School of Electrical and Computer Engineering

College of Engineering

UNIVERSITY OF GEORGIA

Lab 2b

ELEE 4230

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Deliverable 4: Model of Thermistor and Linearization

Objective

The objective of this deliverable is to model the thermistor's behavior using three different methods: least-squares fitting, the Beta model, and the Steinhart-Hart model. Additionally, we linearize the thermistor's response using the 3-point method and the "forced inflection point" method. Finally we analyze the results and discuss the implications of linearization on the sensor's dynamic range and sensitivity.

Thermistor Modeling

The thermistor datasheet provides a table of resistance values at various temperatures ranging from -50℃ to 150℃. Using this data in table 1 , we can plot the resistance versus temperature and fit a least-squares model to the data.

Ohm / Temperature figure

TMP	-50℃	-40℃	-30℃	-20℃	-10℃	0℃	10℃	20℃	25℃	30℃
Ω	44130	23980	13520	7891	4754	2949	1879	1226	1000	819.4

TMP	40℃	50℃	60℃	70℃	80℃	90℃	100℃	110℃	120℃	130℃
Ω	559.2	389.3	276	199	145.8	108.4	81.68	62.35	48.18	37.64

TMP	140℃	150℃
Ω	29.72	23.7

Table 1: Thermistor Ohm / Temperature Figure

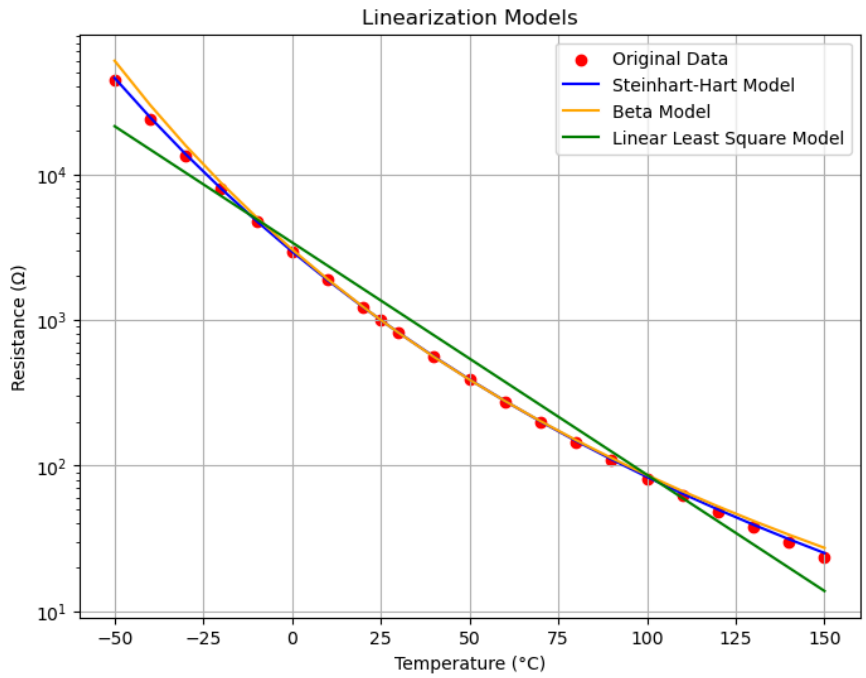

Figure 1: Thermistor Models

Figure 1 shows the three models (least-squares, Beta, and Steinhard-Hart) plotted over the entire range of the thermistor's operating temperature. The Steinhart-Hart model provides the most accurate fit while the Beta model is a good approximation for most temperature ranges. The least-squares model is also a reasonable fit, but does not capture nonlinearity as well as the Steinhart-Hart model.

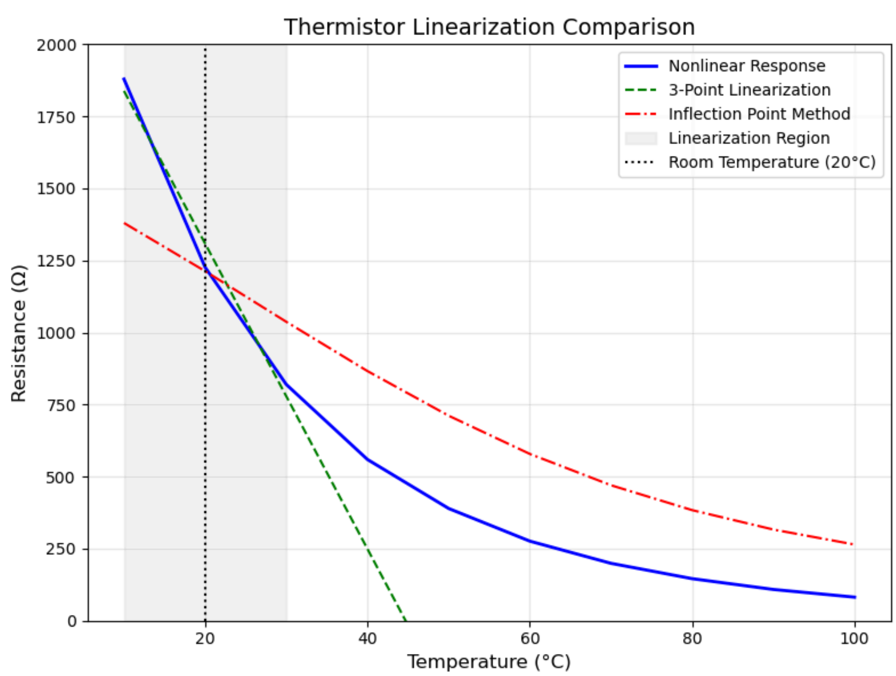

Figure 2: Thermistor Linearization Comparison

Figure 2 shows the nonlinear model of the thermistor over the small region from 10℃ to 30℃, along with the linearized responses using the 3-point method and the “forced inflection point” method. Both methods provide good linearization within the small region, but the “forced inflection point” method is slightly more accurate around the chosen temperature of 20℃. It is also worth noting that the 3-point method is more accurate at 10℃ and 30℃ rather than 20℃. This is due to the nature of this method.

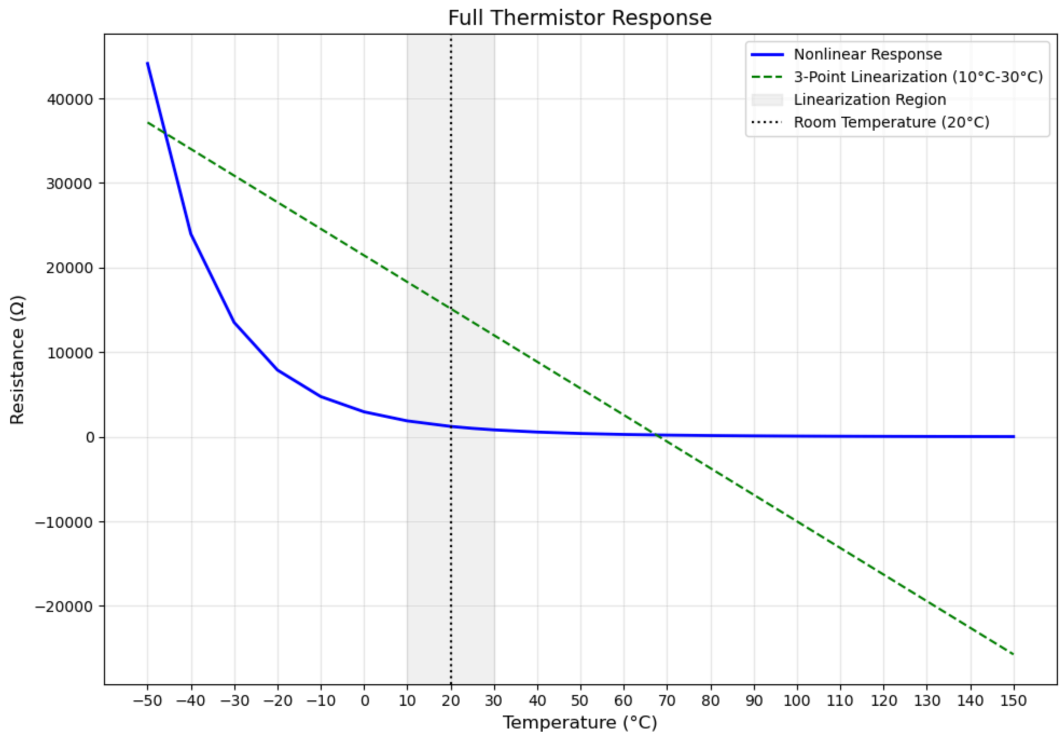

Figure 3: Thermistor Linearized Response Using 3-point Method over Maximum Range

Figure 3 shows the nonlinear model of the thermistor over its entire operating range, along with the linearized response using the 3-point method. The linear response deviates significantly from the nonlinear model at the extremes of the range, but it provides a good approximation for the endpoints of the range (-50℃ and 90℃).

Capacitive Sensor Analysis

To linearize the response of a capacitor, an integrator circuit similar to the one in figure 4 can be built.

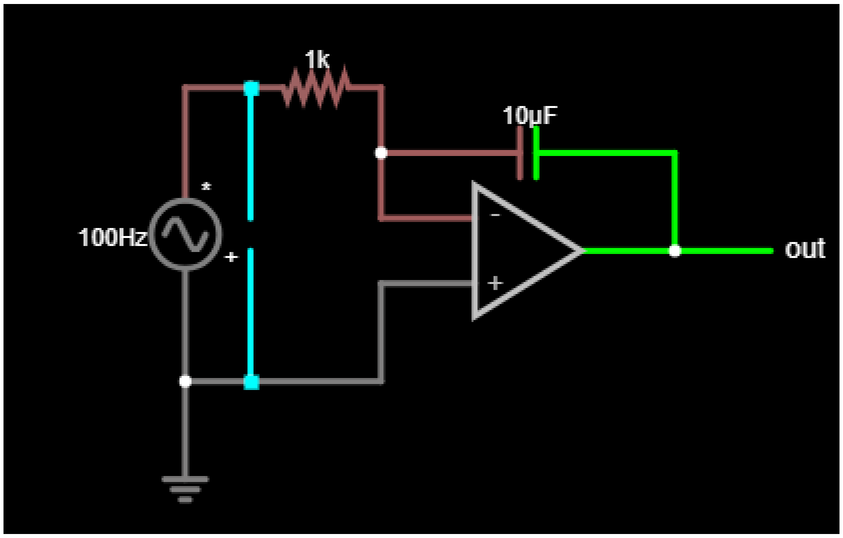

Figure 4: Op-Amp Integrator Circuit

A DC voltage bias is applied to ensure that the input AC voltage is always greater than or equal to 0. The voltage input/output relationship is shown in figure 5. One thing to note would be that the output is limited by the voltage supply to the op-amp. In this case, where V_{CC} is +/- 15V, the output flatlines at 15V. While the output voltage is not perfectly linear, the integrator circuit does a good job of linearizing the input/output relationship of the capacitor.

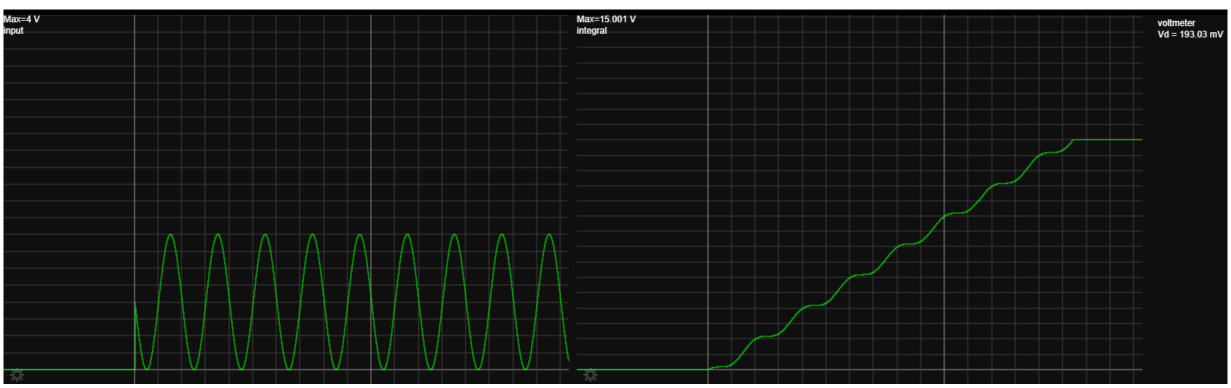

Figure 5: Integrator Voltage Input/Output Relationship

Deliverable 5: Resolution Simulation

“Going Up the Mountain”

This section of the lab explores the relationship between sensor signal processing and resolution in ADC conversion. Using a thermistor modeled by the Beta equation, a wheatstone bridge, and an instrumentation amplifier, we map temperature measurements to a 12-bit ADC. Two cases were analyzed: one with a small range from 15℃ to 30℃ and the other over the entire range of -50℃ to 150℃. The following equations were used:

```python
# Create a new array of resistance values for the closely spaced temperature values
B_model_resistance_15_to_30 = R0 * np.exp(beta * ((1/T_kelvb) - (1/T0)))
```

EQ 1: Thermistor's Resistance, where R0 is the Resistance at T0 in Kelvin

```python
# Calculate the slope between 15 and 30 degrees celcius
slope = (NL_R[-1] - NL_R[0]) / (T_kelvb[-1] - T_kelvb[0])
```

EQ 2: Slope Formula Used for the 3-Point Method from 15℃ to 30℃

```python
# Calculate the bridge output voltage
def V_Wheatstone(R, R_fixed=1000, V_in=5):
    V_out = ((R / (R + R_fixed)) - 0.5) * V_in
    return V_out
```

EQ 3: Wheatstone Bridge Transfer Function given R1=R2=R3

Equation 3 is based on the wheatstone bridge transfer function provided in the "Signal Processing 2" slides from class.

```python
# Calculate the Instrumentation Amplifier Output Voltage
def V_instrumentation_amplifier(V_bridge, V2=0, Gain=4.3):
    V_out = (V_bridge - V2) * Gain
    return V_out

V_instrumentation = V_instrumentation_amplifier(V_bridge)

# DC Voltage Bias to get the output voltage to be between 0 and 3.3V
V_Bias = 0 - V_instrumentation[-1]
print("DC Voltage Bias: ", V_Bias)
```

EQ 4: Instrumentation Amplifier Equation along with DC Bias Voltage Calculation

Equation 4 is derived from the INA115 datasheet that is linked in the appendix.

```python
TF_Final = ((1296 * V_ADC_output) - 188).round(0)
```

EQ 5: Final Transfer Function to Calculate ADC Output

Equation 5 is derived from Lab 1 where we characterized our ESP32 ADC. The same equations were then used to calculate the ADC output over the entire range of the sensor, -50℃ to 150℃. Signal conditioning is critical for the optimization of ADC resolution. By amplifying a small temperature range, the system's resolution is greatly increased while the full-range measurements prioritize span.

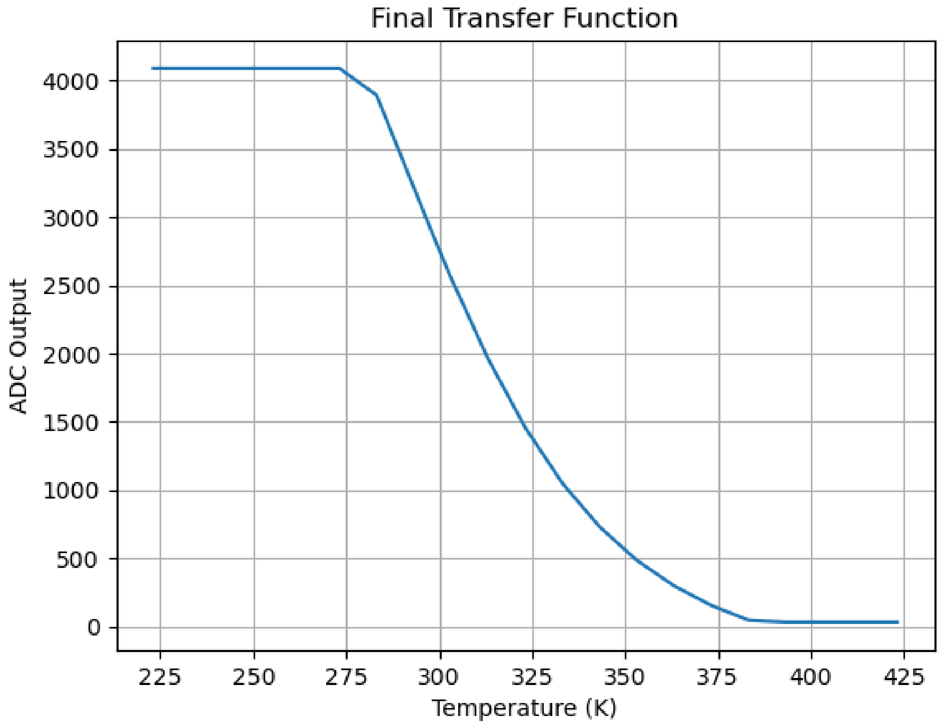

Figure 6: Final Transfer Function Graph Over Full Range (-50℃ to 150℃)

“Going Down the Mountain”

For this aspect of the lab it consists of taking our generated ADC value and converting it back to the theoretical value from the sensor itself. In this specific case it would be the thermistor value for either a small range or a large range as requested in deliverable 5 of this lab. This part starts with going back to the original code gathered for printing the value of the ADC and its general voltage value generated from the transfer function found in Lab1.

To start off this lab the calculated voltage bias needs to be added to the ADC code to remove the error from the transfer function.

```
float Vwithoutbias = ((float voltage) + 2.367); //get the voltage without bias
```

***EQ 6*: Removing the Bias Voltage**

To complete this step, the value of the DC bias voltage was removed from the value of our generated float voltage variable. The value was generated through a function on the “Going up the mountain” at which takes (0 - V_instrumentation).

Then the next step was to take the inverse of TF4 at which places the value of Vout back to the Vbridge value mentioned in the previous part of this lab.

```
float Vbridge = ((float Vwithoutbias - 0)/4.3); //the bias divided by the gain
```

***EQ 7*: Removing instrumentation gain**

This formula was gathered from the datasheet in the appendix, considering the layout of our design for the specific resistors used for it, the gain is the constant 4.3 value and the 0 would be our comparative voltage which was not needed for our layout.

```
float LinearResistance = ((-float Vbridge + 5)1000/(2 Vbridge -5));
```

***EQ 8*: Transferring to Linear resistance**

This code takes the Vbridge value and converts it to a linear resistance through the inversion of our Wheatstone bridge formula which was used to calculate the Vbridge value in the first place. At which the value of 5 and 1000 comes from a constant in terms of the Vin and the Fixed Resistor values respectively.

```
float T_KelvReversed = ((float LinearResistance - b)/ slope);
float NonlinearR = (( slope * T_KelvReversed) + b);
```

***EQ 9*: Going from Linear Resistance to Nonlinear and Back to Kelvin**

This code takes the linear resistance and goes back to the nonlinear model based on the reversal of the 3 point method that was used originally to produce the b and slope value based on chosen values for the expected range of the experiment.

```
float FarhenT = (T_KelvReversed - 273.15);
```

EQ 10: Kelvin to Fahrenheit

To complete this cycle, essentially we go from Kelvin to Fahrenheit to complete the "Down the mountain" part of this lab.

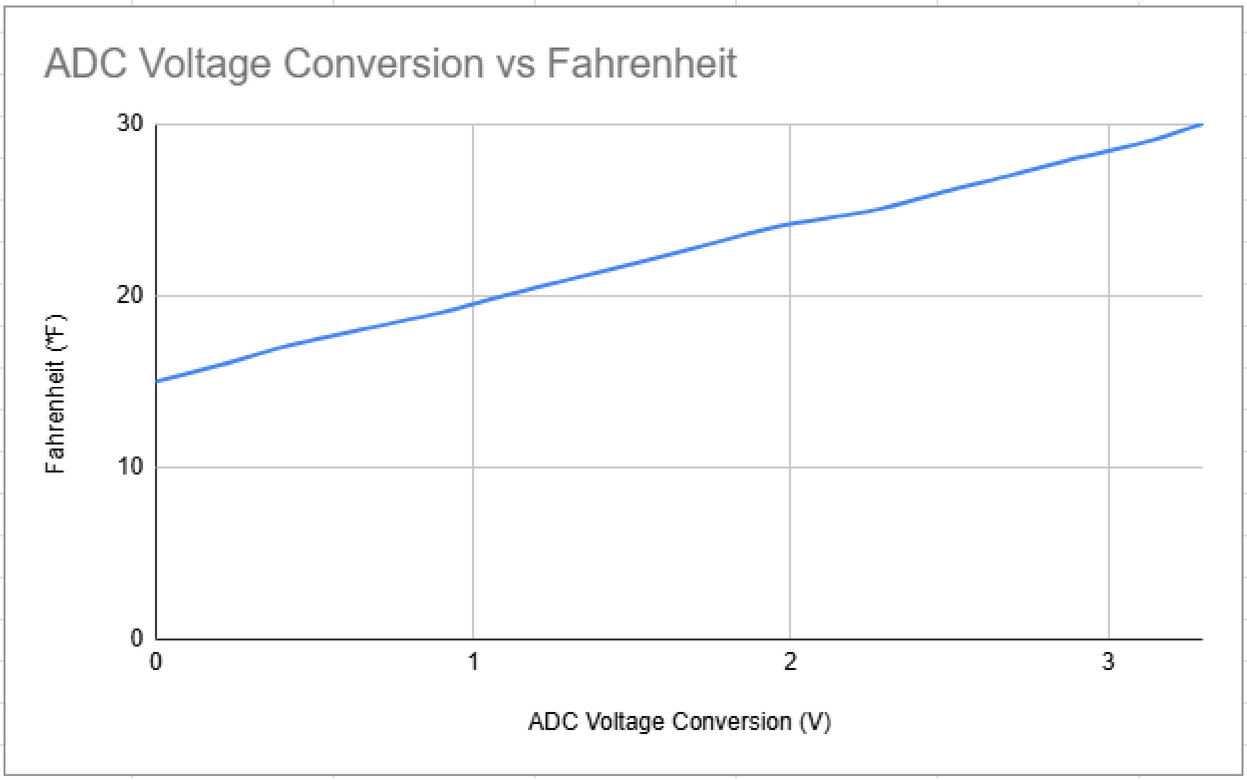

Figure 7: Final Down the Mountain start vs final value

The resolution of the ADC is 0-4095 which would be a 12-bit resolution, however considering the instructions to create a range of values from 15-30 degrees in case one at which our code makes the step size of 0.001. Then it should be around 15000 possible values, which means that the resolution should be around 14-bits, which should allow for 16,384 values of range.

Deliverable 6: Instrumentation Op-Amp from In-Amps

Objective

The objective for this part of the lab is to create an instrumentation amplifier using our designated TL084 Op-amps to create a form of amplifying a sensor's output voltage to be read over the entire range of the built in ADC for our ESP32. Using Multisim, and the documentation for the INA126, a instrumentation amplifier was created with two TL084 Op-amps that would boost our given voltage from 0.1V - 0.55V to 0.6V - 3.3V as desired to expand the ADC range based on our given inputs for greater resolution and accuracy when there is a non-linear response.

Instrumentation Op-Amp

This image below is a simulation of the INA126 instrumentation amplifier at which its datasheet for its schematic could be found in this document (https://www.ti.com/lit/ds/symlink/ina126.pdf?ts=1739461052605&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FINA126).

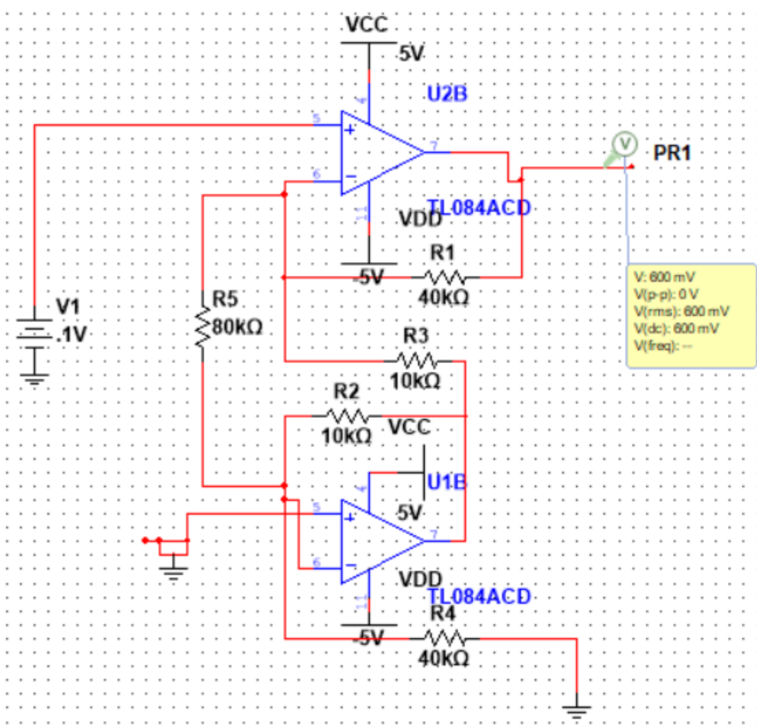

Figure 8: Multisim Simulation of INA126

This specific layout of the INA126 results in a gain of 6 times the V1 value as can be seen in the image. For the sake of this lab, a +-5 rail was used to power both Op-amps which allowed for the amplification to the desired 3.3 volts. Resistor 5 is the value that controls the Gain of the INA126 based on the formula listed below.

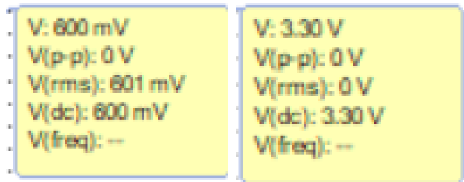

Figure 9: 0.1V and 0.55V as inputs and resulting outputs

The specific voltages were applied to the instrumentation amplifier, there was no need for bias voltage as the Op-Amps work in the desired range as needed for the future experimentation with the thermistor.

Appendix

INA115 Datasheet:
https://www.ti.com/lit/ds/symlink/ina115.pdf?ts=1739704995293

Thermistor Datasheet:
https://www.jameco.com/Jameco/Products/ProdDS/207483.pdf

Github Repository Link:
https://github.com/ajt36382/Sensors-Group-1/tree/main