

Power Scavenging Enables Maintenance-Free Wireless Sensor Nodes

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1.1. Introduction

There is a rapid increase in the deployment of wireless devices for industrial and commercial applications. Wireless devices are being used for applications such as security, surveillance, process monitoring, and machinery condition monitoring. Although the wiring costs for communications and power cables are eliminated with wireless devices, these costs are replaced with the ongoing cost of battery maintenance.

The ability to scavenge energy from the environment represents an important technology area that promises to eliminate wires and battery maintenance for many important applications. This technology is enabling and permits deploying self-powered sensor nodes that never require access in inaccessible locations or embedded into machinery.

A limited scope shipboard trial of wireless self-powered sensor nodes was conducted in collaboration with BP technology and shipping staff. Two self-powered sensor nodes were installed on the BP tanker *Loch Rannoch* (Figure 1) with the objective of establishing the viability of deploying wireless sensor nodes operating in a harsh shipboard environment for machinery condition monitoring.



Figure 1. BP Ship *Loch Rannoch*

1.2. Background

There are important technology changes occurring that promise to change the character of machinery monitoring. These changes will affect future machinery condition monitoring, safety, control, re-configuration, and security. New developments in diagnostic and prognostics algorithms, emerging CBM architectures and standards (e.g. OSA-CBM, MIMOSA Open O&M, and OPC/ISA), and new, low-power wireless communications standards and components (e.g. motes, Bluetooth and IEEE 802.15.4) enable the deployment of many low-cost distributed sensors. An array of distributed sensors can provide superior capabilities for mission-critical applications and can directly reduced maintenance cost and total life-cycle cost. Wireless sensor nodes often employ energy efficient processors, memory, radios, and energy-management logic. These systems have been under development for over 10 years and are targeted for applications such as surveillance, target acquisition, and machinery monitoring [Pister, Marcy, et al. 1996][Discenzo, Loparo, Chung, Twarowski 2001]. In spite of their energy efficiency, the need for a reliable, long-term energy source remains a roadblock to the broad-scale deployment of thousands of distributed sensor nodes.

For many distributed sensor applications it is not practical to provide wire-line power due to factors such as cost, weight, reliability, safety, or environmental hazards (e.g. explosive environments). For example, in many industrial applications the cost of wiring may be \$40 USD per foot or more and often exceeds the cost of the remote sensor. The need for costly wiring can be eliminated if the distributed sensor node is self-contained and is self-powered. Options for self-powering sensor nodes include batteries, micro-fuel cells, micro-generators, and power-scavenging technologies.

Harvesting power from stray energy for remote sensors is well-suited for CBM sensor applications. CBM systems often require periodic sampling from sensors which may be distributed across a machine, vessel, or facility. Remote sensor processing can typically be performed periodically and at a frequency consistent with the rate of local power generation.

Self-powered sensing devices are typically composed of elements capable of transducing energy from the environment, storing data and programs, communicating via RF modules, and sensing. The core elements that comprise a self-powered sensor nodes is shown below in Figure 2.

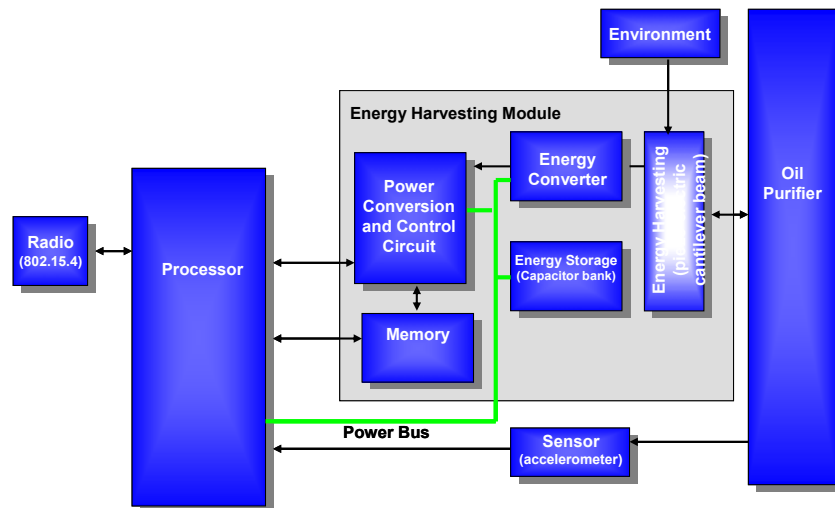


Figure 2. Components of a Self-powered Sensor Node

1.3. System Integration

The amount of energy that can be scavenged from the environment from machinery vibration is limited. Care must be taken in optimizing the generation and utilization of available power. A power budget is managed in the design and operation of the self-powered sensor node. The approach often taken is to optimize each component shown in Figure 2. However, due to the coupling that exists among the elements, optimization of individual components will likely result in a suboptimal system design. A series of analytical laboratory studies were conducted to determine the power consumption characteristics of

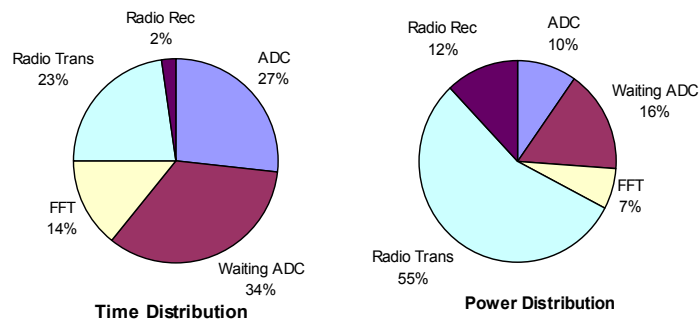


Figure 3. Time and Power Distribution for Wireless Sensor Node Operation

the system elements. An FFT algorithm was implemented in a wireless sensor node as a representative calculation for machinery health assessment.

While the percent of time is spent transmitting data is typically very small, the power requirements are significant (Figure 3). Power utilization in the self-powered sensor node may be optimized by judiciously balancing the amount of processing done locally in the sensor node with the amount of data that will be sent to a central processor for subsequent processing and analysis. The implication of this decision and the uncertainties in future processing demand and communications requirement provide the parameters for a dynamic optimization problem. The experimental results from the shipboard experiment provide realistic data to begin framing this optimization problem.

1.4. Shipboard Machinery Monitoring

Regular machinery monitoring is particularly valuable for shipboard systems. Routing power and signal cables on ships is frequently very difficult due the presence of thick compartment walls, limited free space for cable trays and conduits, and watertight compartment requirements. Similarly, manually capturing data at machines below deck is time consuming for the ship's crew and can be dangerous during high seas or in the presence of water, power cables, rotating machinery, hot surfaces, or hazardous fluids or gases.

A program was defined to evaluate the feasibility of using energy harvesting technologies to power wireless, sensor nodes for machinery condition monitoring. BP staff have supported this project by providing technical information, project guidance and access to the tanker *Loch Rannoch* (Figure 1) [The Economist v371, n8379][Merritt 2004].

1.4.1. Shipboard Trial

The objective of this program was to establish the viability of an energy harvesting system for machinery condition monitoring in a harsh environment (e.g. a ship machine room).



Figure 3. Self-powered Sensor Node

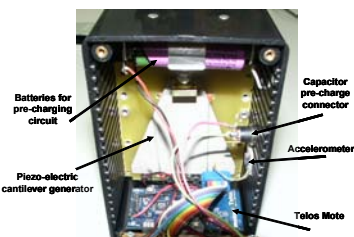


Figure 4. Assembled Self-Powered Sensor Node

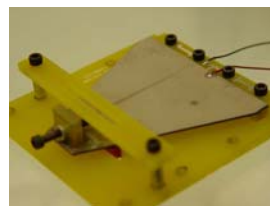


Figure 5. Piezo-electric Generator

Previous work conducted by the authors and published results from others indicates that piezo-electric material is the most appropriate generator technology for this application [Ghandi 2000][Roundy 2003 thesis][Roundy 2003 presentation].

The self-powered sensor nodes for this study were designed to continuously scavenge energy from a vibrating machine using a piezo-electric cantilever beam. The scavenged energy is converted and stored in a capacitor bank and used to power sensors, analog to digital converters (ADC), a microprocessor, local LED's, and radio communications. A picture of the self-powered sensor node is shown in Figure 3 Self-powered Sensor Node. The processor and radio boards used are commercially available motes (Telos mote from Moteiv Corporation).

Two self-powered sensor nodes were constructed. Each device is programmed to sample three analog inputs. The first analog input is the sampled data from an accelerometer. The accelerometer is a single-axis sensor mounted on the inside of the sensor node enclosure. Vibration data is sampled for one second at 1 kHz. The second analog input is the voltage generated from the piezo-electric generator. The third analog input is the state of charge of the capacitor bank. Each of these three inputs are stored in the local processor memory and also transmitted to a third processor. The third module receives the data transmitted from the two self-powered sensor nodes and sends the data through a serial port to a PDA with a memory card. Software on the PDA displays the time waveform data received from the two remote sensor nodes on an LCD and also archives the data to a memory stick in the PDA. To insure the success of the shipboard trial even in the event of a device fault or due to inadequate power generation capability, two identical self-powered wireless sensor nodes were constructed. One node was deployed using batteries plus power scavenging. This permits prolonged monitoring of power generation and energy utilization even if insufficient energy for operation is generated. The second self-powered sensor node was deployed without batteries and relies solely on power scavenging for continued operation. The sensor node components described above are housed in a small plastic enclosure attached to a stiff, non-ferrous mounting bracket (Figure 4).

An oil pump was identified as the candidate machine for monitoring since it operates continuously with a relatively high rotational speed. The target frequency where most of the vibrational energy exists for this oil pump is 7800 cps (130 Hz). A cantilever beam was designed with a resonant frequency of roughly 130 cps (Figure 5). Commercially available piezo-electric bi-morph material was used to construct the generator element (T220-A4 from Piezo Systems Inc.).

1.4.2. Shipboard Installation & Operation

There were many uncertainties in this experiment including the reliability and efficiency of the energy harvesting device during prolonged unattended operation at sea. Other shipboard uncertainties include the machinery duty cycle and operating characteristics, expected weather conditions in the North Atlantic and ambient vibration caused by other shipboard machines, sea state, climate, and ship operation. Research indicates it is likely that that harsh weather conditions and high seas occurred during the sea trial [Shetland Islands Council 2003].

Once an hour each sensor node is programmed to wake up, sample the vibration, the voltage from the piezo-electric generator and voltage from the capacitor bank. The

sampled data is transmitted to a third mote connected to a PDA and displayed graphically for the ship's maintenance crew and also archived. The third mote and the connected PDA are powered from the ship's power supply.

1.5. Experimental Results

The equipment was installed on the oil tanker and was left operating and unattended for four months from mid-August 2004 to mid-December 2004. Periodic readings provided by the ships crew indicated the system continued to operate during this period. Following the sea trial all equipment was removed from the ship and the data files captured from the sensor nodes were copied to a server for analysis. Over 8,000 data files were captured. Most of the captured data looks valid however some corrupt file names and data values were observed. The cause for the data faults is currently being investigated.

Vibration data was captured at 1 kHz with 12bit resolution. This data is used to compute the input power to the energy harvesting device. This output voltage from the piezo-electric generator was also captured to permit computing the output power. The ratio of the input power to the output generated power provides a measure of the conversion efficiency. One of the self-powered sensor nodes consistently generated very low power levels with the maximum power observed on the order of tenths of watts. The other self-powered sensor node was able to reliably generate hundreds of microwatts. Laboratory and analytical results suggest this device is capable of generating up to ten times this amount of power under planned operating conditions. The lower level of power generation observed is likely due to the variation in rotational speed of the motor-pump system and lower amplitude of vibration. Figure 6 below shows the power generated for the more efficient self-powered sensor node.

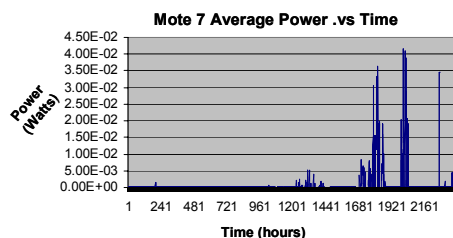


Figure 6. Plot of Average Power Versus Time for Mote 7

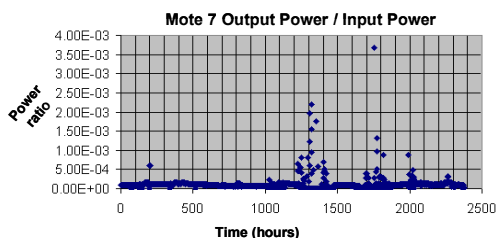


Figure 7. Mote 7 Power Conversion Ratio

The above diagrams suggest that the oil purifier runs periodically. It is instructive to view the ratio of the power generated to the input power. The power generated is recorded at each sample interval by the mote as the rectified voltage from the piezoelectric generator. The input power to the device may be approximated by the vibration sensed from the accelerometer attached to the inside of the power scavenging enclosure. At each sample interval, acceleration data is recorded. The power conversion efficiency may be calculated as the ratio of output power to input power.

The following equation is used to compute this ratio:

$$\text{Power Ratio Equation} \quad \frac{\frac{1}{50} \sum_{i=1}^{50} \frac{V_i^2}{2 \times 34.8 k\Omega}}{\frac{1}{500} \sum_{i=1}^{500} |A_i|} \quad (1)$$

The power ratio captured roughly every hour is shown in Figure 7. During operation, the machinery vibration is likely at an adequate amplitude level for the energy harvesting device but most likely at a frequency distant from the resonant frequency of the energy harvesting cantilever beam. The cantilever beam was tuned for a nominal rotational frequency of 7800 cps or 130 Hz. The data plots obtained from the onboard machinery database indicate a frequency of 7968 cps. This results in a stimulus relatively far from the 7800 cps target resonant frequency of the cantilever beam. This will result in reduced amplitude of vibration of the cantilever beam and a corresponding significant reduction in the amount of energy generated.

1.6. Conclusions

The design of the integrated energy harvesting module must be compatible with the expected operating environment. The generator design employed was optimized to extract the maximum energy from low levels of vibration of a pump operating at 7800 cps. However, when the machinery strayed from the targeted resonant frequency, this caused the device to produce significantly reduced power levels. Efforts are currently in progress to dynamically change the frequency response of the energy harvesting device in response to changes in the environment and operating equipment energy spectrum.

A systems approach is essential for defining the requirements of each of the system elements and how they integrate into an operational system. For example, power used to re-charge the capacitor bank affects the dynamics of the piezo-electric generator. Tuning the system to accommodate a wider range of frequencies rather than optimizing for the synchronous speed would have permitted power generation even as the pump speed varies. Finally, a greater threshold voltage for the power conversion electronics would permit scavenging a very small amount of energy even during conditions of low-amplitude vibration. The following summarizes the conclusions from this study.

1. There is a need for adaptive self-powered systems to accommodate uncertainties in the environment, analysis requirements, and equipment operation,
2. Energy Harvesting is a viable technology for wireless self-powered sensor nodes for applications such as shipboard machinery monitoring
3. It is important to establish hardened devices that operate reliably in harsh, dynamic environments, and require minimum set-up and installation effort.
4. A systems approach to design that incorporates a model of the environment is essential for a robust, efficient self-powered sensor node.
5. Collaborative development and in-field technology evaluation can accelerate development.

The shipboard trial has demonstrated the significant benefits provided by wireless sensor nodes for shipboard machinery monitoring. The potential benefits include increased machinery reliability, reduced maintenance cost, reduced maintenance effort, and enhanced safety. The benefits demonstrated with the shipboard trial of wireless sensor nodes have been recognized by a recent trade publication award [Infoworld 2004]. These benefits are enhanced by implementing self-powered systems designed to never require maintenance. This is an enabling technology that not only improves the economics of deploying sensor nodes but also permits devices to be located in inaccessible locations and embedded in un-powered rotating machinery.

The fundamental technologies demonstrated in this limited scope shipboard trial promise to change the way machinery will be monitored in the future.

1.7. Acknowledgement

The BP CTO organization is to be commended for providing the vision, the leadership, and the commitment to this innovative program. Special recognition goes to BP Shipping including the captain and crew of the *Loch Rannoch* for supporting this important field evaluation program.

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