Pump Condition Monitoring Using Self-Powered Wireless Sensors

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Fluid pumps are critical elements in many industrial, commercial, and marine systems. Continuous monitoring of pump systems is the most effective technique to insure efficient operation, help prevent unexpected pump failures, reduce repair costs and downtime, and provide early warning to avoid loss of pumped fluid. Wireless sensors are gaining increasing interest for equipment monitoring and surveillance applications. An alternative to battery-powered sensor nodes is the use of energy scavenged from the environment that may be converted and stored as needed to power remote sensors, processors, and RF communications. This article describes the development of a prototype, self-powered, wireless sensor node. Power is extracted from vibration using tuned piezoelectric elements. The self-powered sensor node performs local processing and transmits analytic results or raw sampled data to a central node for database storage and more extensive diagnostics and prognostics. The frequency of data analysis and transmission is a function of the available generated power. Examples are presented from a laboratory pump system and from a recent shipboard trial. Power efficiencies obtained are reported along with opportunities for adaptive power scavenging and dynamically optimizing power consumption.

There is a growing proliferation of wireless devices for many industrial and commercial applications – for security, safety, surveillance, 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. This includes battery cost, manpower, logistics, environmentally conscious disposal, protection from potential leakage, and potential equipment downtime due to unexpected battery failure.

A critical technology is the ability to scavenge energy from the environment and use this energy to power remote, distributed sensors, radios, actuators, processors, memories, and display elements. This technology is enabling and permits power-scavenging sensor nodes to never require servicing and to be deployed in inaccessible locations or embedded into machinery.

Rockwell Automation, in collaboration with BP's chief technology office in the U.K., has developed and deployed two self-powered wireless sensor nodes on the BP tanker *Loch Rannoch* (Figure 1). Wireless sensor nodes were deployed as part of a technology evaluation program to establish the viability of wireless sensor nodes operating in a harsh shipboard environment for machinery condition monitoring. The shipboard trial of self-powered sensor nodes was done in parallel with a larger scope test of wireless sensor nodes on the tanker.

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 prognostic algorithms, emerging condition-based maintenance (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. 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 reduce maintenance cost and

Figure 1. BP ship Loch Rannoch.

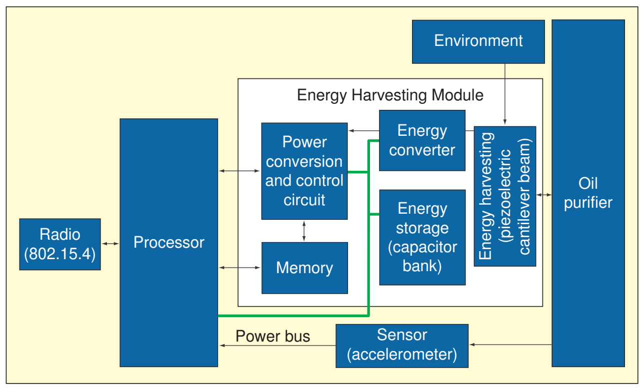

Figure 2. Components of self-powered sensor node.

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 more than 10 years and are targeted for applications such as surveillance, target acquisition, and machinery monitoring.[1,2] Despite 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, microfuel cells, microgenerators, 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 that 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. Newer materials such as certain piezoelectric materials exhibit high coupling efficiencies and can operate at elevated temperatures (>550° F). These materials are already being used for vibration and ultrasonic sensing and are effective for power-scavenging devices for CBM applications.

Figure 3. Self-powered sensor node

Remote self-powered sensing devices are typically composed of elements capable of transducing energy from the environment, data and program storage, radio communications, sensing, and packaging. The core elements that comprise the self-power sensor nodes to monitor the oil pump on the oil tanker are shown in Figure 2.

There are often additional elements such as auxiliary power or digital I/O. The communications link may not be required if the self-powered sensor node is used to locally store information and operate as a "black-box" system or if only a local display such as a tri-state LED (light emitting diode) is used to signal a machine fault.

Shipboard Machinery Monitoring

Regular machinery monitoring is particularly valuable for shipboard systems. Routing power and signal cables on ships is frequently very difficult due to the presence of thick compartment walls, limited free space for cable trays and conduits, and water-tight 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, or hazardous fluids or gases.

A program was defined to evaluate the capability of existing energy-harvesting technologies and to establish the deployment issues and operational benefits afforded by wireless, self-powered machinery condition monitoring system. A set of preliminary specifications was developed and a shipboard target application was established. BP has supported this project by providing technical information, project guidance and access to the tanker *Loch Rannoch* (Figure 1).[3,4]

Shipboard Trial

The objective of this program is to establish the viability of an energy-harvesting system for machinery condition monitoring in a harsh environment such as a ship machinery room.

Device Design. Several integrated self-powered sensor nodes were designed and constructed for this program. The self-powered sensor nodes continuously scavenge energy from the environment, convert and store the scavenged energy, and use the stored energy to periodically power sensors, operate analog to digital converters (ADC), operate a microprocessor, illuminate local LEDs, and perform radio communications. A picture of the self-power sensor node is shown in Figure 3. The connector shown at the top is used to temporarily provide DC power to initially charge the array of storage capacitors. After the capacitor bank is charged, the energy scavenged need only be enough to replace the depleted power from the operation of the sensor node.

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 are sampled for one second at 1 kHz. The second analog input is the voltage generated from the piezoelectric generator. The third analog input is the state of charge of the capacitor bank. The generator voltage and the capacitor state of charge are sampled to provide an RMS or DC voltage level. Each of these three inputs are stored in the local processor memory and also transmitted to a third processor.

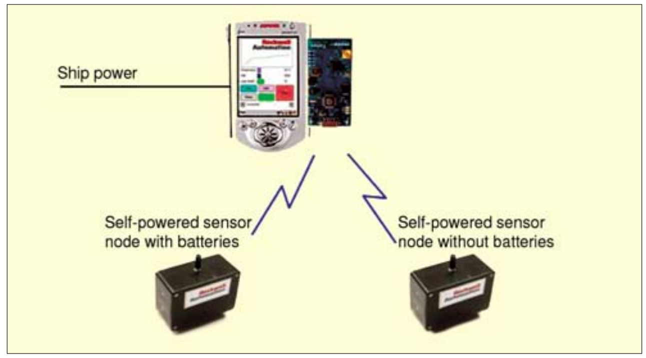

Figure 4. Configuration of sensor nodes.

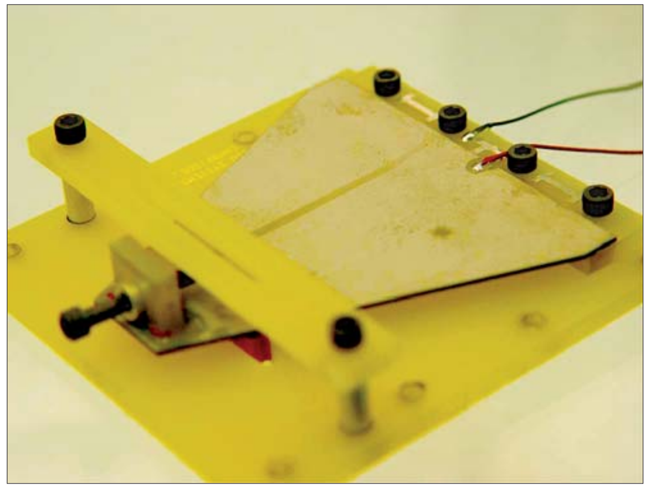

Figure 5. Piezoelectric generator.

The third module receives the data transmitted from the two self-powered sensor nodes and sends the data through the serial port to a peresonal digital assistant (PDA) with a memory card. Software on the PDA displays the time waveform data received from the two remote sensor nodes on a liquid crystal display (LCD) and also archives the data to a memory stick in the PDA. To reduce the risk of failure due to 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 configuration of the sensor nodes is shown in Figure 4.

The objective is to scavenge enough energy from the environment to replace the power needed to support the machinery monitoring and data transmission functions. Previous work conducted by the authors and published results from others indicate that piezoelectric materials are the most appropriate generator technology for this application.[5,6,7]

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).

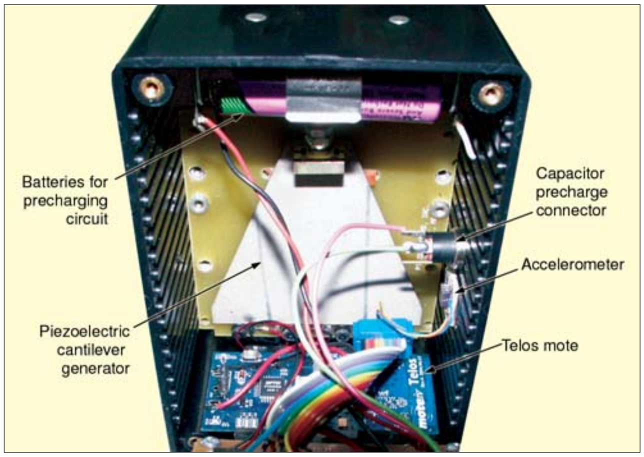

Figure 6. Assembled self-powered sensor node.

A cantilever beam was designed with a resonant frequency of roughly 130 cps (Figure 5). The narrow end of the beam has a seismic mass consisting of a small bolt that can be used to tune the resonance frequency of the beam. Commercially available piezoelectric bimorph material was used to construct the generator element (T220-A4 from Piezo Systems Inc.).

A power conversion circuit was developed to rectify the sinusoidal voltage from the piezoelectric generator, scale this voltage for charging the super-capacitor bank, convert power from batteries for precharging the capacitor bank, provide a voltage signal for monitoring the generated power and the capacitor state of charge, and regulate the power going to the processor and radio. An array of nine super-capacitors was used to store the generated power.

The sensor node components described above are housed in a small plastic enclosure attached to a stiff mounting bracket (Figure 6). The processor and radio used are a commercially available remote wireless transceiver (Telos mote from Moteiv Corporation). The piezoelectric generator is shown mounted to the bottom of the enclosure. The battery holder is mounted to the side of the enclosure and is shown with two lithium batteries installed. The batteries are used to precharge the capacitor bank prior to deploying the system. Alternatively, the capacitor bank may be precharged with a DC supply through the connector on the side of the case. Precharging the capacitor bank eliminates the need to wait days or weeks for the generator to build up a sufficient charge to operate the processor, sensors, and radio.

Shipboard Installation and 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 uncertainties include not knowing the expected duty cycle or operating characteristics of the machinery providing our source of power. Even if the machine operates continuously, it must operate with an appropriate level of vibration near our targeted, tuned frequency. Other shipboard uncertainties include the weather and ambient vibration caused by other shipboard machines, sea state, climate, and ship operation. Research has been done in each of these areas, and it is expected that harsh weather conditions and high seas are likely during the sea trial.[8] Movement of the ship's crew, closing compartment hatch doors, and radio interference are also considerations for this trial. Work was done prior to installing the self-powered sensor nodes to minimize these risks and insure a successful sea trial.

Background work included laboratory testing of components and system-level testing of the self-powered sensor nodes. A site survey was conducted aboard the ship prior to installing the equipment that included monitoring radio transmission performance at the planned radio frequencies while operating various shipboard machines such as motors and radar. Detailed documents were developed defining the procedures for the site survey, equipment testing, shipboard installation, and equipment decommissioning.

Two identical wireless sensor nodes were installed on the same oil pump in the machine room. One sensor node had batteries to augment the scavenged energy, and the other sensor node relied on scavenged energy for continued operation.

Each sensor node is programmed to hibernate for one hour. The sensor node wakes up each hour and turns on the accelerometer and samples vibration after an appropriate settling time. The accelerometer is turned off, and voltages are then sampled from the piezoelectric generator and from the capacitor bank. The radio is then cycled on. After a suitable delay to permit the radio to power up and synchronize, the sampled data values are transmitted to a third mote connected to a PDA, as shown in Figure 4. The self-powered sensor node then turns off the radio and returns to hibernate mode. The third mote receives the sampled data and sends the values to a PDA through the serial port. The PDA displays the time waveform data from both sensor nodes and logs the sampled data to a memory stick. The third mote and PDA are powered from the ship's power supply.

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 ship's crew indicated the system continued to operate during this period. Following the sea trial, all equipment was removed from the ship, and the 8,000+ data files captured from the sensor nodes were copied to a server for analysis. Most of the captured data look valid; however, some corrupt file names and data values were observed. The cause for the data faults is currently being investigated.

Vibration data were captured at 1 kHz with 12-bit resolution. This information can be used to compute the input power to the energy-harvesting device. This output voltage form the piezoelectric 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 perhaps 10 times this amount of power under the expected 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 7 shows the power generated for the more efficient self-powered sensor node.

Figure 7 suggests the oil purifier runs periodically. It is instructive to compute 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 average input power to the device may be approximated by the RMS value from the vibration sensed from the accelerometer attached to the inside of the power-scavenging enclosure. At each sample interval, acceleration data are recorded. The power conversion efficiency may be calculated as the ratio of the average output power to average input power.

The power ratio captured roughly every hour is shown in Figure 8. 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 on-board 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.

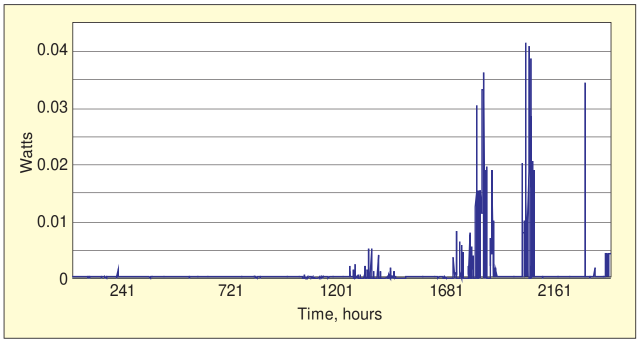

Figure 7. Plot of average power vs. time for Mote 7.

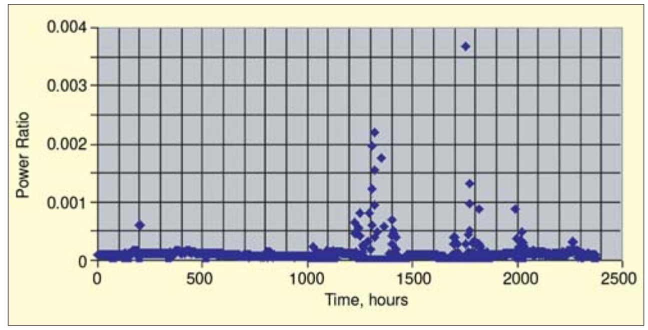

Figure 8. Mote 7 power conversion ratio.

Conclusions

The design of the integrated energy-harvesting module must be compatible with the expected operating environment. The generator design employed was based on extracting maximum energy from the relatively low levels of vibration observed. This caused the device to provide reduced power levels when straying from the targeted resonant frequency. Efforts are currently in progress to dynamically change the frequency response of the energy-harvesting device in response to changes in the environment and energy spectrum of the operating equipment.

A systems approach is essential for defining the requirements of each of the system elements and how they integrate into an operational system. A systems approach will ensure that the needed power is stored and used efficiently to accomplish the sensor node functions. The power budget includes requirements for sensors, radio, processing duration and frequency of operation, power conversion efficiencies, and power losses and leaks. The following summarizes the conclusions from this study:

- There is a need for adaptive self-powered systems to accommodate uncertainties in the environment and equipment operation,
- Energy harvesting is a viable technology for wireless self-powered sensor nodes for applications like shipboard machinery monitoring
- It is important to establish hardened devices that operate reliably in harsh, dynamic environments and require minimum set-up and installation effort.
- Data analysis requires more than sampled data from the sensor node.
- 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 and effort, and enhanced safety; these have been recognized by a recent trade publication award.[9] These benefits are further expanded 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 inside 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.

Acknowledgement

We commend the BP chief technology office for providing the vision, leadership, and 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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