COLORADO SCHOOL OF MINES
1874

Design Challenge: Scale - Final Report
MEGN 300 Sec: A

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Table of Contents

Abstract

This project develops a compact, low-cost weighing instrument capable of measuring masses in the 0-150 gram range. The design combines spring displacement principles with lever mechanics, where an applied mass on one end of a lever arm creates proportional displacement at the opposite end via spring expansion. This displacement is measured using a nichrome wire potentiometer system, with a wiper contact mechanically linked to the moving spring assembly. As mass changes, the wiper position varies along the resistive wire, producing corresponding voltage outputs. Voltage readings are acquired through a data acquisition system and converted to mass values using a calibrated transfer function. The instrument's performance accuracy is characterized through systematic calibration and error analysis, providing predictable measurement reliability within the target mass range.

Introduction

Our chosen scale design is the lever arm with a Nichrome wire potentiometer. This concept utilizes the mechanical advantage of a lever to transform a small input force into a larger, easily measurable displacement. The design features a rigid base supporting a fulcrum and a lightweight lever arm seen in Figure 1. An unknown mass is placed on the short, effort arm of the lever, while the long, sensor arm is connected to a restoring spring and a custom potentiometer made from a Nichrome wire and a wiper. The wiper, which is attached to the sensor arm, moves along this wire as the lever pivots. The movement changes the circuit's resistance, producing a variable output voltage. This voltage signal is read by an NI DAQ and converted in LabVIEW into a numerical value representing the mass.

Design

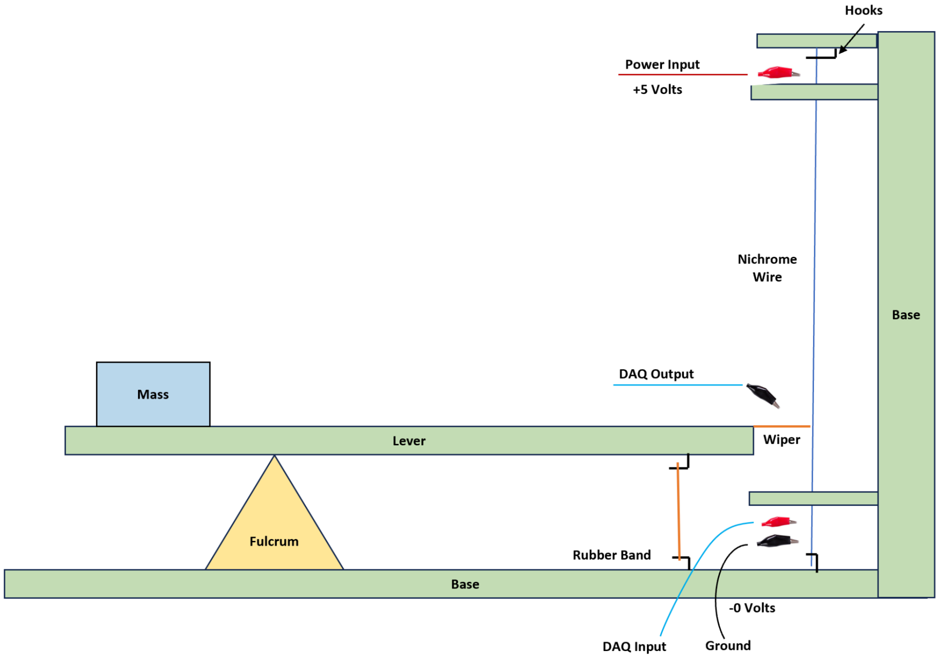


Figure 1: Computer created drawing of design

Mechanical and Electrical System Design:

The scale system integrates mechanical components that convert mass to displacement with electrical elements that translate displacement to measurable voltage. The core operating principle employs a nichrome wire and movable wiper contact functioning as a potentiometer, where weight-induced displacement changes the voltage division ratio along the resistive element.

Component Fabrication and Selection:

The lever and fulcrum are 3D printed to ensure precise geometry and consistent mechanical advantage. The potentiometer system consists of a nichrome wire with the wiper contact mechanically linked to the lever system, creating a position-dependent voltage divider. Electronic components are sourced from MEGN laboratory inventory, with the DAQ configured for single-ended voltage measurement between the wiper and ground reference.

Calibration Methodology:

The system is calibrated using objects of known mass to establish the voltage-to-mass transfer function. The calibration procedure involves:

- Measuring the resting voltage ($V_{original}$) with no applied mass
- Applying known masses and recording voltage measurements relative to ground
- Calculating voltage differences ($\Delta V = V_{measured} - V_{original}$)
- Generating a scatter plot with mass as the independent variable and voltage difference as the dependent variable
- Applying linear regression to establish the calibration curve
- Implementing the resulting equation to convert voltage differences to mass values

1.

LabVIEW Automation:

The calibration equation is programmed into a subVI that converts voltage differences to mass values. The main VI acquires single-ended voltage data from the DAQ and subtracts the resting voltage constant. When the tare button is pressed, the VI captures the current reading as a tare offset and subtracts it from subsequent samples so the stream is zeroed. The tare-adjusted signal is then passed through the calibration algorithm to compute mass, and the front panel displays the resulting mass, yielding a fully automated measurement system.

System Operating Principle:

- Input Mass: The unknown mass to be measured via the process outlined in Figure 2
- Lever and Fulcrum: Translates gravitational force into vertical displacement as the spring displaces
- Spring: For the mass range (1 - 150 g), finding a spring with a stiffness constant that could balance the stretching without over-displacing or not displacing enough was not optimal, seeing as no springs with such a stiffness constant were provided in the class. To mitigate this, a different type of spring (a rubber band) was implemented. Both rubber bands and springs store elastic potential energy as they are stretched or compressed, and therefore, both are considered springs. For purposes of the report, the rubber band will continue to be referred to as the “spring.”
- Nichrome Wire Potentiometer: Creates a position-dependent voltage divider ($R_1 + R_2 =$ constant)
- Wiper: Movable contact that taps different voltage points along the wire proportional to mass as shown in Figure 3 at one resting point
- Output Signal: Voltage measured between wiper and ground reference (0V to 5V range)
- Signal Processing: Voltage difference calculated as $\Delta V = V_{out} - V_{original}$
- DAQ: Converts analog voltage to digital values for computer processing
- LabVIEW: Implements a calibration algorithm to convert voltage differences to mass display

This integrated approach ensures that mechanical displacement is linearly translated to electrical signals, with calibration compensating for all system parameters, including spring constant, lever ratio, and electrical characteristics.

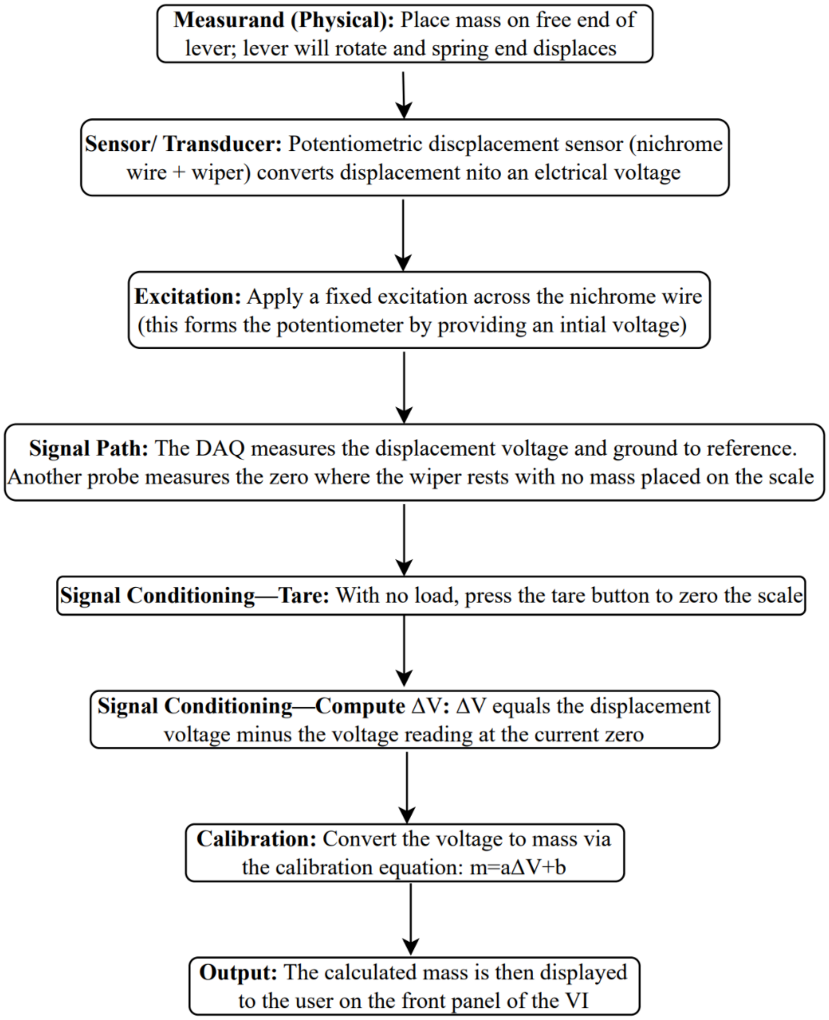
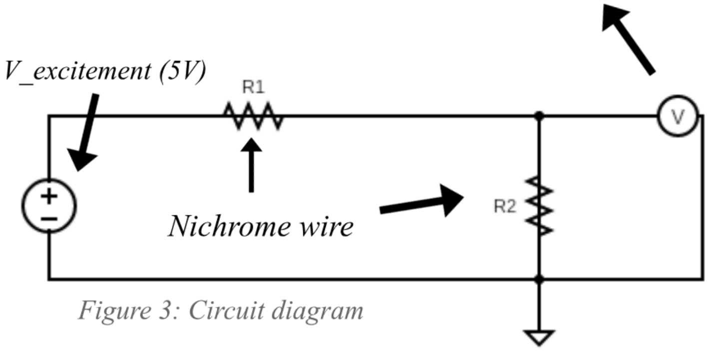


Figure 2: Flow diagram of scale process


Voltmeter reads one voltage where the wiper rests when the mass is attached to the lever, and one voltage at ground (0V).

V_excitement (5V)

Nichrome wire

Figure 3: Circuit diagram

Analysis and Design Considerations

Design Parameters and Optimization:

The scale's performance can be optimized by adjusting several key parameters (the geometry of each parameter can be seen in Figure 4):

1. Spring constant (k): Controls displacement sensitivity vs. measurement range
2. Lever ratio (L_1/L_2): Determines mechanical advantage and displacement amplification
3. Nichrome wire length: Affects voltage resolution and measurement precision
4. Wire diameter: Influences resistance gradient and power requirements
5. Reference voltage ($V_{excitement}$): Sets the output voltage range

System Visualizations:

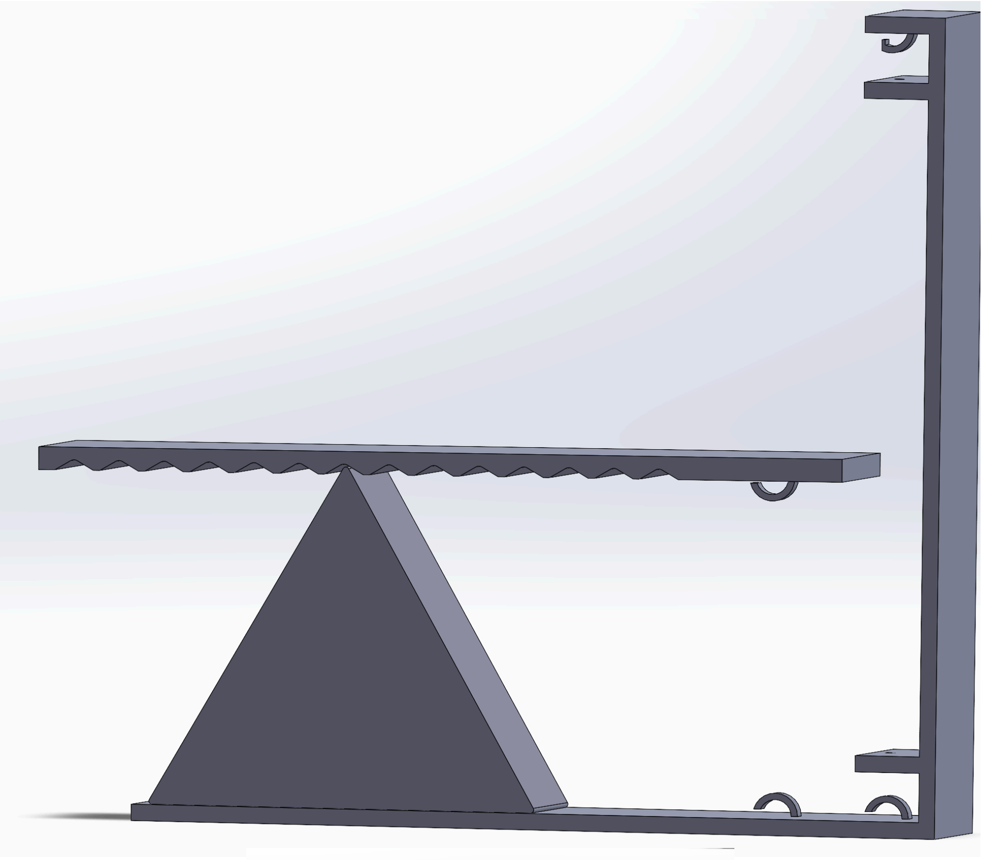


Figure 4: CAD model of base, Isometric

Mathematical Analysis:

1) Theoretical Calibration Curve Mathematics:

   a) Weight calculation:

   $W = m \cdot g$ $Mass\ (m):\ kilograms$

   $Gravity\ (g):\ 9.81\ meters/second^{2}$

   b) Spring (Band) calculation:

   $F = k \cdot \Delta x$ $Spring\ Constant\ (k):\ N/mm$

   $Displacement\ (x): mm$

   c) Displacement calculation:

   $\Delta x = x - x_0$ $Spring\ Constant\ (x):\ mm$

   $Displacement\ (x_0): mm$

   d) Force calculation:

   $F = W$ $Force\ (F):\ N$

   $Weight\ (W): N$

I) Rearrangement of equations a - d:

$$m = x \cdot (k \div g)$$

   e) Voltage (out) calculation:

   $V_{out} = V_{excitment} \cdot (x \div L)$ $V_{excitment}\ (given):\ Volts$

   $Nichrome\ wire\ Length\ (L): mm$

   f) Voltage (original) calculation:

   $$V_{original} = V_{excitment} \cdot (x_0 \div L)$$

   g) ΔVoltage calculation:

   $$\Delta V = V_{out} - V_{original} = V_{excitment} \cdot (\Delta x \div L)$$

II) Rearrangement of equations e - g:

$$\Delta x = L \cdot (\Delta V \div V_{excitment})$$

III) Mass rearrangement of equations I & II:

$m = L \cdot (k \div g) \cdot (\Delta V \div V_{excitment}) + V_0$ $Constant\ (V_0): grams$

IV) Voltage rearrangement of equation III:

$$\Delta V = (V_{excitment} \cdot g \cdot (m - V_0)) \div (k \cdot L)$$

Our scale operates on a direct, empirical relationship between mass and voltage. During the initial calibration, a reference scale was used to record the true weight (and thus mass) of known objects. The measurement principle is then set by a nichrome-wire potentiometer: the change in output voltage is proportional to the wiper's displacement, which is driven by the applied mass through the spring. A model was created using the voltage-divider equation, relating $V_{excitement}$ to V_{out} and $V_{original}$. Rearranging the divider for displacement (Δx) and equating the spring force to weight ($m \cdot g = k \times \Delta x$) gives a single relationship in terms of mass and the measured voltage difference, once the other parameters are known as shown in Figure 5.

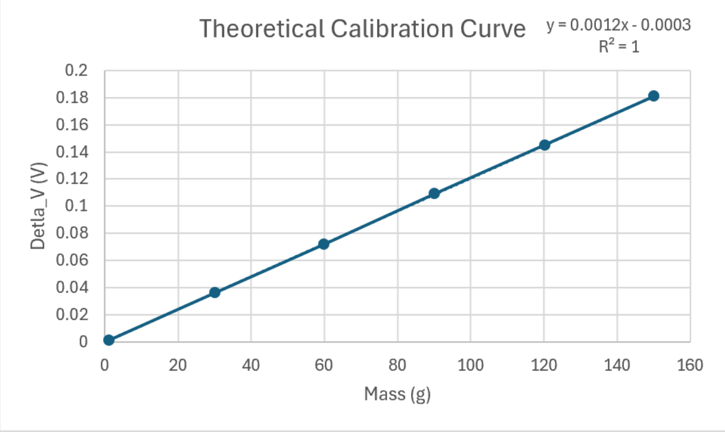


Figure 5: Theoretical calibration curve

To obtain the stiffness constant k, a known load was placed on a force gauge and then on the elastic element ("rubber band"), measured the corresponding displacement, and computed $k = \Delta F \div \Delta x$. The excitation was set as a fixed voltage $V_{excitement}$ and used Ohm's law with the wire's total resistance (resistance-per-length times length) to verify that the resulting current stayed well below 500 mA to avoid heating the nichrome.

2) Experimental Calibration Curve Equation

$$m = a \cdot \Delta V + B$$

$Mass(m)\colon\ grams$

$Voltage\ Difference\ (\Delta V)\colon\ volt$

$Calibration\ slope\ (a)\colon\ grams/volt$

$Calibration\ offset(B)\colon\ (unitless)$

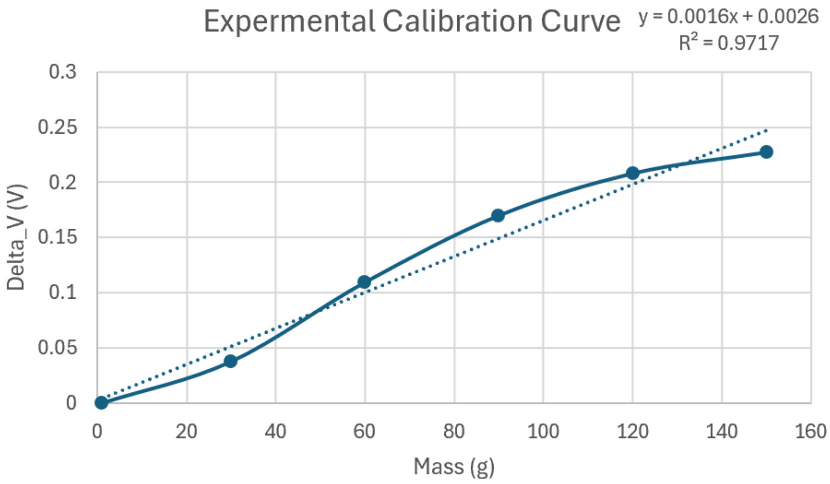


Figure 6: Experimental Calibration Curve

Summary of Operation

Our project involves the development of a compact digital scale with a 150-gram capacity, utilizing a lever-spring mechanism paired with a nichrome wire potentiometer. Its operation is based on a direct, empirical relationship between mass and voltage. When a mass is applied, the lever expands the spring, displacing a wiper on the nichrome wire to produce a voltage shift. This signal is captured by a DAQ system, and LabVIEW processes it using a calibration function shown in Figure 6 that converts the voltage differential into a precise mass reading. This method bypasses the need to directly measure system parameters like the spring constant or lever geometry, as their combined effect is captured within the calibration constants, ensuring simple yet reliable operation.

Supporting Documentation and VI

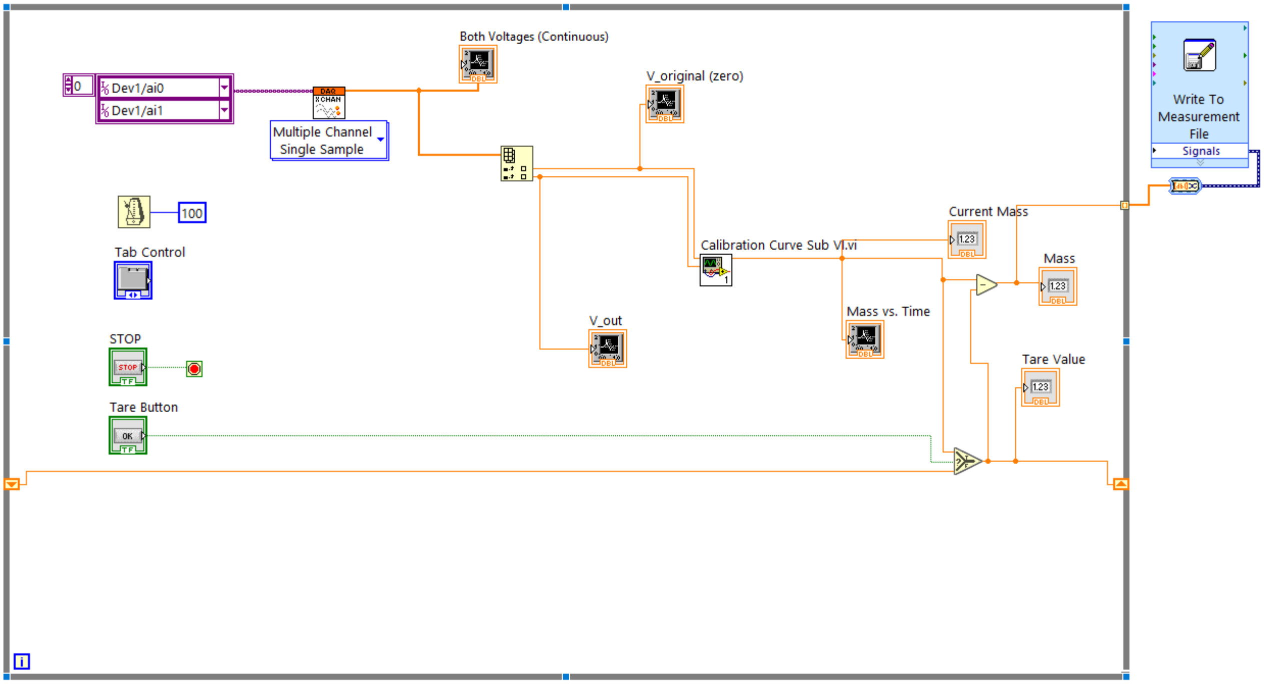


Figure 7: Block Diagram of the main VI

The calibrated scale worked as expected by using a direct mass-to-voltage relationship. To run the scale, the system is left to settle with no load and press the tare button. Inside the VI, the tare button captures the current reading as a ‘tare value’ and stores it. On every new sample, the code subtracts this stored value from the live voltage difference before applying the calibration. That way, insignificant weight on the lever is nulled out and only added mass is reported. The offset persists until the tare is pressed again or the VI restarts. After pressing the tare button the object is placed on the lever. The added mass deflects the lever–spring and slides the wiper along the nichrome wire, which changes the measured voltage at the wiper. LabVIEW reads that voltage through the DAQ and uses our calibration curve (built from known test masses) to convert the voltage change into mass.

The following VI (Figure 7) was used for data acquisition and the voltage-to-mass conversion. The acquired $V_{original}$ (wire zero) on ai0 and V_{out} (wiper node) on ai1 using differential inputs, ±5 V range. $V_{excitement} = 1.2$ V was supplied from a regulated source; total current was limited to < 500 mA to avoid heating. The calibration SubVI computes the current mass from the live voltage difference:

$$m = a \cdot \Delta V + B$$

where a = 612.36 and b = −1.60 g (offset) as shown in Figure 8. These coefficients were obtained by least-squares fitting of the experimental calibration data (known masses vs. measured ΔV). The units are enforced so that a 1 V change at the wiper corresponds to ~612 g, consistent with the lever/spring sensitivity over our operating range.

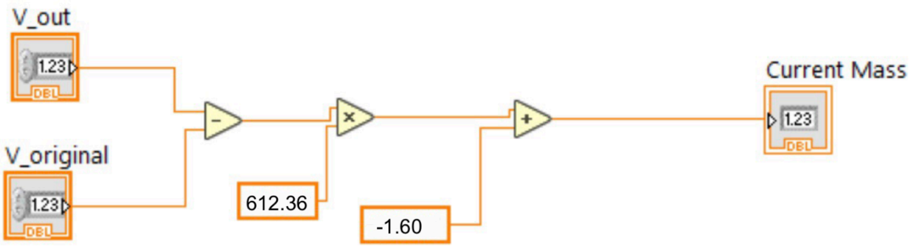
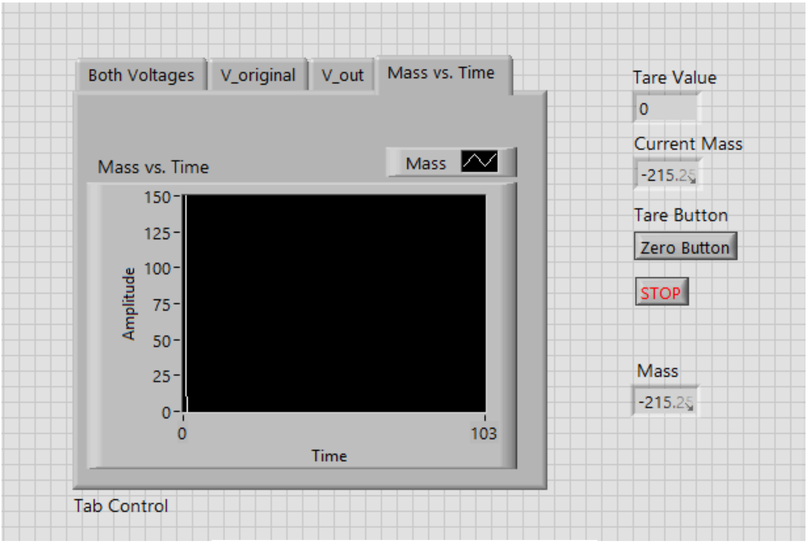


Figure 8: Block Diagram of the Sub VI



Tare Value: 0
Current Mass: -215.2
Mass: -215.2

Figure 9: Front panel for the main VI

ΔV,m data pairs were collected from 0–150 g in 30 g steps, three repeats per point, always approaching from below to minimize hysteresis. The slope and offset were computed by linear least squares and stored as front-panel constants a and b in the SubVI as seen in Figure 9.

Comparison of Theoretical and Actual Performance

It is important to note that, in sprint one, the “theoretical” calibration curve was not derived from governing equations because no mass-to-ΔV model had been established. A linear line through (0 g, 0 V) and (150 g, 5 V) was used, assuming a 5 V excitation across the nichrome wire and full wiper travel along the potentiometer. That implied ~0 V at zero mass and ~5 V at 150 g. This assumption proved unrealistic for two reasons: (1) the lever tip’s vertical displacement does not inherently match the usable length of the nichrome wire—linking those requires lever-geometry calculations or a redesign of wire length—and (2) because a fulcrum is required, the wiper does not start at the ground end; in this build it began approximately mid-span rather than at 0 V.

There is a clear gap between the theoretical and experimental calibration curves as seen in Figure 10, most likely from a stack-up of human and instrument effects. In our setup, the biggest contributors were

1. The wiper wasn’t perfectly straight, so contact with the nichrome wire was intermittent, and contact resistance varied.
2. The nichrome wire flexed upward as the wiper pressed on it under higher loads, subtly changing the geometry.
3. The fulcrum/lever assembly shifted slightly as weight was added.
4. The tape securing the wiper shifted slightly under higher loads.
5. Placement sensitivity—the same mass read higher when set closer to the lever tip (larger moment arm), and placing the mass vertically at the tip also produced a higher reading.

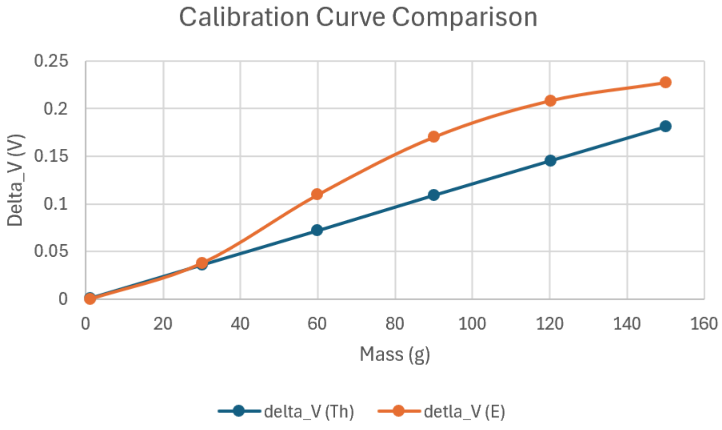


Figure 10: Comparison of the Theoretical and Experimental Calibration curves

6. The probes were reattached by hand on different days; despite aiming for the same locations, small differences in placement affected the zeros and displacement readings.
7. The slight curvature and eventual plateau in the experimental calibration curve can be attributed to the fact that early weights caused larger vertical displacement, but as the lever approached its geometric limit (a larger angle), equal added weight produced smaller incremental displacement, reducing sensitivity near the top end.

Together, these effects reduce repeatability and pull the experimental curve away from the ideal model, which assumes rigid supports, fixed geometry, and perfect electrical contact.

For the final system, an experimental calibration curve was adopted because it reflects the hardware as assembled. The closed-form equations in the Mathematical Analysis section rely on ideal parameters and perfect alignment; the realized device deviates from those ideals. Calibrating with measured ΔV versus known masses yields a linear fit whose coefficients are specific to this scale and that inherently accounts for non-idealities (offsets, gain error, small misalignments, friction, etc.). In effect, the instrument self-calibrates, making the experimental curve the most accurate representation of performance.

Determination of Static Sensitivity and Resolution

The scale's measurement precision is quantified by its static sensitivity and experimental resolution. These values define the instrument's ability to detect small changes in mass and establish the uncertainty for all measurements.

Experimental Procedure

The experimental resolution was determined by assessing the repeatability of the voltage measurement system, including the consistency of the wiper's return to its zero position. The procedure involved a cyclic test with a known mass:

1. An initial zero measurement ($V_{original}$) was recorded with no mass on the scale.
2. The known mass was applied, and the resulting output voltage (V_{out}) was recorded to establish the displacement voltage (ΔV) for that mass.
3. The mass was removed, and a subsequent zero measurement was taken to verify if the wiper returned to its original position on the nichrome wire.
4. This cycle was repeated five times to generate five sets of zero and displacement voltage data.

The standard deviation of the resulting ΔV readings quantifies the combined electrical noise and mechanical hysteresis in the system.

Static Sensitivity

To determine the instrument's resolution, the repeatability of the voltage signal was analyzed. Numerous voltage-difference (ΔV) readings were recorded and these values were consistent across trials. Using the student t table for the applicable confidence level for N-1 data points (N, number of trials), the precision interval was calculated. The value from the Student T table for 4 data points was 2.77. The mean from the voltage difference data was 0.0195 V and the standard deviation was calculated to be 0.000944 V. Applying the precision interval formula,

$$x = \bar{x} \pm t_{v,p} \cdot S_x = 0.0195 \pm 2.77 \cdot (0.000944) = 0.0195\,V \pm 0.00261$$

gives the confidence interval for the voltage reading under this load.

The instrument's mass resolution was then determined by calculating the mass value corresponding to the upper bound of this voltage interval. Using the rearranged calibration equation for mass:

$$Mass = 612.36 \cdot (0.0197) - 1.60 \approx 12 \text{ g}$$

This yields an estimated resolution of ≈ 12 g, indicating that with 95% confidence, if the mass is heavier than 12 grams.

Error

The calculated voltage precision interval of $\pm$ 0.00261 V is represented by vertical error bars on each data point of the experimental calibration curve as seen in Figure 11. These error bars visually communicate the uncertainty in the voltage measurement originating from system noise and mechanical non-repeatability. The mass values for the known calibration weights are treated as reference values with negligible error.

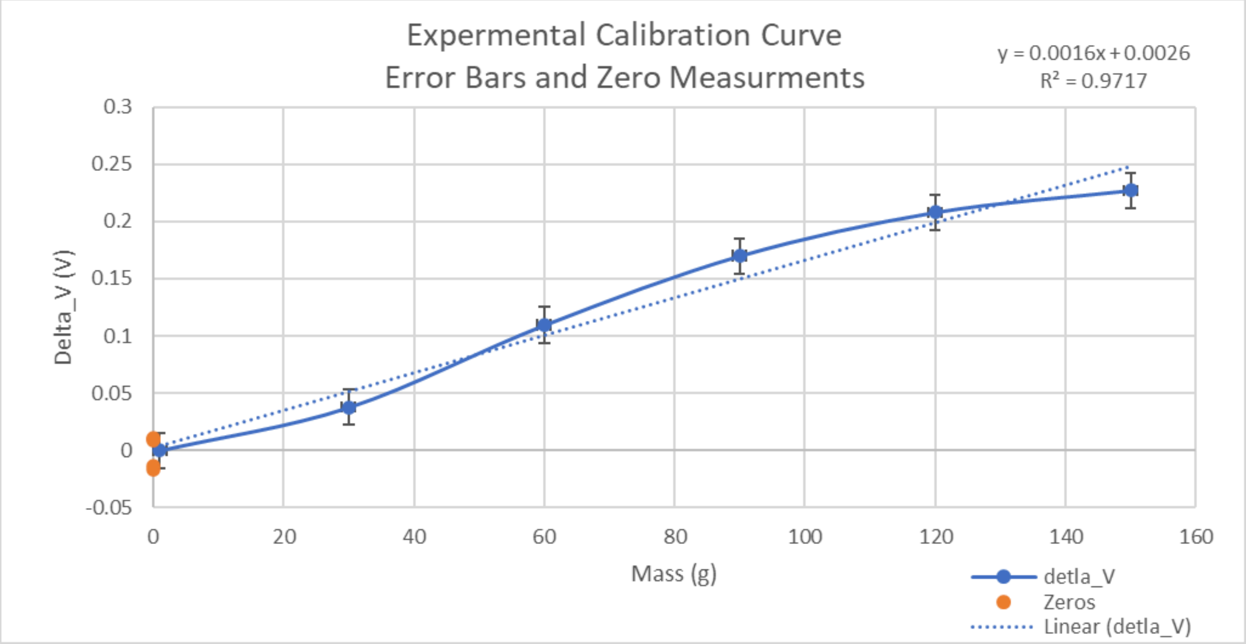
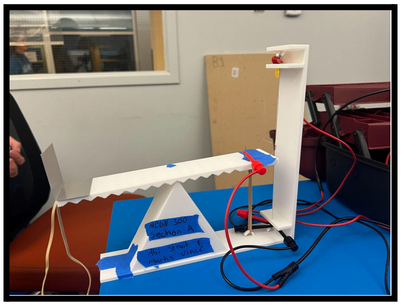


Figure 11: Block Diagram of the Sub VI

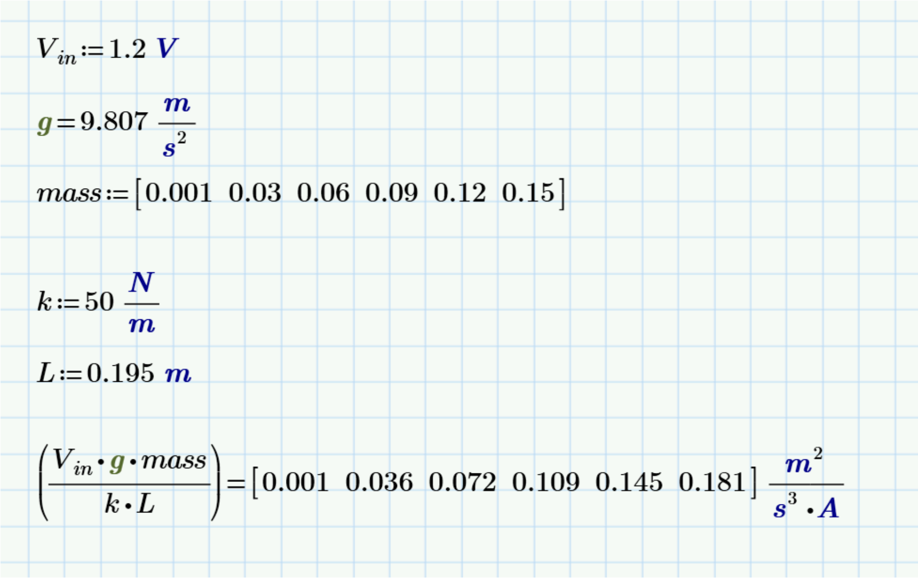
Video Demonstration of System



[Scale Demonstration Video - HERE]

Appendices

Appendix A: Mathematical Analysis Calculations



$V_{in} := 1.2\ V$

$g = 9.807\ \frac{m}{s^2}$

$mass := [0.001\ \ 0.03\ \ 0.06\ \ 0.09\ \ 0.12\ \ 0.15]$

$k := 50\ \frac{N}{m}$

$L := 0.195\ m$

$$\left(\frac{V_{in} \cdot g \cdot mass}{k \cdot L}\right) = [0.001\ \ 0.036\ \ 0.072\ \ 0.109\ \ 0.145\ \ 0.181]\ \frac{m^2}{s^3 \cdot A}$$

Appendix B: Measured Zeros

Mass (g)	V_out Zeros (Volts)
0	0.01076
0	0.0092
0	-0.01345
0	-0.01623
0	0.01003

Appendix C: Mean Equation

$$\bar{x} = \sum x_i \div n$$

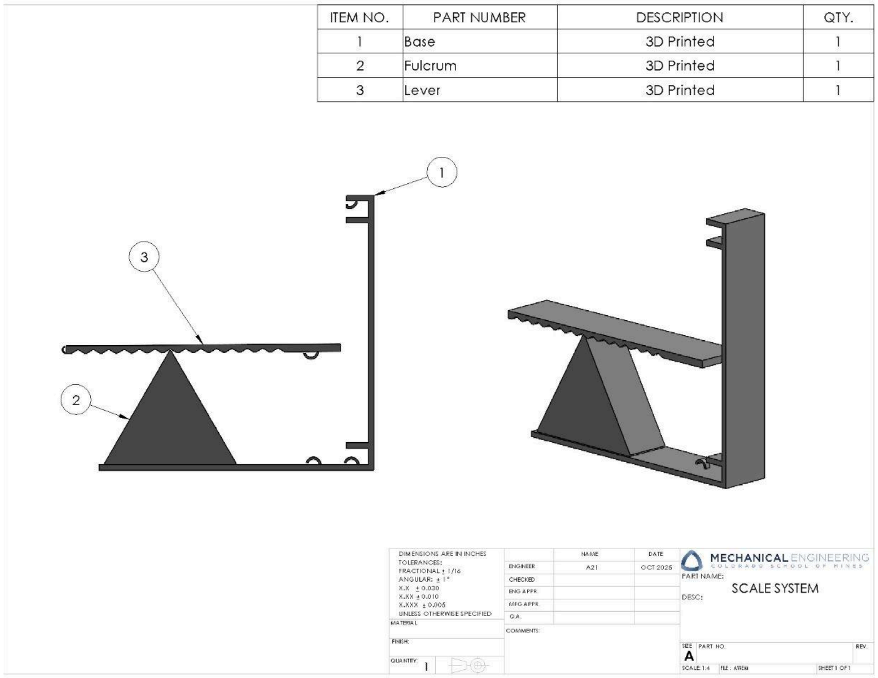
Appendix D: Standard Deviation Equation

$$S_x = \sqrt{\sum(x_i - \bar{x}) \div (n - 1)}$$

Appendix E: Student T table

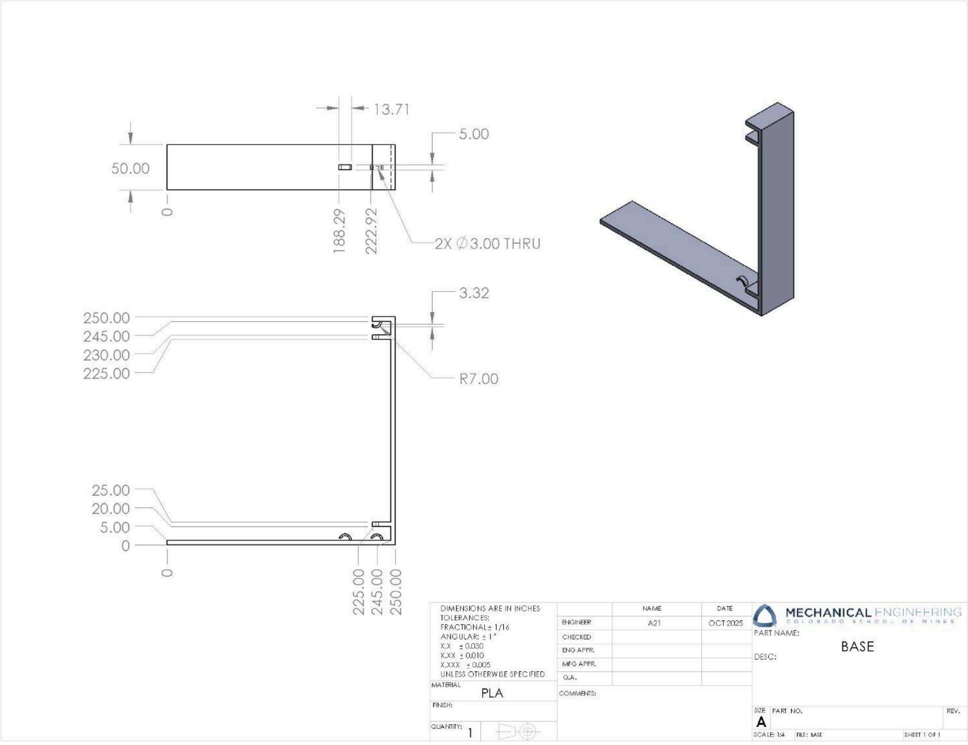
V (#dof)	t_{50}	t_{90}	t_{95}
1	1	6.314	12.706
2	0.816	2.920	4.303
3	0.765	2.353	3.182
4	0.741	2.132	2.770
5	0.727	2.015	2.571

Appendix F: Scale Assembly Drawing

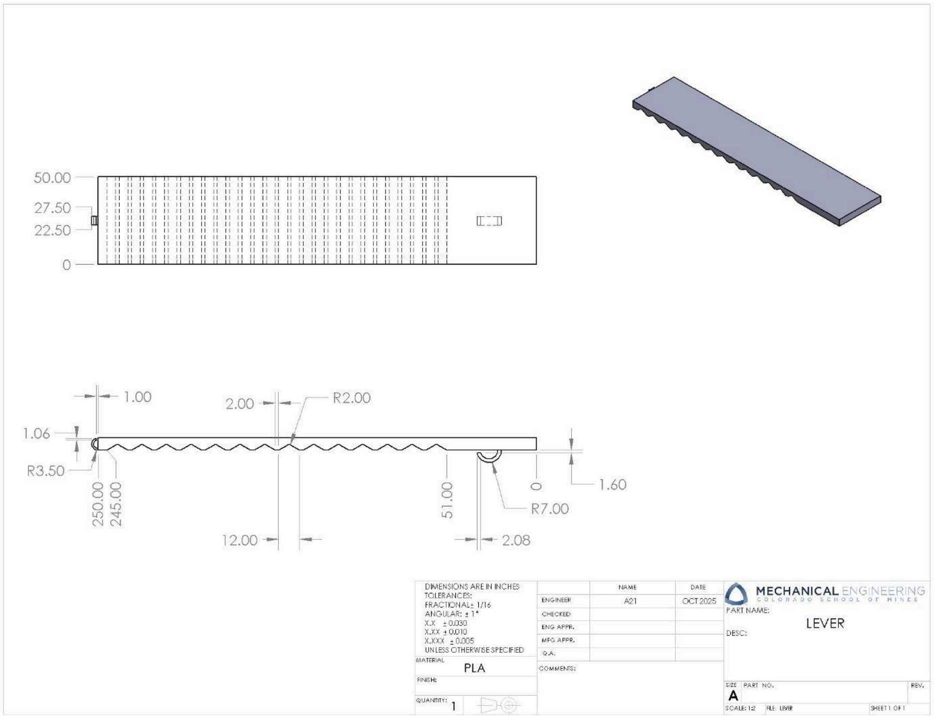


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Base	3D Printed	1
2	Fulcrum	3D Printed	1
3	Lever	3D Printed	1

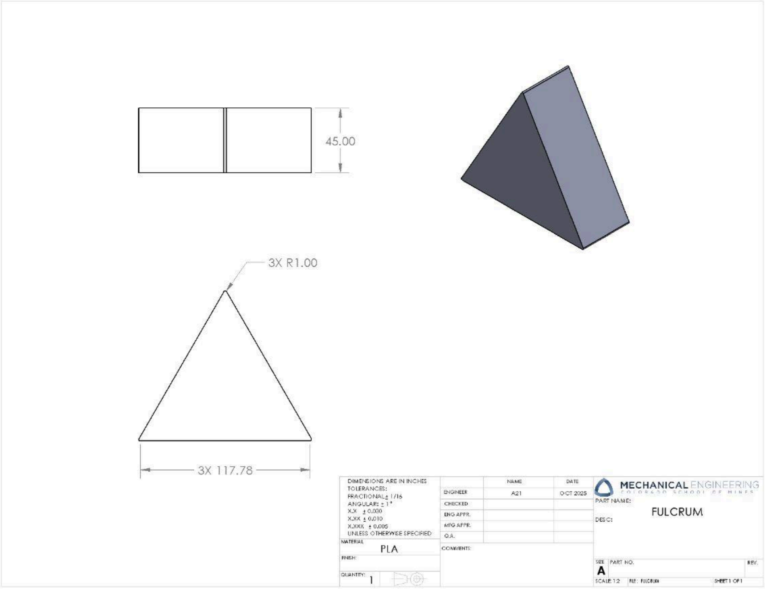
Appendix G: Base SolidWorks Drawing



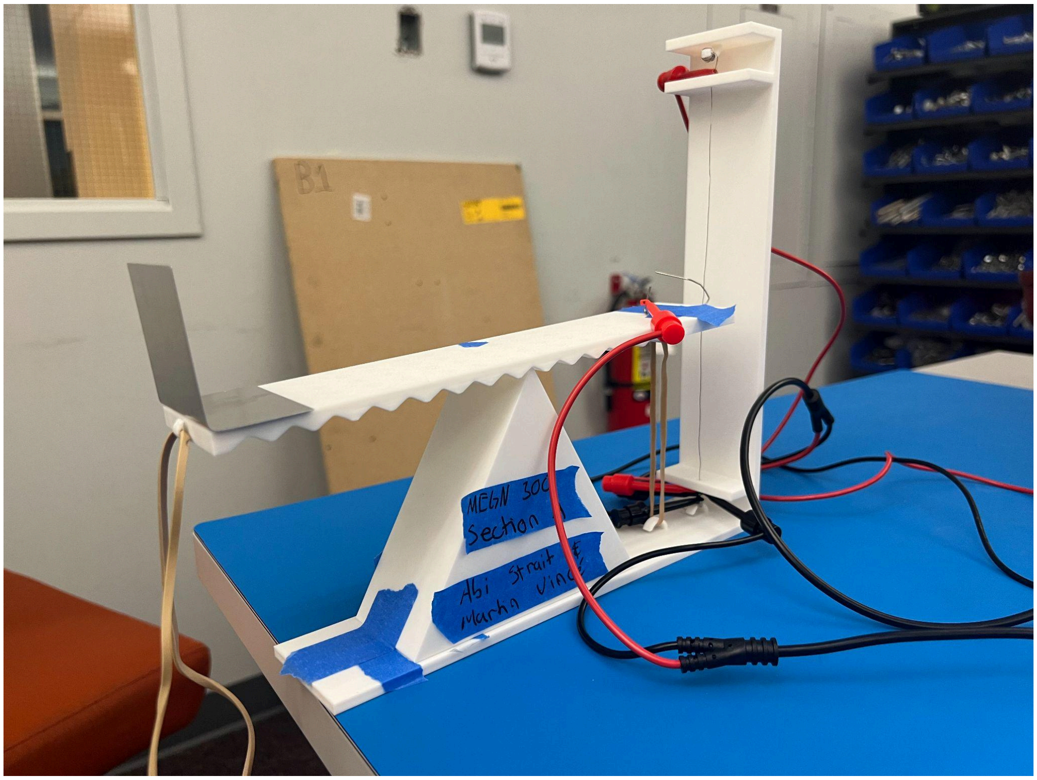
Appendix H: Lever SolidWorks Drawing



Appendix I: Fulcrum SolidWorks Drawing



Appendix J: Picture of Scale: Front



Appendix K: Picture of Scale: Back