Temperature Sensing System for Hypothermia Detection in Frigid Environments

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***Abstract*—People who are in continuous exposure to frigid environments (ie. homeless, hikers, snow athletes, etc.) are at high risk of hypothermia, a medical emergency where the human body begins to lose heat faster than it produces it. The proposed system aims to combat the negative physical effects of hypothermia by providing a method for hypothermia detection and a counteractive response. It consists of five temperature-sensing circuits that serve as inputs to an Arduino Nano microcontroller, and each corresponds to a heating pad at the microcontroller output. Thus, we have 5 inputs and 5 outputs per finger/toe, and we have 4 of these systems built into a glove/sock for each extremity area: Right Arm, Left Arm, Right Leg, and Left Leg. In the temperature sensing circuit, we use an NTC thermistor to establish a relationship between voltage and temperature. We also implement an inverting op-amp with gain in order to amplify our input signal before use in the microcontroller. Because of the nature of our project which aims to create protective gear, we choose to focus on the earliest stage of hypothermia to supply a preventative means to addressing the medical issue.**

I. Introduction

Hypothermia is a medical emergency where the human body begins to lose heat faster than it is produced. This occurs when body temperature drops below 35℃ [1]. To sustain and increase blood flow to more vital organs, bodily extremities like hands and feet are typically the first to lose blood under frigid environmental conditions. Prolonged exposure to the cold can lead to discomfort, frostbite, lack of dexterity, and in severe cases, loss of limbs. According to the National Institute of Health (NIH), in Britain, the USA, and Canada, there are about 20,000, 25,000, and 8,000 hypothermia-related deaths a year, respectively [2]. Examples of people at high risk of hypothermia include the homeless, hikers, snow athletes, and others who are exposed to cold environments for long periods of time.

Swiss system[2]	Symptoms	By degree[9]	Temperature
Stage 1	Awake and shivering	Mild	32–35 °C (89.6–95.0 °F)
Stage 2	Drowsy and not shivering	Moderate	28–32 °C (82.4–89.6 °F)
Stage 3	Unconscious, not shivering	Severe	20–28 °C (68.0–82.4 °F)
Stage 4	No vital signs	Profound	<20 °C (68.0 °F)

Fig. 1. Hypothermia Classification [3]

The proposed system aims to combat this issue by providing a method for hypothermia detection and a counteractive response. This solution falls under the category of protective gear - a preventative measure against hypothermia. Therefore, we are mainly concerned with combating the mild, early stage (Stage 1) of hypothermia where hands and feet begin to lose blood flow and experience numbness. As shown in Fig. 1, this occurs around 32°C-35°C. The system consists of a temperature-sensing circuit that serves as an input to an Arduino microcontroller. From there, the microcontroller outputs control the heating pads. This paper includes LTSpice circuit simulations and analysis to validate our design. We imagine the design to be configured inside a glove or sock to form the protective gear, as shown in Fig. 2.

Fig. 2. Design Inside Glove

II. System Design

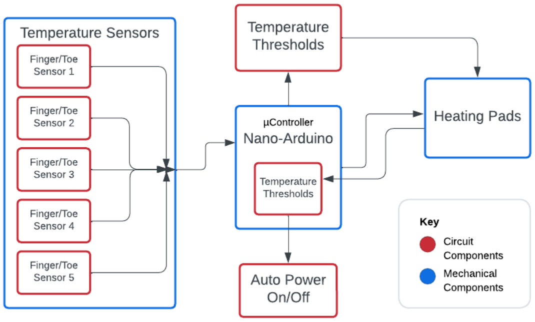


Fig. 3. Block Diagram of System

Fig. 3 provides a block diagram of our system and the circuit components it depends upon. The temperature sensors act as inputs into the microcontroller while the heating pads act as outputs. The next section will primarily focus on providing deeper technical analysis for each component described in Fig. 2 and Fig. 3.

III. Analysis and Results

A. Transducing Temperature into Voltage via Temperature Sensing Circuit

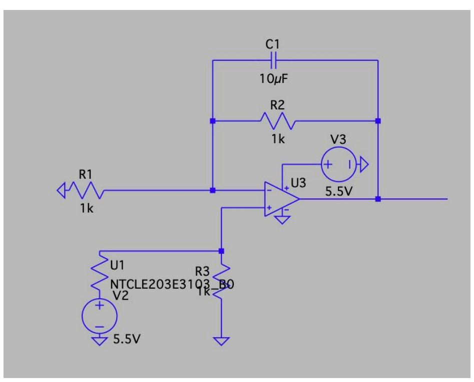


Fig. 4. Circuit Diagram of Temperature Sensing Circuit

Since our microcontroller only takes voltage inputs, we must transduce the temperature readings into electrical signals. To do so, we utilize the properties of the Negative Temperature Coefficient (NTC) thermistor. This component is temperature sensitive, such that as temperature increases, resistance decreases. This allows us to build a relationship between temperature and voltage as well, since voltage and resistance are linearly related through Ohm's Law. To implement this in our circuit design, we take the input voltage of the op-amp to be the voltage divider between the NTC thermistor and a fixed 1kΩ resistor.

$$V_{in} = V_s \frac{R_3}{R_3 + R_{NTC}} \quad (1)$$

where R_{NTC} varies with respect to temperature.

The chosen NTC thermistor (NTCLE203E3) operates most accurately between 25℃ and 85℃ [4]. This allows us to capture and define threshold voltage values that correspond to hypothermic and non-hypothermic temperatures. These values will be used as inputs by the microcontroller to output controls for the heating pads.

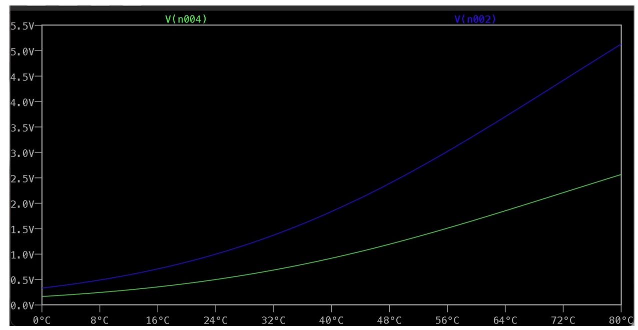


Fig. 5. Simulation of Proposed Temperature Sensing Circuit. V_{in} (green) and V_{out} (blue) are plotted with respect to increase in temperature.

Fig. 5 illustrates the input voltage, represented by the green line, and the output voltage, represented by the blue line, with respect to temperature. As indicated in the simulation, our V_{in} was very small (less than 1V) across the temperature range of interest of 30℃ to 40℃. To combat this, we introduced a constant gain factor using closed-loop feedback through the negative op amp terminal. For our non-inverting op amp, gain can be defined by the equation:

$$A_v = 1 + \frac{R_f}{R_{in}} \quad (2)$$

where $R_f = 1k\Omega$, $R_{in} = 1k\Omega$. Thus we are left with a constant gain factor of 2.

We also included a 10 μF capacitor in parallel with the feedback resistor in order to increase stability and reduce noise in the signal. This is because the impedance of the capacitor is frequency dependent:

$$Z_c = \frac{1}{j\omega C} \quad (3)$$

As $\omega \rightarrow \infty$, $Z_c \rightarrow 0$, effectively causing the capacitor to short the feedback resistor. This causes a reduce in gain since at higher frequencies, $R_f \rightarrow 0$ and $A_v \rightarrow 1$. This means that high frequencies suppress amplification between V_{in} and V_{out} because for $A_v = 1$, $V_{out} = V_{in}$. Conversely, as $\omega \rightarrow 0$, $Z_c \rightarrow \infty$, effectively causing the capacitor to behave as an open circuit at low frequencies. This leaves only R_3 as the feedback impedance and gives us the same constant gain factor of 2 derived from eq. (3). The sum of these behaviors that the capacitor provides can be condensed into the term "low pass filter." It essentially reduces the effects of high frequency noise while allowing low frequencies through its passband.

The low pass filter can be characterized and verified by the system's frequency response:

$$H(j\omega) = \frac{V_{out}(j\omega)}{V_{in}(j\omega)}$$

Using Kirchoff's Current Law:

$$\frac{V_{out} - V_-}{Z_C \,||\, Z_{R_f}} = \frac{V_- - 0}{R_1}$$

$$\rightarrow V_{out} = V_-(\frac{Z_C \,||\, Z_{R_f}}{R_1} - 1)$$

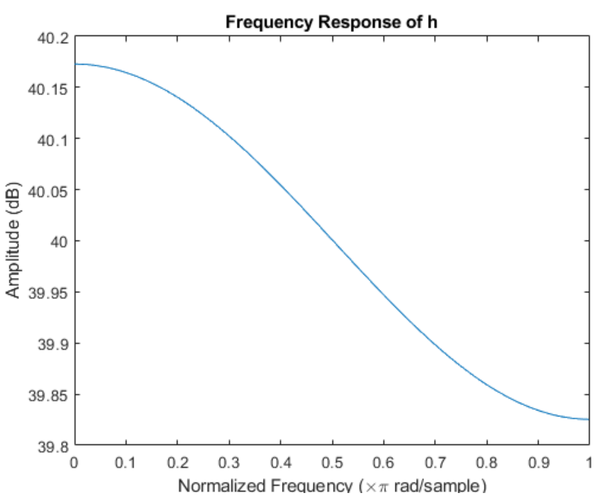
Assuming ideal op-amp conditions:

$$V_- = V_+ = V_{in}$$

$$\rightarrow V_{out} = V_{in}(\frac{Z_C \,||\, Z_{R_f}}{R_1} - 1)$$

$$H(j\omega) = \frac{V_{out}}{V_{in}} = (\frac{Z_C \,||\, Z_{R_f}}{R_1} - 1)$$

$$H(j\omega) = H(s)|_{s=j\omega} = \frac{(10\times10^{-3})s}{(10\times10^{-3})^2 s^2 + 2(10\times10^{-3})s + 1} \quad (4)$$




```
a = [0.01 0];
b = [0.01^2 2*0.01 1];

[h,w] = freqz(b,a)
plot(w/pi,20*log10(abs(h)))
title('Frequency Response of h')
xlabel('Normalized Frequency (\times\pi rad/sample)')
ylabel('Amplitude (dB)')
poles = roots(b)
fc = abs(roots(b))
```

Fig. 6. Frequency Response of Low Pass Filter, h'

From the frequency response in Fig. 6, we can distinctly see the low pass characteristic of the filter introduced by implementing the feedback capacitor in parallel. It allows low frequencies through the passband, while attenuating higher frequencies. The roll off is relatively gradual, with a cut off frequency of 100 Hz (determined using MATLAB). Therefore, we see the ability of this component to provide high frequency noise reduction. Furthermore, the pole is s = -100, which implies system stability because the pole is real and in the left hand plane of the complex plane.

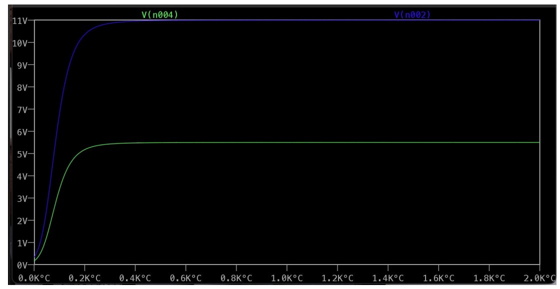


Fig. 7. Similar to Fig. 2, Simulation of Proposed Temperature Sensing Circuit; Shows voltages at very large temperatures. V_{in} (green) and V_{out} (blue) are plotted over temperature.

We verified the gain factor of 2 in our Fig. 7 circuit simulation, where $V_{out} = 2V_{in}$. Note that at extremely high temperatures > 2000℃, the output voltage saturates at approximately 11 V. However, this has no consequence on our design, because these temperature values are well outside our range of interest. Now that we have amplified our signal, we are finally able to determine the threshold voltages that will trigger the heating pad to turn ON or OFF.

We know that normal body temperatures can vary between 36.1℃ and 37.2℃ [5]. And, as mentioned previously, hypothermia is when the body's temperature falls below 35°C [1]. Therefore, based on the simulation in Fig. 2, we determined that the threshold voltage is V_{out} at 35℃, which is 1.54 V. The purpose of this threshold voltage will be described in detail in later sections of this paper. However, it essentially acts as a trigger for turning ON a heating pad. If the body temperature value is transduced into a voltage less than or equal to 1.54 V, this will let the microcontroller know that the heating pad must be turned ON. Similarly, we need a threshold voltage that will trigger the heating pads to turn OFF. As such, we decided this threshold voltage to be V_{out} at 37℃, which is 1.65 V. Likewise, once the body temperature sensed has been transduced into a voltage that is equal to 1.65 V, the microcontroller will tell the heating pad to turn OFF to avoid potentially burning the user.

B. Microcontroller

The microcontroller is designed to interface with five temperature sensors, each strategically positioned to monitor thermal conditions in distinct areas. Upon receiving input, the microcontroller executes a predefined algorithm to analyze the temperature data in real time. This algorithm assesses whether the measured temperatures fall below the set thresholds (35℃), for each respective area. Should the analysis indicate a temperature drop below the predefined limits, the microcontroller activates the heating pads corresponding to those specific areas where insufficient thermal levels are detected. The microcontroller will continue to pull values from the sensors, which will determine the heating pads' responses. This process ensures targeted heating, optimizing energy consumption by activating the heating pads only in zones where thermal augmentation is necessary. The system's architecture allows for real-time thermal management, adapting dynamically to changing conditions to maintain optimal temperatures across all monitored areas.

```
//Define Variables
  // Inputs Include 5 Temperature Sensors
  input1 = extremity(1);
  input2 = extremity(2);
  input3 = extremity(3);
  input4 = extremity(4);
  input5 = extremity(5);
  // Outputs for Each Indidvidual Heating Pad, set to 0
  output1 = extremityPad(1);
  output2 = extremityPad(2);
  output3 = extremityPad(3);
  output4 = extremityPad(4);
  output5 = extremityPad(5);
  //Threshold for hypothermia = 35 C
  threshold  = 35;

//Check for each input X = {1, 2, 3, 4, 5)
for(int X = 1; X <= 5; X++){
  //If below threshold
  if(inputX < threshold)
  {
    //Heating Pad ON unitil temperature back to normal 37 C
    while(inputX < (threshold + 2)){
      outputX = 1;
    }
    //Turn off Heating Pad
    outputX = 0;
  }
  else{
    //Output should be 0 if conditions are not satified
    outputX = 0;
  }
}
```

Fig. 8. Microcontroller Pseudocode

C. *Heating Pads*

The heating pads are activated by the microcontroller to warm up the designated finger or toe. As can be seen in Fig. 2, there is a designated heating pad for each finger and toe instead of one general heating pad. This ensures battery consumption is low, as only the designated heating pad will turn on, and that none of the other limbs can suffer injury from burns. Once the microcontroller senses a drop in temperature below 35℃ for a finger or toe, the heating pad will only activate for that specific finger or toe where the temperature drop was sensed. If there was no other temperature drop sensed in any other finger or toe, then the temperature will remain constant and the heating pads will not be activated for those designated fingers or toes. The heating pad will warm the designated limb until the sensor detects a temperature of 37℃. Once the finger or toe reaches 37℃ the heating pad will turn off to avoid any overheating. This process will continue, aiming to avoid any risk of hypothermia in an individual's extremities.

IV. Conclusion and Discussion

The primary objective of the project was to create a device that will decrease the amount of hypothermia cases. Death caused by hypothermia can be seen worldwide and many different people are at risk. We were able to create a device that uses advanced sensors and microcontrollers to detect changes in temperature for each finger and toe. When the temperature in a certain limb reaches 35℃, the heating pads are then activated for the corresponding limb. Once the temperature for that limb reaches 37℃, the heating pads are turned off. Individuals no longer have to worry about hypothermia, and are able to stay comfortable accomplishing any task at hand.

This is a contribution to the bioengineering discipline, as it presents an example of a bioinstrument that promotes safety by offering a non-invasive solution to early hypothermia through body temperature monitoring and regulation. The glove/sock configuration also improves portability and mobility for users. It may also provide real-time feedback for health data analytics.

While creating the body temperature-regulating gloves and socks, the group had to take many different things into consideration. Some include who our audience will be as well as effectiveness. Customizing our design to meet the needs of our audience is essential as we want to ensure the gloves will be effective for various activities. To do so, we had to fully understand the different factors that go into making this protective gear and be vigilant for any case scenario.

There were concerns about needing a spatial thermal profile to prioritize which parts of the hand or feet would need heating first. However, by choosing to place a temperature sensing circuit at the *tip* of each finger or toe, we are already sensing values that correspond to the body part that gets cold and loses blood flow the fastest. From there, it is dependent upon the microcontroller to determine if the voltage inputs meet certain thresholds that would necessitate a heating pad ON or OFF response. Thus, we choose to exclude a spatial thermal profile, because it is unnecessary in terms of our design to time the heating of different extremities.

A. *Advantages*

The principal advantages stemming from our design come from the temperature sensors and corresponding heating pads for each individual fingers and toes. This provides more accuracy than a sensor attached to a more general area provides insight into areas that are more prone to temperature changes.

Rather than establishing a timing sequence for the heating pads, the temperature thresholds ensure that the afflicted areas will eventually rise to a safe temperature without risk of overheating or failing to sufficiently warm areas subject to hypothermia. The threshold offers an alternative to natural body heat production by safely and consistently returning the at-risk areas to a normal temperature while still operating in frigid environments.

Accompanying these advantages, the inclusion of 4 separate microcontrollers for each extremity allows for maximum flexibility and versatility, hardly restricting the movement of the user while in use. This design facilitates function with greater freedom and versatility.

B. Limitations

Our system is extremely reliant on the accuracy and functionality of our temperature sensors, and their connection to the Arduino. While this optimizes our design with simplicity and efficiency, this also produces several limitations that correlate to the assumptions. The entire power system is limited by the battery life which could be weakened in the environments where this design is directly applicable.

Protection of the hardware also limits the overall functionality of the heating system. If the sensors or µ-controller are damaged during use, then the Arduino's input readings are skewed and the heating pads could be triggered too late, too early or not at all. Also, with our preliminary design, not all hardware components are water resistant. This can pose a problem, especially since contact with water is possible in certain cold environments. This leaves room in the design process for shock protection or water-proofing. This can potentially be accomplished using a step-down transformer, which reduces the voltage coming in from the primary side and can separate the I/O sides.

The Nano-Arduino as our choice of microcontroller pre-determines the threshold temperature which limits the users preferences. The previously mentioned threshold temperatures take into account the average human body temperature which is generally applicable, but limits the comfort and possibly safety for users with alternative preferences or requirements.

C. Future Challenges and Applications

The use of a microcontroller in our design offers future applications such as adjustable temperature thresholds, wireless temperature monitoring through smart device integration. The device needs to be weatherproof, and highly reliable allowing for operation in a variety of environmental conditions without compromising its functionality or reliability. This characteristic is essential, as the device is meant for safety of extremities for users. The use of a microcontroller allows for high flexibility in the use case. The gloves and socks could be adapted for use in extreme altitude climbing, ensuring safety and comfort of users. Additionally, they could offer immersive experiences in virtual and augmented reality where they could simulate thermal sensations that correlate to the digital environment. Some additional challenges include integrating insulation into the gloves to ensure that the temperature sensor is not influenced by the surrounding temperature and is solely measuring the intended extremity. Future implementation can also include a shock protection in case there is a water leakage.

Acknowledgment

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