A SELF-POWERED WIRELESS SENSOR FOR INDOOR ENVIRONMENTAL MONITORING

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ABSTRACT

Wireless sensor networks are an emerging technology with a number of potential applications. One such application is the monitoring of indoor environments to facilitate more efficient use of energy for climate control. Such an application necessitates an infinite-life power source that will work in low-light conditions. This paper details the design, fabrication, and testing of a self-powered wireless temperature sensor node. The sensor node, mounted on a wooden staircase, uses a piezoelectric bimorph to generate electricity from vibrations in the staircase. This generator powers a thermistor and wireless radio to transmit temperature readings to a remote computer. Vibrations generated by continuous traffic on the staircase produced 30μW from the piezoelectric generator, sufficient to power the sensor and radio hardware.

INTRODUCTION

Recent regional energy crises in California demonstrate a need to reexamine the state's overall energy usage. Many of the problems experienced stem from an overburdening of the electrical grid on warm, sunny afternoons when thousands upon thousands of businesses and residences use air conditioning concurrently. On such days, demand for electrical power spikes and the incremental cost of the electrical capacity to cover this demand becomes exorbitant [1].

In response to this issue, researchers are investigating ways to reduce electrical energy use on peak demand days. One part of this program involves placing a network of many small environmental sensors throughout a building to accurately monitor temperature and light levels. The resulting "smart" environment would more efficiently use energy resources, reducing demand while maintaining occupant comfort [2].

For such a system to be ultimately feasible, a suitable power source for these sensor nodes must be found. The labor costs and logistical issues associated with wiring every node for power make the isolation of these nodes from the power grid a practical necessity. Ideally, a power source that provides multiple years of maintenance-free operation will be identified.

Solar power is a promising alternative power source but is not abundantly available in indoor applications. Harvesting energy from vibrations is a more feasible option in these environments. Prior research has been done on vibration-based power generators using electromagnetic [3,4], electrostatic [5,6], and piezoelectric [7,8] conversion.

The authors conducted a proof-of-concept exercise to verify the feasibility of a self-powered wireless sensor node by means of piezoelectric energy conversion for this environmental monitoring application. This paper describes the design and fabrication of such a sensor node using off-the-shelf parts, and the testing of this device both in the laboratory and in a real-world deployment environment.

SELECTING A POWER SOURCE

Environmental monitoring sensor nodes require a self-contained power source. Available options include limited-capacity energy reservoirs such as batteries, and infinite-life energy sources such as solar cells or vibration-to-electricity energy scavenging transducers.

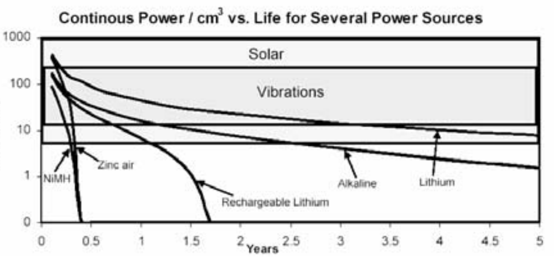

Fig. 1: Comparison of Power Densities for Energy Sources

Figure 1 compares the power density for each of these options over a multi-year service lifetime [8]. An examination of these options reveals even the most advanced battery technologies to be insufficient to power a wireless sensor node over a desired lifetime of several years. Solar power is an attractive option, but indoor lighting often does not provide sufficient light for adequate power generation [9]. Vibration energy scavenging, however, is a viable alternative for an indoor deployment.

Vibrations are abundant in a building environment. Common sources include floors, windows, air ducts, and machinery. Table 1 [9] shows peak frequencies and corresponding accelerations for several common indoor vibration sources.

In this prototyping exercise, vibration energy scavenging was selected as the most suitable method of power generation for the wireless sensor radio device. The three primary options for converting vibrations to electricity include variable capacitor generators, electromagnetic generators, and piezoelectric generators. A design using a piezoelectric bimorph generator was used, as these devices have greater potential power density [8], and because they are most easily fabricated from off-the-shelf parts.

Table 1: Peak Frequencies and Accelerations of Vibration Sources

Vibration Source	Freq. of Peak (Hz)	Peak Accel. (m/s^2)
Kitchen Blender Casing	121	6.4
Clothes Dryer	121	3.5
Door Frame (just after door closes)	125	3
Small Microwave Oven	121	2.25
HVAC Vents in Office Building	60	0.2-1.5
Wooden Deck with People Walking	385	1.3
Bread Maker	121	1.03
External Windows (size 2ftx3ft) next to a Busy Street	100	0.7
Notebook Computer while CD is Being Read	75	0.6
Washing Machine	109	0.5
Second Story of Wood Frame Office Building	100	0.2
Refrigerator	240	0.1

SYSTEM DESIGN

An integrated wireless sensor device comprises the following major components:

- A piezoelectric bimorph generator which converts vibrations to electricity, producing an AC current
- Power conditioning circuitry which converts the AC signal from the generator to a DC current suitable to power the rest of the hardware
- Sensor hardware, in this case a temperature sensor (thermistor)
- Wireless radio hardware which interprets the sensor signal and transmits it to a remote base station

Figure 2 shows a schematic of the sensor node components.

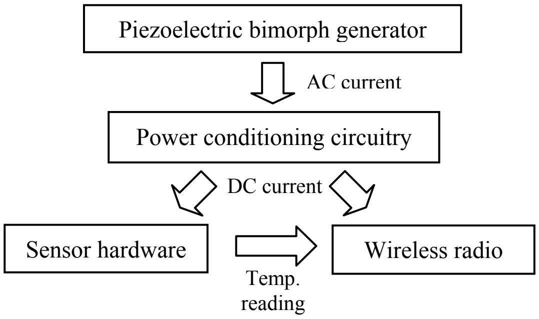

Fig. 2: Overall System Design

Piezoelectric Bimorph Generator

The design of a vibration energy scavenging generator first requires careful examination of the vibration source for the application. In this case, a wooden staircase in a wooden building on a university campus was selected, as it approximates a residential environment and because it vibrates noticeably with foot traffic.

The resonance characteristics of this staircase were analyzed to determine the optimal vibration mode around which to design the piezoelectric bimorph generator. A PCB Piezotronics 357B01 accelerometer measured the vibrations resulting from foot traffic on the staircase, and a frequency spectrum analysis was obtained using a fast Fourier transform. Figure 3 shows this spectrum analysis.

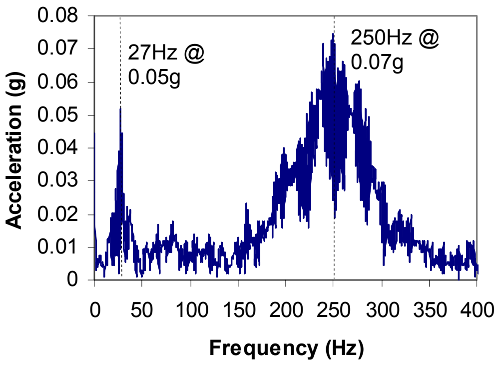

Fig. 3: Frequency Spectrum Analysis of Staircase Vibrations

It is clear from Figure 3 that there exist two primary vibration modes, one at approximately 27Hz and another at 250Hz.

A piezoelectric bimorph generator essentially consists of a metal shim sandwiched by two thin layers of piezoelectric material. A proof mass is attached to one end, and the other end is held in a clamp coupled to the vibration source. As the proof mass oscillates, stress occurs in the top and bottom piezoelectric layers, alternating in tension and compression, creating a sinusoidal charge difference across the beam over time. Figure 4 shows a schematic of such a generator.

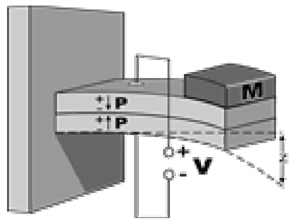

Fig. 4: Schematic of Piezoelectric Bimorph Generator

In building a piezoelectric bimorph power source, it is essential to design the generator around the resonance characteristics of the vibration source. Power generation is optimal when the resonant frequency of the generator exactly matches the frequency of the vibration source [9]. As there were two resonant peaks identified in the vibrations from the wooden staircase, further analysis is required to determine which is more appropriate for our design.

The piezoelectric bimorph generator can be modeled as a spring-mass-damper system. This analysis produces the following expression for maximum power generation [8].

$$P_{\max} = \frac{m\xi_e A^2}{4\omega\xi_T^2}$$

In this expression m is the proof mass, A is the acceleration magnitude, ω is the vibration frequency, and ξ_e and ξ_T are electrical and mechanical damping constants, respectively. It is important to note that, as power is directly proportional to the proof mass, it is always desirable to use the most massive proof mass feasible for a given application. Careful inspection of this expression also reveals that the resonant peak which maximizes the ratio A^2/ω has the greatest potential for power generation. Thus the 27Hz mode was chosen because its A^2/ω value is roughly five times the corresponding value for the 250Hz peak. Using the above expression for power, this frequency mode, and its corresponding acceleration magnitude of 0.05g, predicts a theoretical power output of about 30µW.

A piezoelectric bimorph from Piezo Systems with the dimensions 31.5x12.7x5.1mm (1.25x0.50x0.02") was used in constructing the generator. This bimorph uses a brass center shim and PZT-5A4E, a commercially available piezoelectric material selected for its favorable fatigue characteristics. A 52g tungsten mass was affixed to one end using cyanoacrylate glue, and the device was mounted in a rigid plastic clamp. Figure 5 shows a photograph of the generator.

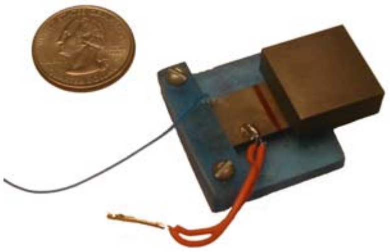

Fig. 5: Piezoelectric Bimorph Generator Prototype

The resonant frequency of the generator was tuned by making small adjustments to the position of the bimorph with respect to the clamp. A LabWorks vibrating actuator was used to generate test vibrations for resonance tuning purposes.

Power conditioning circuitry

The AC voltage produced by the generator is inappropriate to power the sensor and radio hardware directly. A circuit was devised to condition the signal from the generator, transforming it into a usable DC voltage.

Whereas the generator produces an unsteady, foot traffic dependent AC output with peak-to-peak voltages anywhere from 0–35V, the sensor and radio hardware require 3.3VDC signal for operation. The generator also does not produce enough power for continuous operation of the sensor and radio. The power circuit thus had to perform two tasks:

- Store the generator's output until sufficient energy was collected to take and transmit a temperature measurement
- Output a steady 3.3VDC current to the sensor and radio hardware

A schematic of the power circuit is shown in Figure 6. The output signal of the piezoelectric bimorph generator is first rectified then stored in a storage capacitor.

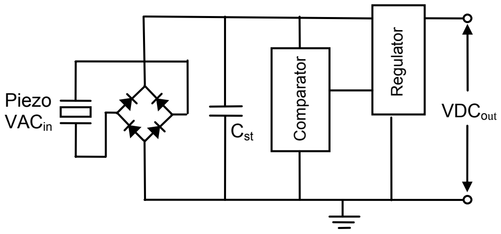

Fig. 6: Power Conditioning Circuit Schematic

A Maxim MAX6433 comparator and a Texas Instruments TPS72501 voltage regulator provide a DC pulse to the sensor and radio hardware. Normal operation of the piezoelectric generator causes voltage to build on the storage capacitor. When that voltage reaches 5 volts, the comparator allows charge to flow from the capacitor through the regulator. The regulator outputs a steady 3.3VDC pulse to the sensor and radio hardware, triggering a temperature reading. Once the voltage on the storage capacitor drops to 3.5 volts, the comparator stops the flow of charge through the regulator, and the circuit once again begins storing the generator's output. All voltage levels on the comparator and regulator are programmed using feedback resistors.

The majority of the power circuitry components were mounted onto a custom-fabricated printed circuit board. The printed circuit board is round in shape and roughly 30mm in diameter to closely match the form factor of the wireless radio hardware. Figure 7 illustrates this circuit.

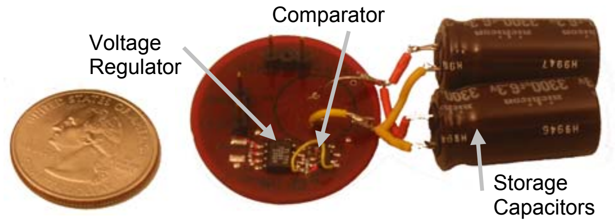

Fig. 7: Power Conditioning Circuit Prototype

Two 3300µF aluminum electrolytic capacitors were wired in parallel to provide 6600µF of storage. Appropriate storage capacitance was found experimentally. Capacitance must be sufficient to take and transmit a temperature reading. Excess capacitance is undesirable, as it necessitates a longer charging period between temperature readings given the comparator voltage limits designed into the circuit.

Sensor and Wireless Radio Hardware

A Crossbow Mica2Dot wireless radio was chosen as the wireless platform for this project. The Mica2Dot provides low power consumption, compact design, computational ability, and programmability. A VSI H10000 thermistor temperature sensor and a 9.83kΩ resistor were used to create a voltage divider. This voltage divider was wired directly to the analog-to-digital converter (ADC) input on the Mica2Dot. Figure 8 shows the Mica2Dot.

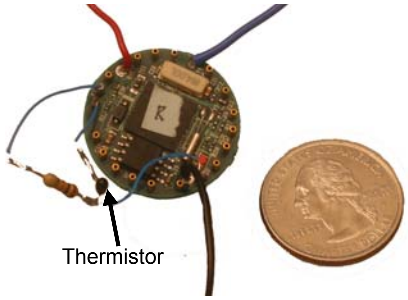

Fig. 8: Crossbow Mica2Dot Wireless Sensor Network Node

In operation, the sensor and radio hardware were turned off while the power circuit collected power from the generator. When a 3.3VDC pulse was released from the power conditioning circuit, the Mica2Dot was programmed to power on, initialize, measure the ambient temperature, and broadcast the result. Another Mica2Dot connected to a nearby notebook computer received and displayed the temperature data on screen.

Packaging

A custom-designed compact casing was fabricated from ABS plastic using a Fused Deposition Modeling (FDM) rapid-prototyping machine. The outer dimensions of this casing are 70x54x47mm. Figure 9 shows the design.

Fig. 9: Package Prototype

A window on the bottom of the casing allows the piezoelectric bimorph generator's base clamp to directly contact the source's vibrating surface, thus assuring the most direct mechanical coupling. A small hole allows the thermistor unshielded access to the ambient environment. Figure 10 shows the complete self-powered wireless temperature sensor device in its packaging.

RESULTS

The self-powered wireless environmental sensor device was first tested in the laboratory. It was mounted atop a LabWorks ET-126 vibrating actuator driven by an Agilent 3312OA signal generator and a LabWorks pa-138 power amplifier. The vibrating actuator was set to mimic the 27Hz frequency mode of the staircase.

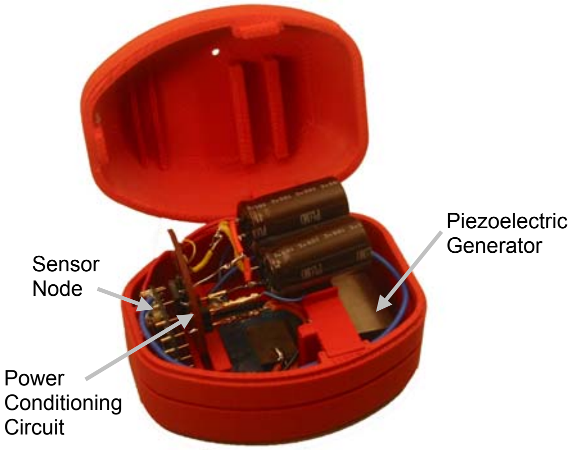

Fig. 10: Assembled Prototype

Results of the experiment are shown in Figure 11. The top signal trace illustrates the charging of the capacitors to the upper threshold value of 5V, followed by a discharge to the lower threshold of 3.5V. The lower trace represents the signal output from the power conditioning circuit. The discharge of the capacitors produces a 816ms pulse of constant 3.3VDC signal output to the sensor and radio. A pulse of this length was sufficient to power up the hardware, read temperature, and transmit a temperature reading to a base station.

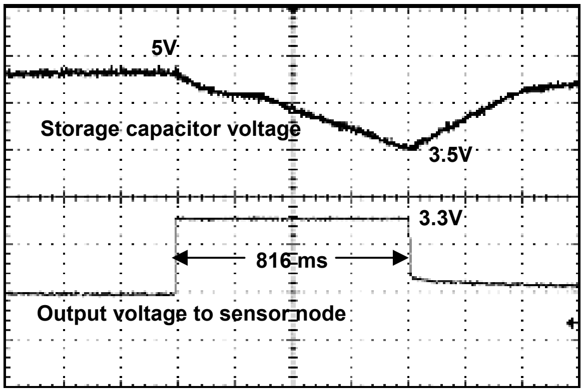

Fig. 11: Capacitor Discharge and 3.3VDC to Mote

The sensor node was programmed to transmit a temperature reading every 10ms once initialized. With an 816ms pulse of power, only two temperature readings were transmitted. The sensor and radio hardware took nearly 800ms to power on and initialize before transmitting the first temperature reading.

The device was then tested in situ. The storage capacitors were pre-charged to 3V using two AA batteries. Fifty minutes of continuous traffic provided by two people walking on the staircase were required to replicate the transmission of temperature readings achieved in the laboratory. Current flow through the system is illustrated in Figure 12. Energy collected in the capacitors between pulses was 88mJ. Average power transfer from the piezoelectric generator to the capacitors was 29.3µW. This value closely matches the predicted power output of the piezoelectric generator as described previously. Once the capacitors reached the threshold value of 5V, the capacitors discharged. Power transfer from the capacitors through the remaining portion of the power conditioning circuit was 108mW. Power input to the sensor and radio hardware was found to be 45mW. Therefore, the efficiency through the power circuit is estimated to be 42%.

CONCLUSIONS

Previous studies proved that it is possible to power a wireless sensor and radio using a vibration energy scavenging generator in a laboratory environment [9,10]. Unlike these previous studies, this exercise verified the feasibility of powering such a device in a real-world deployment situation, in this case a wooden staircase in a wooden building.

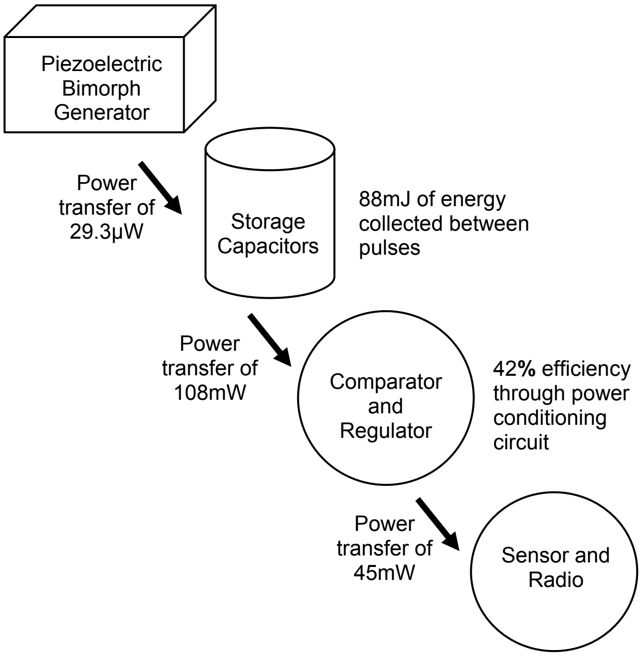

Fig. 12: Power Flow and System Characteristics of Device

The prototype detailed in this paper required 50 minutes of continuous staircase foot traffic from two people to take and transmit a set of two temperature readings. This cycle time is driven largely by the roughly 800 milliseconds the sensor and radio hardware require to initialize before transmitting a reading. Charge leakage within the storage capacitors further hindered performance by extending the charge-up period between readings.

A number of areas of improvement have been identified for future prototypes. The use of lower-power and more rapidly-initializing radio hardware such as the PicoRadio [11] can dramatically increase the frequency of temperature readings. The simple power circuit can be replaced by much more sophisticated solutions developed for this type of application [7]. Efficiency can further be improved with the substitution of capacitors exhibiting lower leakage characteristics.

Finally, it must be considered whether a staircase provides the most appropriate vibration source for this type of application. Steadier, more constant vibrations are present on a ventilation duct or an appliance casing. Such vibrations might more easily drive the generator to resonance, increasing power output.

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