Powering Wireless Sensor Nodes with Ambient Temperature Changes

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ABSTRACT

Power remains a challenge in the widespread deployment of long-lived wireless sensing systems, which has led researchers to consider power harvesting as a potential solution. In this paper, we present a thermal power harvester that utilizes naturally changing ambient temperature in the environment as the power source. In contrast to traditional thermoelectric power harvesters, our approach does not require a spatial temperature gradient; instead it relies on temperature fluctuations over time, enabling it to be used freestanding in any environment in which temperature changes throughout the day. By mechanically coupling linear motion harvesters with a temperature sensitive bellows, we show the capability of harvesting up to 21 mJ of energy per cycle of temperature variation within the range 5 ℃ to 25 ℃. We also demonstrate the ability to power a sensor node, transmit sensor data wirelessly, and update a bistable E-ink display after as little as a 0.25 ℃ ambient temperature change.

Author Keywords
Sensing, Thermal energy harvesting, battery-free sensors.

ACM Classification Keywords
B.0. Hardware: General

INTRODUCTION

The ubiquitous computing community craves low-power and long-lived sensing networks; however, such sensors are currently hindered by the lack of progress in battery technology. Power harvesting provides an alternative solution for developing sensors that can last without battery changes or an external power supply. Such approaches are desirable, especially for sensors that may be placed in hard-to-reach locations. Common approaches such as solar, RF, and thermoelectric harvesting are often limited to specific environments: the environment requires sunlight in the case of solar, a thermal differential for thermoelectric harvesting, and a strong RF source for RFID.

Figure 1. Temperature-based harvester and sensor node

In this work, we introduce a new approach that relaxes those environmental constraints slightly by leveraging the minute and slow temperature fluctuations already present in the environment. Using a time derivative of temperature rather than a spatial gradient allows the use of battery-free sensors in places with no temperature gradient, such as in attics, basements, crawl spaces, walls, and outdoor structures.

Our approach consists of a specially tuned mechanical bellows filled with a temperature sensitive gas, linear motion harvesters that are attached to the bellows, a harvester circuit designed optimally for powering the microcontroller, a wireless transmitter, and an E-ink display. We are able to generate up to 21 mJ of energy per cycle of temperature variations in the range 5 ℃ to 25 ℃. We demonstrate the capability of this method to power a low-power sensor node, transmit sensor data wirelessly over 5 meters, and update a bistable E-ink display after as little as a single 0.25 ℃ change in ambient temperature.

RELATED WORK

In recent decades, self-powered wireless sensor nodes have risen in popularity. Thermal, kinetic, solar, and piezoelectric transducers have been developed [5]. For long-term sensors with low sampling rate, self-powered nodes usually harvest energy from the same stimulus that the device is designed to detect, such as WATTR [1] and the MIT Pushbutton [4]. However, there is a desire to build power harvesting systems that are more general purpose. Solar is a common example to serve that need, and thermal is the other.

For temperature-based harvesting, the typical method of energy extraction is using thermoelectric generators

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(TEGs), such as the NASA JPL Air/Soil energy-harvester [7]. TEGs are based on a phenomenon called the Seebeck effect [3]. Harvesting energy from TEGs requires spatial temperature differences, which means TEGs need both a heat source and a cooling source through a heat sink simultaneously, thus it cannot be used for a freestanding long-term sensing device.

Our approach is inspired by the Atmos Clock, which was invented by Jean-Léon Reutter in 1928. It is an ambient thermal driven clock. The clock has an expansion bellows, which has a round spiral tube filled with chloroethane [6]. As the ambient temperature varies, the bellows expands and contracts. This small displacement causes enough motion in the mechanism of a chain and a pulley to wind a mainspring, which in turn spins gears to display the time. A mathematical simulation [6] of the Atmos Clock shows that the displacement of the bellows could store 57 mJ of potential energy in the clock mainspring during a typical room temperature fluctuation of 2 ℃ over 24 hours.

HARDWARE DESIGN

To convert the ambient thermal energy to electricity, we experimented with various harvesting designs, including a brushless motor connected to the clockwork mechanism similar to the Atmos Clock design and a linear motion harvester-based system connected to a custom temperature sensitive bellows. Our custom bellows (purchased as an Atmos clock's spare part) measures 120 mm × 72 mm (at 25 ℃) and is filled with chloroethane (or ethyl chloride). Ultimately, we found the linear motion power harvester design provided the most design flexibility and provided more efficient mechanical coupling to the bellows, which is the design[1] we describe in this paper.

For our design, we use EnOcean ECO 200 linear motion harvesters designed for self-powered wireless light switches. Each motion harvester only needs to be driven by 1.2 mm of linear movement with 4 N of force in either direction and generate up to 0.21 mJ per actuation [8]. That energy is enough to power an ultra-low-power wireless sensor node, such as a SNUPI node [2] or an ECO PTM-330C [9] wireless transmitter. Benefitting from their small mechanical dimensions (29.3 x 19.5 x 7 mm), the harvesters can be stacked as an array around our custom bellows using a mechanical couple.

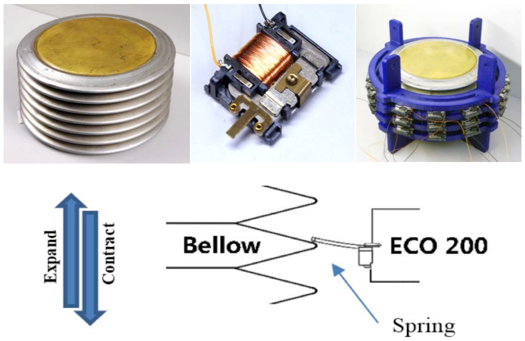

Figure 2. The bellows, ECO 200 linear harvester, and the temperature power harvester (top). Mechanical coupling to the bellows (bottom).

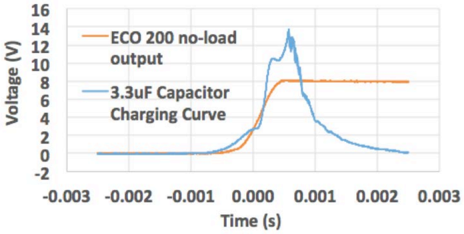

Figure 3. The output voltage of the motion harvester and 3.3 uF capacitor.

To determine the feasibility of using slow changing temperature changes as a power source, we put 12 ECO 200s around the perimeter of the bellows using a custom plastic attachment mechanism (see Figure 2). The thickness of each layer is 12 mm (7 mm + 5 mm of plastic), which can be reduced by a metallic structure. In this design, up to 36 motion harvesters can be installed in 3 layers around the bellows. It should be noted that our harvester design can be built using off-the-shelf components, unlike much of the prior work.

As shown in Figure 3, the open circuit (*i.e.* no-load) output of the motion harvester is a 13 V peak pulse. The energy stored in a capacitor is given by $E_{stored} = \frac{1}{2}CV^2$, where V is the voltage applied to a capacitance C. We need a capacitor with a specific amount of capacitance to satisfy the power supply requirements of our demonstration devices. To demonstrate the capability of this harvester design, we built a typical sensor node consisting of a low-power MSP430 microcontroller, a 433 MHz wireless transmitter, and a small bistable E-ink display. To power the bistable E-ink display, we connected a 3.3 μF electrolytic capacitor and a diode to each motion harvester. Each capacitor can be charged to 8 V (0.105 mJ) for updating the E-ink display. For the wireless sensor node, we use a 22 μF capacitor which can be charged to 3.3 V (0.12 mJ) by one motion harvester. As shown in Figure 4, a 433 MHz RF transceiver

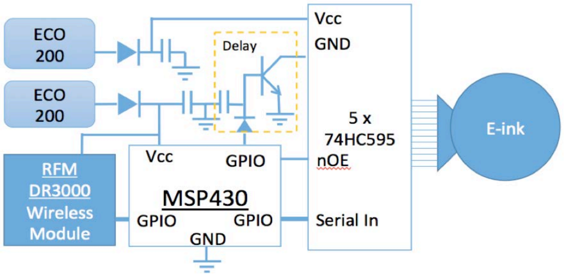

Figure 4. Block diagram of the demonstration device

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[1] Design files, source code and the bill of materials: http://ubicomplab.cs.washington.edu/projects/TemperaturePowerHarvester

(RFM DR3000) and 5 74HC595 shift-registers are connected to a Texas Instruments MSP430G2231 microcontroller through the GPIO Pins. Since the MSP only can run for 50 ms in this system, we use 5 shift-registers to store the output state of the MSP for a few seconds after the MSP runs out of power. A 2.5 digit numeric E-ink display is used as a temperature gauge in our demonstration and is driven by shift-registers.

EVALUATION

To measure the performance of our harvesting method, we evaluated the sensitivity of our bellows to temperature changes and the amount of force exerted as the bellows expands and contracts. We chose to empirically measure these parameters due to the unavailability of a proper datasheet and physical model for the gas expansion in the bellows.

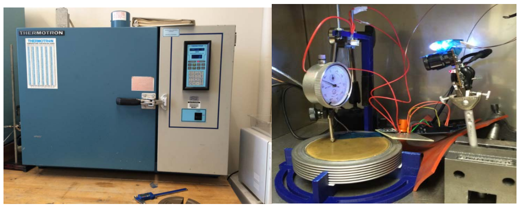

Figure 5. Temperature controlled chamber (left). Bellows distance and force testing system (right).

Temperature Sensitive Bellows Test

To simulate fluctuating ambient temperature, we used a benchtop temperature controlled chamber with a Thermotron 2600 temperature controller (see Figure 5), which has a temperature range of -73 °C to +180 °C. As tested in a pre-experiment, our custom bellows fully contracts to 22.6 mm at approximately 0 °C and fully expands to 72.2 mm at 31 °C. Due to the non-linear characteristics of the bellows-temperature relationship, the height between 10 °C and 20 °C was recorded at 1 °C intervals while all other measurements were taken at 3 °C intervals. The bellows and all measuring equipment were placed in the temperature-controlled environment. Subsequent changes in height were measured with a granite check surface comparator as the temperature was gradually raised to 31 °C. Tests were then performed to find how the height–temperature relationship varies when masses of 1 kg, 5 kg, and 10 kg are added on top of the bellows to simulate applied forces from the linear motion power harvesters.

The resulting characterization curves are shown in Figure 6 (left). The data from these tests show largely similar rates of expansion regardless of the mass added. This supports the theory that a substantial number of power harvesters can be used with the bellows for energy harvesting purposes. The result of the 10 kg mass test shows that it can drive up to 25 ECO200 simultaneously, while the force threshold of each motion harvester is 4 N [8]. To avoid damging the bellows, we limited the weight on top of it to 10 kg; however, we believe that the bellows could potentially support more. Since the bellows is made of a soft metal (*i.e.* the stiffness is negligible), the maximum contraction force can be estimated by the atmospheric pressure function $f = \pi r^2 p$. Given the bellows' radius r = 6 cm and the standard air pressure p = 1 atm, the maximum force works out to be 1145.95 N. At 12.3 °C, the boiling temperature of chloroethane, a 1 °C change moves the 10 kg mass 5 mm, thus a single 0.25 °C change is enough to drive 1 layer of the motion harvesters.

Evaluating the System

We evaluated the entire system in an outdoor environment. With a 22 µF capacitor and a diode connected to the output of the harvester, we measured the output voltage. To keep the bellows balanced, we placed 3 layers of motion harvesters around the bellows with 12 motion harvesters each, and only use the end top edge of the bellows to swipe the motion harvesters. We collected measurements from a BMP085 (a barometric air pressure and temperature sensor) from 1am to 1pm, during which the temperature increased from 5.3 °C to 16.2 °C. As shown in Figure 6 (right), this device generated 4.320 mJ (*i.e.* an average power of 0.1 µW over 12 hours).

Working Sensor Node

In each packet of the transmitting and receiving signal, the node sends 10 bits of temperature data from the MSP's onboard temperature sensor. When placed indoors in an air-conditioned space, we found that each motion harvester powered the entire sensor node to measure the temperature 16 times and wirelessly transmitted that data 5 m away 8 times with a single actuation, *i.e.* 15 µJ per data packet (see Figure 7). With 3×12 linear harvesters on the same bellows,

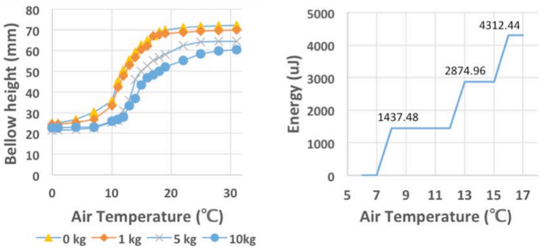

Figure 6. The bellows height changes with various weights (left). Energy stored in the capacitor with increasing temperature (right).

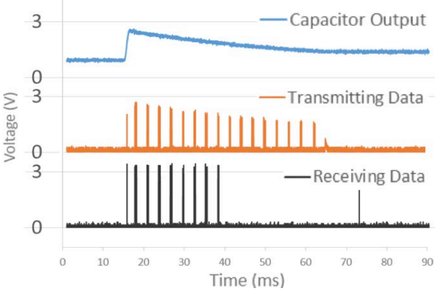

Figure 7. The power output and received data in a single actuation of one linear motion harvester

we can send data 288 times during the temperature increase from 5.3 ℃ to 16.2 ℃.

Meanwhile, the MSP charges the delay circuit to connect the shift registers' GND pins with the ground and sends data to shift registers. Powered by another capacitor which is charged beforehand, shift registers work for about 1 second to change the corresponding segments of the E-ink display. The 0.105 mJ of energy stored by the 3.3 µF capacitor can update the display 5 times. Because the sensor node starts to work immediately once the capacitor is charged, the leakage from capacitor is negligible.

DISCUSSION

To maximize efficiency, we can attach up to 7 layers and 25 motion harvesters in each layer to the bellows with a metallic structure. In this case, this device generates 21 mJ in one period with temperature increases and decreases, within the 5 ℃ to 25 ℃ range. The other option is to modify the motion harvesters such that the harvesters will be reset after each actuation and driven by all 7 ridges of the bellows. Improving the linear harvester geometry would also allow us to more effectively couple and increase the number of harvesters connected to the bellows, thus increasing the power output.

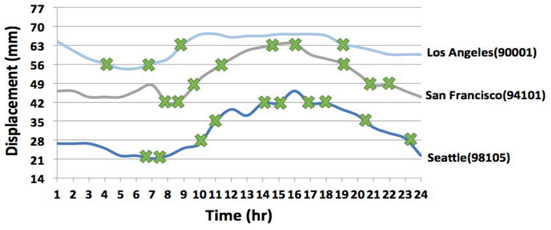

Figure 8. The displacement changes in different area.

In Figure 8, we estimated the displacement of the bellows in 3 cities based on the temperature history of March 17, 2014 [10] and the 10kg mass test results (from Figure 7). With 7×25 linear harvesters, it can generate 12 mJ (0.13 µW over 24 hrs) in Los Angeles, 27 mJ (0.31 µW) in San Francisco, and 30 mJ (0.35 µW) in Seattle. We also estimated the generated energy within every 24 hours from August 2013 to March 2014 (see Figure 9). The data is recorded by a Wally node[11] that is installed in a typical house attic in Seattle.

Clearly, the specific gas in the bellows determines the working temperature range of the entire harvester. Our bellows is filled with chloroethane, which is ideally suited for the climate in our region. Table 1 shows the boiling temperature of various gases and the approximate working temperature range. Other gases like acetaldehyde, butane, or trichlorofluoromethane, can be used in different climates. Furthermore, we imagine extending the operating range by using a mixture of these gases or even using different chambers within the bellows.

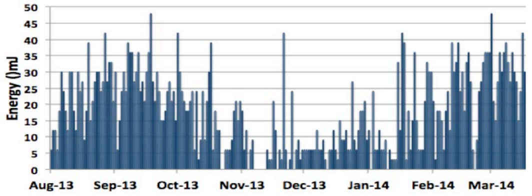

Figure 9. The generated energy within every 24 hours

Gas	Boiling Temperature	Operating range (Approx.)
Butane	-0.5 ℃	-8 ℃ ~ 12.2 ℃
Acetaldehyde	20.2 ℃	12.7 ℃ ~ 32.9 ℃
Chloroethane	12.3 ℃	4.8 ℃ ~ 25 ℃
Trichlorofluoromethane	23.77 ℃	16.27 ℃ ~ 36.47 ℃

Table 1. Boiling temperatures of gases.

In a future iteration, the size of the bellows could be reduced while still generating usable power. The pressure rise inside the bellows can be expressed by the ideal gas law: $p_b \mathrm{v} = \mathrm{m}R_{specific}\mathrm{T}$, where p_b is the absolute pressure of the bellows, v is the volume of gas, m is the mass, and T is the thermodynamic temperature. The gas constant R of chloroethane is 129. Ignoring the stiffness of the bellows (which is relatively small), the equation of the bellows' driving force, f, can be estimated by Newton's law as

$$f = a_b p_b - a_b p_a = \frac{\mathrm{m}R_{specific}\mathrm{T}}{h} - a_b p_a$$

where a_b is the bellows end cap surface area. Thus, we can estimate the maximum number of single linear motion power harvesters as

$$h \times f = \frac{\mathrm{m}R_{specific}\mathrm{T}}{1 + \frac{a_b p_a}{f}}$$

When $a_b p_a$ is much larger than the f, $h \times f$ is a linear function of m, which implies the volume of the bellows in steady state will linearly determine how much electrical energy the system can generate. For instance, if we reduce the size of our current prototype size to ⅔ we would still be able to generate 14 mJ of power and if we further reduced the size to ⅛ of our current prototype (roughly the size of a D size battery), we could theoretically generate 2.6 mJ of power with the same temperature changes.

CONCLUSION

In this paper, we presented details of a new power harvesting system capable of harvesting energy as a result of changing ambient temperature. We also presented a prototype that is capable of generating up to 21 mJ of electrical energy with one period of ambient temperature change, and further demonstrated how a single 0.25 ℃ room temperatures change could be used to power a wireless sensor node and update an E-ink display. Although our current design is may be bulky for certain applications, we argued that a reduction in the bellows size could be made without compromising the usable energy it produces.

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