Demo: Ground Temperature Difference Driven Sensor for Environmental Monitoring

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Abstract

In this paper, we present a novel approach to the realization of a battery-free soil profile probe that uses the temperature difference between the near-surface air and the underground soil as a power source. The temperature change in the underground soil is slower than that in the near-surface air, and thus a large temperature difference occurs between the near-surface air and the underground soil for most of the day. Hence, we developed a sensor prototype driven by a thermoelectric generator (TEG) that directly converts this temperature difference into electricity. The results of an experimental implementation of the prototype proved that when the difference in temperature between the near-surface air and the underground soil is only 3 °C, which is much lower than the average temperature difference in an actual field, the measured output power is about 80 μW. Because the typical sensing interval of a soil profile probe is 1 h, the average power consumption (e.g., for a Texas Instruments CC2650) is about 5 μW, which is much lower than the expected amount of harvested energy.

Author Keywords

Energy Harvesting; Thermoelectric Generator

ACM Classification Keywords

B.0. Hardware: General

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Figure 1: (Upper image) SenSprout battery-driven agricultural soil profile probe for monitoring soil moisture and temperatures at multiple depths of (10 cm, 20 cm, 30 cm), as well as the ground surface temperature. (Lower image) Agricultural soil profile probe covered with vegetation.

Figure 2: Thermoelectric generator KELK KTGM199-2.

Introduction

A profile probe (Figure 1 (Upper image)) monitors the distribution of the soil moisture and temperature at different underground depths, which is valuable for irrigation management and the other agricultural operations. Because many sensors are deployed in farm fields, manually replacing the batteries is impractical when considering the labor cost. Taking the soil profile probe that we developed as an example [8], the theoretical battery life is limited to around 1 year despite a sensing interval of only 1 h. When operating in a severe environment such as under hot and humid conditions, the battery life is limited to only a few months because of battery deterioration. Therefore, battery-free sensors are preferred for reducing the maintenance costs. Moreover, because the sensors are installed near the ground surface, they will inevitably become covered with vegetation (Figure 1 (Lower image)). Solar panels [5] are not suitable for such scenarios, because the panels need to compete with the vegetation to acquire sunlight. The temperature change in the underground soil is slower than in the near-surface air, and thus a large temperature difference occurs between the near-surface air and the underground soil for most of the day (Figure 3) [7]. Hence, we developed a sensor prototype driven by a thermoelectric generator (TEG) and showed the variability of our proposal through an experimental implementation.

Thermoelectric generator (TEG)

TEG is a solid-state device (Figure 2) that converts the heat flux (temperature difference) directly into electrical energy through a phenomenon called the Seebeck effect. The Seebeck coefficient, also known as thermoelectric power, of a device is a measure of the magnitude of the thermoelectric voltage induced in response to the temperature difference across the device, as occurring through the Seebeck effect. The SI unit of the Seebeck coefficient is volts per kelvin.

Figure 3: Near-surface air and underground soil temperature data from an actual field ((a) Omitama, Ibaraki, Japan / (b) Benoda, India).

Using the Seebeck coefficient (α [V/K]) and the temperature difference (ΔT [K]), the induced thermoelectric voltage (V_{TEG} [V]) can be explained as follows:

$$V_{\text{TEG}} = \alpha \times \Delta T \quad (1)$$

A TEG functions similarly to a heat engine, but it differs in that it has no moving parts and has a high fault tolerance. Many types of studies on a TEG have been conducted in different fields [1, 6, 9]. For example, Gou *et al.* showed the viability and further performance capability of a TEG for waste heat recovery in the industrial area [1]. Leonov

Figure 4: (a) Current soil profile probe (left side) and cross-sectional view of our proposed battery-free sensor (right side). (b) Schematic of the electric circuit.

Table 1: Characteristics of the TEG.

Electric resistance	2.16 Ω
Thermal resistance	1.066 K/W
Seebeck coefficient	72 mV/K
Size	48×56.5×1.35 mm

et. al. discussed an approach to provide power autonomy to devices on a human body, and showed that a TEG on the skin can provide more power per square centimeter than solar cells, particularly under adverse illumination conditions [6]. Tan *et. al.* proposed a hybrid of indoor ambient light and thermal energy harvesting scheme that uses only one power management circuit under conditions of combined output power harvested from both energy sources [9].

System Overview

Figure 4 (a) shows a current soil profile probe (left side) [8] and our proposed battery-free version (right side). In the

proposed system, the temperature of the underground soil (30 cm) is guided toward the lower side of TEG (KELK KTGM199-2 [4]) using a copper rod wrapped with a thermal insulator. Table 1 shows the characteristics of the TEG. A heat sink (ALPHA LC100-30B [3]) is attached to the upper side of the TEG to accelerate the heat exchange with the near-surface air. Because the differences in temperature between the near-surface air and the underground soil constantly fluctuate (Figure 3), the TEG output voltage changes dynamically, and the electric current direction switches daily. A power manager for the TEG (Analog Devices LTC3109 [2]) manages this variability using auto-polarity, step-up DC-to-DC conversion, and energy storage (Figure 4 (b)). When the output voltage of LTC3109 (V_{OUT} [V]) is 3.3 V, the relationship between the TEG voltage (V_{TEG} [mV]) and the output current of the LTC3109 (I_{OUT} [μ A]) is as described below [2]:

$$I_{OUT} \simeq \begin{cases} 0 & (|V_{TEG}| \leq 30 \text{ mV}) \\ 3 \times V_{TEG} - 90 \frac{[\mu\text{A}]}{[\text{mV}]} & (|V_{TEG}| \geq 30 \text{ mV}) \end{cases} \quad (2)$$

Demonstration Experiment

We prepared an experimental environment simulating typical situations in farm fields. As shown in Figure 5, we arranged a box surrounded by a thermal insulator and filled it with soil. We heated the bottom of the box with an experimental hot plate to reproduce the field environment where the temperature gradient occurs in the vertical direction of the soil. When the difference in temperature between the near-surface air and the underground (30 cm) is 3 °C, the output power of LTC3109 is 80 μ W. Note that this difference in temperature is much lower than the average temperature difference in the field. Considering an ultra-low power MCU (e.g., Texas Instruments CC2650), the power consumption in standby-mode is 2.1 μ W, and the power consumption for

Figure 5: Experimental environment simulating typical situations in farm fields.

each sensing and data-transmission is 100 μ J. Because a typical sensing span of a soil profile probe is 1 h, the average power supply required is approximately 5 μ W, which is much lower than the expected harvested energy. Thus, we realized battery-free soil profile probes driven by the difference in temperature between the near-surface air and the underground soil.

Conclusion

In this paper, we showed the feasibility of taking advantage of the temperature difference between the near-surface air and the underground soil, and proved through an experimental implementation that soil profile probes can be driven using a TEG. In the future, we will conduct a demonstration in a real field to validate the utility of our proposal.

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