Temperature feedback loop incorporation to self-powered thermoregulating insole

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Abstract

HVAC systems and energy resources are two of the top contributors to wide-scale environmental compromise. A self-powered thermoregulating insole prototype may have the potential to regulate body temperature by introducing temperature differential to feet extremities. The paper aims to incorporate a primitive temperature feedback loop to minimize Peltier activation time thereby optimizing PZT capability to supply self-powering to the mini-HVAC insole. The primitive developed prototype utilizes a servo and DHT11 temperature sensor to demonstrate feedback mechanism.

Keywords: HVAC, enery harvesting, feedback loop

1 Self-powered thermoregulating insole

The feet extremities are considered to be an efficient heat exchanger by containing arteriovenous anastomoses, connections of arteries and veins, where dramatic elevations in skin blood flow occur when shunts of these vessels open and a surface area to mass ratio of 2.5 and 3 times larger relative to the entire body of a male and female, respectively leading to a theoretical peak heat transfer from the core to both feet of 16 W.

In one developmental study [1],a battery replenishing, thermoregulating insole was developed capable of harvesting 500 mW of power with an efficiency of 0.3, heating the foot up to 40°C with a COP of 1.89, and cooling the insole surface down to 23°C with a COP of 0.89.

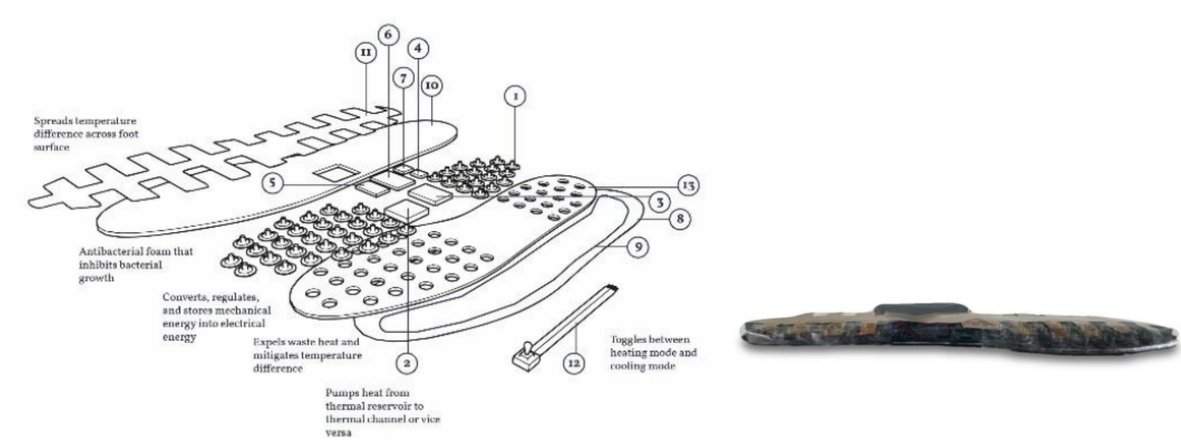

Figure 1: Image shows self-powered thermoregulating insole components.

The objective of the insole is to provide a solid-state foot two-way thermoregulating insole which is compact, light-weight, and with the ability to replenish the battery by harvesting energy when walking capable of heating and cooling as necessary. This is done by using an array of piezoelectric discs with the energy harvesting mechanism facilitated by LTC3588 energy harvesting module and using a mini thermoelectric Peltier device as to produce heat flow. The temperature differential produced the the Peltier device is conducted to a copper sheet which serves as the medium of heating or cooling in direct contact with the socks (which is highly recommended in the current prototype). As of the latest version, the working mechanism of the prototype still lacks practical usage; incorporation of thermoregulation automation can drastically increase efficiency of usage to be able to suffice with the energy allowance gathered from the piezoelectric array.

To do so, the paper aims to design a simple temperature feedback loop concept to serve as a baseline prototype design of a thermoregulating mechanism. Such system must be able to detect if the foot temperature rises or drops to a specific threshold value, provide an activating pulse of heat pumping, and to assess when to end the pulse.

2 Temperature feedback loop

The study provided transient response to the heating and cooling mechanism. In order to provide a basic temperature feedback loop system, we can refer to the following heating and cooling curves.

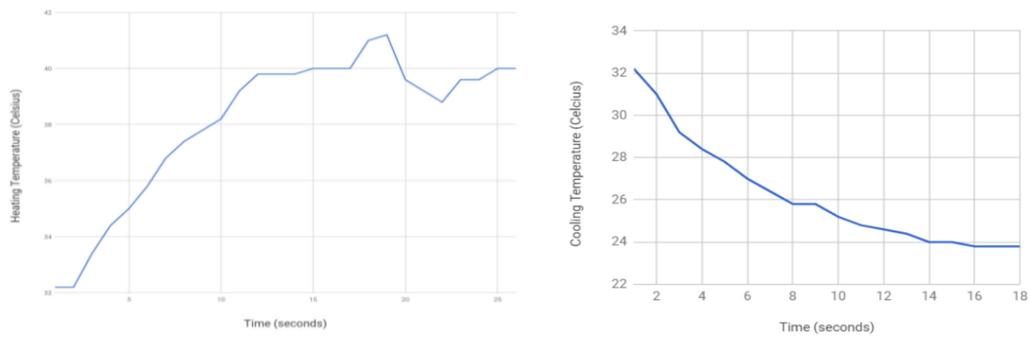

Figure 2: Left plot shows insole cooling curve while right plot shows insole heating curve on the conductive surface layer.

Graphically, it can be observed that the heating mechanism has the presence of overshoot and settling time before achieving steady-state temperature while the cooling curve has the characteristic of a first-order low-pass filter. In the referenced developmental study, the primary activation mechanism send a step input function by flicking the switch of the system which can be deactivated by flicking the switch again in the opposite direction. To provide an automation mechanism with the aim to maintain the insole surface at a constant reference level, the temperature must be continuously monitored and deviations from the set reference temperature must be fed to the Peltier device by activating it for an appropriate amount of time before deactivating as a square pulse. To do so, a feedback loop shall be designed to continuously facilitate temperature regulation.

The feedback loop can be constructed by choosing an appropriate sampling rate to measure the current temperature, choosing activation time for heating and cooling mechanism taking into account the variation of rise and fall times for each mechanism, and choosing an appropriate cooldown time after each heat pumping mechanism. The cooldown serves as the conduction time window for the feet surface to absorb the temperature differential. Of course, there already exists several efficient controller for the Peltier device (i.e. TEC PID controllers). For the purposes of this paper, we aim to design a primitive feedback control system. From the calibration plots, the time taken for the heating mechanism to achieve a steady-state is approximately 25 seconds while the time taken for the cooling mechanism to achieve a steady-state is approximately 18 seconds. Due to the limitations of the power source, this time duration of Peltier activation is not optimal.

3 System design

The average temperature of a human midfoot is approximately 29°C [2]. We can define a threshold parameter $\delta T = 1°\text{C}$ such that given a temperature reading of $29 \pm \delta T$, we can consider the system to be in *optimal state*. Observe from the calibration curve that the initial 6°C deviation from the initial temperature is approximately linear. Specifically, we can linearize the plot at the initial time period corresponding to the initial 6°C degree level as:

$$T(t)_{\text{heat}} = T_0 + m_{\text{heat}} t, \qquad T(t)_{\text{cool}} = T_0 + m_{\text{cool}} t \tag{1}$$

where, from the calibration curve, $m_{\text{heat}} = 0.60$ and $m_{\text{cool}} = 0.75$, where T_0 corresponds to the measured temperature and $T(t)_{\text{state}}$ corresponds to the time-dependent temperature increase/decrease after Peltier activation. Hence, the automation should be restricted to the linear range of $\pm 6°\text{C}$. The m_{state} factor denotes the rate of heating/cooling. To find out how much activation time is needed at each heating/cooling pulse, we measure the deviation from the central temperature 29°C. If the measured temperature is within the range $(29° \pm \delta T)\text{C}$, the system skips the pulse, proceeds to cooling down state for a period t_{cd}, and measures temperature again. Should the temperature lies outside $(29^\circ \pm \delta T)$C, the deviation $\Delta T = T_0 - 29$ is measured. For $\Delta T > +\delta t$, cooling mechanism is activated for a time $t_{\text{cool}} = \Delta T / m_{\text{cool}}$. For $\Delta T < -\delta t$, heating mechanism is activated for a time $t_{\text{heat}} = \Delta T / m_{\text{heat}}$. After the activation time t_{state}, the system, again, enters cooldown state for t_{cd}, measuring the temperature T_0 again, and resetting the loop. This way, we can optimize the relatively power-hungry TEC activation to be viably powered by the piezoelectric array.

As an early prototype, we simulate the TEC activation as a servo motor swipe. A swipe to the right represents heating mechanism while a swipe to the left represents cooling mechanism. The time take for the servo motor wiper to return to its original state (pointing at 90° mark) represents either t_{heat} or t_{cool}. For simulation purposes, T_0 represents the room temperature measured from a DHT11 temperature-humidity sensor setting $\delta T = 0.5$°C

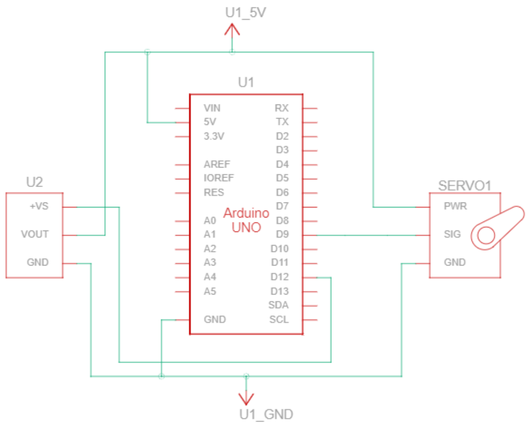

Figure 3: Circuit feedback simulation uses servo (SERVO1) and DHT11 (U2) as primary components to demonstrate the mechanism controlled by Arduino UNO

We simulate a feedback loop mechanism using an Arduino UNO microcontroller to measure temperature, display data, and to program feedback logic into the servo motor. The following is a code snippet of the Arduino code. The full code block can bee seen at https://github.com/schwarzschlyle/electronics-and-instrumentation/blob/master/feedback-loop/code/src/main.cpp.

```
void setup() {
Serial.begin(9600);
servo.attach(9); // First, we tell the system what pin was the servo motor attached to
servo.write(90);  // The servo was set to an initial angle state at 90 degrees
}

void loop() {
DHT11();
if (DHTError == false)
{
Serial.print(" Temp = ");
Serial.print(Temp);
Serial.print(",");
Serial.print(TempComma);
Serial.println("°C "); // This prints the temperature on the serial monitor
dT = t0 - Temp; // Defining temperature deviation...
if (dT > 0.5 ){ // We use delta T = 0.5 for faster simulation
servo.write(180); // Servo swipes left to simulate cooling mechanism
delay(dT/0.75); // Delay corresponds to t_cool
servo.write(90); // Servo rests to original state
delay(100);
}
if (dT < -0.5){
servo.write(0); // Servo swipes right to simulate cooling mechanism
```

```
delay(dT/0.60); Delay corresponds to t_heat
servo.write(90); // Servo rests to original state
delay(100);
}
delay(5000); // Cooldown time is set to five seconds
}
```

4 Final product

Using the circuit design and code, the final product presents a basic prototype of the heat pumping feedback loop mechanism of the thermoregulating insole. Again, one swipe of the servo motor corresponds to the heat pumping action of the Peltier. Swiping left represents heating mechanism while swiping right represents cooling mechanism.

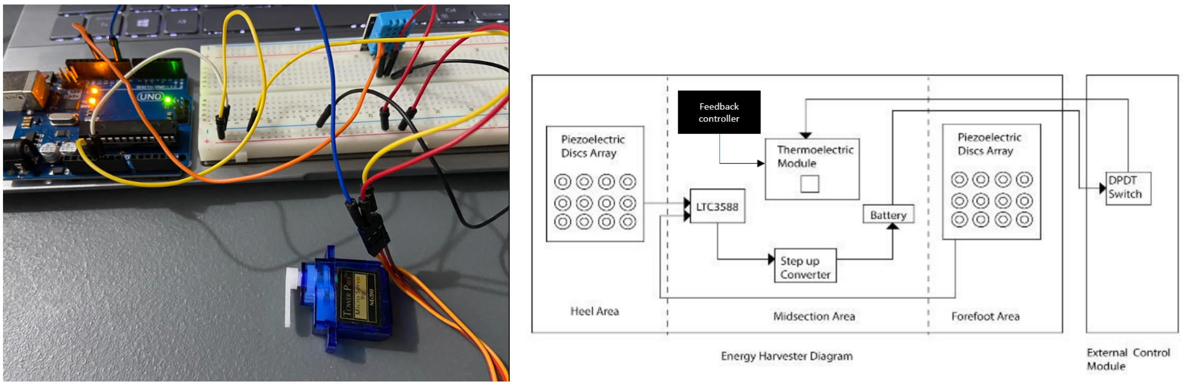

Figure 4: The simulation was tested on a breadboard prototype using step input by placing hot and cold objects near the sensor.

As a step input, we place cold and hot canned drink near the DHT11 sensor. A video sample of the simulation can be seen here: https://github.com/schwarzschlyle/electronics-and-instrumentation/tree/master/feedback-loop/video-samples. For the heating simulation, a can of cold drink was placed on the sensor cooling down the temperature reading. Observe that as the temperature reaches 27.9°C, the servo swipes left. Similarly, for the cooling simulation, a can of hot drink was placed instead and the servo swipes right as the temperature reaches 29.0°C. Ultimately, we want to incorporate this primitive feedback loop into the black-filled portion of the insole circuit.

5 Conclusion

The paper aims to incorporate automated temperature regulating mechanism to Peltier modules suitable for applications to the self-powered thermoregulating insole. Upon calibration, the feedback loop activates when temperature difference $\Delta T = 29^\circ \pm \delta t$, $\delta t = 1.0^\circ$C is $|\Delta T| > 1$. For $\Delta T > 1$, Peltier module pumps of $t_{\text{cool}} = \Delta T/0.75$. For $\Delta T < -1$, Peltier module pumps of $t_{\text{heat}} = \Delta T/0.65$. Of course, such implementation of feedback loop is primitive at best and only serves as a baseline concept for advanced feedback controller such as PID feedback.

References

[1] L. K. M. Geraldez, E. M. Villegas, and R. Z. T. Cawaling, Design and development of gait-powered active thermoregulatory insole using thermoelectric module (tec) powered by lead zirconate titanate (pzt) piezoelectric discs, *Publiscience* **2**, 93–98 (2019).

[2] B. M. Schmidt, S. Allison, and J. S. Wrobel, Describing normative foot temperatures in patients with diabetes-related peripheral neuropathy, *Journal of diabetes science and technology* **14**, 22 (2020).

6 Codes and Raw Data

All files regarding the experiment can be found here: https://bit.ly/38JsOtE

7 Reflections

7.1 Technical correctness

The main supposed objectives of the activity are to demonstrate motor control and feedback loop. However, in this paper, I took the opportunity to implement a feedback loop to temperature control. The product, although primitive at best, was successfuly designed and developed. Codes were written with sufficient comments. However, actual feedback control (such as gain or PID control) we're not implemented.

Self-score: 30/35

7.2 Presentation quality

Circuit diagrams and code were all presented on the paper. Plots have appropriate labels and figure captions stand alone. Texts and graphs were also laid down to be visually understandable.

Self-score: 35/35

7.3 Self reflection

The limitations of the implemented loop was discussed on the paper. The paper only aims to demonstrate the working mechanism. As such, there should be a plethora of adjustments that needs to be made and improved for a successful integration with the main system. Due to currently missing the main components (especially the Peltier modules), the developed feedback system could not be directly tested and relies only on the servo motor proxy. The sources were properly cited.

Self-score: 30/30

7.4 Initiative

The papaer is essentially an extension to the insole prototype I have developed years ago using the past lesson I have learned in AP184. Hence, motor and feedback control were tested on external applications that we're not discussed on the main course. Codes, such as the use of DHT11 without using libraries (for some reason, using the DHT library does not work on my machine) were self-studied and original code that implements the logic of the system design was created. Hence, this may correspond to a self-score of 20 for initiative.

Self-score: 20/20

Total self-score: 115