FACULTY OF SUSTAINABLE DESIGN ENGINEERING, UPEI

Lab 4 – Electronically Amplified Measurement

Engn 3220 – Engineering Measurements

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ABSTRACT

A series of labs were undertaken in order to develop a working understanding of measurement systems with electrical outputs which could be amplified, interpreted and recorded. Temperature and strain measurement were explored as well as the implementation of linearization circuits, Wheatstone bridges, instrumentation amplifiers and microcontrollers. While measurement figures were recorded in these labs, the outcomes were overwhelming in general understanding of underlying principles and lab bench problem solving.

1. Background Information

This report spans several in-lab exercises which introduced thermistors, thermocouples and strain gages. The circuits used to ensure that these measurement sensors could provide meaningful outputs were linearization networks acting as voltage dividers and Wheatstone bridges. Finally, the concept of boosting these signals operational amplifiers was applied so that meaningful voltage outputs could be sampled and interpreted by a microcontroller. This section serves to introduce the sensors used as well as the concepts behind their implementation.

Sensors Used

Thermistors are passive electrical components which have a variable electrical resistance dependent on the temperature of the thermistor itself [1]. The dynamic resistance of thermistor does not share a linear relationship with the change in temperature; this introduces the need for calibration to determine the curve which results when you graph temperature vs. resistance. A linearization circuit which will be touched upon later within this section was developed and used to account for this.

A thermocouple, another sensor used to measure temperature, is made of two wires of dissimilar metals. When the metals experience a change in temperature there is a resulting current that flows within the circuit [2]. The relationship between temperature and this small voltage is linear, which removes the need for linearization present in thermistors.

While the first two sensors used in this series of labs measured temperature, a concept that is easily understood and perceived, the final sensor measures strain. Strain is the deformation of a material under stress related to the original state of that material under no stress [3]. In order to measure strain, strain gages are used which consist of a thin film sandwich containing a length of electrically conductive wire. When the gage is not under strain it has a known electrical resistance, when the gage is stretched the resistance of the gage increases as those thin leads are stretched and vice versa when the gage is compressed [4].

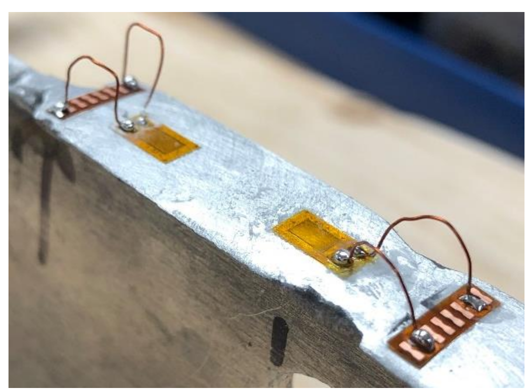

Figure 1 - Strain Gages Adhered to Aluminum

Circuits Used

The sensors used in this lab required different circuit layouts to output meaningful voltage readings that could be interpreted as measurements. The non-linear resistive load of the thermistor uses a voltage divider linearization network, the thermocouple has a very small differential voltage which was amplified directly by the instrumentation amplifier, and the strain gages used a Wheatstone bridge to produce a very small differential voltage which could then be amplified. All three of these circuits produced outputs of at most 20mV which was amplified by the instrumentation amplifier developed earlier in the series of labs.

A voltage divider linearization network is a simple circuit which takes advantage of the change in resistance of a thermistor to vary a voltage output that can be amplified. Resistor values used depend on which temperature range is of interest in the experiment. The values that were chosen and the circuit layout will be explored in the procedure section of this report.

The strain gages which were used do not experience the same significant swings in resistance of the thermistors. Due to the small change in resistance it is necessary to incorporate a Wheatstone bridge shown in figure 2. The purpose of this bridge is to establish values for R1 and R2 which perfectly balance the values of the strain gages when there is no force applied to the object which would cause it to experience strain. In this case the voltage across $V1_{out}$ and $V2_{out}$ would be zero and changes in strain gage resistances would result in a change in potential across these two points.

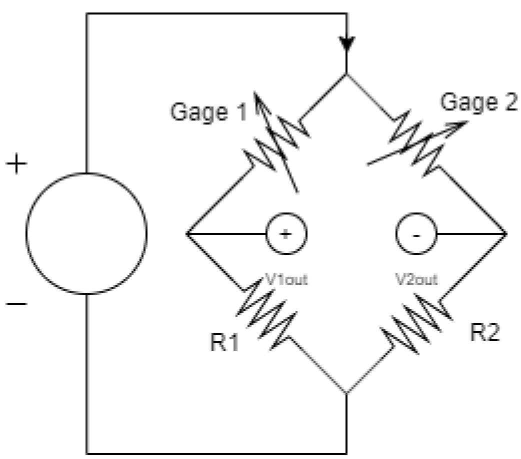

Figure 2 - A Two Arm Wheatstone Bridge

Instrumentation Amplifier

The thermistor circuit in this lab required very little amplification to achieve reasonable voltage outputs which could be interpreted, the thermocouple and strain gage circuits required significantly more amplification. To do this, an instrumentation amplifier was needed. The design used for this lab uses three operational amplifiers in two stages to achieve high gain. Gain being the factor that the amplifier multiplies the input voltage by. The circuit diagram can be seen in figure 3, this particular amplifier design has a gain that behaves according to the following formula: $Gain = \left[1 + \frac{2R_2}{R_G}\right]\left[\frac{R_4}{R_3}\right]$. The specific resistor values chosen as well as the gain achieved in practice will be touched upon in the procedure and results sections of this report.

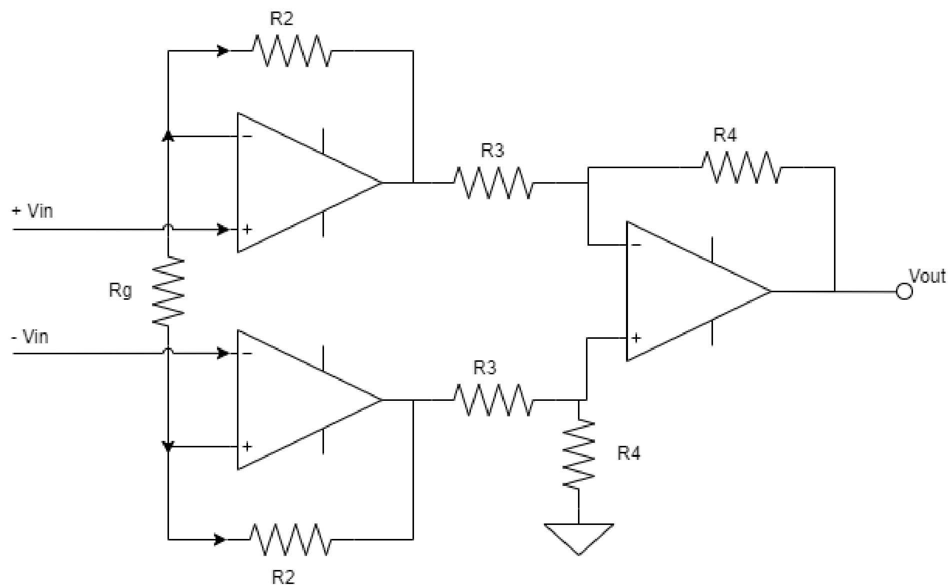

Figure 3 - A Two Stage Instrumentation Amplifier

2. Materials

The manufacturer of the passive and active electrical components for this lab are unknown at this time, they were procured by the university from Digikey.

- Thermistor - 10kΩ
- Thermocouple – K-Type
- Strain Gages - 350Ω
- Operational Amplifier – LM324 by Texas Instruments
- Arduino Nano
- DC Power Supply – Both National Instruments Virtual Bench and GWInstek GPS-3030D
- Multimeter – Amprobe AM-530
- Fluke 1551A Ex Stik Thermometer
- Capacitor – 470nF
- Resistors – Assorted Values
- Kettle
- Insulated Water Bottle
- Generic Breadboard
- Copper Jumper Wire
- Cyanoacrylate Glue
- One 2′ length of steel 3″ wide by 1/16th “ thick
- Acetone
- Sandpaper – Variety of Grits

3. Procedure

The procedure for this series of labs will be separated into three phases which built upon each other. The first phase was calibrating a thermistor and assembling a single stage low gain amplifier. The second was the development of an operational amplifier with a much higher gain for use with a thermocouple. Finally, the third phase covers application of strain gages to metal and the balancing of a Wheatstone bridge. The third phase also uses the amplifier developed in phase two and tests of strain on the metal used were performed.

Phase 1

The first task was to confirm the relationship between temperature and the resistance of the thermistor. To do this, the multimeter was connected to the two ends of the thermistor and it was subjected to an ice-water bath, boiling water and room temperature so that we could observe the change in resistance. While the temperature at sea level of boiling water and water with ice are known, the Fluke thermometer was used as a secondary check and those values were noted along with the resistance values in table 1. These values were plotted in excel to observe the relationship and a line of best fit was applied. With the thermistor acting as expected and the non-linear relationship between temperature and resistance shown in figure 9 in the results section, we moved on to linearization.

The circuit seen in figure 4 was assembled on the breadboard. To begin, we used the same value of 27kΩ for R1 and 10 kΩ R2. The DC power supply was set to supply 5V to the circuit and the multimeter was connected to ground and V_{out} to measure the voltage output from the voltage divider.

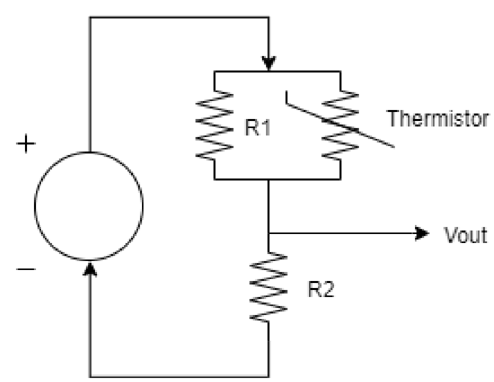

Figure 4 - Thermistor in Voltage Divider Network

The thermistor was then placed in the ice-water bath, the elbow crook of a student, boiling water and room temperature and the results of these tests were recorded in table 2. These tests were repeated with different combinations of resistors until a more linear response was found. These curves can be seen in figure 10 in the results section.

A single stage amplifier was then assembled as seen in figure 5 in order to introduce us to the concept of operational amplifiers. The formula used to determine the gain factor of a non-inverting operational amplifier is $Gain = \left[1 + \frac{R_F}{R_G}\right]$. The multimeter was attached to measure the voltage input into the op-amp circuit, the input was the output of the voltage divider with thermistor assembled earlier. Tests were done at room temperature and body temperature. Resistors of 6.7 kΩ (Rf) and 10 kΩ (Rg) were measured with the multimeter to determine their actual resistance before being put into the amplifier circuit. The multimeter was used to measure both the input going into the amplifier circuit and the output and recorded.

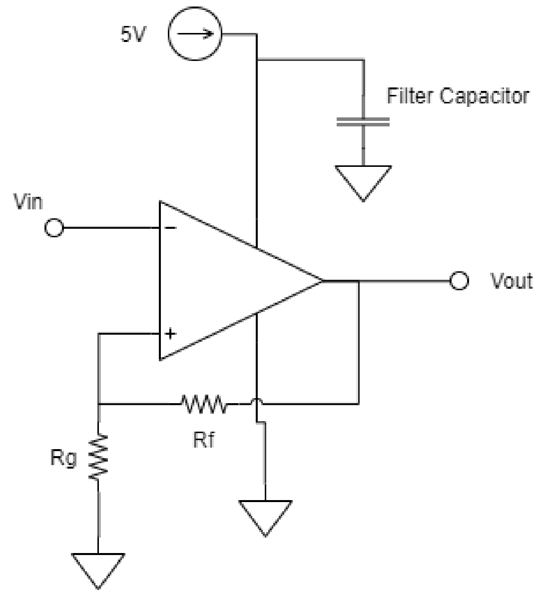

Figure 5 - Single Stage Operational Amplifier

Phase 2

This phase of the lab was meant to explore thermocouple measurements of temperature. Due to the nature of a thermocouple and their very small differential voltage output, they require significant amplification. The instrumentation amplifier design chosen for this task was that seen earlier in figure 3. The values for the resistors are shown in table 1 and the theoretical gain of the amplifier is based on this gain equation $Gain = \left[1 + \frac{2R_2}{R_G}\right]\left[\frac{R_4}{R_3}\right]$ which using the values from the table gave us a gain of 720.

Table 1 – Resistor Values for Instrumentation Amplifier

RG	5k Ω
R2	100k Ω
R3	1k Ω
R4	18k Ω

To test the amplifier, we needed a reliable low voltage source. For this we used a voltage divider as seen in figure 4 that when fed with a 5V DC supply output a reliable 3.6mV. The leads from either side of the 150Ω resistor were used as the inputs for the amplifier.
While the results were reasonable at first, we then experienced constant outputs of 0.65V regardless of input. Heat was also building up on the operational amplifier which led us to believe there was a mistake in the circuit.

The following troubleshooting steps were followed:

- Continuity was checked throughout the circuit to ensure there were no short circuits
- The resistance of each resistor was checked with the multimeter
- The amplifier circuit was dismantled and re-assembled step by step ensuring that each part worked as expected
- Polarity of connections was checked.

After exhaustive troubleshooting it was determined that earlier in the lab the power supply for the operational amplifier itself was wired incorrectly. The positive lead was going into the ground terminal of the op-amp which we believed damaged the op-amp itself.

With a new op-amp we carefully rebuilt the circuit and tested it with the voltage divider input from earlier. The resistor values were all measured and recorded in table 6 along with the expected gain and measured gain. The output was recorded in table 7 and compared to the expected output derived from the gain calculation of the circuit. Unfortunately, time was a limiting factor at this point due to the extensive troubleshooting done on the amplifier so temperature measurements using the thermocouple were not taken.

Phase 3

This phase focused on strain gages and using the instrumentation amplifier assembled earlier to amplify the signal output of the new measurement sensors. The first step was to adhere the strain gages to the piece of steel being tested. The steel was sanded where the gages were to be applied first with 80 grit sandpaper, then 220 and finally 600. Once the surface was smooth and sanded it was cleaned with acetone to ensure the surface was free of contaminants and the gages could be adhered to the steel. The placement of the gages was measured to be 10cm from the end of the piece of steel, centered so that the gages would be aligned on each side of the piece. Cyanoacrylate glue was used to adhere the gages to the surface as well as two small solder pads seen in figure 6. The purpose of these pads was to ensure there was no tension on the leads of the strain gages which could result in inaccurate strain measurements. Hot glue was also used on the lead wires themselves to minimize any strain on the solder joints.

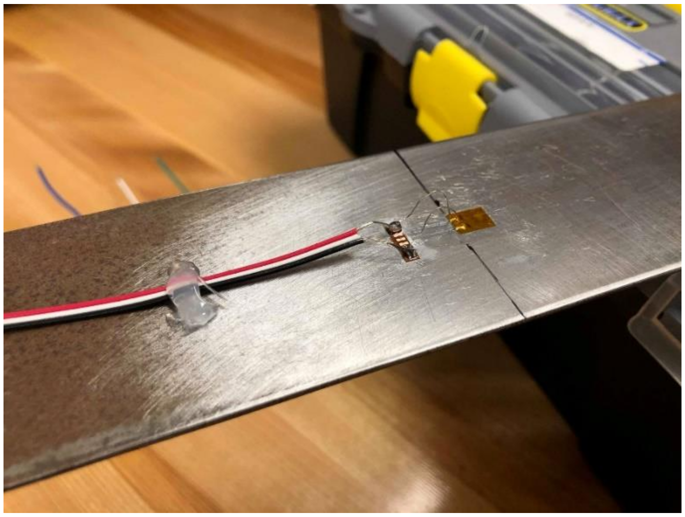

Figure 6 - Strain Gages and Solder Pads

With the strain gages attached to each side of the piece of steel it was then time to assemble the Wheatstone bridge. The gages used have a resistance of 350 Ω each when under no strain, the resistors chosen for the other side of the bridge based on measurements with the multimeter to match the gages as closely as possible. For ours we used resistors in series to achieve this balance, using 320Ω resistors in series with 20Ω resistors we were able to get measured values of 349.7Ω and 350.5Ω respectively. This balance achieved a differential voltage output across Vout of 2.2mV with a 9V source under no tension rising to 22mV under positive load and -18mV under negative load. The outputs were then connected to the instrumentation amplifier as seen in Figure 7.

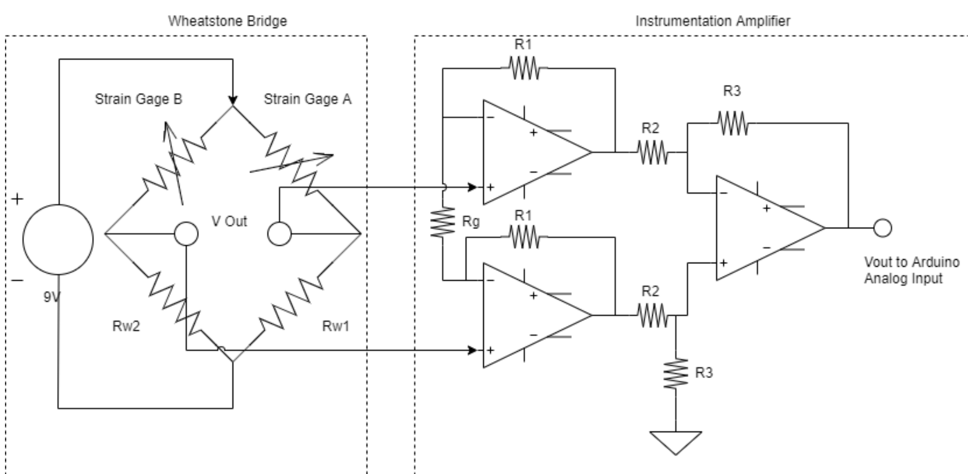

Figure 7 - Strain Gage Amplifier Circuit

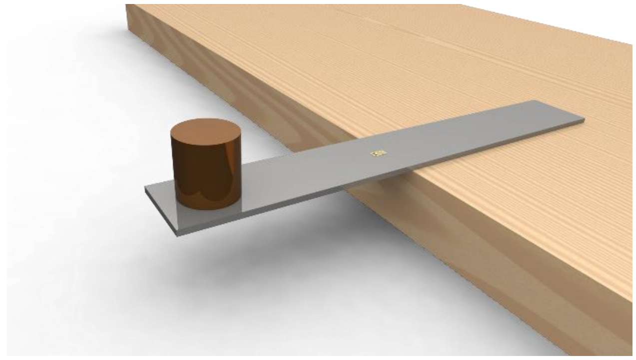

Figure 8 - Experiment Layout

The next step was to test the strain the metal plate was experiencing under different loads. The metal was clamped to a work bench with the strain gage just over the edge of the bench where it would experience the most strain, weights were then placed on, or hung off (with attached hooks) the central point at the end of the piece of steel 50mm from the strain gage itself as shown in figure 8. The weight itself was placed 145mm from the overhang.

With the setup assembled we then hung weights from 20g to 1kg from the bar and measured the voltage output of the amplifier circuit using the multimeter. Measurements were recorded at 1 second intervals for 20 seconds for each weight. These voltage values were recorded in table 8 in Appendix A.

Using an Arduino to record this data would have been much more accurate and resulted in more meaningful data, unfortunately we did not have the time to implement this solution.

4. Results

Table 2 – Resistance Values of 10kΩ Thermistor at Varying Temperatures

	Assumed Temperature (°C)	Thermometer Reading (°C)	Resistance (kΩ)
Ice Bath	0	0.07	27.43
Room Temperature	22	22.31	11.15
Body Temperature	36	34.77	6.91
Boiling Water	100	99.31	0.98

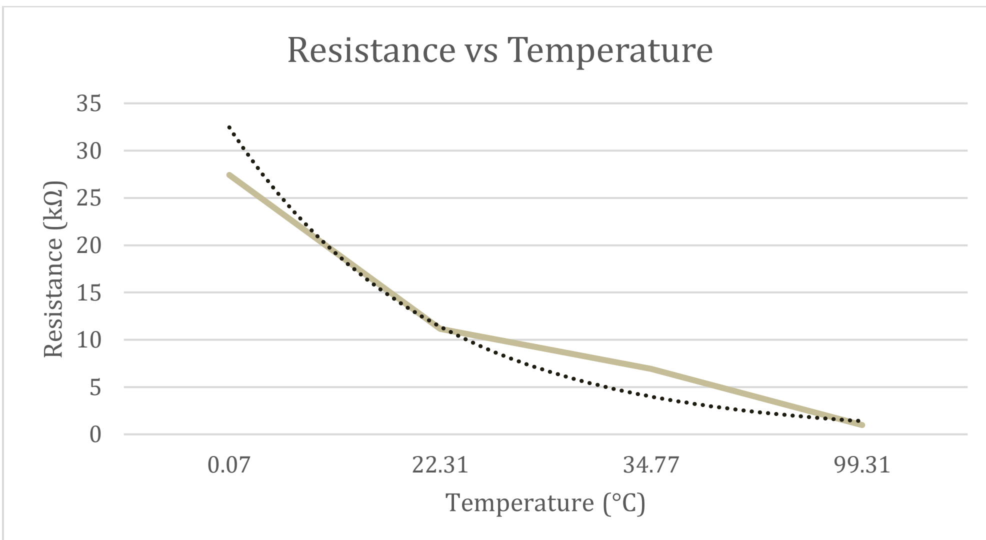

Figure 9 - Resistance vs Temperature Relationship

Table 3 – Voltage Outputs with Varying Combinations of Resistors

		Voltage Outputs			
	Assumed Temperature (°C)	R1 - 10kΩ R2 - 27kΩ	R1 - 27kΩ R2 - 10kΩ	R1 - 5.6kΩ R2 - 27kΩ	R1 - 27kΩ R2 - 5.6kΩ
Ice Bath	0	2.099	3.924	4.262	0.842
Room Temperature	22	2.786	4.175	4.388	1.679
Body Temperature	36	3.18	4.314	4.469	2.18
Boiling Water	100	4.545	4.823	4.832	4.217

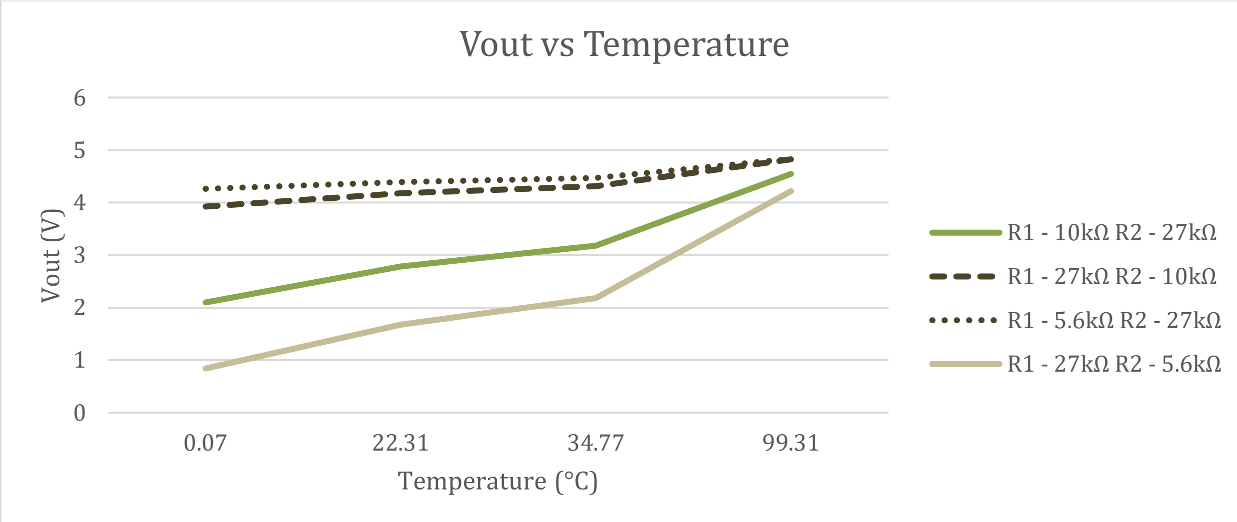

Figure 10 - Linearization Results

Table 4 – Resistor Values for Operational Amplifier

	Rf (kΩ)	Rg (kΩ)	Gain
Marked Values	6.7	10	1.67
Measured Values	6.72	9.85	1.68

Table 5 – Gain Results from Operational Amplifier Testing

	Assumed Temperature (°C)	Input (V)	Output (V)	Observed Gain	% Difference
Room Temperature	22	1.7	2.87	1.69	0.36%
Body Temperature	36	1.95	3.25	1.67	0.93%

Table 6 – Instrumentation Amplifier Resistor Values and Expected Gain

	Rg (kΩ)	R2 (kΩ)	R2 (kΩ)	R3 (kΩ)	R3 (kΩ)	R4 (kΩ)	R4 (kΩ)	Gain
Resistance	5.00	100.00	100.00	1.00	1.00	18.00	18.00	738.00
Measured Resistance	5.08	99.60	98.70	0.98	0.99	17.80	17.96	726.37

Table 7 – Instrumentation Amplifier Test Results

Input (mV)	Output Expected (V)	Actual Output (V)	% Difference
3.6	2.61	2.698	3%

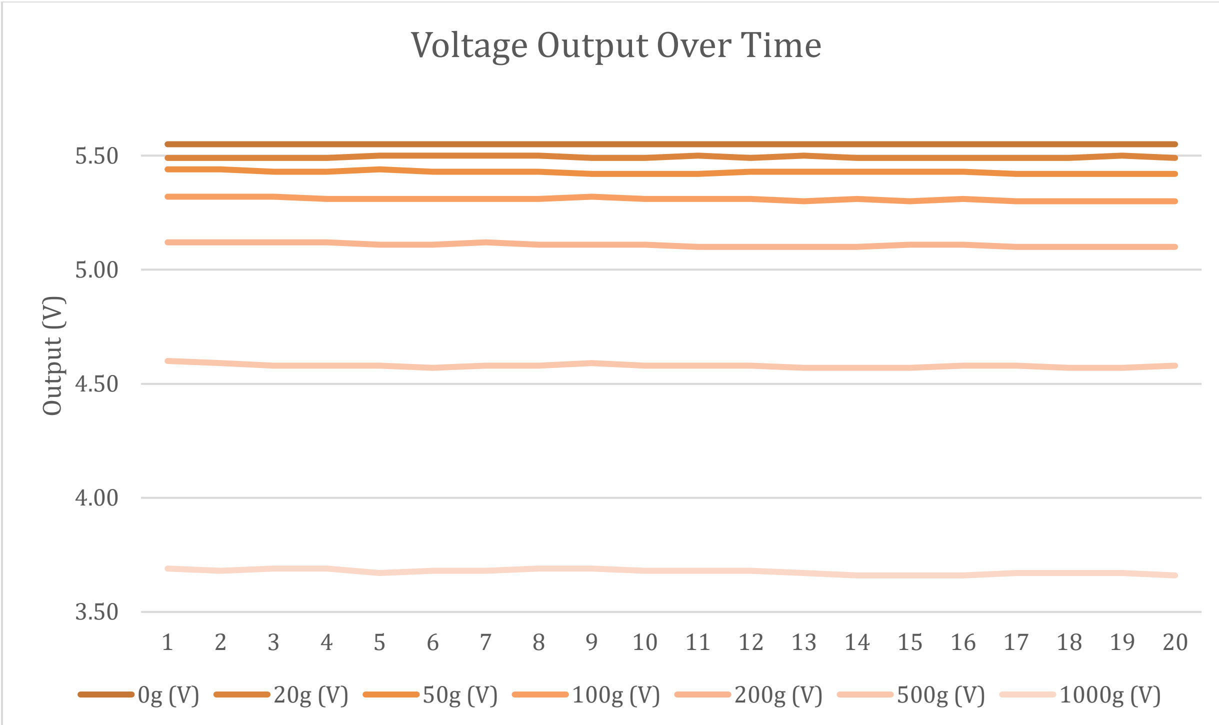

Figure 11 - Strain Gage Voltage Outputs

5. Discussion

The desired outcome of these labs was to gain a broad understanding of temperature and strain sensors, operational amplifiers and how to use one properly for your application, data logging, measurements and interpretation of said data.

The first phase of this lab, exploring linearization of thermistors was a success. The resistance of the thermistor when originally tested at a variety of known temperatures showed a non-linear response to temperature changes which was expected. The exercise of trying a variety of resistor values in different configurations to linearize the network was also a success. The real world, observable voltage outputs changing as these values were changed could be easily visualized once plotted in Excel. This clear shift from an exponential curve to a reasonably linear relationship demonstrated the effectiveness of the linearization circuit.

Assembling the operational amplifier and testing the gain that the input experienced was an effective way to put into practice the theory that was presented in lecture. A point which became very important was the measurement of the resistor values themselves, simply picking resistors out of the available pile and assuming their values introduced error into the system that could be compounded depending on which way the error for each component drifted. The measured gain of this amplifier was less than 1% off from what was expected when the calculations were made using the measured values of the resistors.

The second phase of this lab was more of a war of attrition with our instrumentation amplifier circuit than a meaningful collection of temperature data. Significant lessons were learned that may not necessarily have been the desired learning outcomes of this lab, but they were arguably just as, if not more, important. Resilience, patience, and developing a system of logical troubleshooting was key to our eventual success. While an op-amp was damaged early in the process this gave us the opportunity to learn to isolate components, test, verify and move on. Assumptions as to what was not functioning were never made and it made us more confident at the end of the process as to what the problem was to begin with. The concept of "rail to rail" amplifiers was understood through testing as well as offset. Our amplifier output with a 5V supply seemed to constantly put out around 0.6V or 3.65V it was understood that the 0.6V output was the offset of the amplifier with no signal and 3.65V was the point at which the amplifier was saturated and could not amplify the signal past this point.

Once troubleshooting was complete and a properly working amplifier was assembled it was a more rewarding experience and the number of times it was assembled and disassembled in the process made us both much more familiar with the workings of the circuit.

In phase 3 we encountered a downfall of shared workspaces, our strain gage apparatus appeared to have misplaced itself over the weekend between it being assembled and us setting up the strain experiment, due to this our experiment was postponed until it found itself a week later. This delay, in addition to the struggles in phase 2, combined to make microcontroller data logging, exploring the concepts of sampling rates, burst sampling and applying the Nyquist frequency to eliminate noise impossible to achieve in the time given. This was an unfortunate consequence as these would have been very useful concepts to test in a hands-on environment.

While we were not able to implement the microcontroller for data logging that was no excuse to avoid collecting meaningful data manually. The results from using the multimeter to measure the output from our strain gage circuit were consistent and demonstrated the relationship between a change in moment and a change in voltage which can be seen in table 8.

Table 8 – Voltage Changes Related to Changes in Strain

Weight (g)	Force Applied (N)	Distance to Weight (mm)	Distance to Strain Gage (mm)	Moment (Nm)	Average Voltage Output Offset	Voltage Change per Nm
20	0.1962	145	50	0.028	-0.06	1.986
50	0.4905	145	50	0.071	-0.12	1.715
100	0.981	145	50	0.142	-0.24	1.694
200	1.962	145	50	0.284	-0.44	1.552
500	4.905	145	50	0.711	-0.97	1.365
1000	9.81	145	50	1.422	-1.87	1.317

Noise was difficult to ascertain in the output of our amplifier as the strain measurements were taken when the material was in a static state and the resolution of our measurements was limited by the multimeter itself. There were slight variations in voltage output as we took our measurements over time that can be seen in figure 11 which could be attributed to the relatively low sensitivity of the multimeter.

Conclusion

This series of labs consisted of a series of challenges which were unexpected at the outset. While ostensibly a series of labs with the purpose of gathering measurements for analysis the result was a series of labs which taught the fundamental concepts behind electronic measurements. Patience and perseverance were the central attributes tested in troubleshooting and repairing circuits and sensors throughout the lab. Thermistors and linearization were used, understood and manipulated. Building amplifier circuits with a target gain factor feels second nature and the electrical concept behind a Wheatstone bridge is much easier to grasp after observing it work in a lab environment.

In conclusion, while this lab was at times one of the more frustrating experiences this semester it was also one of the most rewarding.

References

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APPENDIX A

Voltage Output from Strain Gage Tests

Time (s)	0g (V)	20g (V)	50g (V)	100g (V)	200g (V)	500g (V)	1000g (V)
1	5.55	5.49	5.44	5.32	5.12	4.60	3.69
2	5.55	5.49	5.44	5.32	5.12	4.59	3.68
3	5.55	5.49	5.43	5.32	5.12	4.58	3.69
4	5.55	5.49	5.43	5.31	5.12	4.58	3.69
5	5.55	5.50	5.44	5.31	5.11	4.58	3.67
6	5.55	5.50	5.43	5.31	5.11	4.57	3.68
7	5.55	5.50	5.43	5.31	5.12	4.58	3.68
8	5.55	5.50	5.43	5.31	5.11	4.58	3.69
9	5.55	5.49	5.42	5.32	5.11	4.59	3.69
10	5.55	5.49	5.42	5.31	5.11	4.58	3.68
11	5.55	5.50	5.42	5.31	5.10	4.58	3.68
12	5.55	5.49	5.43	5.31	5.10	4.58	3.68
13	5.55	5.50	5.43	5.30	5.10	4.57	3.67
14	5.55	5.49	5.43	5.31	5.10	4.57	3.66
15	5.55	5.49	5.43	5.30	5.11	4.57	3.66
16	5.55	5.49	5.43	5.31	5.11	4.58	3.66
17	5.55	5.49	5.42	5.30	5.10	4.58	3.67
18	5.55	5.49	5.42	5.30	5.10	4.57	3.67
19	5.55	5.50	5.42	5.30	5.10	4.57	3.67
20	5.55	5.49	5.42	5.30	5.10	4.58	3.66