Design and implementation of a soil profile probe powered by air and soil temperature differences

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Abstract. In this paper, we present a novel approach to realizing a battery-free soil profile probe that uses the temperature difference between the near-surface air and the underground soil as its power source. Temperature changes in the underground soil are slower than that in the near-surface air, and thus a large temperature difference exists between the near-surface air and the underground soil for most of the day. We develop a sensor prototype driven by a thermoelectric generator (TEG) that directly converts this temperature difference into electricity. Simulations are performed using real field data, and results show that our prototype can harvest an average of several tens to several hundreds of microwatts. 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. Furthermore, the results of an experimental implementation of the prototype proved that when the temperature difference between the near-surface air and the underground soil is only 3 K, which is much lower than the average temperature difference in an actual field, the measured output power exceeds 80 µW.

1. Introduction

Soil profile probes (figure 1 (a)) monitor the distribution of the soil moisture and temperature at different underground depths, and this information is valuable for irrigation management and other agricultural operations. Because many sensors are deployed in farm fields, it is impractical to manually replace the batteries considering the required labor cost. Taking the developed soil profile probe as an example [1], the theoretical battery life is limited to around 1 year despite a sensing interval of only 1 h. When operating in severe environments 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 cost. Moreover, because the sensors are installed near the ground surface, they will inevitably become covered with vegetation (figure 1 (b)). Solar panels [2] 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 that in the near-surface air, and thus there is a large temperature difference between the near-surface air and the underground soil for most of the day (figure 2) [3]. Hence, we developed a sensor prototype driven by a thermoelectric generator...
Figure 1. (a) SenSprout battery-driven agricultural soil profile probe for monitoring soil moisture and temperatures at multiple depths (10 cm, 20 cm, 30 cm), as well as the ground surface temperature. (b) Agricultural soil profile probe covered with vegetation.

Figure 2. Near-surface air and underground soil temperature data obtained from an actual field (Obihiro, Hokkaido, Japan).

(TEG) that directly converts this temperature difference into electricity. Unlike many existing studies using TEG [4, 5, 6] the temperature on both sides of the TEG constantly fluctuates (figure 2), so we conducted transient thermal analysis using real field data collected by the soil profile probes to calculate the amount of power that our battery-free sensor can generate in the field. In addition, for further evaluation, we conducted an experimental implementation using the prototype in a lab environment.

2. Background and related works

2.1. Energy harvesting for agriculture

In the agricultural field, there have been many existing studies using solar [2] and wind [7] technologies as an energy-harvesting (EH) method. While solar panels are commonly used in this field because of their high efficiency, they are not usable in areas receiving little sunshine. Because soil sensors are stationary and can be located in shaded areas resulting from trees, or may be covered by vegetation or mud, solar panels are not suitable for soil monitoring applications. Further, although wind power is suitable for locations at which the wind blows throughout the year, such as hills, it generally tends to select installation location very much. In addition, they are at risk of malfunctioning owing to the presence of moving parts.
2.2. Thermoelectric generator

Thermoelectric generators (TEGs) are solid-state devices that convert heat flux (temperature difference) directly into electrical energy through a phenomenon called the Seebeck effect. The Seebeck coefficient 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 because of the Seebeck effect. The SI unit of the Seebeck coefficient is volts per kelvin. Using the Seebeck coefficient ($\alpha$ [V/K]) and the temperature difference ($\Delta T$ [K]), the induced thermoelectric voltage ($V_{TEG}$ [V]) can be explained as follows:

$$V_{TEG} = \alpha \times \Delta T$$

The function of a TEG is similar to that of heat engines, but it differs in that it has no moving parts and has a high fault tolerance. Many types of studies involving the use of TEG have been conducted in different fields [4, 5, 6]. For example, Gou et al. showed the viability and performance of a TEG for waste-heat recovery in an industrial area [4]. Leonov 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 poor illumination conditions [5]. Tan et al. proposed a hybrid of an indoor ambient light and thermal EH scheme that uses only one power-management circuit under conditions of combined output power harvested from both energy sources [6].

3. System overview

Figure 3 (a) shows a current soil profile probe [1] and our proposed battery-free version. In the proposed system, the temperature of the underground (30 cm) soil is guided toward the lower side of the TEG (KELK KTGM199-2 [8]) using a copper rod wrapped with a thermal...
4. Simulation

We simulated by a thermal network method the amount of power that our battery-free soil profile probe can generate using long-term temperature data of actual fields collected by the soil profile probes (figure 1). The thermal network method is a thermal analysis technique that uses the similarity between heat and electricity (table 2) [11]. By dividing the subjects for analysis into appropriate areas and setting values to them (e.g., thermal resistance and fixed temperature), thermal analyses can be handled in the same way as electric circuit analyses. For example, as shown in Figure 4 (a), in the thermal equivalent-circuit where \( n \) nodes are connected to node \( N_i \), Thermal Kirchhoff’s law, which is law of conservation of thermal energy, is established and explained by:

\[
\sum_{j=1}^{n} \frac{1}{R_{ij}} (T_i - T_j) = Q_i - \frac{C_i}{\Delta \tau} (T_i - T_i')
\]

(3)

\( R_{ij} [K/W] \) is the thermal resistance which combines node \( N_i \) and node \( N_j \), \( T_i [K] \) (\( T_j [K] \)) is the temperature of node \( N_i \) (\( N_j \)), and \( Q_i [W] \) is the exothermic energy amount of node \( N_i \). When handling a transient state, the heat-storage amount during \( \Delta \tau [s] \) is added. \( \Delta \tau [s] \) is the step width of the calculation time, \( T_i' [K] \) is the temperature one step before, and \( C_i [J/K] \) is the heat capacity of node \( N_i \).

4.1. Modeling of proposed battery-free soil profile probe using thermal network method

The thermal resistance (\( R_T [K/W] \)) and heat capacity (\( C_T [J/K] \)) in solids are explained by:

\[
R_T = \frac{L}{A \lambda}, \quad C_T = MC_p = \rho V C_p
\]

(4)

\( A [m^2] \) is the sectional area, \( \lambda [W/(m \cdot K)] \) is the thermal conductivity, and \( L [m] \) is the length of the heat transfer direction. \( M [kg] \) is the weight, \( V [m^3] \) is the volume, \( \rho [kg/m^3] \) is the

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**Table 2.** Similarity between heat and electricity [11].

| Potential            | Flow              | Resistance         |
|----------------------|-------------------|--------------------|
| Temperature [K]      | Heat flow [W]     | Thermal resistance [K/W] |
| Voltage [V]          | Electric current [A] | Electric resistance [Ω] |

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insulator. Table 1 shows the characteristics of the TEG. A heat sink (ALPHA LC100-30B [9]) 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 2), the TEG output voltage changes dynamically, and the electric current direction switches daily. A power manager (Analog Devices LTC3109 [10]) manages this variability using auto-polarity, step-up DC to DC conversion, and energy storage (figure 3 (b)). When the output voltage of LTC3109 (\( V_{OUT} [V] \)) is set to 3.3 V, the relationship between the TEG voltage (\( V_{TEG} [mV] \)) and the output current of the LTC3109 (\( I_{OUT} [\mu A] \)) is as described below [10]:

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

(2)

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Figure 4. (a) Thermal network method. (b) Analysis subject including the near-surface air and underground (30 cm) soil used in thermal network method.

Table 3. Values of the circuit elements.

| Symbol | Description                                      | Value (K/W) |
|--------|--------------------------------------------------|-------------|
| $R_{HS}$ | Thermal resistance of heat sink (wind speed 0.25 m/s) [9] | 0.8         |
| $R_{HS}$ | Thermal resistance of heat sink (wind speed 3 m/s) [9] | 0.27        |
| $R_{TIM}$ | Thermal resistance of thermally conductive adhesive (T: 100 µm) | 0.0025      |
| $R_{TEG}$ | Thermal resistance of TEG [8] | 1.066       |
| $R_{IHS}$ | Thermal resistance of copper heat spreader (T: 10 µm) | 0.01        |
| $R_{ROD}$ | Thermal resistance of copper rod (Φ: 20 mm) | 2.38        |
| $C_{ROD}$ | Thermal capacity of copper rod (Φ: 20 mm) | 320 J/K     |

density, and $C_p [J/(kg \cdot K)]$ is the specific heat. “$R_T \times C_T$” is called the “time constant $\tau$,” and the temperature change slows when the time constant increases as well as the electric circuit.

When an electric current flows through the TEG, the Peltier effect (endothermic reaction ($Q_{EN} [W]$) on the hot side of the TEG and exothermic reaction ($Q_{EX} [W]$) on the cold side of the TEG) occurs on both sides of the TEG:

$$Q_{EN} = -\alpha T_h I_{TEG}, \quad Q_{EX} = \alpha T_c I_{TEG} \quad (5)$$

$\alpha [V/K]$ is the Seebeck coefficient per unit temperature, $T_h [K]$ and $T_c [K]$ are the temperatures on the hot side and cold sides of the TEG, respectively, and $I_{TEG} [A]$ is the electric current through the TEG.

The thermal resistance of the heat sink depends on the surrounding wind speed, and it decreases with an increase in the wind speed. With respect to the Beaufort wind-force scale [12], which is an empirical measure that relates wind speed to observed conditions on land, we adopt wind speeds 0.25 m/s and 3 m/s as the wind speeds corresponding to “scale 0” (Calm, smoke rises vertically) and “scale 3” (constantly moving leaves and small twigs, light flags extended), respectively.

The power consumed inside the TEG ($P_{TEG} [W]$) and the power extracted from the LTC3109 output ($P_{OUT} [W]$) are explained by:

$$P_{TEG} = r_{TEG} I_{TEG}^2, \quad P_{OUT} = I_{OUT} V_{OUT} = f(V_{TEG}) V_{OUT} \quad (6)$$

$r_{TEG} [\Omega]$ is the electric resistance of the TEG (table 1), $V_{OUT} [V]$ is the output electric voltage of the LTC3109, as mentioned in section 3, $V_{TEG} [V]$ is the thermoelectric voltage of the TEG, and $I_{OUT} [A]$ is the output electric current of the LTC3109, and is a function of $V_{TEG}$, as shown in Equation (2).

Thus, the object being analyzed, including the near-surface air and underground (30 cm) soil, can be expressed as in figure 4 (b). Table 3 shows the values of the circuit elements.
### Table 4. Long-term temperature data of actual fields using simulation.

|   | Field Type            | Location                  | Period              |
|---|-----------------------|---------------------------|---------------------|
| (a) | Open cultivation     | Obihiro, Hokkaido, Japan | 2016/08–2016/09    |
| (b) | Greenhouse            | Omitama, Ibaraki, Japan  | 2016/10–2017/11    |
| (c) | Frozen soil           | Shin-hidaka, Hokkaido, Japan | 2017/01–2017/02 |
| (d) | Tropical wet-dry climate | Benoda, India       | 2016/11–2016/12    |

### Table 5. Simulation result.

|   | Avg. temp. diff. of TEG | Avg. output power ($P_{OUT}$) | wind speed |
|---|-------------------------|-------------------------------|------------|
| (a) | 0.65 K                 | 236 µW                        |            |
| (b) | 0.97 K                 | 402 µW                        | 0.25 m/s   |
| (c) | 1.41 K                 | 668 µW                        |            |
| (d) | 1.34 K                 | 721 µW                        |            |
| (a) | 0.74 K                 | 291 µW                        |            |
| (b) | 1.10 K                 | 492 µW                        | 3 m/s      |
| (c) | 1.61 K                 | 802 µW                        |            |
| (d) | 1.52 K                 | 864 µW                        |            |

#### 4.2. Evaluation

Using the long-term temperature data of actual fields (table 4) and adapting them to $T_{AIR}$ and $T_{SOIL}$ in figure 4 (b), we calculated the amount of power that our battery-free soil profile probe can generate. Table 5 shows the simulation results, which contain the average temperature difference on both sides of the TEG and the average output power from LTC3109 for each field. The upper half of table 5 is the result when the wind speed is assumed to be 0.25 m/s, and the lower half is the result when the wind speed is assumed to be 3 m/s. Considering an ultra-low power MCU (e.g., Texas Instruments CC2650), the power consumption in standby-mode is 2.1 µW, and the power consumption for each sensing and data-transmission is 100 µJ.

Because the typical sensing span of a soil profile probe is 1 h, the average power supply that is required is approximately 5 µW, which is much lower than the expected harvested energy. In extreme environments such as (c) frozen soil and (d) tropical wet-dry climates, the temperature differences between the near-surface air and underground soil tend to become larger, and it is easier to harvest power. For example, in tropical wet-dry climates, the daily temperature frequently rises sharply and reaches 40 °C. Similarly, in frozen soil, regardless of how cold the air becomes, the underground soil temperature remains constant at 0 °C because of the freeze.

Thus, sensors that are powered by air and soil temperature differences are more suitable for these extreme environments in which the battery life is limited to only a few months because of battery deterioration.

#### 5. Experimental Implementation

As shown in figure 5, we prepared an experimental environment that simulates typical situations in farm fields. When the difference in temperature between the near-surface air and the underground (30 cm) soil is 3 K, the output power of LTC3109 is about 80 µW. Note that this difference in temperature is much lower than the average temperature difference in the field. Owing to the incomplete insulation et al., the amount of power that is generated is reduced by about 30 % compared with the theoretical simulation result (section 4), but it is still satisfactory for hourly soil measurements.
6. Conclusion
In this paper, we presented a novel approach to realizing a battery-free soil profile probe that uses the temperature difference between the near-surface air and underground soil as its power source. By developing a sensor prototype driven by a TEG and simulating this performance, we showed the feasibility of our proposed prototype.

Acknowledgments
We would like to thank Ikemori A (Obihiro, Hokkaido, Japan), Union-Farm (Omitama, Ibaraki, Japan), Professor Adinarayana J (Indian Institute of Technology Bombay), and members of the Soil Science Laboratory of Hokkaido University for providing the data used in this research. This work was supported by JST ERATO, Japan under Grant No.: JPMJER1501.

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