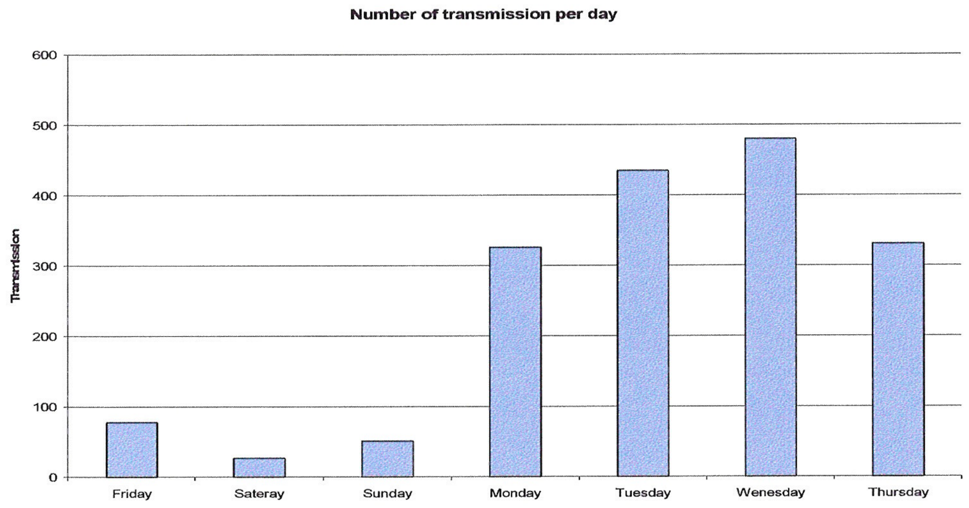

Fig. 4.6 Total number of transmission per day of week

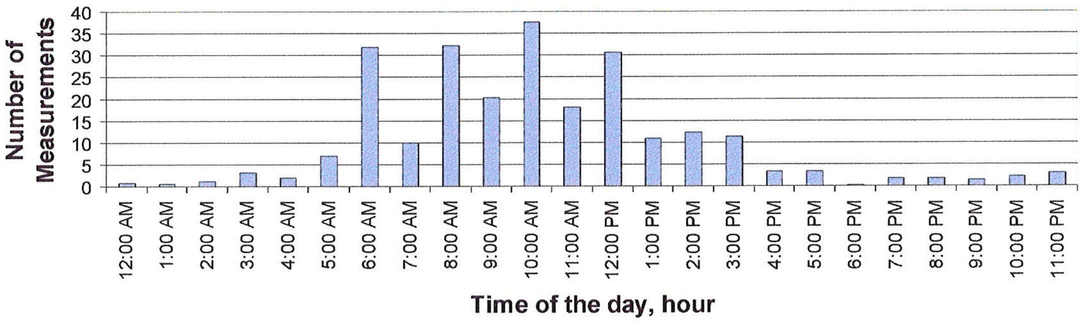

Fig. 4.7 Average measurements per hour for one week

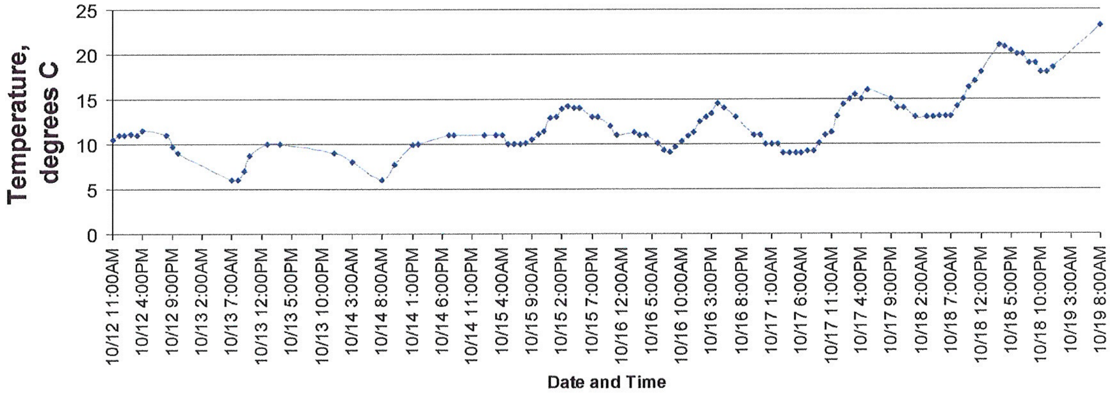

Fig. 4.8 Average hourly temperature acquired over a week

The hourly data suggest that the majority of traffic on RT11 bridge occurs between 5am and 3pm. Fig. 4.8 shows average temperature per hour of recording during the 7-day period. As it can be seen from Fig. 4.8 the sensor reliably operated in a range of ambient temperatures. However, long-term testing on a scale of year would be more conclusive.

Both the daylong and the weeklong tests demonstrate that self-powered sensors are capable of performing continuous monitoring of the bridge infrastructure. We achieved completely self-powered operation on a rural bridge with relatively low traffic. Critical high-traffic bridges on major roads will have higher levels of vibration energy available and therefore can perform more energy demanding measurements or sample the value of interest more often.

5. PLANS FOR IMPLEMENTATION

Self-powered sensors have a great market potential and will offer unprecedented convenience for monitoring applications. Competing technologies (such as RFID) operate only on demand and cannot achieve the same level of proactive monitoring as self-powered sensors.

Unattended self-powered sensors may be used to monitor a variety of bridge conditions. As an example, a self-powered sensor can monitor freezing conditions on the bridge and provide information for release of deicing agents. Unattended sensors installed on rural bridges may detect overload conditions created by overweight farmer vehicles. Self-powered sensors may serve as permanent traffic counters. Vibration-powered sensors can be embedded inside concrete structures and monitor locations (such as weld joints, for example) which otherwise are not accessible. Finally, self-powered sensors can be used in structural health monitoring applications using vibration and strain signals, and/or lamb wave sensors.

The technological solutions designed during this project are very competitive. For example, the energy conversion circuit utilized in conjunction with the linear generator allows for energy gain up to 400% compared to a rectifier-capacitor. Such results have been previously only confined to laboratory conditions where a personal computer was controlling the conversion process. In this project the conversion of the same level of efficiency has been implemented into an embedded self-powered device.

The implemented prototype can be packaged in a relatively small enclosure (8"x4"x4"). We believe that further reduction in size is also possible. The cost of the components in this sensor prototype is low (<$200 qty.1) and in mass production such sensors can be sold at a price of about $200 plus the cost of sensor. Such price point could make the proposed solution competitive in respect to any battery technology.

The investigators are trying to proceed from the research stage into practical stage and bring self-powered bridge technology into practice. The technical solutions designed during this project have been submitted as a provisional patent application in January of 2007 with the full patent application being prepared for submission during the first week of January 2008.

The technology has been licensed by Clarkson University to a start-up company AmbioSystems LLC (www.ambiosystems.com). At the current time, AmbioSystems manufactures and self-powered wireless sensor platforms based on electronic solutions developed during this project. These platforms can operate from a variety of energy sources and are not specifically targeted to bridge monitoring.

With additional research and development effort the current prototype of a self-powered bridge sensor platform can be converted into a market-ready device that could be used by the Departments of Transportation worldwide.

We suggest proceeding into Phase II of the research with AmbioSystem LLC as commercial partner. We will:

1. Identify a specific bridge application that would be of interests to most bridge operators (for example, detecting, storing and reporting information on overload conditions)
2. Design the sensing element and estimate the energy requirement of the application
3. Scale the generator to match the established energy requirement
4. Develop a packaged design with considerations of manufacturability and ease of installation/tune up
5. Commercialize the sensor

As results of this project demonstrate, bridge vibration created by traffic is sufficient for powering a monitoring application. Further development of this technology will allow better maintenance of the bridge infrastructure.

6. References

1. Del Grosso, D. Inaudi, and L. Pardi, *Overview of European Activities in the Health Monitoring of Bridges*, First International conference on Bridge Maintenance, Safety and Management, IABMAS'02', CIMNE, Barcelona, 2002.
2. Federal Highway Administration, *Tables of Frequently Requested NBI Information*, retrieved from http://www.fhwa.dot.gov/bridge/britab.htm, 2006.
3. K. Siggerud, *HIGHWAY INFRASTRUCTURE: Physical Conditions of the Interstate Highway System Have Improved, but Congestion and Other Pressures Continue, Testimony Before the Subcommittee on Highways and Transit*, Committee of Transportation and Infrastructure, House of Representatives, 2002, retrieved from http://www.house.gov/transportation/highway/09-26-02/siggerud.pdf
4. Sazonov, E., Janoyan, K.D., and Jha, R. (2004) "Wireless Intelligent Sensor Network for Autonomous Structural Health Monitoring," Smart Structures/NDE 2004, San Diego, California.
5. Sazonov, E., Janoyan, K.D., and Jha, R. (2004) "Sensor network application framework for autonomous structural health monitoring of bridges" Proceedings of Structural Materials Technology (SMT): NDE/NDT for Highways and Bridges 2004. Buffalo, NY.
6. S. Alampalli, M. Ettouney, *Workshop On Engineering Structural Health,* NYSDOT, 2002.
7. S. C. Liu, *Smart Structures and Materials 2003: Smart Systems and Nondestructive Evaluation for Civil Infrastructures*, Proc., SPIE - The International Society for Optical Engineering, 700 pages; 69 papers; Pub. Aug 2003.
8. Fu-Kuo Chang, *Structural Health Monitoring 2003: From Diagnostics & Prognostics to Structural Health Management*, Proceedings of the 4th International Workshop on Structural Health Monitoring, Stanford University, September 15-17, 2003.
9. D.M. Frangopol, *New Directions and Research Needs in Life-Cycle Performance and Cost of Civil Infrastructure,* Proceedings of the 4th International Workshop on Structural Health Monitoring, Stanford University, September 15-17, 2003, pp.53-63.
10. A. Elgamal, J.P.Conte, S. Masri, M. Fraser, T. Fountain, A. Gupta, M. Trivedi, and M.E. Zarki, *Health Monitoring Framework for Bridges and Civil Infrastructure*, Proceedings of the 4th International Workshop on Structural Health Monitoring, Stanford University, September 15-17, 2003, pp.123-130.
11. E. Aktan, K. Ciloglu, K. Grimmelsman, M. Pervizpour, and X. Qin, *Monitoring*

the Operations, Security and Structural Health of Major Long-Span Bridge Hyper-systems, Proceedings of the 4th International Workshop on Structural Health Monitoring, Stanford University, September 15-17, 2003, pp.123-130.

12. J. P. Lynch, A. Sundararajan, K. Law, A. Kiremidjian, E. Carryer, H. Sohn, and C. Farrar C., *Field Validation of a Wireless Structural Monitoring System on the Alamosa Canyon Bridge*, SPIE 10th Annual International Symposium on Smart Structures and Materials, San Diego, CA, USA, March 2-6, 2003.
13. E. Sazonov, K. Janoyan, and R. Jha, *Wireless Intelligent Sensor Network for Autonomous Structural Health Monitoring*, Proceedings of SPIE's Annual International Symposium on Smart Structures and Materials, San Diego, CA, 2004.
14. Texas Instruments, www.ti.com
15. Chipcon Inc., www.chipcon.com
16. ZigBee Alliance, www.zigbee.com
17. G. K. Ottman, A. C. Bhatt, H. Hofmann, and G. A. Lesieutre, "Adaptive piezoelectric energy harvesting circuit for wireless remote power supply," IEEE Trans. Power Electron., vol. 17, pp. 669–676, Sept. 2002.
18. N. Shenck and J. A. Paradiso, "Energy scavenging with shoe-mounted piezoelectrics," IEEE Micro, vol. 21, pp. 30–42, May-June 2001.
19. Chopra I., (2002) Review of State of Art of Smart Structures and Integrated Systems, AIAA JOURNAL Vol. 40, No. 11, November 2002.
20. Lee, C.-K., (1992), "Piezoelectric Laminates: Theory and Experiment for Distributed Sensors and Actuators," *Intelligent Structural Systems*, Tzou, H. S., and Anderson, G. L. (eds.), Kluwer Academic Publishers, pp. 75-167.
21. Ghandi K. (2000), *Compact Piezoelectric Based Power Generation,* ContinuumControl Corporation, Presentation to DARPA, Apr 13-14, 2000.
22. Ottoman G. K., Hofmann H.F., Leisieutre G.A., (2003), *Optimized Piezoelectric Energy Harvesting Circuit Using Step-Down Converter in Discontinuous Conduction Mode",* IEEE Transactions on Power Electronics, vol 18., No 2., March 2003.