FACULTY OF SUSTAINABLE DESIGN ENGINEERING, UPEI

ENGN 3220: Engineering
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Lab 4 – Construction of a Weigh Scale Using Strain Gauges

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***Abstract*— The goal of the lab sessions for this course was to gain practical engineering experience working on the bench. This report documents the construction of a weigh scale that could interpret and display data from strain gauges via an Arduino microcontroller. The data from the strain gauge was measured by creating a Wheatstone bridge circuit, so that any change in the resistance of the gauge would result in an output voltage that could be quantified. Once the circuit was constructed, the gauge was attached to an elevated piece of plexiglass. The end result was a functioning weigh scale that was calibrated using several materials of a known weight.**

I. INTRODUCTION

The purpose of this report is to document and explain the lab work that was completed to create a weigh scale measurement device. These lab sessions were spread across a period of three months, and dealt with topics such as:

- Errors and statistics
- Strain gauges, thermistors, thermocouples
- Operational amplifiers, potentiometers, voltage dividers
- Amplification gain
- Data collection and sampling

Many of these topics were incorporated in the construction of the final device.

Two main aspects of the lab sessions were preparation and troubleshooting. There were no specific directions as to what system should be constructed or which sensors should be used. As a result, it was our responsibility to plan the building, testing, calibration and data collection for our specific system. Since every system was unique, it was also our responsibility to troubleshoot any issues that arose. The end goal was to create a practical, useable system that could read and interpret data from a sensor. The system then needed to display a meaningful value, such as force or temperature, based on the sensor measurements.

II. BACKGROUND

The labs were divided into three main sections:

1) Mechanical Measurements: The focus of this section involved the planning and approach for taking physical measurements. The point was to emphasize that there is no set method to measure something. It is up to the individual to determine the optimal device and technique to acquire data. They must then be able to calculate the accuracy of the measurement strategy and identify possible sources of error. These errors might include measurement bias, statistical noise, manufacturing errors, tolerances or simple human error.

2) Measurement Devices: The three main devices discussed in this course were thermistors, thermocouples and strain gauges. Thermistors are thermally sensitive resistors that exhibit a change in resistance when exposed to a change in temperature [1]. These changes in resistance are not always linear with temperature [2]. Therefore, it is necessary to calibrate thermistors by testing their resistance at known temperatures. By incorporating a thermistor into a circuit such as the one shown in Figure 1, the voltage output from the circuit can be linearized over a certain temperature range by altering the resistance values of R_1 and R_2.

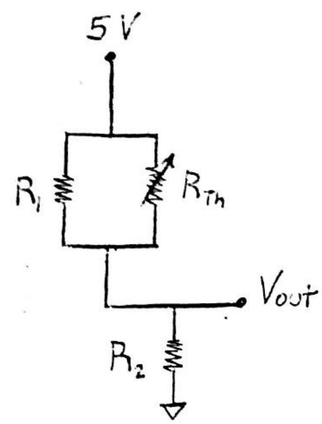

Figure 1: Diagram of thermistor circuit

In that way, a direct relationship can be created between the temperature sensed by the thermistor and the voltage output.

Thermocouples are two dissimilar metals that are jointed together at one end [3]. When one of the ends is heated or cooled, there is a continuous current that flows in the thermoelectric circuit. If this circuit is broken at the center, the open circuit voltage is a function of the temperature at the junction and the composition of the two metals. This means that heating or cooling the junction produces a voltage output that can be linked back to temperature [4]. The voltage output is very small, but unlike thermistors, it is always linear with temperature.

A strain gauge is an extremely common measurement device that consists of a long thin piece of metal arranged in a grid pattern. The gauge is secured, typically via glue, to a test material that will experience some type of force. As it expands or contracts as a result of this force, the metal in the strain gauge gets longer or shorter with the material, changing its resistance [5]. The resistance varies in proportion to the amount of strain in the material.

In order to measure the small changes in the resistance, the strain gauge can be wired to a Wheatstone Bridge circuit (see Figure 2).

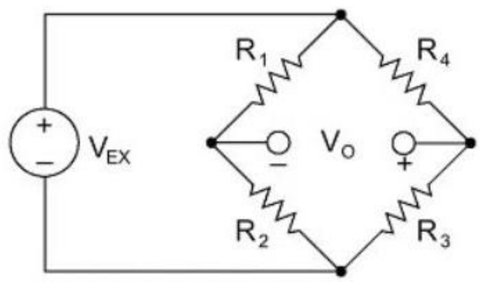

Figure 2: Diagram of typical Wheatstone Bridge Circuit [6]

A Wheatstone Bridge is essentially two parallel voltage dividers. The voltage output, V_O, is given by Equation 1.

(1) $$V_O = \left[\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + 2}\right] * V_{EX}$$

Whenever $\frac{R_1}{R_2} = \frac{R_4}{R_3}$, the voltage output is equal to zero and the bridge is balanced [6]. Therefore, if any of the four resistors are replaced by a strain gauge, the change in resistance from the gauge will result in a non-zero voltage output that can be quantified [7].

3) <u>Amplification and Data Collection</u>: Once the measurement strategy has been determined the sensors have been selected, it is still necessary to interpret and output meaningful values from the raw data. Because the voltage output from the sensors discussed in this course were so small, this meant creating a way to amplify the output signal in order to produce a wider range of values. This was accomplished using operational amplifiers.

Ideal op-amps are governed by two main rules: 1) No current flows into the + or – terminals and 2) In a circuit with negative feedback, the op-amp will adjust its output so that the voltage difference between the + and – inputs is zero. Voltage gain can be achieved by incorporating an op-amp into a circuit such as the one in Figure 3.

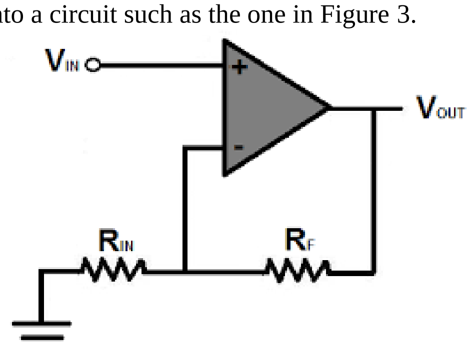

Figure 3: Diagram of Non-Inverting Op Amp Gain Circuit [8]

The gain from this circuit is given by:

(2) $$\boldsymbol{Gain = 1 + \frac{R_f}{R_{IN}}}$$

The final step is to record the amplified output and convert it to a meaningful result. For these labs, the selected method was to use an Arduino microcontroller to read the analog signal from a sensor. This requires that the sensor be calibrated in order to determine the relationship between the analog output and the property being measured (force, temperature, etc). The Arduino can then be programmed to take readings at certain intervals depending of the sampling that is required. Once the device is calibrated, the calculation to convert the analog signal to the desired property can be built into the Arduino program.

III. Equipment

- 350 Ohm Strain Gauge (2)
- 10kΩ Thermistor @ 25C
- Type J Thermocouple
- Plexiglass (14 x 6”)
- Plywood (6 x 0.5 x 1”)
- 1” Wood Screws (4)
- Glue
- Electrical Tape
- Breadboard and Sauter Board
- Arduino Nano (V3.0)
- LM324 Quad Op-amp
- 0.1 pF Capacitor
- 5 kΩ Potentiometer (2)
- GPS-303000 Laboratory DC Power Supply
- Keithley 2110 51/2 Digital Multimeter
- Wide range of resistors (330 Ω – 100 kΩ)
- Duracell Procell 9V Battery (21)

IV. Procedure

Due to the layout and schedule of the course, the procedure to create the measurement system began with the introduction of thermistors and thermocouples. The goal was to become familiar with the three main sensors and then decide for ourselves which one(s) we wanted to incorporate into our measurement system.

The first step was to calibrate the rated 10kΩ Thermistor @ 25C using four objects of known temperature. These objects were ice water (0℃), room temperature (22.1℃), body temperature of our fingers (~ 32℃) and boiling water (100℃). The corresponding resistance of the thermistor was measured using a multimeter at each of these calibration temperatures.

After acquiring these values, we constructed a thermistor linearization circuit as shown in Figure 4.

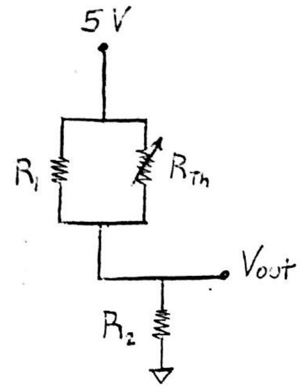

Figure 4: Diagram of thermistor linearization circuit

With the thermistor incorporated into this circuit, we once again used it to measure the four known calibration temperatures. We then recorded the voltage output that the circuit produced with the thermistor reading the different temperatures. This process was completed using three different resistor combinations for R_1 and R_2. The reason for this was to determine which combination of resistor values would produce the most linear output between temperature and voltage. After recording the data and graphing the results, we concluded that the output was most linear when using 56 kΩ and 4.4 kΩ for R_1 and R_2 respectively.

Once the ideal resistor combination was set, we amplified the voltage output by connecting to it a simple non-inverting op-amp circuit (see Figure 5).

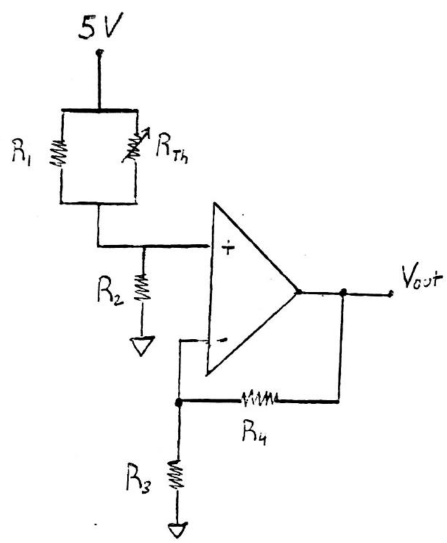

Figure 5: Diagram of op-amp thermistor circuit

The voltage output from the thermistor circuit was connected to the inverting (+) terminal of the op-amp. At first, we just wanted to ensure that the op-amp circuit was working. So, we selected 330kΩ and 170kΩ as the resistor values for R_4 and R_3, which (from equation 2) should have produced a gain around 3. However, the voltage output was not what we expected.

We tried many different techniques to troubleshoot why the circuit wasn't working as expected, such as

- Reviewing the datasheet for the op-amp to ensure that it was wired to the correct pins
- Soldering the components together to eliminate loose connections
- Using a different op-amp in case the current one was broken
- Trying different values, both larger and smaller, for R_4 and R_3
- Simplify the troubleshooting process by color-coding the wires and cutting them to precise lengths. This made the breadboard extremely neat and made it much easier to identify if something was wired incorrectly

Eventually, we discovered that the circuit contained a diode drop of approximately 1.3 volts. We had been using a 5V power supply, so that meant that the maximum V_{out} that we could record was ~3.7 V. If the output voltage was any greater, the reading remained at the 3.7 V threshold. To account for this, we halved the gain of the circuit by switching R_4 and R_3. This kept V_{out} under the threshold and produced the values we expected. Once the thermistor circuit was working properly, we moved on to the thermocouple.

We began the thermocouple section by building a voltage divider. This was used to reduce the 5V DC input to simulate the small voltages that would be created by the thermocouple. The values for R_1 and R_2 were 100 kΩ and 550 Ω respectively (see Figure 6). This reduced the 5V DC supply to approximately 3.6 mV, which we used as inputs for a single stage op-amp circuit.

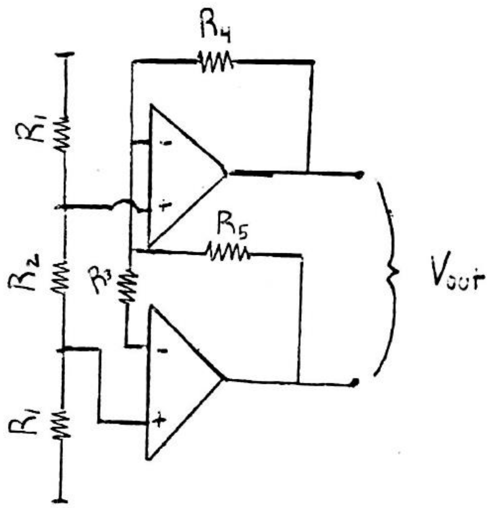

Figure 6: Diagram of voltage divider to single stage op-amp circuit

The gain for this op-amp circuit is given by equation 3:

$$\textbf{(3)} \qquad \boldsymbol{Gain = 1 + \frac{(R_4)(R_5)}{R_3}}$$

We created a gain of approximately 40 by using values of 10 kΩ for R_4 and R_5 and 500 Ω for R_3. This amplified the 3.6 mV input from the voltage divider to around 122 mV, as expected.

Once this first stage was functioning, we built a second stage op-amp circuit and connected it to the first. The goal was to achieve a combined gain of close to 1000. The finalized circuit is displayed below in Figure 7.

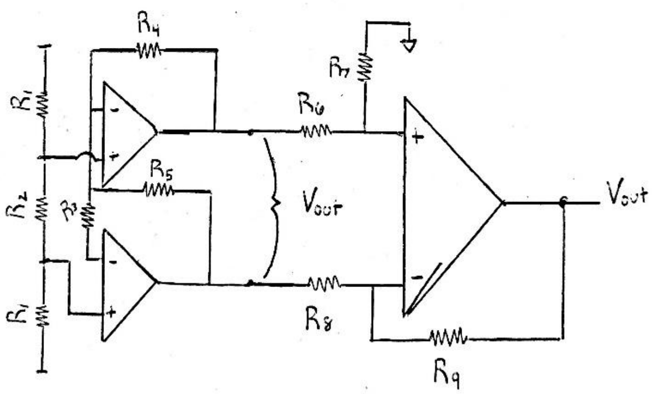

Figure 7: Diagram of final two stage op-amp circuit

By setting $R_6 = R_8 = R_G$ and $R_7/R_6 = R_8/R_9$, the gain from the second stage of the circuit is given by equation 4:

(4) $$\boldsymbol{Gain = \frac{R_9}{R_G}}$$

Our goal was to achieve a second stage gain of ~25, so we selected resistance values of 100 kΩ and 4 kΩ for R_9 and R_G respectively. This should have resulted in an overall two-stage gain of approximately: 40 x 25 = 1000. However, the circuit did not initially produce the output that we expected. After more troubleshooting, we discovered that the positive and negative outputs from the first stage were connected to the negative and positive of the second stage. After making the switch, we measured a gain of approximately 860, from the 3.6 mV input to a 3.1 V output. This output was deemed acceptable and it completed our setup of the thermocouple, which could now be connected in place of the voltage divider.

The final sensor that we dealt with were the strain gauges. In order to convert the resistance changes from the gauges into a voltage output, we constructed a Wheatstone Bridge circuit. As previously mentioned, if $\frac{R_1}{R_2} = \frac{R_4}{R_3}$, the bridge is balanced, and the voltage output will equal zero. However, this relationship needs to almost perfect for the voltage to actually equal 0. To account for this, we included two 5 kΩ potentiometers in the circuit which allowed us to precisely control the resistance values. The potentiometers were then connected in series to two 10 kΩ resistors. A diagram and image of the circuit is shown below in Figure 8.

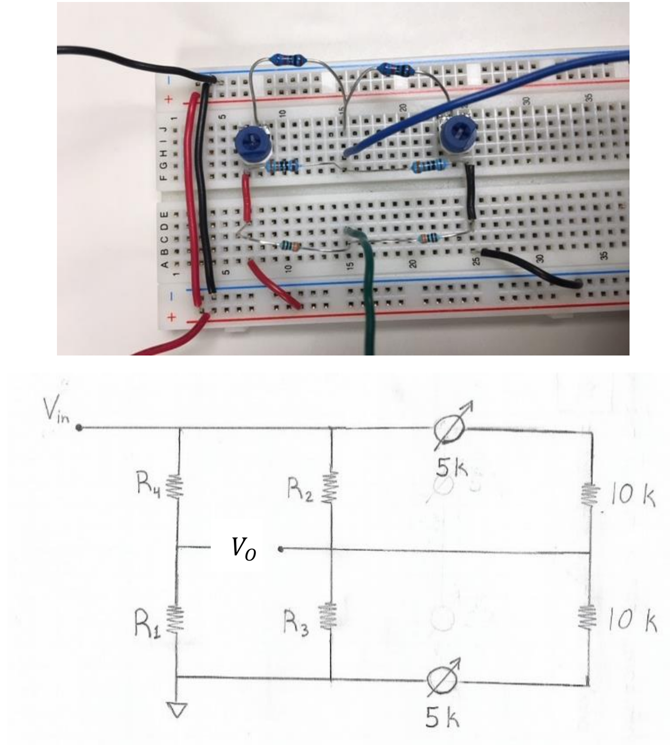

Figure 8: Diagram of Wheatstone Bridge circuit

In this circuit, R_1 and R_4 were replaced with the 350 Ω strain gauges. We had initially hoped to use 350 Ω resistors for R_2 and R_3, so the circuit would require a minimal amount of balancing. Unfortunately, the closest resistor values available were 330 Ω. Another problem was that the 5 kΩ potentiometer that we used were not very precise, as they could only be adjusted one revolution. We also found that the voltage output took an extremely long time to settle whenever we adjusted the potentiometers. Consequently, a great deal of the lab time was spent adjusting the potentiometers in order to achieve a desired output reading. This time was compounded by the fact that were some unreliable connections on the breadboard that would occasionally cause a nonsensical output reading.

This completed the setup for using the strain gauges. The voltage output from the Wheatstone Bridge circuit was extremely small and needed to be amplified, but we already had a functioning amplification circuit from the thermocouple setup.

At this point, we were given the choice of using any of these sensors to create our own measurement system. We chose to use the strain gauges to construct a weigh scale. This process began by choosing a material to attach the strain gauges that would serve as the table of the scale. We chose a 14 x 6" piece of plexiglass, simply because it was flexible and would not require extremely heavy objects to produce a reading.

We sanded, filed and cleaned the plexiglass so the gauges could be securely attached with glue. They were attached directly in the center on either side of the plexiglass. We drilled holes through the center in order to easily attach the ends of the two gauges. The ends were sauntered together and secured to the glass via electrical tape to ensure they would not be disconnected with sudden movements. An image of this setup is shown in Figure 9.

Figure 9: Image of strain gauge connection to plexiglass

The next step was cutting two pieces of plywood that were used to support the plexiglass at each end. The top part of the wood supports was cut with a miter saw so that it came to a point. We then drilled oversized holes into the plexiglass and used 1" wood screws to loosely secure the plexiglass to the supports. This effectively modeled the plexiglass as a simply supported beam (see Figure 10).

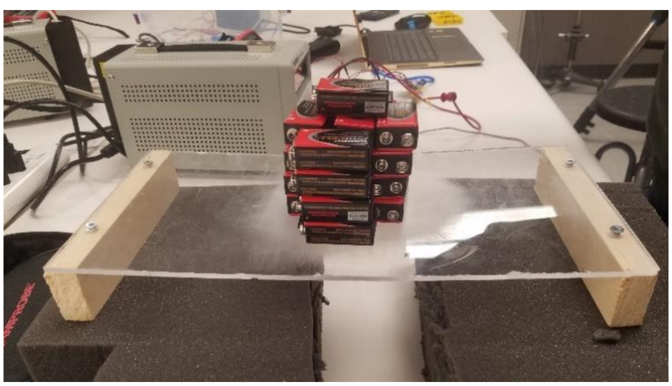

Figure 10: Image of completed scale

We then connected the strain gauges to the Wheatstone Bridge and adjusted the potentiometers so that the baseline voltage output was just under the threshold of 3.7 V: approximately 3.3 ± 0.1 V. We originally wanted to set the baseline closer to 3.7 V, but it continued to fluctuate and due to time constraints we were unable to let it settle at a higher value.

For the final step of the construction, we needed to connect an Arduino Nano to read the voltage output from the Wheatstone Bridge circuit. To do this, we soldered both the op-amp circuit and Arduino to a solder board. In this way, the amplified voltage output could easily be jumpered to an input pin and the entire system could be contained as one unit. Due to a lack of space on the solder board, two of the pins on the Arduino had to be cut. Once the connection was made, V_O was wired to pin A6 on the Arduino.

Images of the completed op-amp circuit/Arduino connection are displayed in Figure 11.

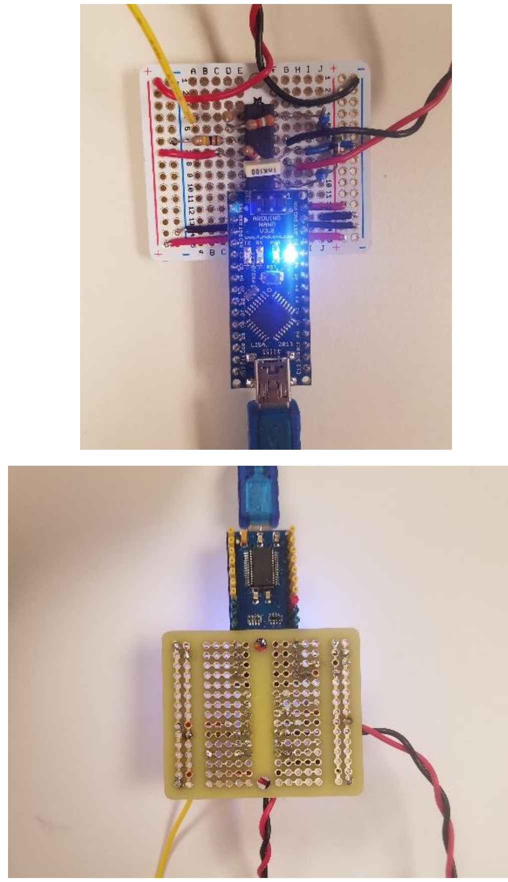

Figure 11: Images of op-amp circuit/Arduino Nano connection

To calibrate our device, we used the precision scales in the lab to weigh ten 9V Duracell batteries. After acquiring the average weight and standard deviation of the batteries, we tried placing one on the scale a few times in order to see how long it took for the output value to settle. We found that this usually took between 2-3 seconds. We made the decision to have the Arduino take a reading every 300 milliseconds and wait 10 seconds before adding another battery to the scale. This would give us around 33 data points per battery. We initially wanted to wait longer between calibration points, but time constraints limited us to 10 seconds.

For the actual calibration, we started the serial monitor on the Arduino and took readings for 30 seconds to allow the device to settle at a baseline value. Then, we placed 21 batteries onto the scale, one after another, at the selected 10 second intervals. After all the batteries had been placed, we waited another 30 seconds to allow the scale to settle. Once we had acquired this relationship between weight and analog voltage output, we tested the accuracy of our scale by weighing our phones. Each phone was placed on the scale for 10 seconds and the device was given 30 seconds to settle in between the weighing of each one. We would have liked to weigh more objects and collect more data points, but after this session our focus in the lab shifted to our final project for the course.

V. Measurements

The first set of measurements that we took were the weights of batteries that were used to calibrate the scale. We had initially planned to record the exact weight of each individual battery and then keep track of which one we placed on the scale. However, we decided it would be just as valid to simply weigh ten batteries and record the average weight and standard deviation. The data is shown below in Table 1.

Table 1 - Data from Duracell 9V Batteries

Battery	Weight (g)
1	45.3153
2	45.6306
3	45.4041
4	45.585
5	43.3429
6	45.333
7	45.0304
8	45.0227
9	45.5671
10	45.4148
Average	**45.37**
Standard Deviation	**0.2**

The next set of measurements were the analog output readings that were recorded by the Arduino Nano. As mentioned, the Arduino was programmed to take a reading every 300 milliseconds. With a 10 second interval between the addition of batteries, this resulted in nearly 700 data points. For convenience sake, we took the average output value of the 30 or so data points that we had for the addition of each battery.

Table 2 - Analog Output from Batteries

Number of Batteries	Average Analog Output Value
0	729
1	701
2	656
3	633
4	615
5	593
6	565
7	522
8	505
9	465
10	428
11	387
12	361
13	339
14	305
15	252
16	227
17	201
18	173
19	147
20	117
21	93

The final measurements that we took were the analog outputs from the weight of our phones. Each of the phones were weighed individually, with output being allowed to settle to a baseline value in between each measurement. The resulting data is shown below in Table 3.

Table 3 - Analog Output from Phones

Phone	Average Baseline Value	Average Analog Output Value
A50	650	561
iPhone 7	703	620
Galaxy S7	697	585
iPhone 6s	676	585

VI. Results

The purpose of using the batteries to calibrate the scale was so we would have a clear relationship between items of a known weight and the resulting change in the analog output. This would give us a ratio that could then be used to calculate the weight of anything placed on the scale. This calculation could be built into the Arduino program so that the only output from the measurement system is a meaningful property that the user can recognize. Namely, the weight of the object in grams, kilograms, pounds or whatever unit is built into the calculation.

For the calibration, we would ideally expect a graph of the Analog Output vs. Number of Batteries to be linear, as the addition of each battery should reduce the output by the same amount every time. The actual graph is displayed below in Figure 12.

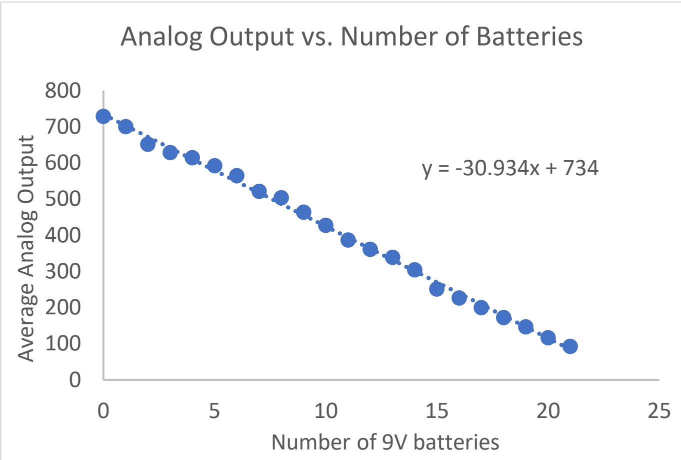

Figure 12: Graph of Analog Output vs. Number of Batteries on the scale

The slope of the linear trendline on this graph gives the average output drop that occurred with the addition of each battery. In this experiment, that value was equal to approximately **31**. The known weight of each battery was 45.37 grams with a standard deviation of 0.2 grams. Therefore, the relationship between analog output and weight (in grams) is equal to:

30.934 : 45.37 or approximately **1 : 1.467**

With these calibration values, we can determine the weight of our phones based on the analog output. These values can then be compared to the actual weight of the phones to determine the accuracy of our scale. Table 4 contains the average output drop for each phone as well as the calculated weight based on the 1 : 1.467 conversion ratio found during the calibration process. This is then compared to the actual known weight of the phones and the percentage error is given.

Table 5 – Data Results from Phones

Phone	Average Output Drop	Calculated Weight (g)	Actual Weight (g)	Error
A50	89	130.56	166	27%
iPhone 7	83	121.76	138	13%
Galaxy S7	112	164.30	179	9%
iPhone 6s	91	133.50	143	7.1%

VII. Discussion

It is clear from the discrepancies in the results that there were numerous possible sources of error in this experiment. For example, we found that the average output drop for the batteries was approximately 31. Therefore, we should have expected the drop for each battery to be fairly close to 31. Instead, there were instances where this value was as high as 53 and as low as 17. One possible source of error is that we may have not given the output value enough time to settle out. We did not actually begin taking measurements until the final 15 minutes of the last lab period. So, we were forced to rush through the process of calibrating the scale. If we had given the output value a full minute to settle instead of only 10 seconds, we may have seen a more consistent pattern. Nevertheless, the final graph of the output vs the number of batteries was very close to linear.

We also noticed that the output would take longer to settle if the battery was dropped onto the scale rather than gently placed. A few times during the calibration process we accidentally dropped and/or had to slightly adjust the position of a battery. This increased settling time and could have accounted for some of the inconsistencies in the average analog output drop.

Another possible source of error was the lack of space on the scale. The first few batteries were stacked directly on top of one another right in the center of the scale: the point of maximum deflection. However, as can be seen in Figure 10, we were forced to stack the batteries farther from the center as the scale became crowded. The batteries that were placed closer to the edge of the scale would not have produced as much strain as the ones in the middle. This could also explain why the drops were not consistently equal to 31.

An additional concern was that the wooden "legs" of the scale would bend outward under weight when the scale was placed on a slippery table. This effectively lessened the deflection of the plexiglass. To correct this, we placed the scale on two thick foam pads to prevent the legs from sliding. However, due to its slight compressibility, it is possible that some of the weight was transferred to the foam and not directly to beam deflection. This could explain why the measured values for the weights of the phones are consistently smaller than the actual values.

Finally, imperfections in sampling of the calibration process could have resulted in error. As mentioned in the procedure section, it usually took around 2 seconds for the analog output to settle after the addition of each battery. We figured that the additional 8 seconds of our 10 second intervals would give us enough readings (~25) at a stable value to where the average would be an accurate representation of each drop. However, when calculating the average, we used all the values from the 10 second interval. Our calibration might have been more accurate if we excluded the first 7-8 fluctuating data points from the calculation, and only use the values after the output had stabilized. It would have been even more accurate if we took a 30 second sample and excluded the first 5 seconds from the calculation. This would have eliminated the uncertainty of settling and given a greater range of values which would have produced a more accurate average.

VIII. Conclusions

The actual measurements from this experiment were quite simple and straightforward. If we repeated this experiment, there are several improvements that could be made in the measurement procedure. For example, we could use actual weights (50 g, 100 g, 200 g, etc) to calibrate the scale. We could also allow more time for the output value to settle. Another fix would be to screw the scale supports to another board to prevent them from sliding. We could have also taken a larger sample of readings during calibration and eliminated the fluctuating values from the calculation of the average output.

The main difficulty that we encountered in the construction of the weigh scale was the balancing of the Wheatstone Bridge circuit. The imprecise potentiometers, unreliable connections of the breadboard and the output reading's inability to settle all provided frustration that we had to work through. However, once we had confirmed that the electrical components were working, the connection and set up of the Arduino Nano to read the output was quite simple.

Overall, the lab sessions in this course emphasized the importance of planning measurements and recognizing possible sources of error in advance. One of the key takeaways was that there is no perfect way to measure something. It is up to the individual to determine the proper strategy, equipment, sensors and sampling for the specific data they want to collect. Different combinations of these can be equally valid for the same measurement, provided you are able identify and calculate sources of error. Having a well-documented plan is also extremely useful when troubleshooting. For the first few lab sessions, especially during the construction of the op-amp circuit, our troubleshooting was aimless and most guesswork when things didn't work properly. This was because we hadn't sufficiently planned the construction of the circuit by studying the components and neatly drawing the circuit connections. After this was done, we were able to identify that the first and second stage of gain were connected at the wrong inputs.

Finally, it was nice that there were no set instructions for how we should incorporate the sensors into a measurement system. This gave us the opportunity to think about the different ways these sensors could be used based on what type of measurements we wanted to take. This was a fantastic learning experience as it made me truly consider the relationship between a sensor and the measurement system that is built around it.

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