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Continuous Machine Health Monitoring Enabled Through Self-Powered Embedded Intelligence and Communication

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Continuous Machine Health Monitoring Enabled Through Self-Powered Embedded Intelligence and Communication

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Abstract. This paper presents a fully self-powered machine health monitoring wireless node. A bismuth telluride thin film thermoelectric generator (TEG) is used to convert the temperature difference between the hot machine and the cooler ambient into electrical energy. By providing an autonomous power supply to the wireless condition-based monitoring (CBM) system, the cost of ownership is significantly reduced and this technology can become readily accessible to a much wider variety of applications. The paper discusses the system operation, component choices, and thermal transport issues that must be addressed to make an autonomous system viable. The system power consumption can range from 12 – 200 μ W depending on the refresh rate which spans the range of 30 s to 30 min. A temperature difference of 2.4 – 10 °C is sufficient to cover this operating span, considering the performance of typical thin-film thermoelectric harvesters.

1. Introduction

Autonomous condition-based monitoring (CBM) has the potential to eliminate downtime, reduce maintenance costs, and improve worker safety. In addition to vibration sources that exist by design, factory equipment can produce telling signs in their vibration signature that warn of things like bearing defects, imbalance and gear meshing, and provide an opportunity for timely corrective actions. Permanent CBM, often prohibitively expensive, is currently reserved for only the most critical pieces of equipment and only in certain industries like energy generation and petrochemical production, which can afford this technology. Other machines are monitored intermittently (or not at all) using hand tools and/or long time intervals that leave much to be desired with respect to the quantity of data, its repeatability, and the cost of having dedicated technicians. Connected devices and the Internet of Things have the potential to fundamentally reshape how CBM is performed and who has access to this type of technology. However, to make it truly cost competitive, wireless devices should not require maintenance themselves; therefore, an energy source that lasts the lifetime of the sensor node is required. This paper presents a fully autonomous CBM node that makes use of thermoelectric energy harvesting technology to supply its own power requirements. A bismuth telluride-based thin film thermoelectric generator (TEG) in the CBM node is used to convert the temperature difference between a hot machine it is installed on and the ambient into electrical energy. Few self-powered system implementations have been presented that use thermoelectric harvesting (for example [1, 2]) and even fewer have made it into the marketplace. Analog Devices seeks to reduce the technological burden of implementing self-powered systems by: 1) providing a wide portfolio of harvesters, power management ICs, and ultra-low-power sensors, microcontrollers and other core components, 2) easing the design and analysis of self-powered



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systems with tools that help in understanding the energy ambient, streamlining the planning and design process, and 3) offering reference designs such as this one that cover important details in both the physical implementation as well as the system design and optimization. The paper describes the system architecture and component selection to enable its ultra-low-power operation and thereby compatibility with energy harvesting.

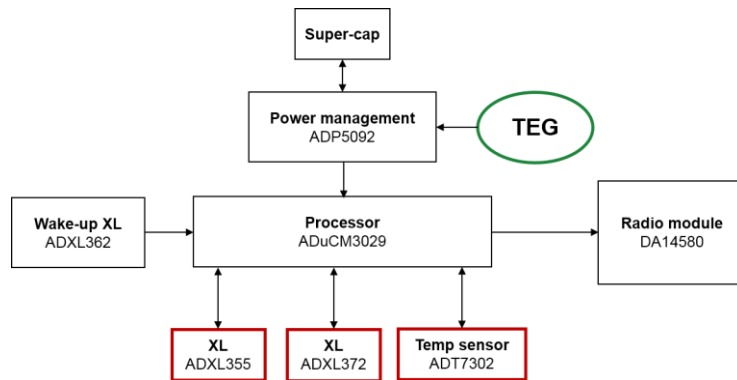


Figure 1. Block diagram of the machine health monitoring system.

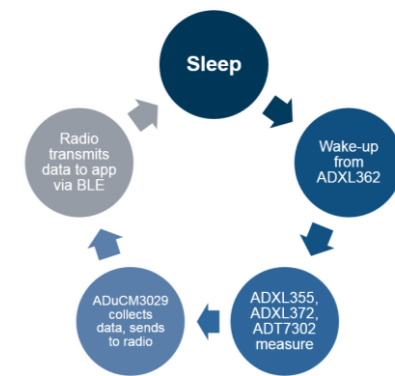


Figure 2. Typical task sequence for continuous self-powered monitoring.

2. Design

A block diagram of the self-powered machine health monitoring system is given in Figure 1. Power is supplied by a thermoelectric generator that can convert waste heat into useable electrical energy. In addition, this system makes use of the Analog Devices ADP5092 power management chip and ADuCM3029 microcontroller. The ADP5092 is designed for efficient conversion of dc power from energy harvesters (typically solar cells and TEGs) to charge storage elements (in this case, a supercapacitor) and power small battery-free devices. The ADP5092 employs a two stage charging process that takes care of system start-up and other cold-start events that may arise when the stored energy has been fully depleted. The ADuCM3029 is designed with 4 programmable active and sleep modes, allowing for excellent control over power consumption. SPI, I2C and UART interfaces allow for communication with a wide range of sensors. Four sensors are included in this system: (1) ADXL362, powered constantly and used only to wake up the microcontroller, (2) ADXL355 and ADXL372, low-power 3-axis accelerometers chosen to cover a dynamic range of 25 μ g to 200 g, and (3) ADT7302, a low-power digital temperature sensor. Data from these sensors is collected by the microcontroller and transmitted via Bluetooth.

2.1. System design

A typical task sequence for the continuous machine health monitoring system is shown in Figure 2. When in sleep mode, only the ultra-low-power ADXL362 and the ADP5092 (continuously storing energy generated by the TEG in the supercapacitor) remain powered. When a wake-up signal is generated from the ADXL362 (either due to a set vibration limit on the board or a fixed timer), measurements are collected from the remaining accelerometers (1024 samples of 9 bytes) and the temperature sensor (one sample of 2 bytes). After performing an FFT on the accelerometer data (reduced down to the 50 largest 12-bit coefficients), it is sent to the radio module for transmission. All components, except the ADXL362 and ADP5092, then return to sleep mode. How often data is transmitted ultimately depends on the particular use case—how much the TEG can generate from the available waste heat, whether data is required on a fixed timer or only on perturbation, etc.

2.2. Thermal considerations

Section 3.1 highlighted the “electrical system” constituting the machine health monitoring sensor node, powered entirely by thermoelectric energy harvesting. Since the TEG output depends strongly on the availability of waste heat and how efficiently that waste heat is accessed, careful consideration must also go into design of the “thermal system”.

A schematic of the system is shown in Figure 3. In this configuration, the sensor node is attached to the machine (heat source) using a magnet and heat is dissipated through an anodized aluminum fin array to the ambient (heat sink); in this way, a temperature gradient is maintained across the TEG. The key to optimizing TEG power generation is to minimize parasitic thermal losses, directing all heat flow through the TEG. Thermal resistances of interfaces and materials along the path of heat flow, in *series* with the TEG, must be minimized. This includes the magnet, the aluminum block standoff, the thermal grease and adhesive layers, and the heat fin. In addition, thermal resistances along heat flow paths in *parallel* with the TEG must be maximized. These parallel heat paths include the plastic standoffs on either side of the TEG, the plastic housing enclosing the entire sensor node, as well as the air around the TEG. Optimization of the thermal system requires careful choice of materials and geometries—typically, at least half of the available temperature drop (between the machine and ambient) should fall across the TEG.

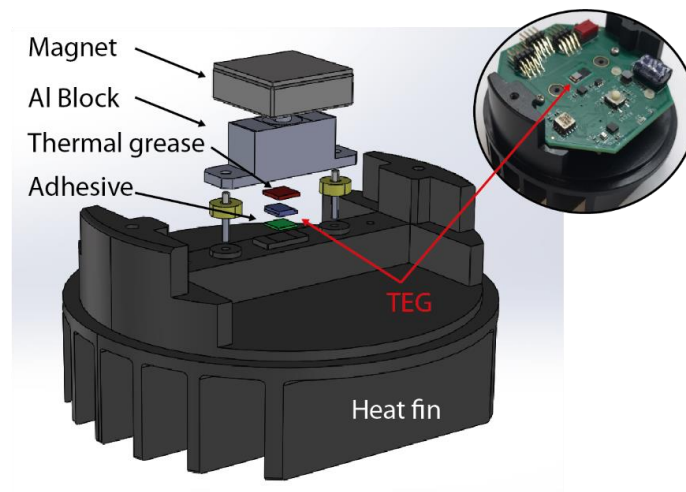


Figure 3. Schematic of the machine health monitoring system. The TEG sits in a hole in the PCB (shown in the inset photograph), directly attached to the heat fin. The plastic housing surrounding the sensor node is not shown.

3. Results

Estimates for the power consumption by component are given in Table 1 for data transmission every 30 seconds and every 30 minutes. For data updates every 30 s, nearly all of the 200 μW is consumed by the radio module. For data updates every 30 min, on the other hand, power consumption is dominated by the wake-up accelerometer (which as mentioned above is always on).

Table 1. Average power consumption in μW by component for two data update rates.

	DA14580	ADuCM3029	ADXL355	ADXL372	ADXL362	ADT7302	Total
30 s	172	16.1	5.56	0.685	4.89	0.240	199
30 min	5.82	0.433	0.093	0.011	5.39	0.004	11.8

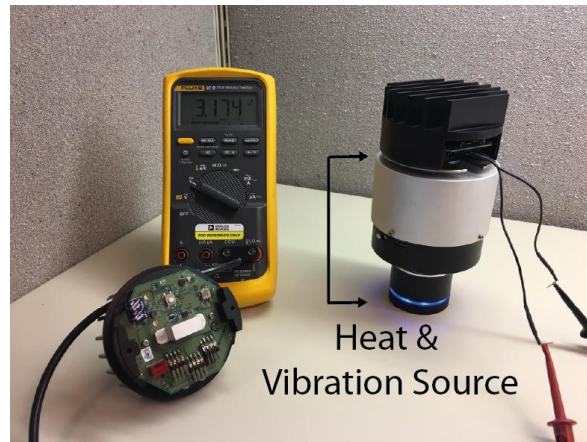


Figure 4. Photograph of the completed demo. A retrofitted speaker serves as the heat and vibration source in lieu of a machine.

Optimized thermoelectric energy harvesters can easily generate power on the order of 10 μW to 200 μW [3-5], depending on the temperature gradient available for a given use case. Using a particularly conservative estimate for TEG power generation, a temperature gradient ΔT of $\sim 10^\circ\text{C}$ would be required to power the sensor node with a 30 s update rate and a ΔT of only $\sim 2.4^\circ\text{C}$ required for a 30min update rate. Further optimization of the machine health monitoring system could mean a reduction in the required ΔT and/or an increase in the data update rates possible—making self-power continuous machine health monitoring available for a wider range of use cases.

A photograph of the completed demo is shown in Figure 4. The CBM system is shown resting on a retrofitted Bluetooth speaker which has been converted into a stand-in for a hot, vibrating piece of factory equipment by integrating a heat source and using the speaker to provide the vibration.

4. Conclusion

Autonomous condition-based monitoring has the potential to change the way in which factories operate machinery today, all the while reducing costs and improving safety. The technology necessary to achieve this is already available today, including sensing (ADXL355, ADXL372, ADXL362, ADT7302), processing (ADuCM3029), and finally power management (ADP5092). While one must take care of a number of issues related to thermal transport and making sure the maximum temperature gradient is seen across the TEG, a wide range of operating conditions and duty cycles are enabled with easily achievable temperature differentials between $2.4 - 10^\circ\text{C}$.

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