Power Management for Energy Harvesting Wireless Sensors

S.W. Arms*, C.P. Townsend, D.L. Churchill, J.H. Galbreath, S.W. Mundell

MicroStrain, Inc., 310 Hurricane Lane, Unit 4, Williston, Vermont 05495 USA

ABSTRACT

The objective of this work was to demonstrate smart wireless sensing nodes capable of operation at extremely low power levels. These systems were designed to be compatible with energy harvesting systems using piezoelectric materials and/or solar cells. The wireless sensing nodes included a microprocessor, on-board memory, sensing means (1000 ohm foil strain gauge), sensor signal conditioning, 2.4 GHz IEEE 802.15.4 radio transceiver, and rechargeable battery. Extremely low power consumption sleep currents combined with periodic, timed wake-up was used to minimize the average power consumption. Furthermore, we deployed pulsed sensor excitation and microprocessor power control of the signal conditioning elements to minimize the sensors' average contribution to power draw. By sleeping in between samples, we were able to demonstrate extremely low average power consumption. At 10 Hz, current consumption was 300 microamps at 3 VDC (900 microwatts); at 5 Hz: 400 microwatts, at 1 Hz: 90 microwatts. When the RF stage was not used, but data were logged to memory, consumption was further reduced. Piezoelectric strain energy harvesting systems delivered ~2000 microwatts under low level vibration conditions. Output power levels were also measured from two miniature solar cells; which provided a wide range of output power (~100 to 1400 microwatts), depending on the light type & distance from the source. In summary, system power consumption may be reduced by: 1) removing the load from the energy harvesting & storage elements while charging, 2) by using sleep modes in between samples, 3) pulsing excitation to the sensing and signal conditioning elements in between samples, and 4) by recording and/or averaging, rather than frequently transmitting, sensor data.

Keywords: energy, harvesting, wireless, strain, sensors, RF, piezoelectric, solar

1. INTRODUCTION

Recent developments in sensing technology, microprocessors, and miniaturized radio transceivers has enabled a new generation of smart structures, machines, & materials to be realized[1]. The dream of the future is that ubiquitous networks of smart wireless sensing nodes will autonomously report on operating conditions, and these data will be used to facilitate structural health monitoring, embedded test & evaluation, and condition based maintenance of bridges, roads, trains, dams, buildings, ground vehicles, aircraft, and watercraft. By alerting us to problems before they become disasters, and by eliminating unnecessary scheduled maintenance, the safety and reliability of our transportation and military system infrastructure could be greatly improved, while the cost to maintain these systems could be greatly reduced[2].

However, in order to provide sensing networks which are truly autonomous, we must develop methods to eliminate the need for battery changes. We have previously reported on the use of piezoelectric materials to convert strain energy from a structure into electrical energy for powering a wireless sensing node[3]. We have also described systems which are capable of energy harvesting from vibrating machinery and rotating structures[4],[5]. Other researchers have been active in this area as well, and have described various strategies for harvesting, or scavenging, energy from the environment[6], [7], [8].

Correspondence: Email: swarms@microstrain.com; tel 802 862 6629 fax 802 863 4093, www.microstrain.com.

Our previous work demonstrated the importance of balancing the “energy checkbook”. When the rate of charge matches the rate of discharge, the checkbook is balanced. When the rate of discharge exceeds the rate of charge, the system will eventually run out of power. We have demonstrated smart electronics to detect this condition, and to then shut down the power consuming elements in order to allow energy storage elements to be re-charged (i.e, the checkbook is provided an opportunity to become balanced again).

By reducing the power drawn by the sensing system, the demand or “appetite” for power output from the harvester is reduced. This allows the energy harvesting wireless sensing system to operate under conditions of lower ambient energy. The strategies required to achieve minimal power consumption is the subject of this paper. By embedding these capabilities within the wireless sensing node, new wireless sensing applications will be enabled.

2. OBJECTIVES

To demonstrate smart wireless sensing nodes capable of extremely low power operation, and to use both piezoelectric materials & solar cells to power these demonstrations.

3. METHODOLOGY

A system level block diagram of the energy harvesting wireless sensing system is provided in Figure 1. A modular design approach provides a flexible and versatile platform to address the needs of a variety of applications [9].

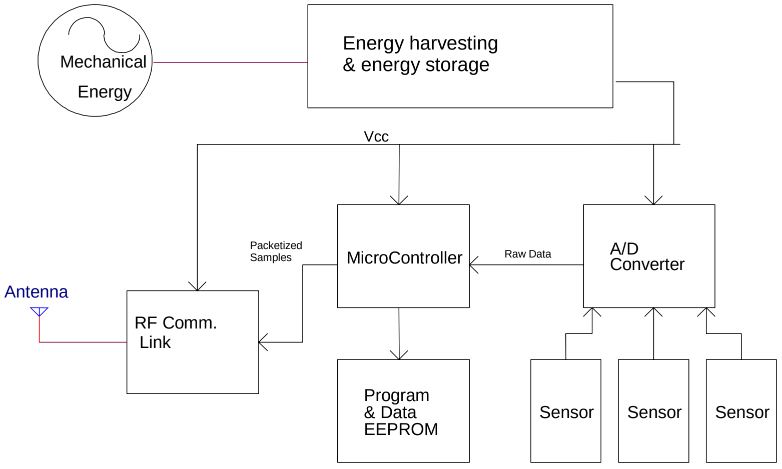

Figure 1. System block diagram for energy harvesting wireless sensing node with data logging and bi-directional RF communications capabilities. The processor manages power to the sensors and data acquisition elements, as well as responds to commands from the base station.

These wireless sensor nodes feature 2 MB flash memory, an embedded 16 bit node ID, on-board programmable data logging from 0.1 to 2048 samples/second/channel, wireless streaming rates up to 1.7 K samples/second, and network synchronization of better than 0.1 milliseconds. Radio transceivers used IEEE 802.15.4 standard communications protocols on 2.4 GHz (ChipCon, Oslo, Norway). The high sensitivity of these transceivers (>110 dBm) allow for license free, narrowband, bi-directional radio frequency (RF) communications over distances of ~150 meters (line of sight). The IEEE 802.15.4 standard was designed for wireless sensors, it specifies multiple data rates and multiple RF transmission frequencies. The radio power requirements are low, and the hardware is designed to allow the radio to sleep to minimize power consumption. When the node wakes up from sleep, rapid synch to network is achieved. This allows for very low average power supply current, since radio may be rapidly switched on/off.

Figure 2 provides a photo of a miniature, strain gauge module as developed by the authors and used in our energy harvesting demonstrations. Accompanying base stations are commercially available with serial (USB) and analog output interfaces.

The power consumed by these wireless sensing nodes, when streaming data over the air continually, is typically ~45 milliwatts. This consumption is greatly reduced, to ~5 milliwatts, by processing and/or logging data, rather than steaming it over the air. Thus it is a great advantage to keep the radio off.

The power consumed by the sensing elements may also add a significant load to the system. For example, a three channel, 1000 ohm strain gauge rosette, when supplied with 3 VDC continuous excitation, adds 27 milliwatts to the load. We have demonstrated that by pulsing excitation to the strain gauges, and synchronously reading the A/D converter, we could reduce the power consumed by this rosette to 270 microamps, while maintaining a 250 sample/sec/channel update rate.

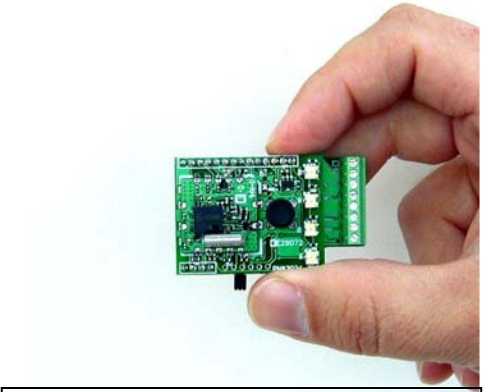

Figure 2. SG-Link ™ wireless strain gauge node (MicroStrain, Inc)

The microprocessor (MicroChip, Chandler, Arizona) is capable of micropower sleep modes. During sleep, the timer function is maintained, but the quiescent power level is reduced to only 20 microwatts. Therefore, for energy harvesting wireless sensors, it is a great advantage to place the processor in sleep mode as frequently as the application will allow, in order to reduce the system's average power consumption.

Power reduction strategies for the **sensing elements** of our wireless nodes are summarized below:

- Turn on power to the sensor only when sampling
- Turn on power to the signal conditioning only when sampling a sensor
- Sample sensor(s) only on event
- Reduce the sensor sample rate to the minimum required by the application
- Sleep between samples
- Utilize lowest standby current electronics
- Maximize bandwidth of electronics to minimize electronics settling time
- Use fast ADC to reduce electronics and sensor "on" time
- In low data rate (5-10 Hz) applications, use higher power components that settle quickly- rather than micropower components that settle slowly.

Power reduction strategies for the **RF transceiver elements** of our wireless nodes are summarized below:

- Reduce the amount of wireless data transmitted through data compression/reduction
- Lower the transceiver duty cycle and frequency of data transmissions
- Implement strict power management – use power down and sleep modes
- Implement an event-driven transmission strategy- transmit only on sensor event(s)

Two types of energy harvesting systems were demonstrated. The first type utilized piezoelectric materials (PZT) to convert vibration energy into electrical energy. It was comprised of a tapered flexure element with PZT mounted on the top and bottom of a cantilever beam. The tapered cantilever structure (50 mm long) was designed to create a nearly uniform strain field on the PZT elements. A proof mass (250 grams) was affixed to the end of the beam, which resonated at a frequency of ~ 60 Hz. Figure 3 is a schematic drawing of the flexure element and proof mass. Figure 4 provides a photograph of the fully integrated vibration energy harvesting wireless sensor node.

Miniature solar cells (quantity 2, Panasonic BP-243318 Solar Modules, 40 x 30 x 0.5 mm^3) were also used to create an ambient light energy harvesting wireless sensor demonstration. Output power was measured w/ the pair of miniature solar cells with various resistive loads (from 100 Ohms to 1 MOhms) in order to determine the optimum charge currents to maximize the power output for each ambient light condition tested. The light sources were of constant intensity during these tests. Incandescent, fluorescent, and halogen light sources were tested indoors, and these data were compared to results obtained outdoors. Figure 5 provides a photograph of the fully integrated light energy harvesting wireless strain sensing node.

Electrochemical thin film rechargeable batteries were used to store energy for these demonstrations. These batteries were chosen because they can be continuously trickle charged, they exhibit very low leakage, they suffer no memory effects, and they maintain their capacity after repeated charge/recharge cycles.

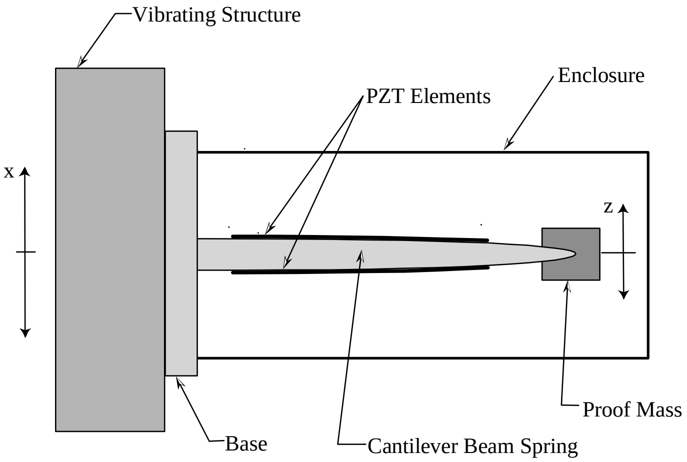

Figure 3. Piezoelectric vibration energy harvester cantilever flexure element with proof mass.

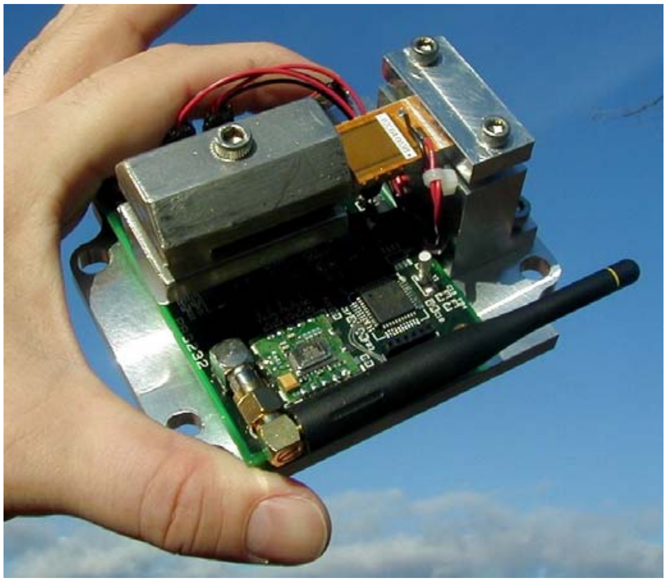

Figure 4. Integrated piezoelectric vibration energy harvester and wireless temperature & humidity sensing node.

Figure 5. Integrated solar energy harvester and wireless strain sensing node.

4. RESULTS

Implementation of strict power management resulted in a significant reduction in the average power consumption of our wireless sensor nodes. Figure 6 below plots the average current (in microamperes) for our wireless strain sensor nodes as a function of the sensor's sampling rate, from 0 to 10 Hz. The supply voltage for these nodes is +3 volts DC. Note that the radio link dominates the current consumption, and is particularly comsumptive at the higher update rates. At sampling rates of 10 Hz, these systems consume ~275 microamps, (less than 900 microwatts at 3 VDC). At update rates of 1 Hz, the power consumption dropped to only 30 microamps (90 microwatts at 3 VDC). Note that wireless sensing systems that do not sleep between samples would draw significantly more current (45,000 microwatts while streaming over the air, and 5000 microwatts while logging only).

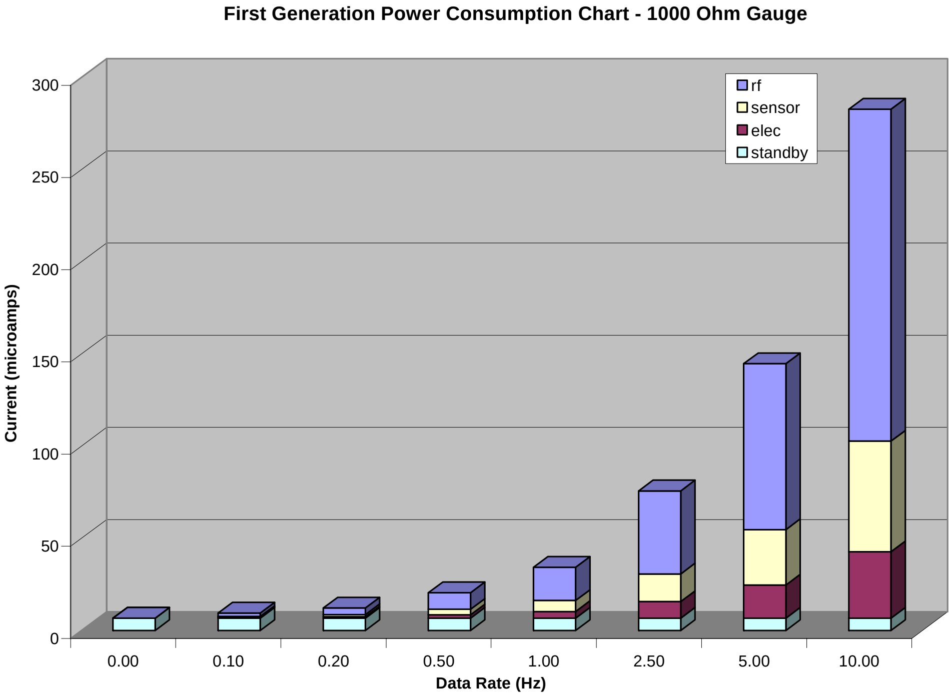

Figure 6. Average current consumed by first generation wireless strain sensing node as a function of sensor update rate.

Additional effort was made to decrease the power consumption at data rates of 5 Hz and higher. This was accomplished by using faster components in the signal conditioning elements of the sensor circuit. In order to better convey these results, the radio's contribution to the current consumption has been eliminated from figures 7 and 8, below. These charts demonstrate that the power management strategies can have a significant impact on the energy consumption of these systems, particularly as the sample rates increase. By using faster components in our second generation design, we were able to achieve lower duty cycles. Our first generation design demonstrated duty cycles of 0.2% (1 Hz sample rate) and 2% (10 Hz sample rate). Our second generation design achieved duty cycles of 0.02% (1 Hz sample rate) and 0.2% (10 Hz sample rate), which is an improvement of approximately tenfold. In table I below, we summarize our results for power consumption of our wireless sensing nodes. The benefits of using faster components are apparent at the higher sampling rates of 5 and 10 Hz.

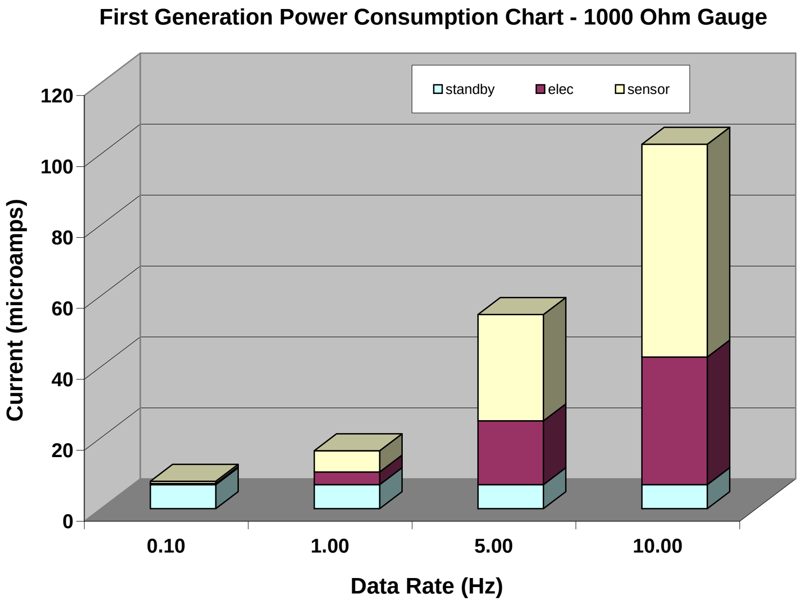

Figure 7. Average current consumed by first generation wireless strain sensing node as a function of sensor update rate, with RF section eliminated for clarity.

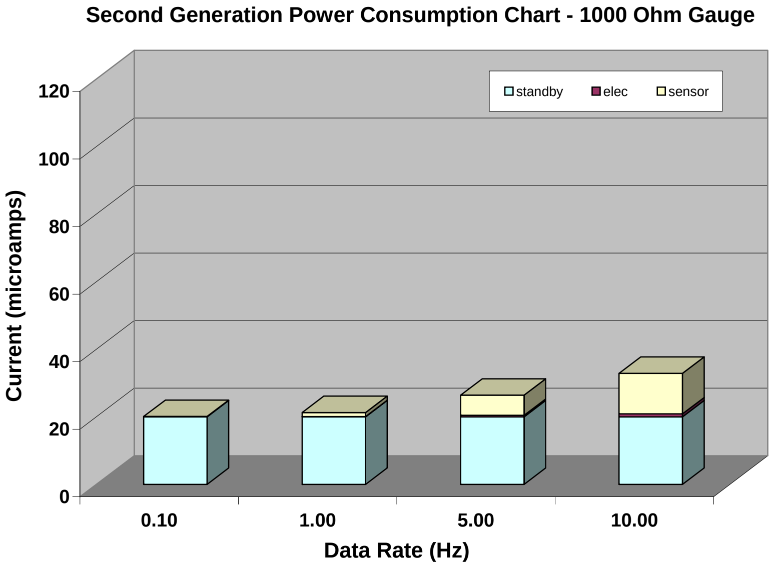

Figure 8. Average current consumed by second generation wireless strain sensing node as a function of sensor update rate, with RF section eliminated for clarity.

Table I. Summary table of power consumption (in microwatts) for both first and second generation wireless sensor nodes with advanced power management strategies implemented in all cases. The second generation system utilized faster settling components in the sensor signal conditioner.

Update rate	**1st gen. with radio (microwatts)**	**1st gen. w/o radio (microwatts)**	**2nd gen. w/o radio (microwatts)**
0.1 Hz	**25**	**20**	**50**
1.0 Hz	**100**	**50**	**55**
5.0 Hz	**420**	**150**	**70**
10 Hz	**825**	**300**	**90**

The results for output power developed by the piezoelectric energy harvester are plotted below in Figure 9. Output power is plotted as a function of maximum strain on the piezoelectric harvesting element. The resonant tapered beam structure delivered significantly more power than a strip of material mounted on a uniform composite beam loaded in three point bending. This underscores the importance of insuring that the piezoelectric material is subject to a uniform strain field. Another important feature of the resonant cantilever flexure element harvester is that it generated a relatively high amount of out put power at low input vibration levels (100 to 130 milliG's) and modest strain levels (+/- 200 microstrain).

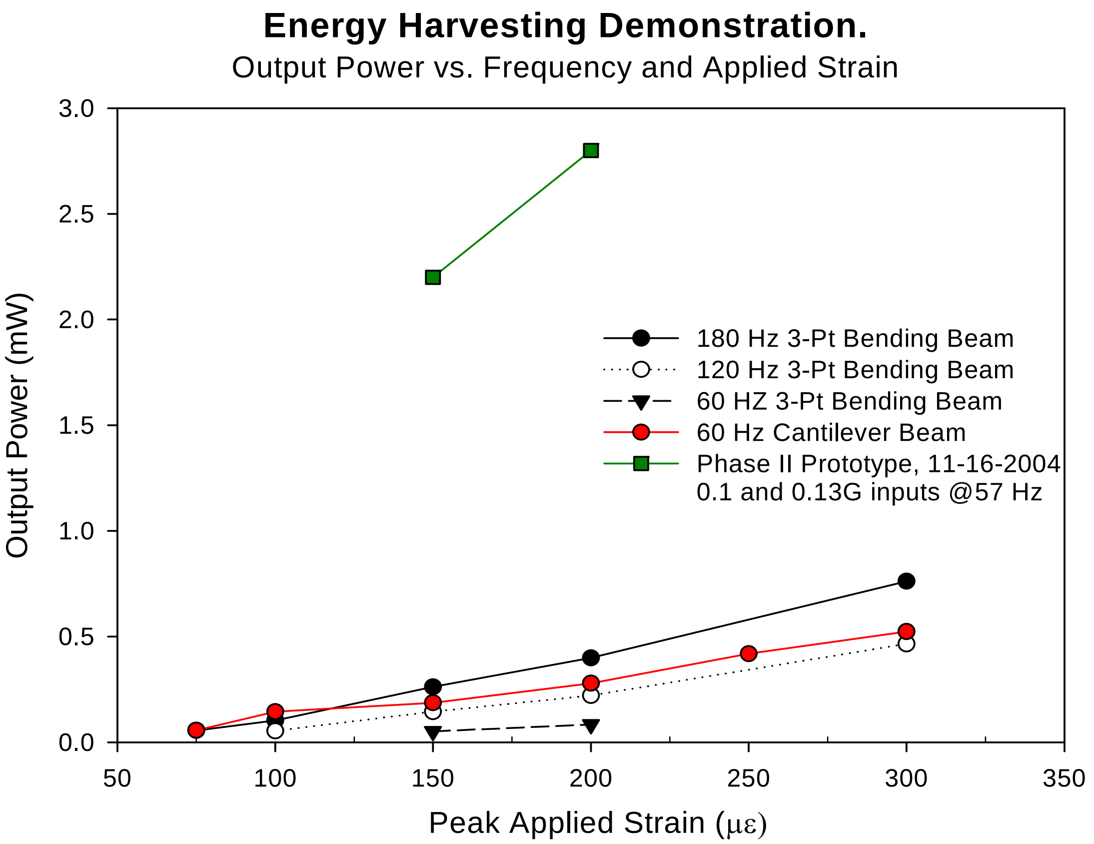

Figure 9. Output power for piezoelectric energy harvesting demonstration systems as a function of strain level

The solar panels produced optimization charge curves typical of the plot provided in Figure 10, below. Table II summarizes the output power generated by the pair of solar panels we tested (Panasonic model BP-243318) under various proximity conditions and under various light sources.

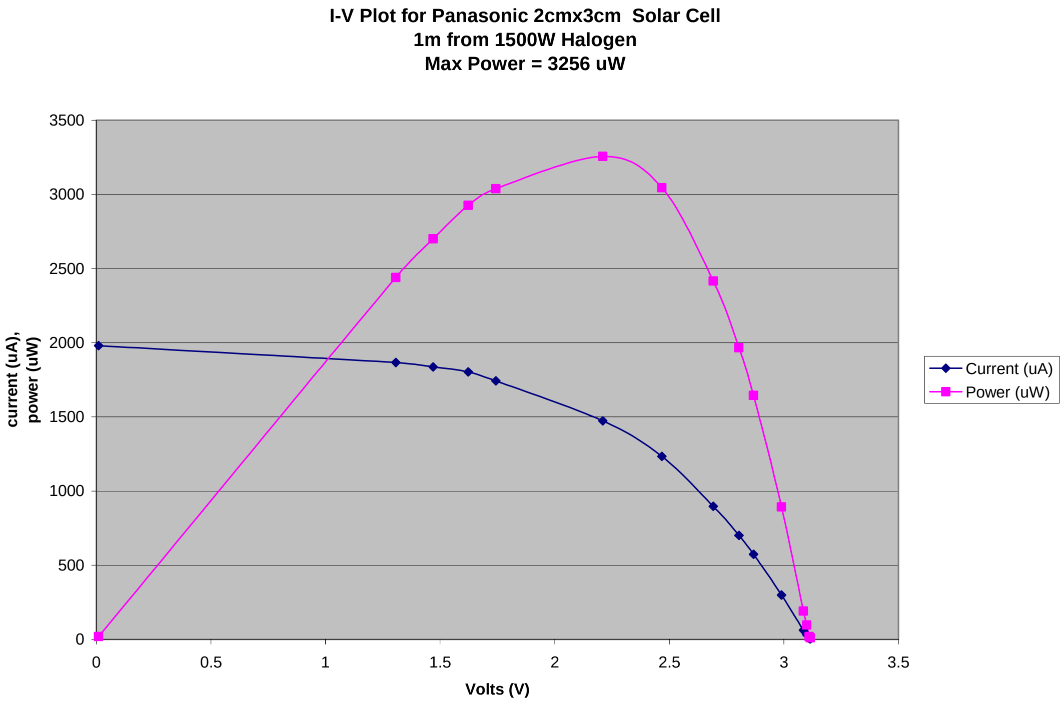

Figure 10. Typical output power and charge current curves for photovoltaic energy harvesting demonstration system as a function of photovoltaic cell output voltage

Light Source	Output Power
34W Fluorescent, 2 m	76 uW
34W Fluorescent, 10 cm	1368 uW
60W Incandescent, 1 m	942 uW
60W Incandescent, 10 cm	4728 uW
Window sill, cloudy day	1564 uW
Window sill, sunny day	19554 uW
Outdoors, sunny day	20612 uW
Indoors, 1500W Halogen, 1 m	6512 uW
Indoors, 1500W Halogen, 3 m	1258 uW

Table II. Summary table of power output (in microwatts) for both first and second generation wireless sensor nodes with advanced power management strategies implemented in both cases.

5. DISCUSSION

The results show that with strict embedded energy management protocols and good overall system design, that both vibration and photovoltaic energy harvesting systems can support wireless sensor nodes at data sampling rates that are suitable for many smart structure health monitoring systems, particularly larger structures, which often utilize sample rates of 1 to 10 Hz. The wireless sensor nodes demonstrated in this paper are capable of measurement of temperature, inclination, and strain at these frequencies. They could also be programmed to sample bursts of data at higher rates, provided that the energy storage element (capacitors or rechargeable batteries) can deliver the peak currents required, and that the average power consumption is consistent with balancing the “energy checkbook”.

The integrated vibration energy harvesting wireless sensor node was demonstrated to operate perpetually, without batteries of any kind, at input vibration levels of 100 milliG’s (60 Hz) and with low duty cycle wireless updates. We note however, that ambient vibration sources typically exhibit a frequency distribution, rather than operating at a specific frequency. The vibration energy harvester demonstrated in this work was highly resonant over a narrow frequency range. It is important to point out that the application’s ambient vibration must have sufficient power density at or near the vibration energy harvester’s resonant frequency in order to develop the maximum output power levels under low level vibration conditions. Ideally, one should endeavor to quantify the vibration levels and frequencies that exist on the actual machines and structures to be instrumented, and then the harvester may be tuned to match the predominant frequencies for the specific application.

6. CONCLUSIONS

Vibration energy harvesting is a viable powering technology for many sensing applications. Balancing the energy checkbook is key to optimizing harvesters performance in a wide range of environments. Energy management enhances the performance of not only energy harvesting systems, but these strategies will also allow battery powered systems to last longer. The application should drive the system design, with sample rates, ambient energy sources, and allowable physical space as key elements in the design process.

7. ACKNOWLEDGEMENTS

The authors gratefully acknowledge support from the National Science Foundation’s SBIR Phase II & IIB programs, and the US Navy’s Phase II SBIR program.

8. REFERENCES

---

[1] C.P. Townsend, S.W. Arms, Wireless Sensor Networks: Principles and Applications, Sensor Technology Handbook, Editor: Jon S. Wilson, publisher: Elsevier Newnes, ISBN: 0-7506-7729-5, Chapter 22, pp. 575-589, 2005

[2] C.P. Townsend, S.W. Arms, M.J. Hamel.; “Remotely Powered, Multichannel, Microprocessor Based Telemetry systems for Smart Implantable devices and Smart Structures”, Proc. SPIE Vol. 3673, p. 150-156, *Smart Structures and Materials 1999: Smart Electronics and MEMS*; Vijay K. Varadan; Ed

[3] D.L. Churchill et al., Strain Energy Harvesting for Wireless Sensor Networks, *Smart Structures and Materials, SPIE, vol. 5005, pp. 319–327, 2003*

[4] M.J. Hamel et al., Energy Harvesting for Wireless Sensor Operation and Data Transmission, *US Patent Appl. Publ. US 2004/0078662A1, filed March 2003*

[5] S.W. Arms et al., Shaft Mounted Energy Harvesting System for Wireless Sensor Operation and Data Transmission, *US Patent Appl. Publ. US 2005/0017602A1, filed Jan 2004*

[6] S. Roundy et al., Energy Scavenging for Wireless Sensor Networks with Special Focus on Vibrations, *Kluwer Academic Press, 2004.*

[7] N.E. DuToit, B.L. Wardle, Sang-Gook Kim; Design Considerations for MEMS-Scale Piezoelectric Mechanical Vibration Energy Harvesters, XIII International *Mat’ls Res. Congress (IMRC) Symp. 9 - Ferroelectricity & Piezoelectricity, 2004*

[8] J.A. Paradiso & T. Starner, Energy Scavenging for Mobile and Wireless Electronics, Pervasive Computing, *IEEE CS and IEEE ComSoc, Vol 1536-1268, pp 18-26, 2005*

[9] Galbreath J.H, Townsend, C.P., Mundell, S.W., Hamel M.J., Esser B., Huston, D., Arms, S.W. “Civil Structure Strain Monitoring with Power-Efficient High-Speed Wireless Sensor Networks”, *International Workshop for Structural Health Monitoring*, Stanford, CA, September 2003