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Starling Medical Showcase

Ibrahim Al-Akash

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Anchor Redesign

Magnetic Attachment Mechanism

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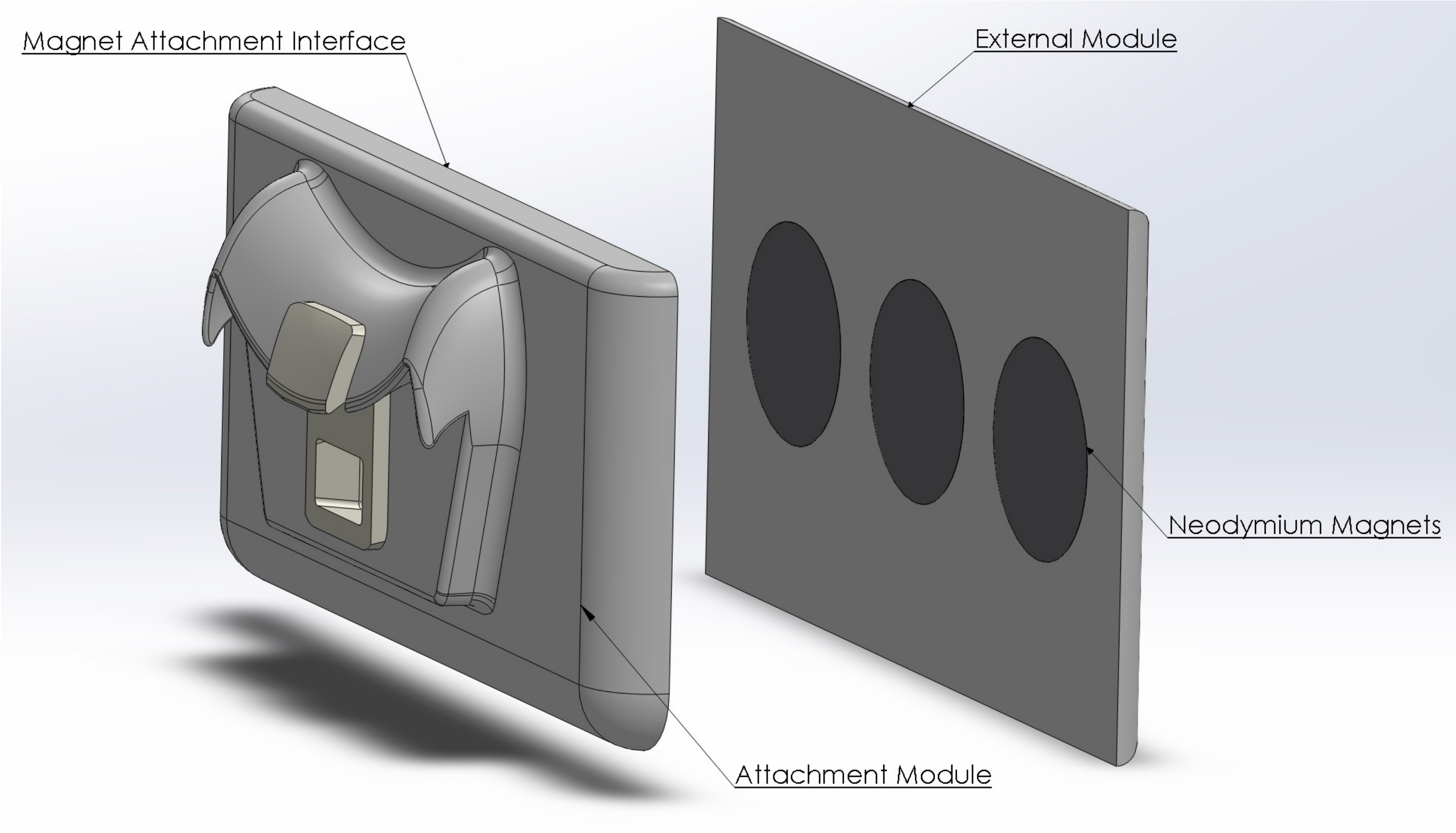
Magnetic Attachment Design



Item	Unit Cost
Magnets	$5.70
VytaFlex 30 (Soft Casing)	$8.58
Task 21 (Connector)	$0.27
Total	**$14.55**

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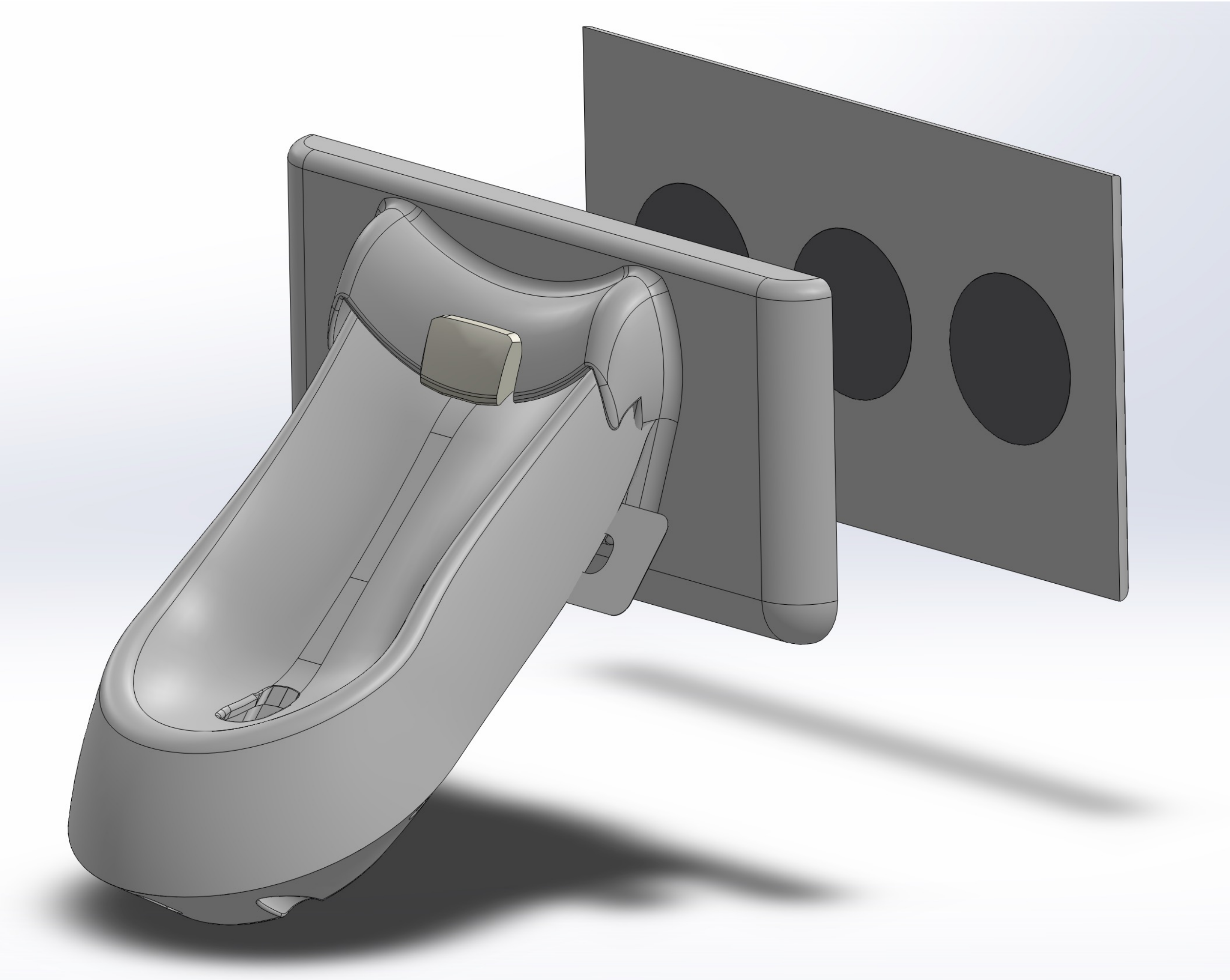
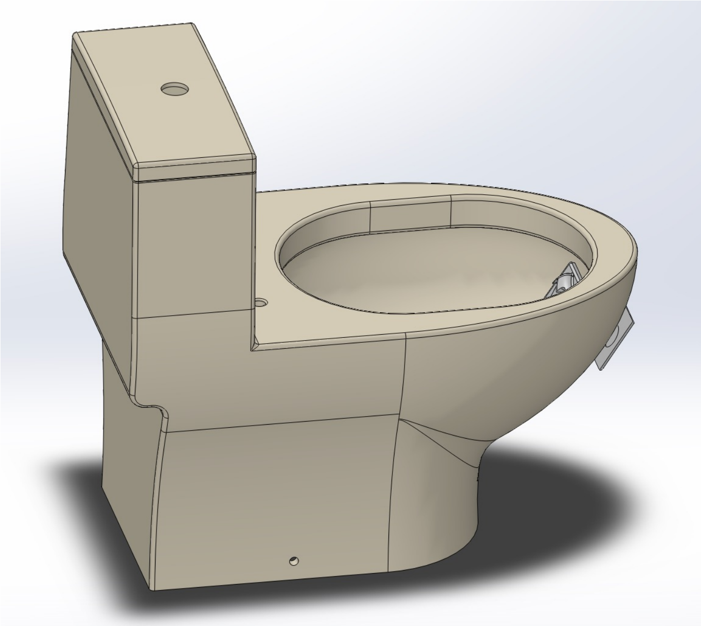
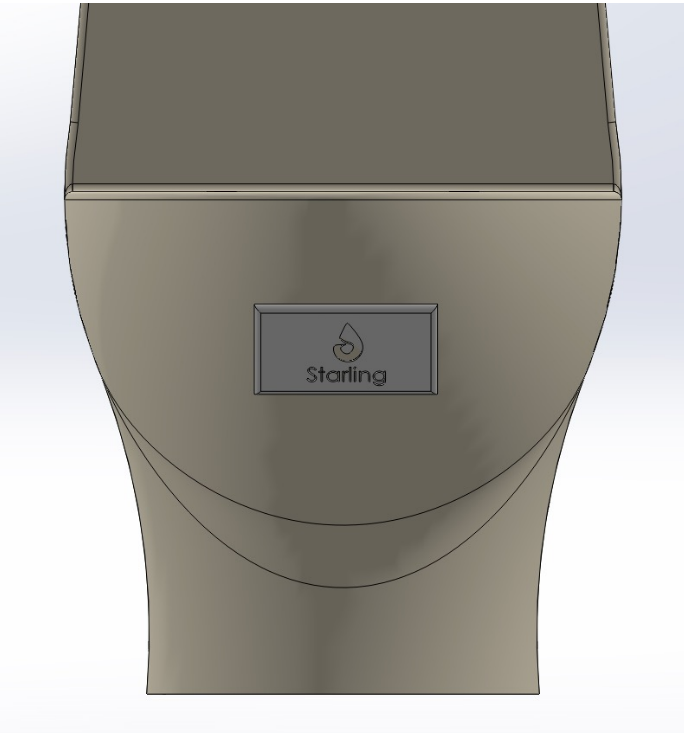
Magnetic Attachment Design







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Testing

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Testing

- The magnetic attachment design passed the initial testing. The anchor was able to hold the UrinDX with a 155g lead weight for a period of 72 hours before failing

- The point of failure in this test was the center magnet tore off and the plastic attachment interface disconnected

- Previous iterations had failed due to the plastic attachment falling off as a result of the adhesives not sticking to the silicone backplate

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Conclusions

- I noticed a weak point during testing of the anchor was the inflexibility of the center section at high curvature in the bowl

- To address this issue, I am making a new iteration with a softer silicone to enable easy forming to the bowl curve

- Additionally, I hypothesize using bar magnets oriented vertically to help the silicone conform better to the bowl curve instead of the circular disc magnets currently used

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BPH Sensor

Magnetometer Sensor

Introduction

- The differential pressure sensor has shown promise, however 2 main issues
  1. High **cost** compared to other sensor techniques (**$40/sensor**)
  2. Potential issues down the line with **sedimentation or corrosion**

- **Magnetometer-based force sensor** solves these issues
  - Low cost ($1.85/sensor)
  - No sedimentation issues
  - Ultra-low power consumption (100uW to 10mW)
  - High resolution (1 mN == equivalent to 0.1 g mass)

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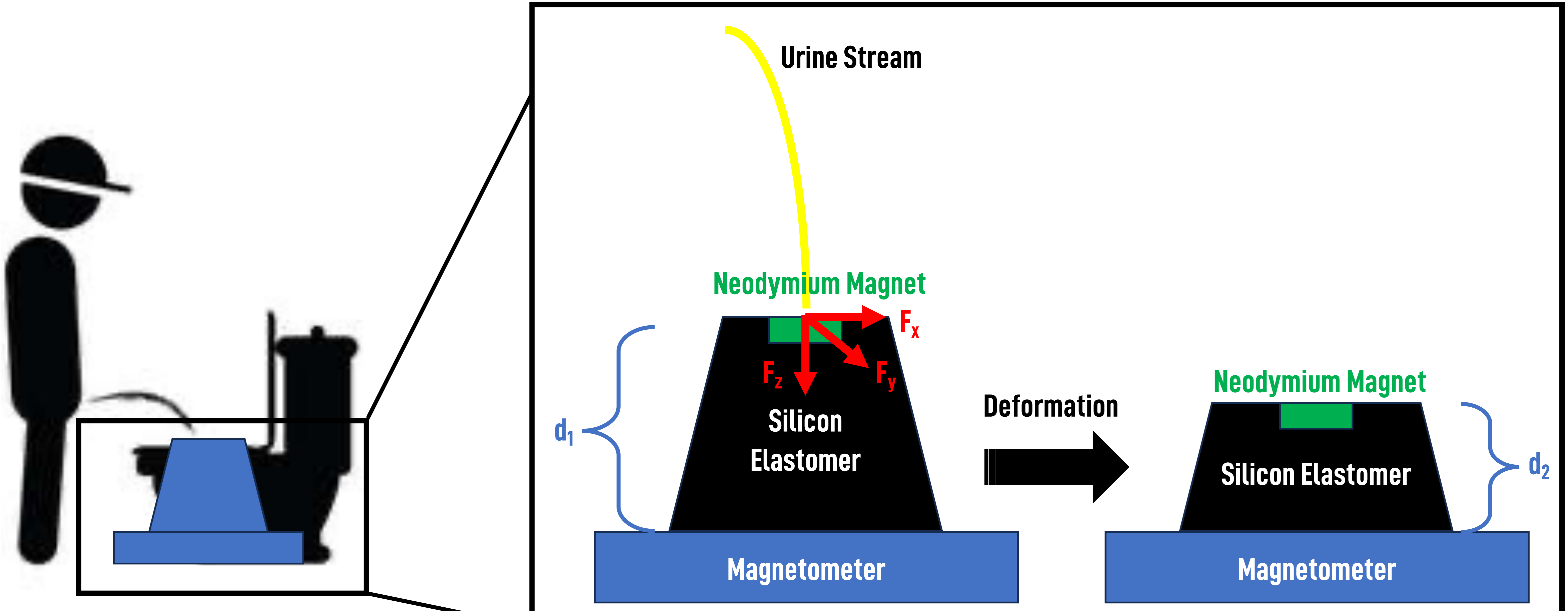
Magnetic Pressure Sensor



Force from urine stream causes shear and normal stress on elastomer, bringing the magnet closer/farther from the magnetometer. Magnetic field changes then corresponds to applied force

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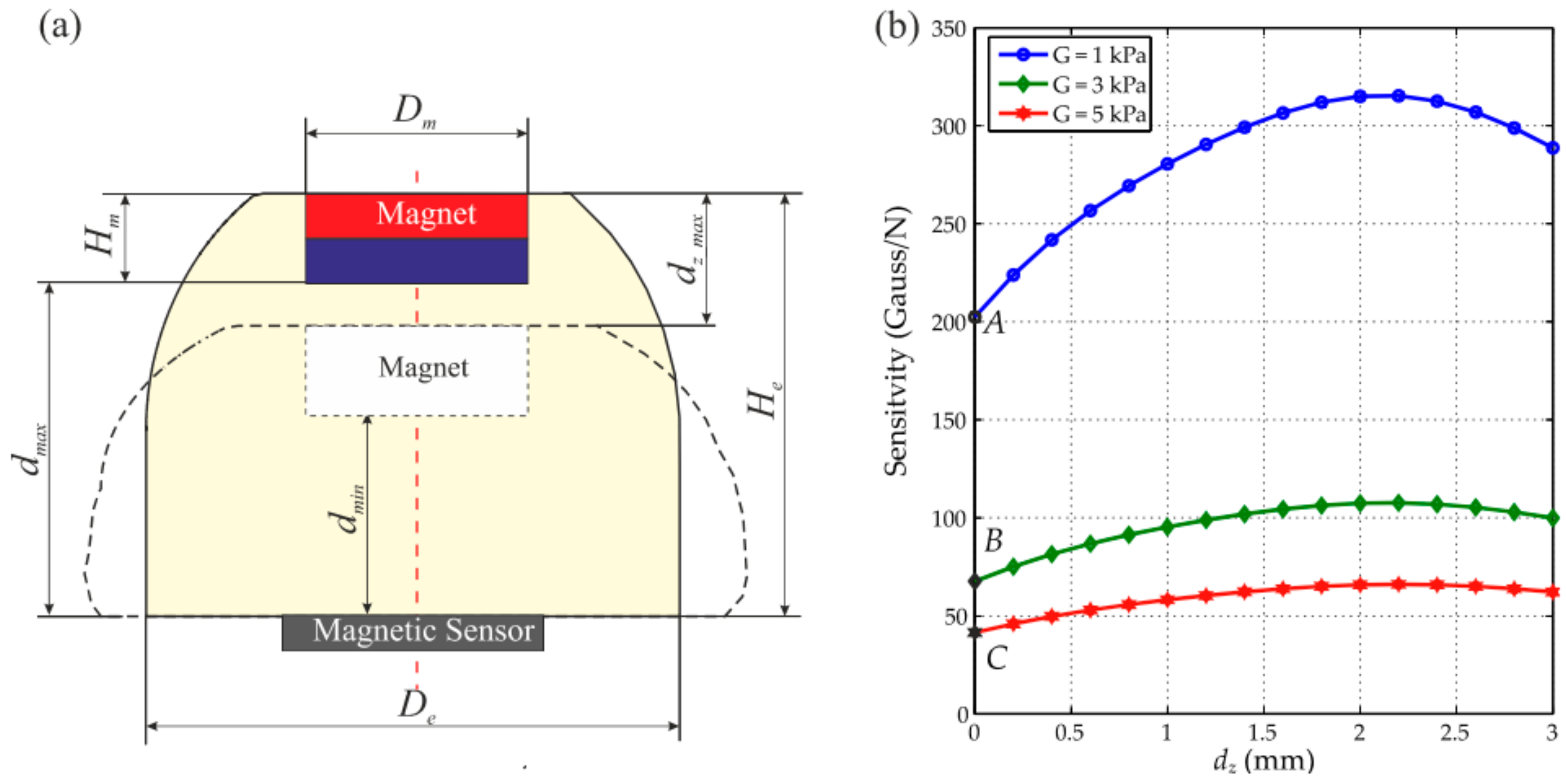

Figure 7. (**a**) The design parameters of the tactile sensor; (**b**) The sensitivity of the tactile sensor with different material properties (shear modulus G = 1, 3, 5 kPa). Points A–C indicate the point of lowest sensitivity for each material.

Manufacturing Process

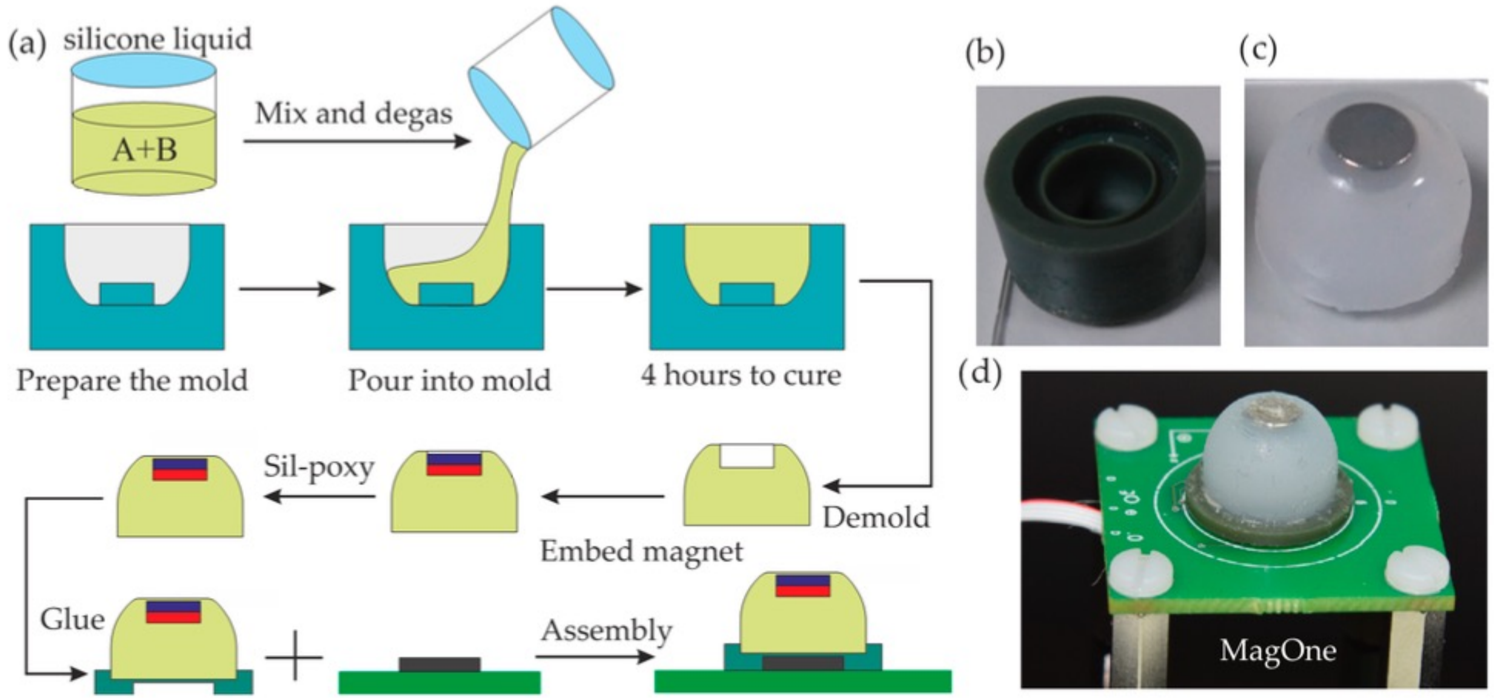

Figure 9. (**a**) Schematic of the fabrication process; (**b**) Photograph of the mould; (**c**) Photograph of the fabricated elastomer; (**d**) Photograph of the MagOne prototype.

1. 3D Print Mold for Elastomer
2. Pour Elastomer (Si) into Mold and Cure
3. Attach the neodymium magnet to the indentation in the elastomer mold using Sil-poxy
4. Connect assembly to PCB using adhesives

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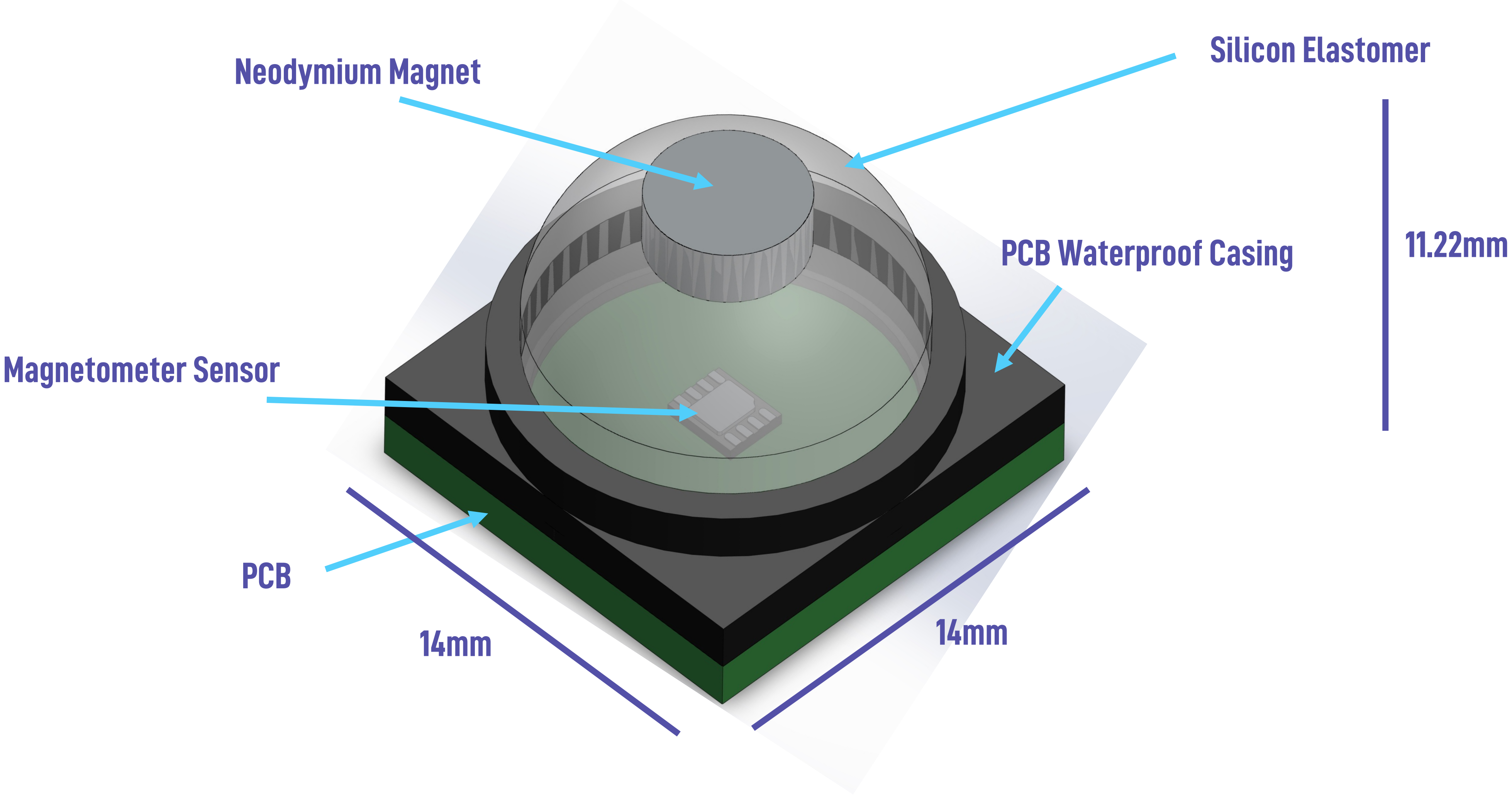
CAD Model



Neodymium Magnet
Silicon Elastomer
PCB Waterproof Casing
11.22mm
Magnetometer Sensor
PCB
14mm
14mm

Further Considerations

- May be difficult to manufacture, since elastomer must be prepared manually
- Elastomer can deform over time due to creep effects, however the geometry of the elastomer and placement of the magnet at the top mitigates this
- Lots of testing required and many different configurations (ie. Elastomer material, elastomer geometry, magnet size, magnetometer)
- Tilting of magnet can cause inaccuracies – can be mitigated with IMU MEMS sensor

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Prototype Materials

Item	Cost
Neodymium Magnets (5mm x 2mm)	$6.99
Magnetometer	$1.85
Microcontroller	Available in lab
Silicon	$42.99 (2lbs)
Sil-poxy	$5.98
Silicon Releasing Agent	$16.99
3D-print	Available in lab

Total Cost of Materials: $74.80

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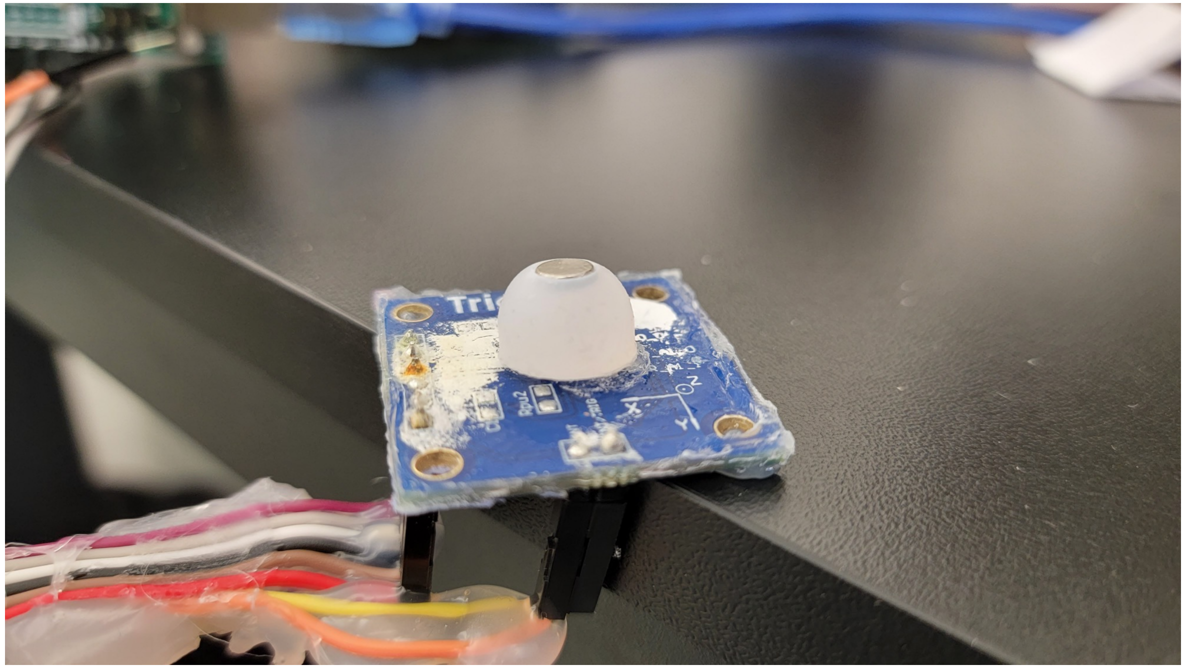
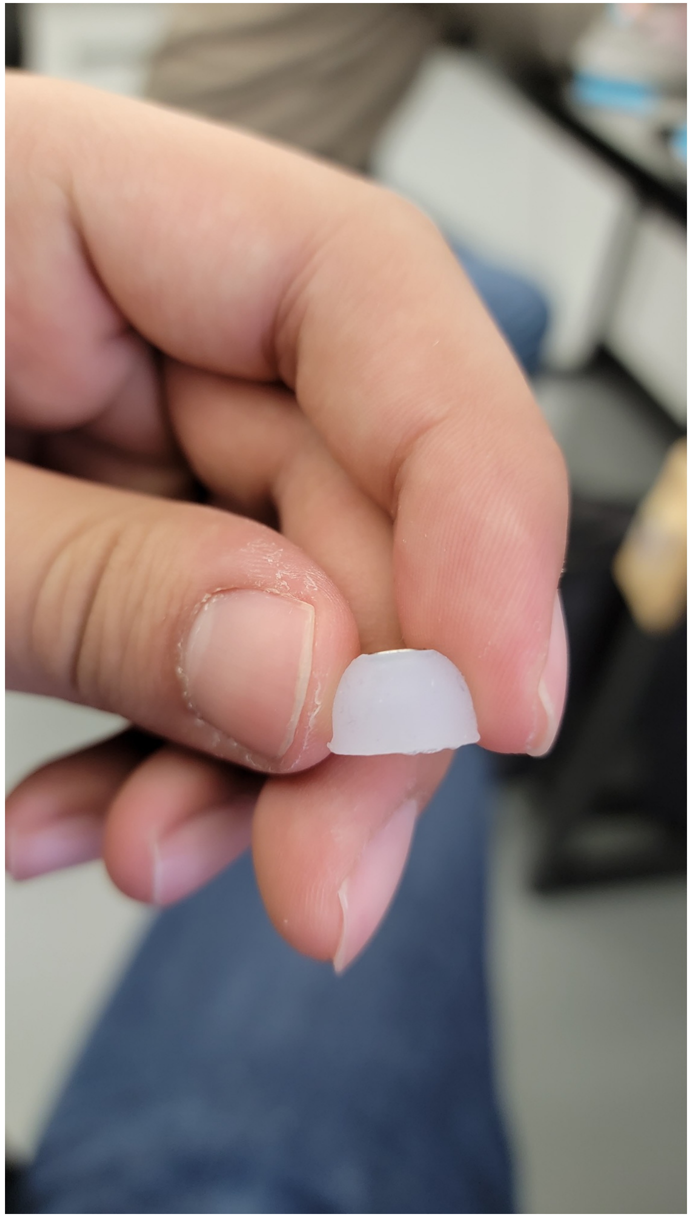
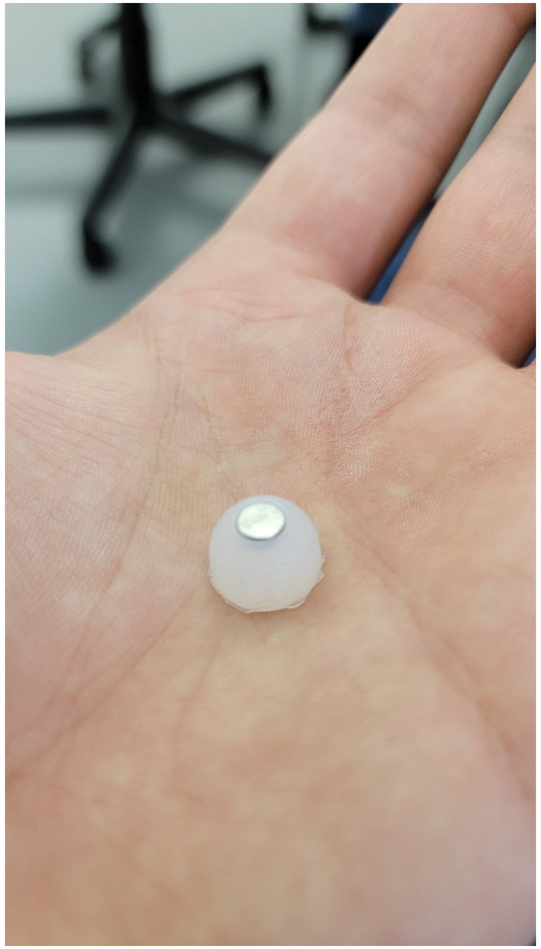
Finished Prototype







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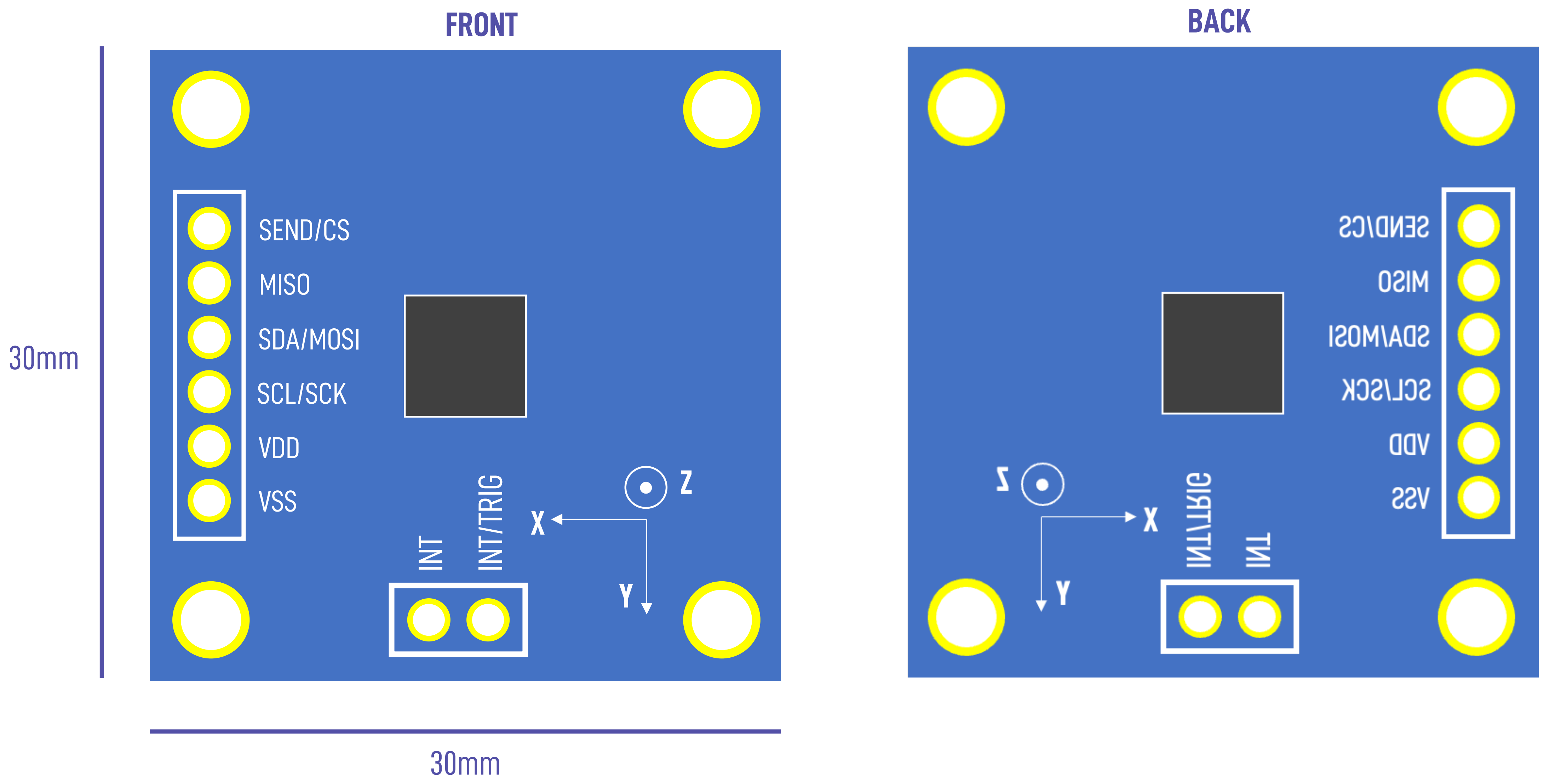
Sensor Pinout



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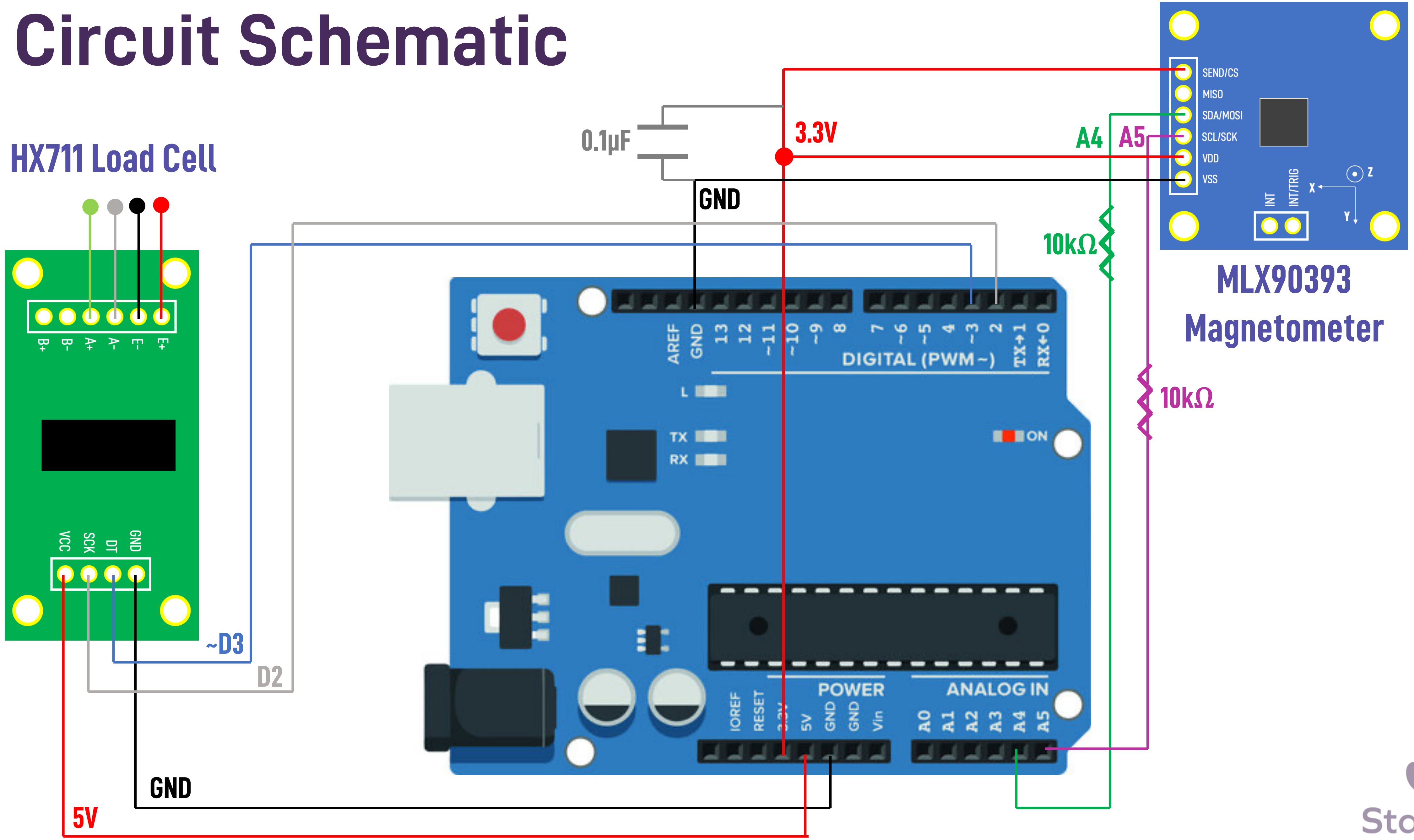
Circuit Schematic



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Prototyping Phase 1

Static Water Testing

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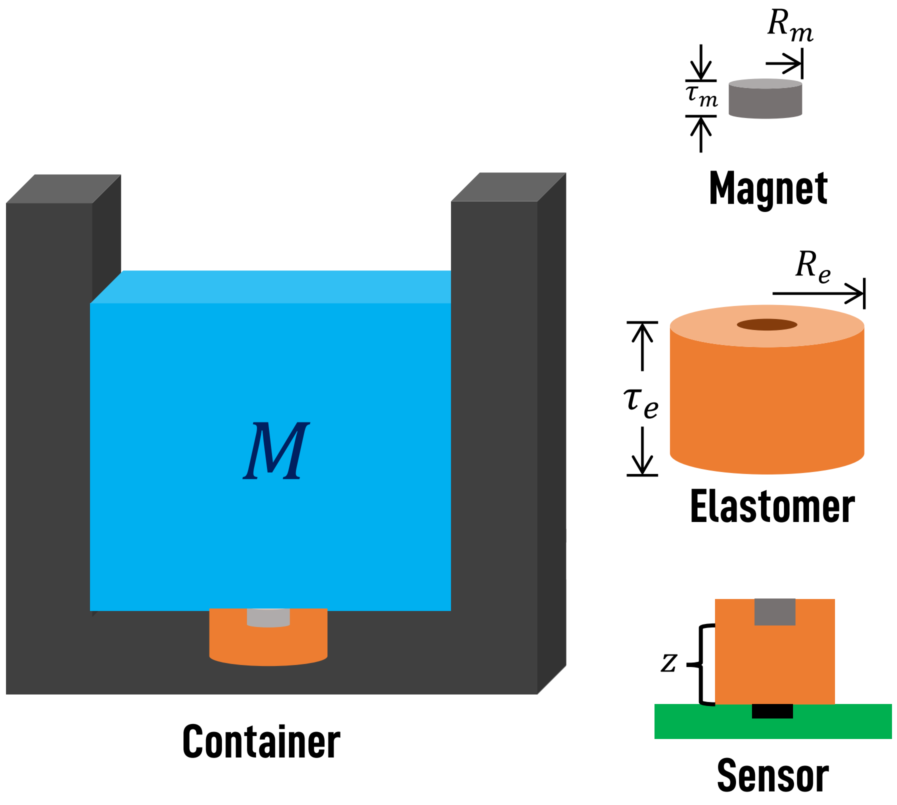
Static Water Derivation



Elastomer Equation

$$z = \tau_e\left(1 - \frac{\beta M}{\pi R_e^2}\right) - \tau_m$$

Magnet Equation

$$B_z = \alpha\left(\frac{z+\tau_m}{\sqrt{(z+\tau_m)^2 + R_m^2}} - \frac{z}{\sqrt{z^2 + R_m^2}}\right)$$

The objective is to solve for the mass M from the B-field B_z, so combining the two equations yields:

$$B_z = \frac{\alpha\tau_e - M\frac{\alpha\tau_e\beta}{\pi R_e^2}}{\sqrt{\tau_e^2 - M\frac{2\tau_e^2\beta}{\pi R_e^2} + M^2\frac{\tau_e^2\beta^2}{\pi^2 R_e^4} + R_m^2}} - \frac{\alpha\tau_e + M\frac{\alpha\tau_e\beta}{\pi R_e^2} - \alpha\tau_m}{\sqrt{M^2\frac{\beta^2\tau_e^2}{\pi^2 R_e^4} + M\left(\frac{2\tau_e\tau_m\beta}{\pi R_e^2} - \frac{\tau_e^2\beta}{\pi R_e^2}\right) + \tau_m^2 + R_m^2}}$$

Variables

$\boldsymbol{M}\ [\boldsymbol{g}]$: mass of fluid
$\boldsymbol{\alpha}, \boldsymbol{\beta}$: fitting parameters (physical properties of apparatus)

$\boldsymbol{A_c}\ [\boldsymbol{mm^2}]$: chamber cross-sectional area
$\boldsymbol{R_m}\ [\boldsymbol{mm}]$: magnet radius
$\boldsymbol{R_e}\ [\boldsymbol{mm}]$: elastomer radius
$\boldsymbol{B_z}\ [\boldsymbol{\mu T}]$: B-field along z-axis

$\boldsymbol{\tau_m}\ [\boldsymbol{mm}]$: magnet thickness
$\boldsymbol{\tau_e}\ [\boldsymbol{mm}]$: elastomer thickness
$\boldsymbol{z}\ [\boldsymbol{mm}]$: magnet distance from magnetometer sensor

Static Water Derivation

Continuing from the previous step, to solve for the mass from the B-field value, numerical methods must be used since the mass is not easily algebraically separable in the below equation:

$$B_z = \frac{\alpha\tau_e - M\frac{\alpha\tau_e\beta}{\pi R_e^2}}{\sqrt{\tau_e^2 - M\frac{2\tau_e^2\beta}{\pi R_e^2} + M^2\frac{\tau_e^2\beta^2}{\pi^2 R_e^4} + R_m^2}} - \frac{\alpha\tau_e + M\frac{\alpha\tau_e\beta}{\pi R_e^2} - \alpha\tau_m}{\sqrt{M^2\frac{\beta^2\tau_e^2}{\pi^2 R_e^4} + M\left(\frac{2\tau_e\tau_m\beta}{\pi R_e^2} - \frac{\tau_e^2\beta}{\pi R_e^2}\right) + \tau_m^2 + R_m^2}}$$

To accomplish this, the equation is rearranged into the form of a root-finding problem:

$$B_z - \frac{\alpha\tau_e - M\frac{\alpha\tau_e\beta}{\pi R_e^2}}{\sqrt{\tau_e^2 - M\frac{2\tau_e^2\beta}{\pi R_e^2} + M^2\frac{\tau_e^2\beta^2}{\pi^2 R_e^4} + R_m^2}} - \frac{\alpha\tau_e + M\frac{\alpha\tau_e\beta}{\pi R_e^2} - \alpha\tau_m}{\sqrt{M^2\frac{\beta^2\tau_e^2}{\pi^2 R_e^4} + M\left(\frac{2\tau_e\tau_m\beta}{\pi R_e^2} - \frac{\tau_e^2\beta}{\pi R_e^2}\right) + \tau_m^2 + R_m^2}} = 0$$

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Static Water Derivation

$$f(m) = B_z - \frac{\alpha\tau_e - M\frac{\alpha\tau_e\beta}{\pi R_e^2}}{\sqrt{\tau_e^2 - M\frac{2\tau_e^2\beta}{\pi R_e^2} + M^2\frac{\tau_e^2\beta^2}{\pi^2 R_e^4} + R_m^2}} - \frac{\alpha\tau_e + M\frac{\alpha\tau_e\beta}{\pi R_e^2} - \alpha\tau_m}{\sqrt{M^2\frac{\beta^2\tau_e^2}{\pi^2 R_e^4} + M\left(\frac{2\tau_e\tau_m\beta}{\pi R_e^2} - \frac{\tau_e^2\beta}{\pi R_e^2}\right) + \tau_m^2 + R_m^2}} = 0$$

The bisection method is used to solve for the mass M using the following algorithm:

1. Provide a bracket for the possible root values. An appropriate bracket would be $[M_{lower} = 0, M_{upper} = 100]$, since the mass will be a value between 0 and 100g in the experiment.
2. Calculate the midpoint value:

$$M_R = \frac{M_l + M_u}{2}$$

3. Evaluate the following:

$$x = f(M_l) \cdot f(M_u)$$

if(x<0): $M_{l,new} = M_l \mid M_{u,new} = M_R \mid M_{R,new} = \frac{M_{l,new} + M_{u,new}}{2}$

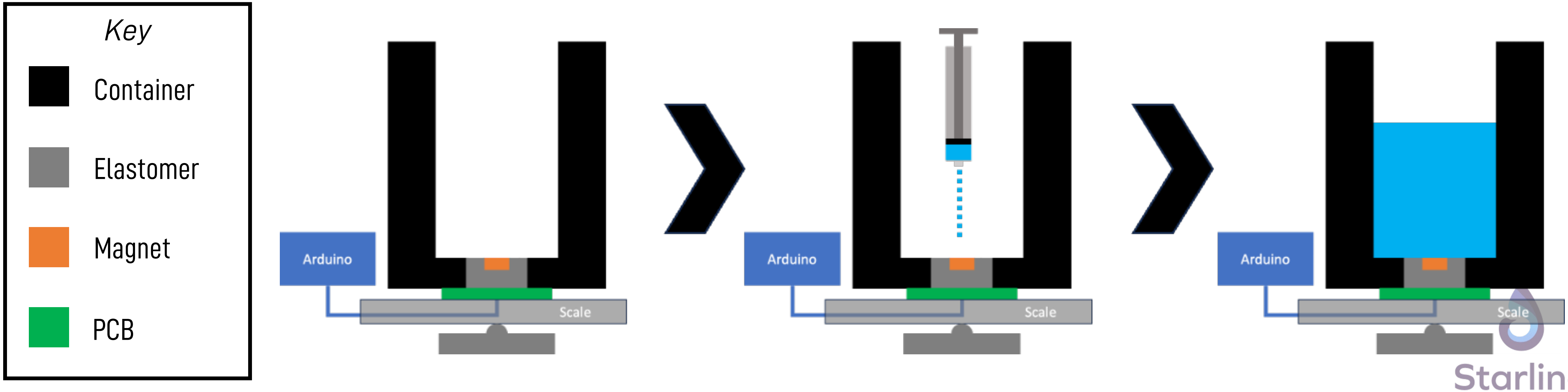
if(x>0): $M_{l,new} = M_R \mid M_{u,new} = M_u \mid M_{R,new} = \frac{M_{l,new} + M_{u,new}}{2}$

if(x=0): root= M_R

4. Iterate step 3 until end condition is met

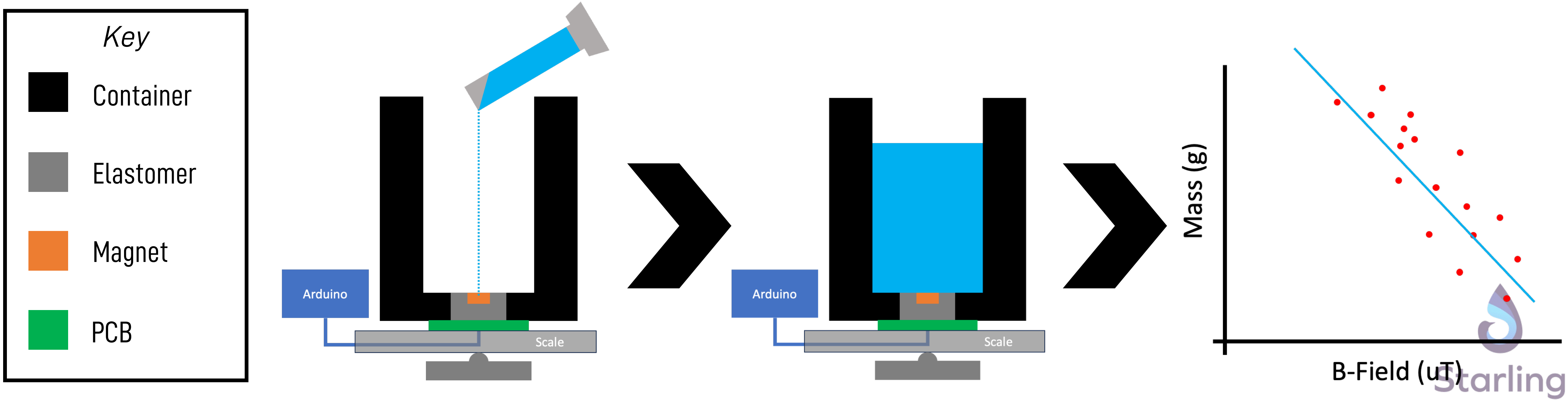
Static Water Calibration Procedure V1

1. Record a magnetometer reading when the container is empty of water
2. Measure out 2 mL of water using syringe and inject onto the elastomer
3. Press the button to record the magnetometer measurement of the B-field value
4. Manually record the mass of the water as shown by the digital scale
5. Repeat this until 125 mL of water has been added



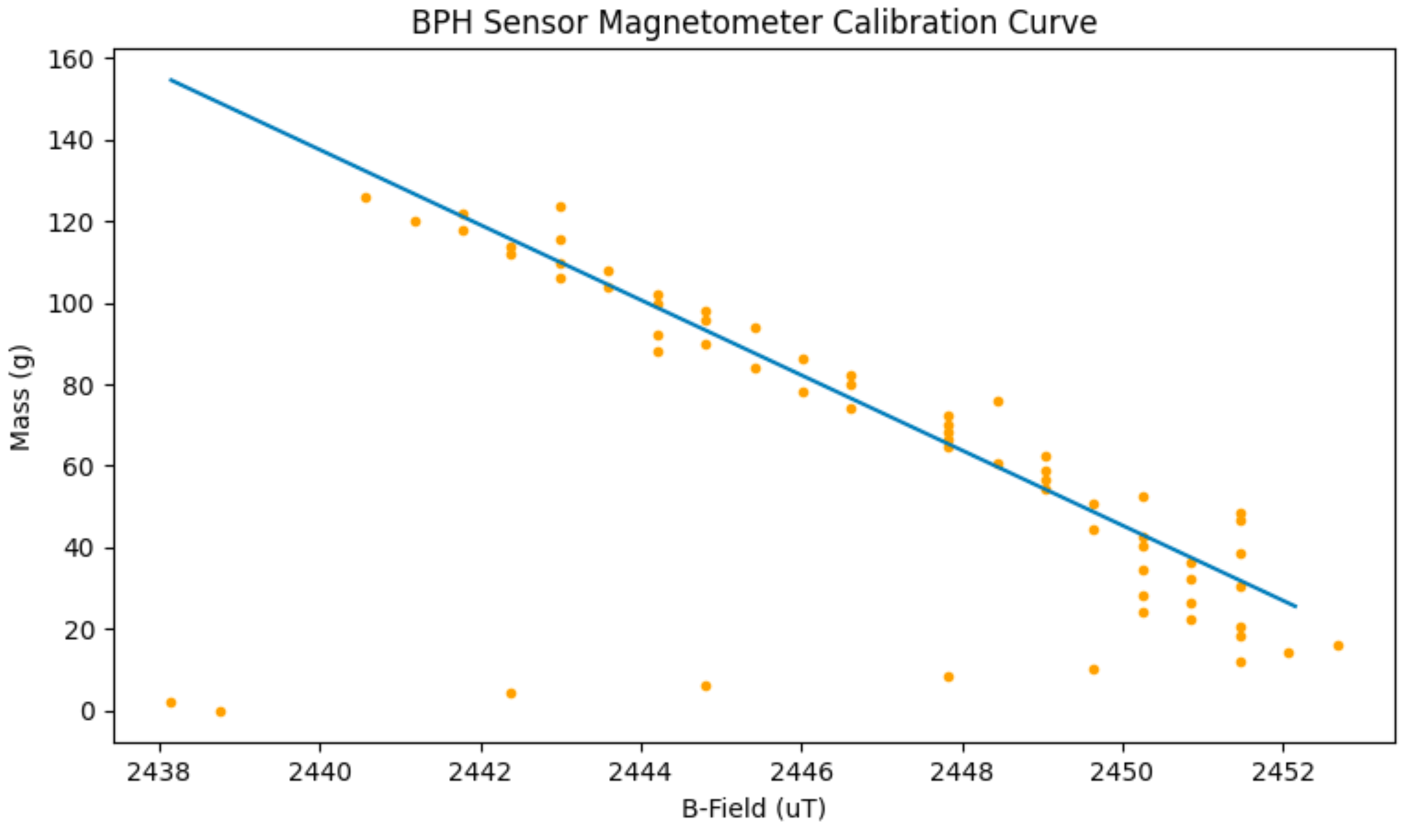
Static Water Test Procedure V1

1. Measure out 100 mL of water using the graduated cylinder
2. Inject the water onto the elastomer
3. Record the measured B-field value
4. Using the linear regression line of best fit from the calibration, calculate the predicted water mass from the B-field value
5. Repeat this for 6 trials and compare to true value of 100 g



Static Water Experiment Data

Calibration Results



Test Results	
Average	104 g
Standard Deviation	12.7 g
Accuracy	95.9 %

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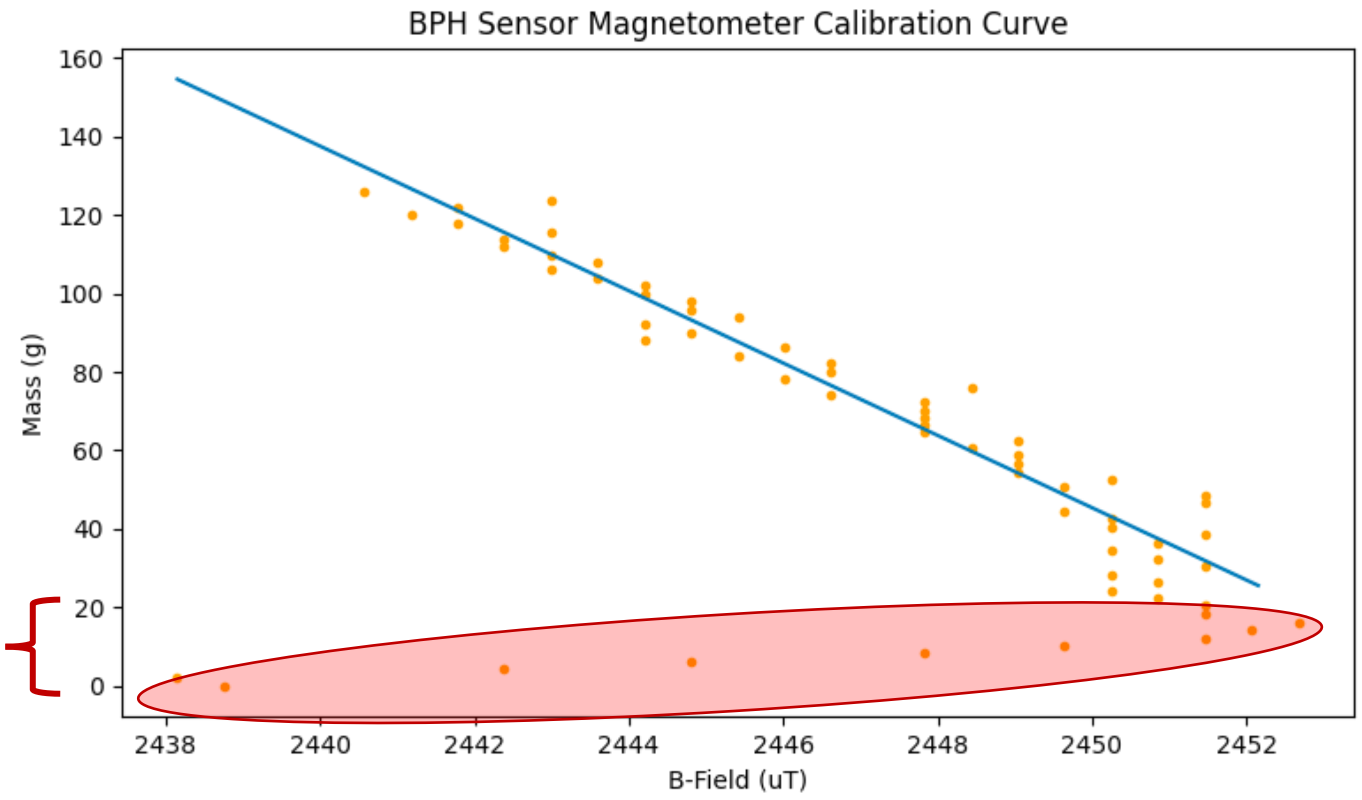
Discussion

Notice the inconsistency with the low mass values (< 20 g). I realized that this was at approximately the mass of water required to completely cover the elastomer sensor. After this critical mass, the measurements are more accurate.



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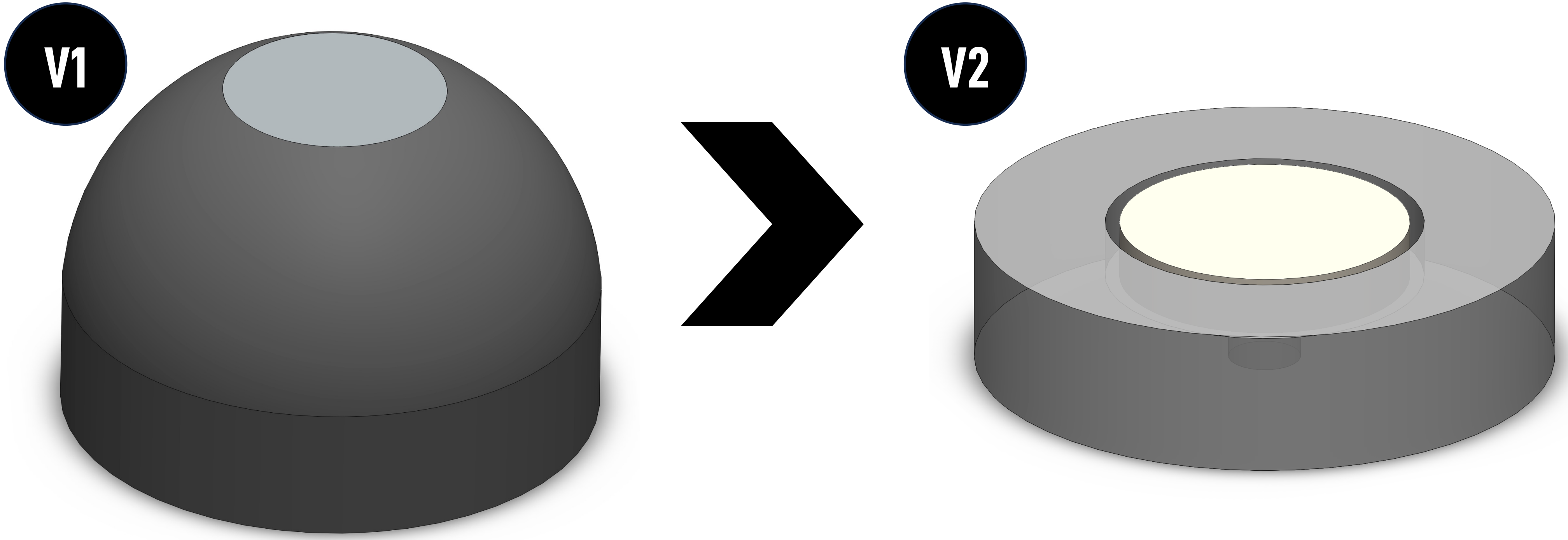
Discussion

To solve this, I redesigned the elastomer geometry to be flush with the surface of the container.



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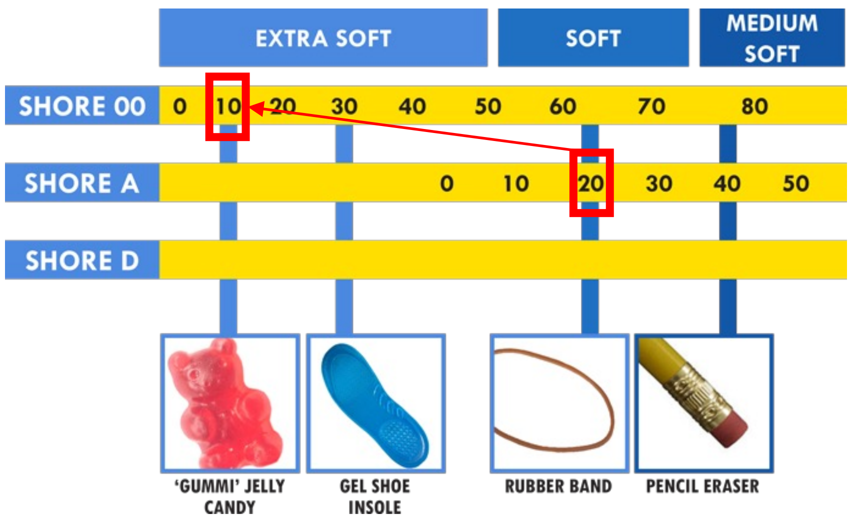
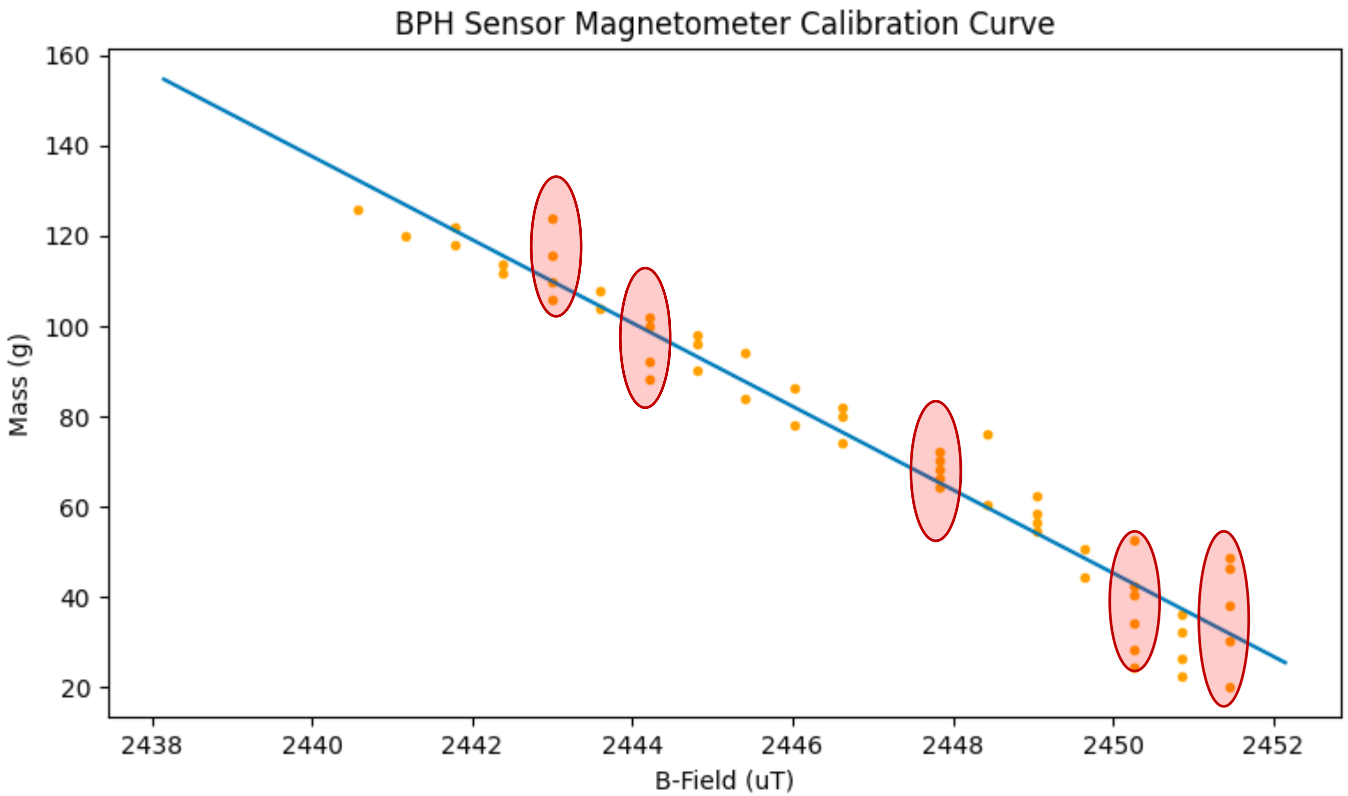
Discussion

Furthermore, the sensor reads the same B-field value for different masses. This indicates the current configuration is not sensitive enough to differentiate between these changes or the environmental B-field is non-negligible relative to the magnet B-field. To fix this, I am using larger magnets (from 5 mm to 10 mm) and softer silicones (from Shore 20A to Shore 00-50).





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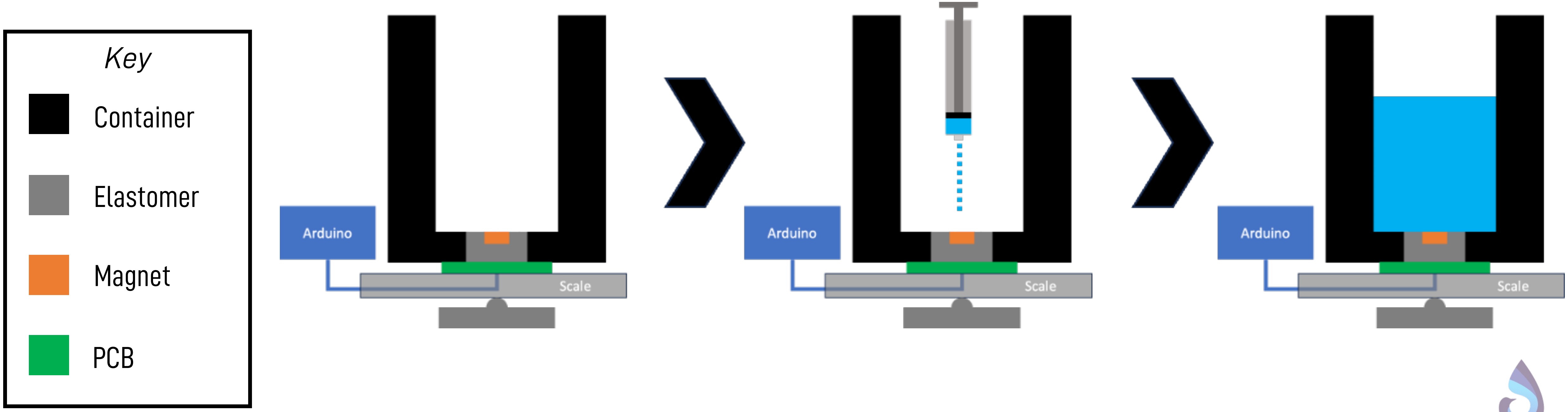
Static Water Calibration Procedure V2

1. Calibrate the load cell with the 10g lead weight
2. The circuit will begin recording both, the mass and the B-field automatically
3. Add 2 mL of water after ~150 readings at the previous mass
4. Repeat this until 100 mL of water has been added



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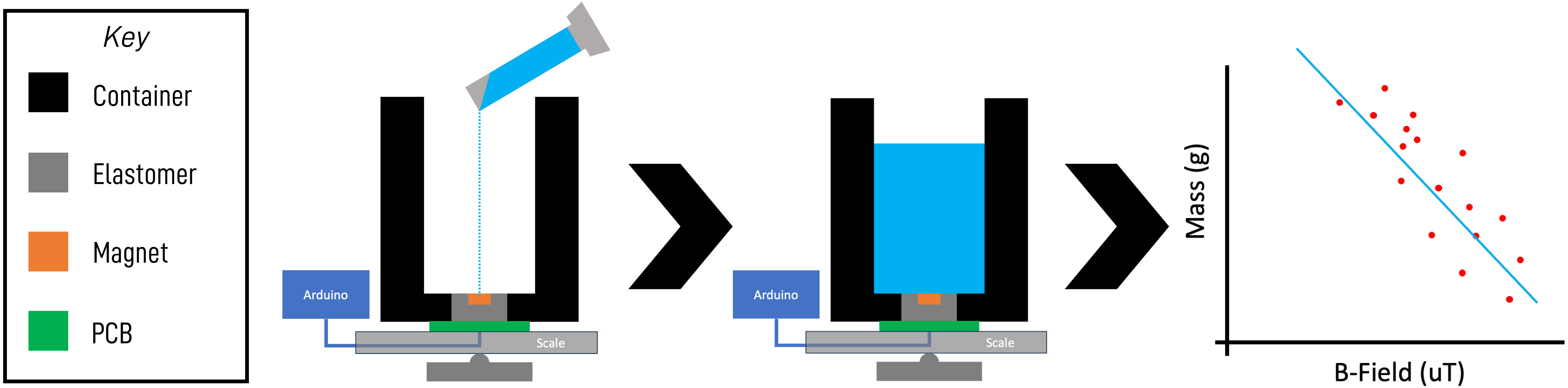
Static Water Test Procedure V2

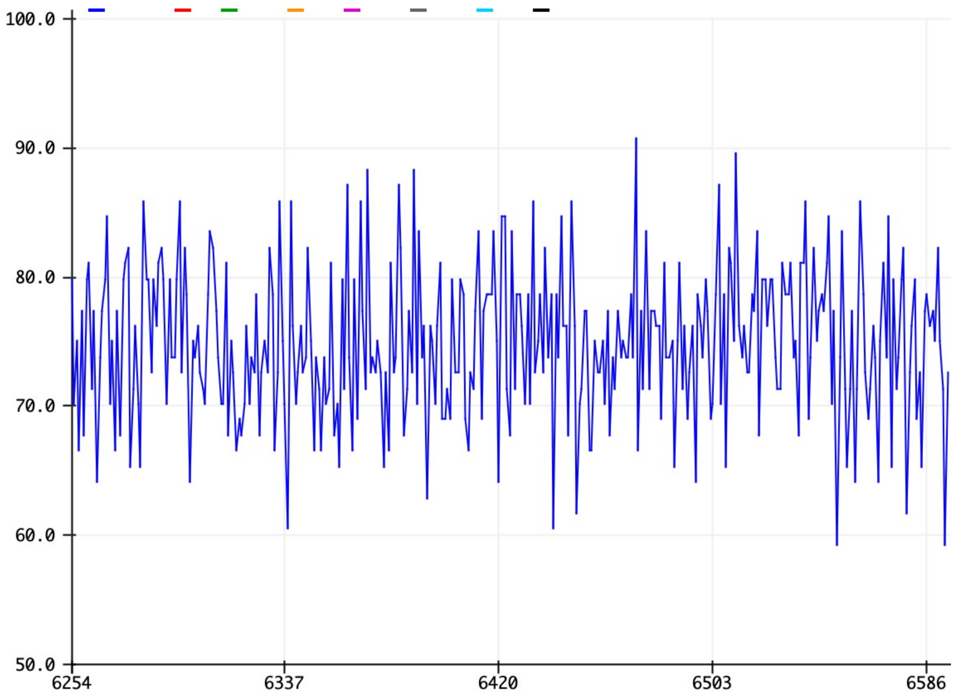
1. Measure out 100 mL of water using the graduated cylinder
2. Inject the water onto the elastomer
3. Record the measured B-field value
4. Using the polynomial fit from the calibration, calculate the predicted water mass from the B-field value
5. Repeat this for 6 trials and compare to true value of 100 g



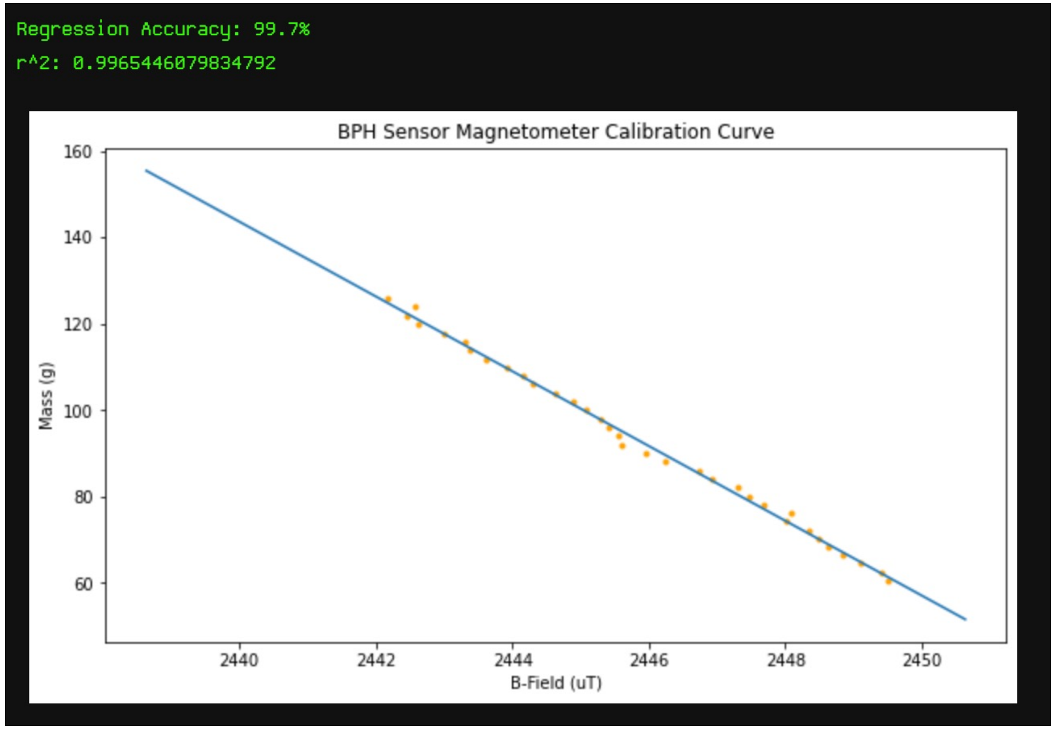
Discussion

While debugging to find the weak points of the design, I noticed that the sensor readings oscillate as shown below. The previous procedure did not account for this oscillation. To address this issue, I implemented a digital filter algorithm (exponential moving average), which increased the r^2 value to ~0.997.

Oscillating Data



Cleaned Data



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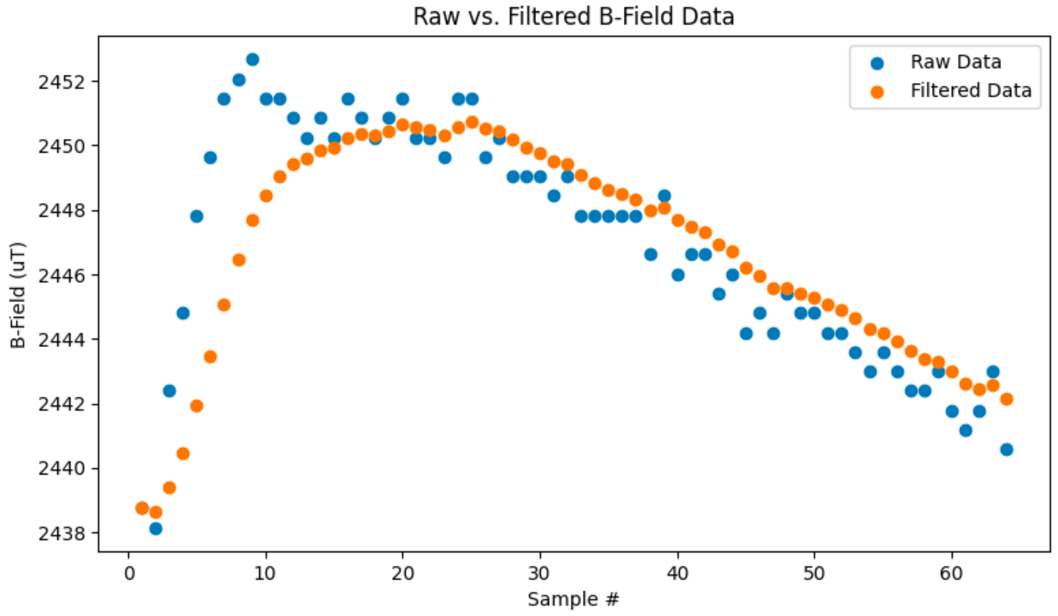
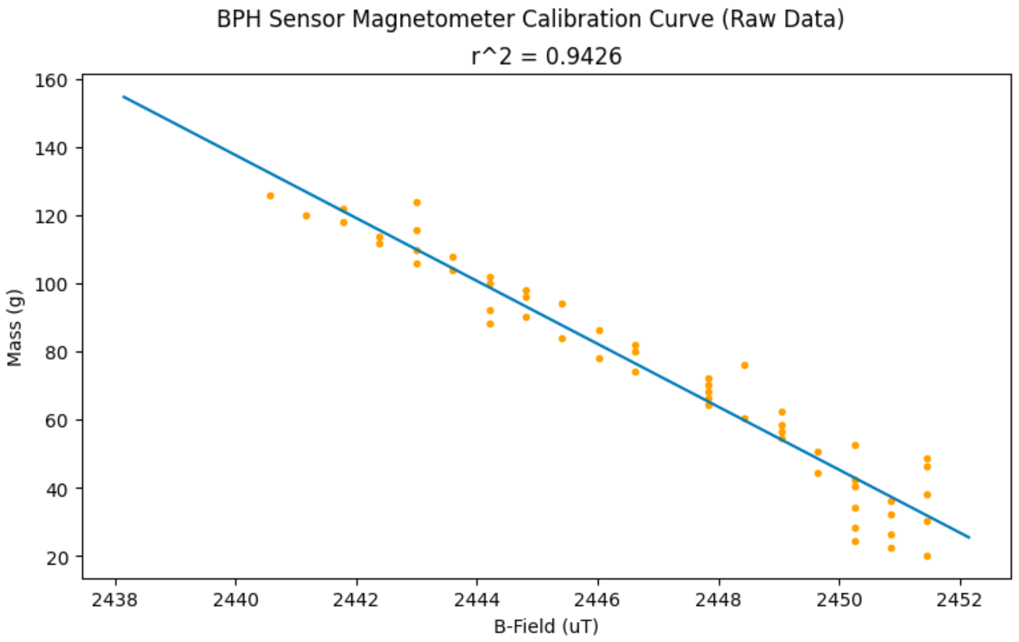
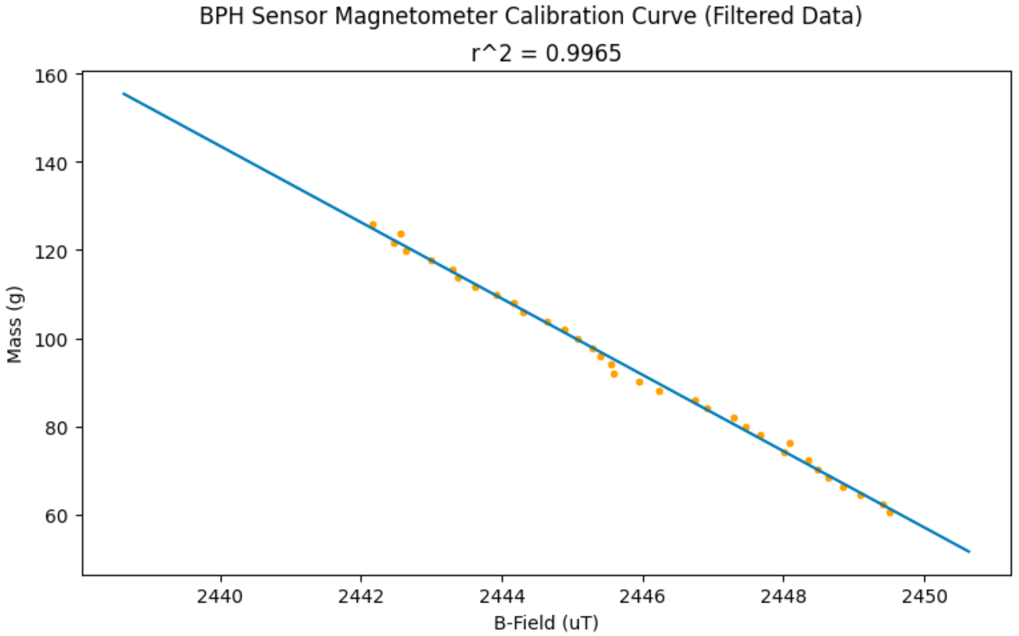
Exponential Moving Average Algorithm

$$y[i] = \alpha \cdot x[i] + (1 - \alpha) \cdot y[i-1]$$





Filter



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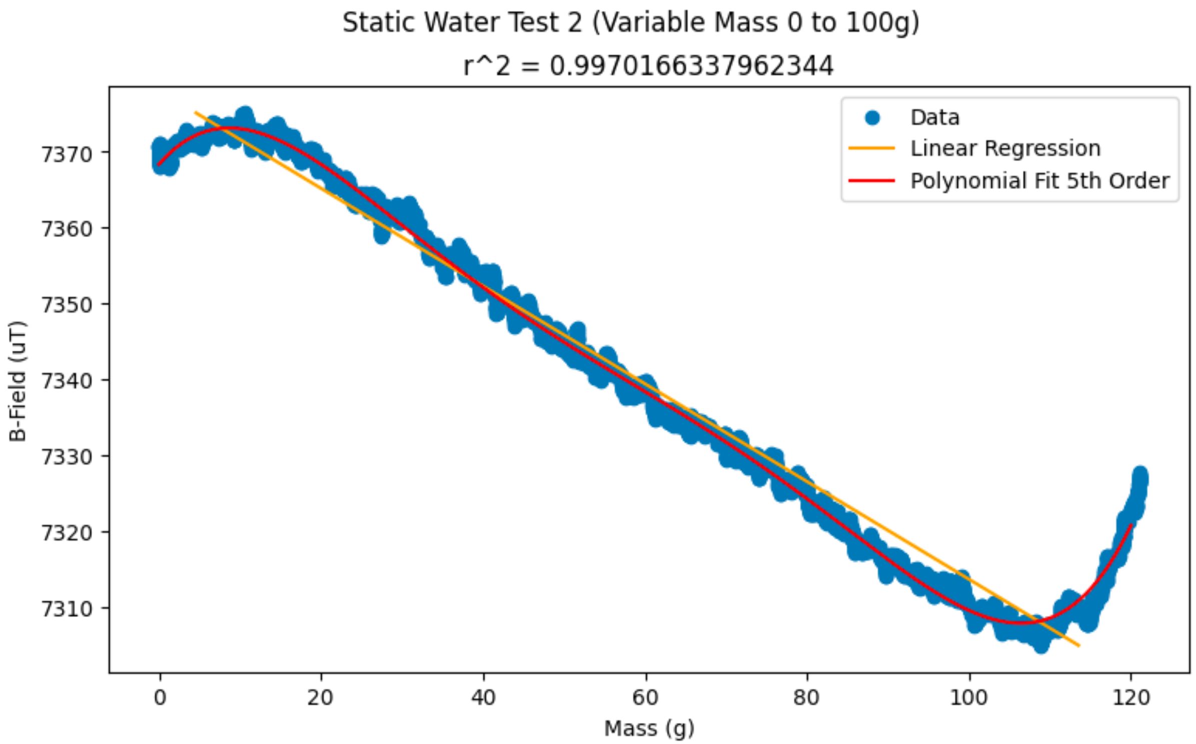
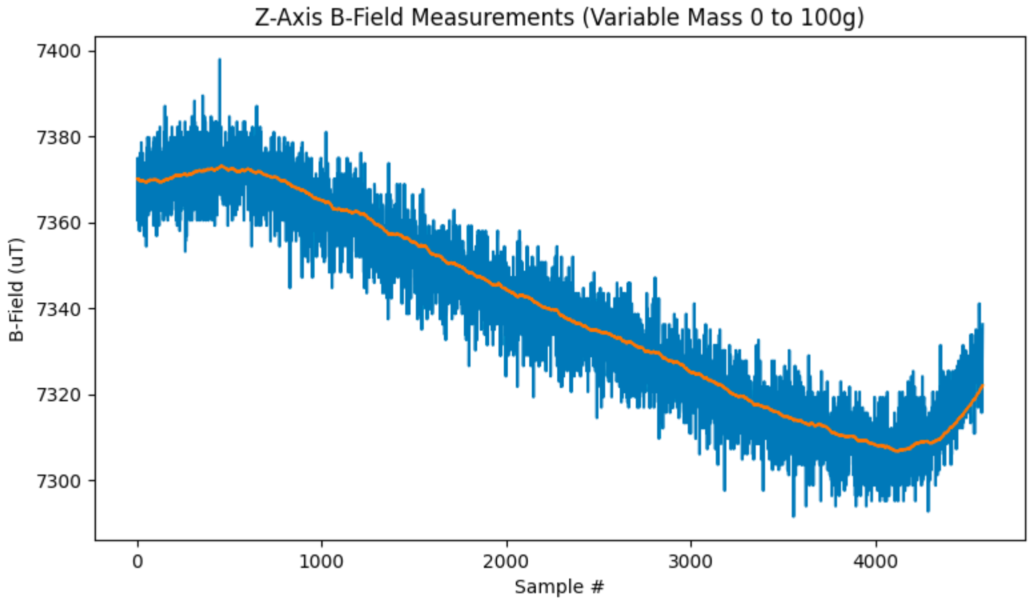
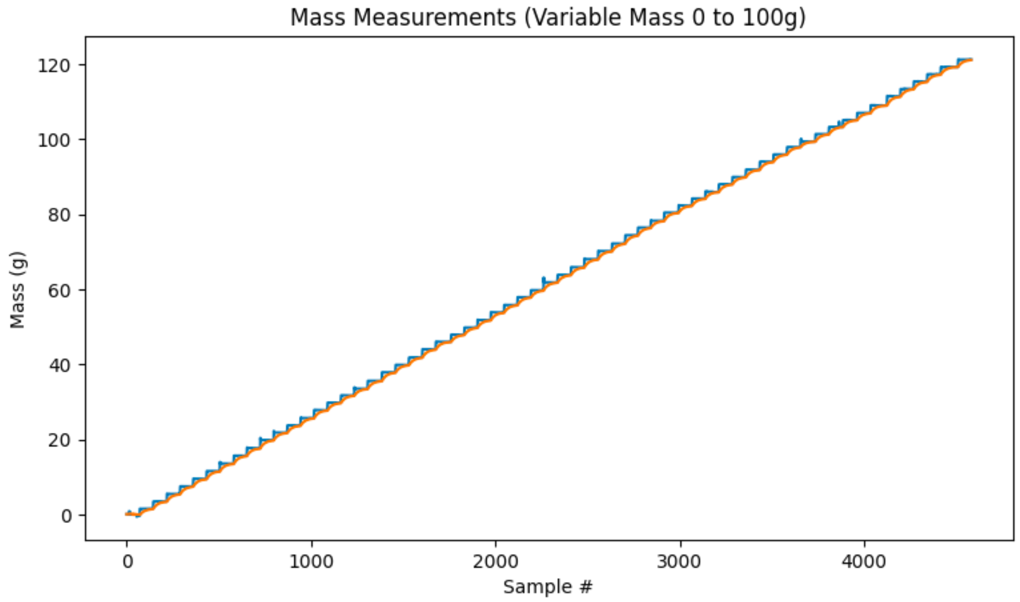

Static Water Test 2 (Variable Mass 0 to 100g)
r^2 = 0.9970166337962344
Data
Linear Regression
Polynomial Fit 5th Order
B-Field (uT)
Mass (g)


Z-Axis B-Field Measurements (Variable Mass 0 to 100g)
B-Field (uT)
Sample #


Mass Measurements (Variable Mass 0 to 100g)
Mass (g)
Sample #

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Problems

After conducting more rigorous tests, I found that this high correlation is attributed to the drift, not the actual mass reading.

1. **False Negative Test** – Did not add any water, but results show a large drift

2. **Reverse Test** – Started with 100g of water and started removing mass, but curve was still the same

3. **Long Term False Negative Test** – Same as #1, except I ran the experiment for an entire day (over 1.1 million data points). Curve displays low frequency sinusoidal noise

4. **Ground Test** – Measured magnetometer readings without including the elastomer

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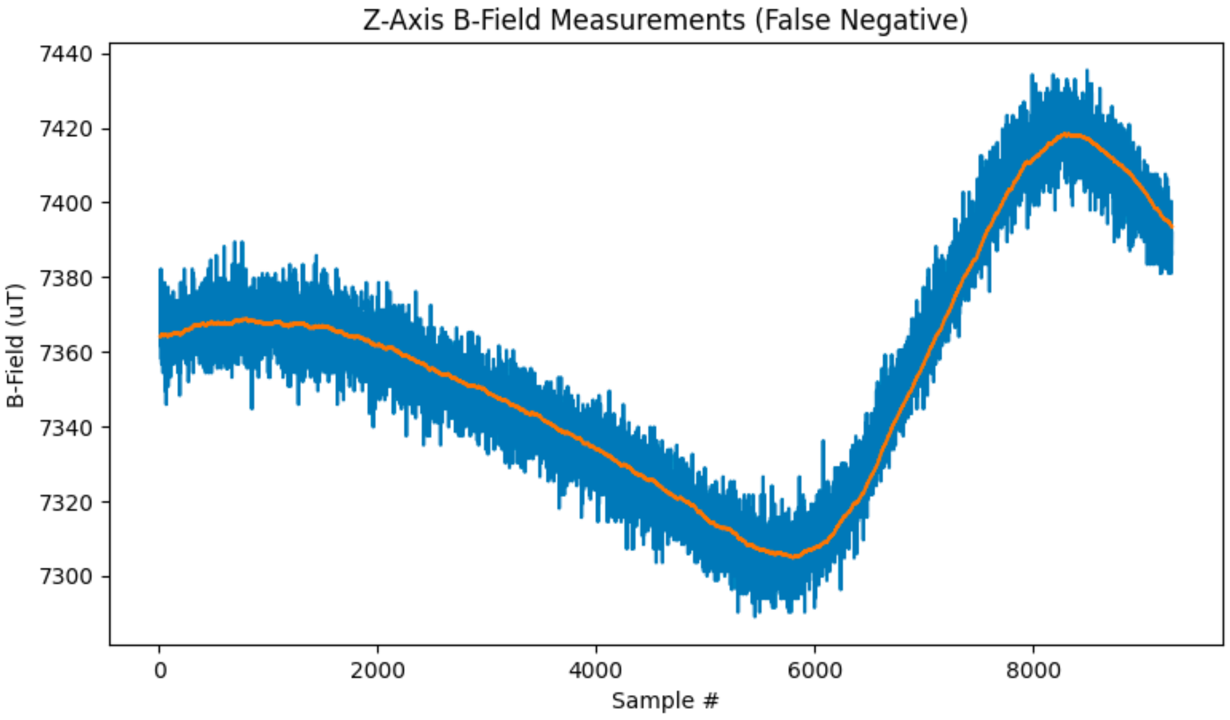
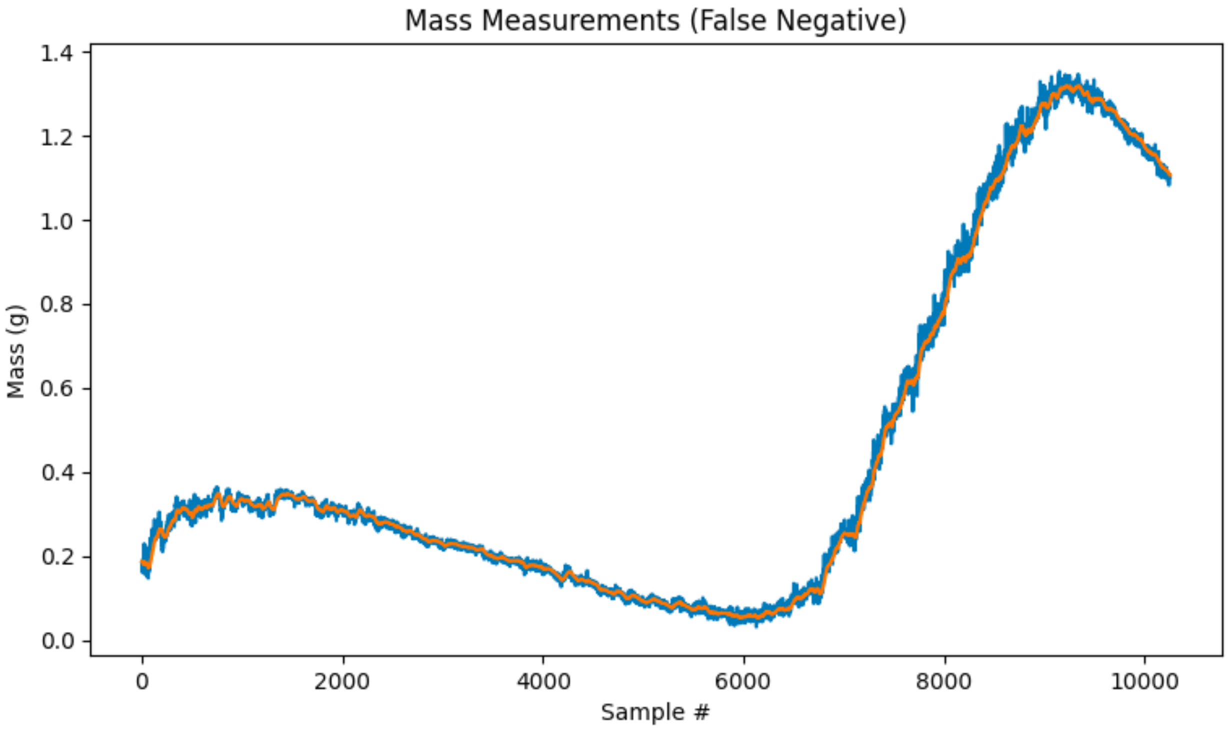
False Negative Test Results





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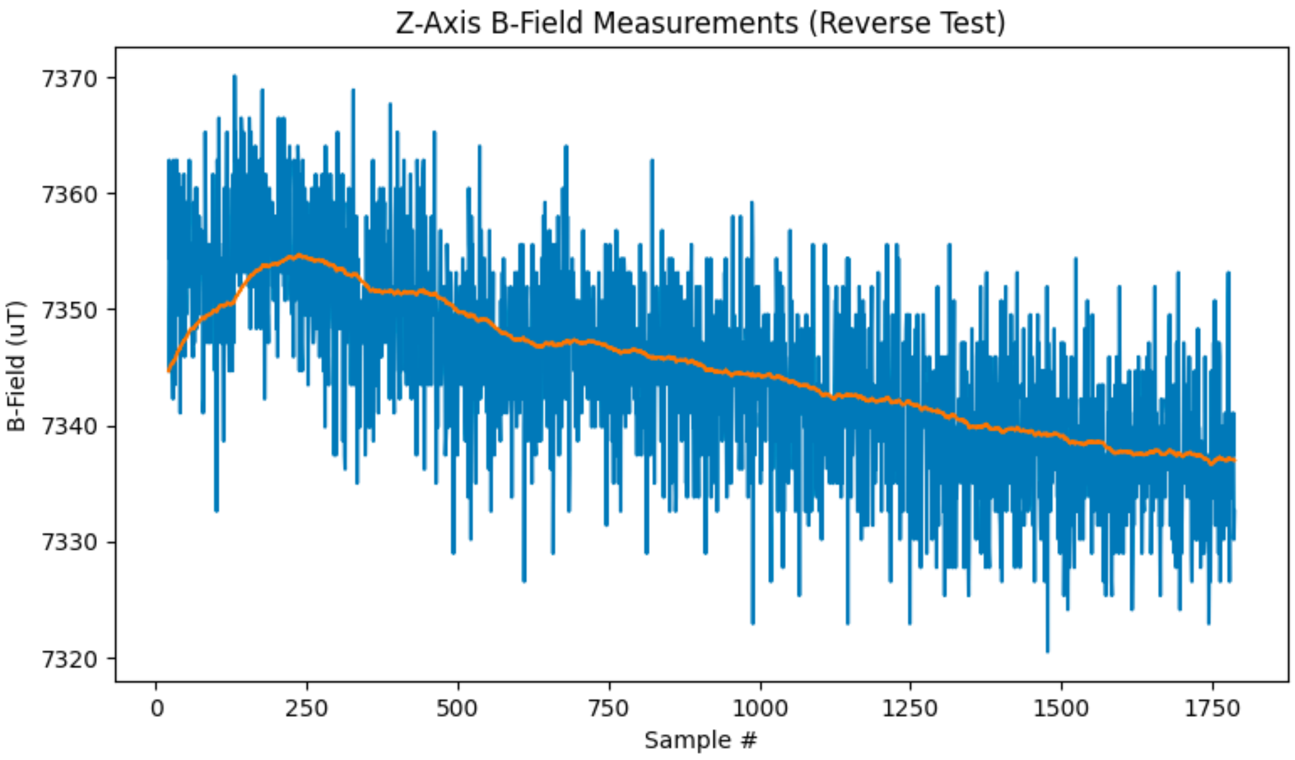
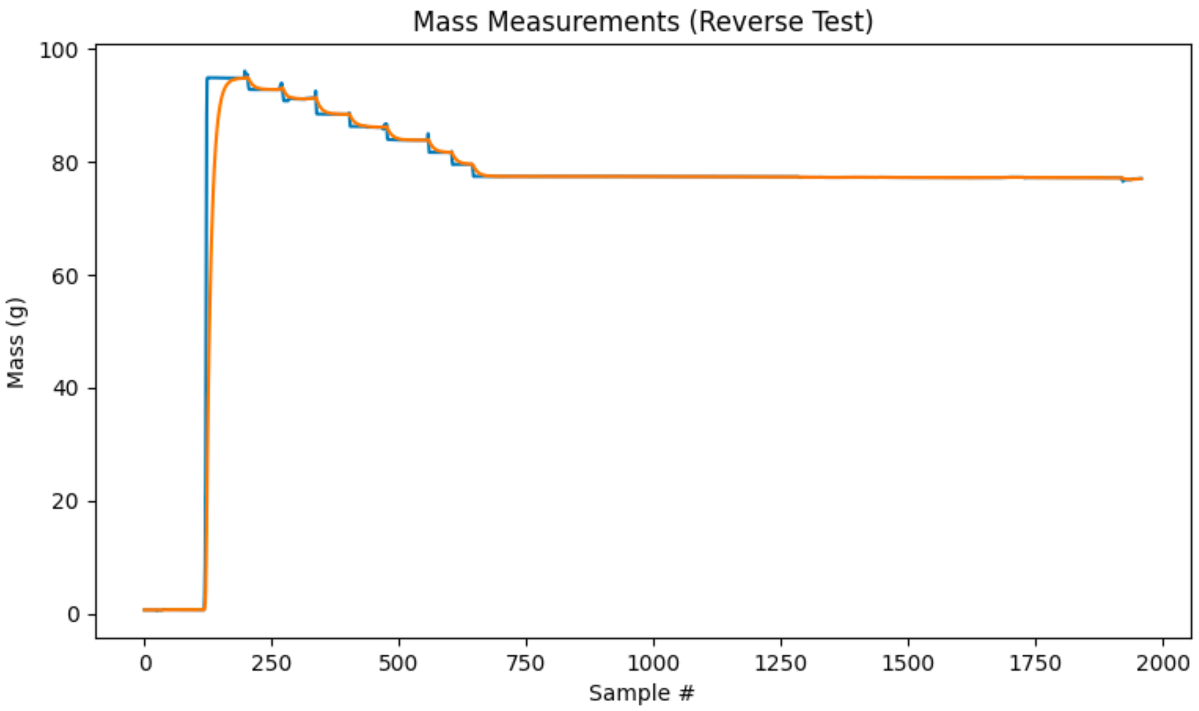
Reverse Test Results





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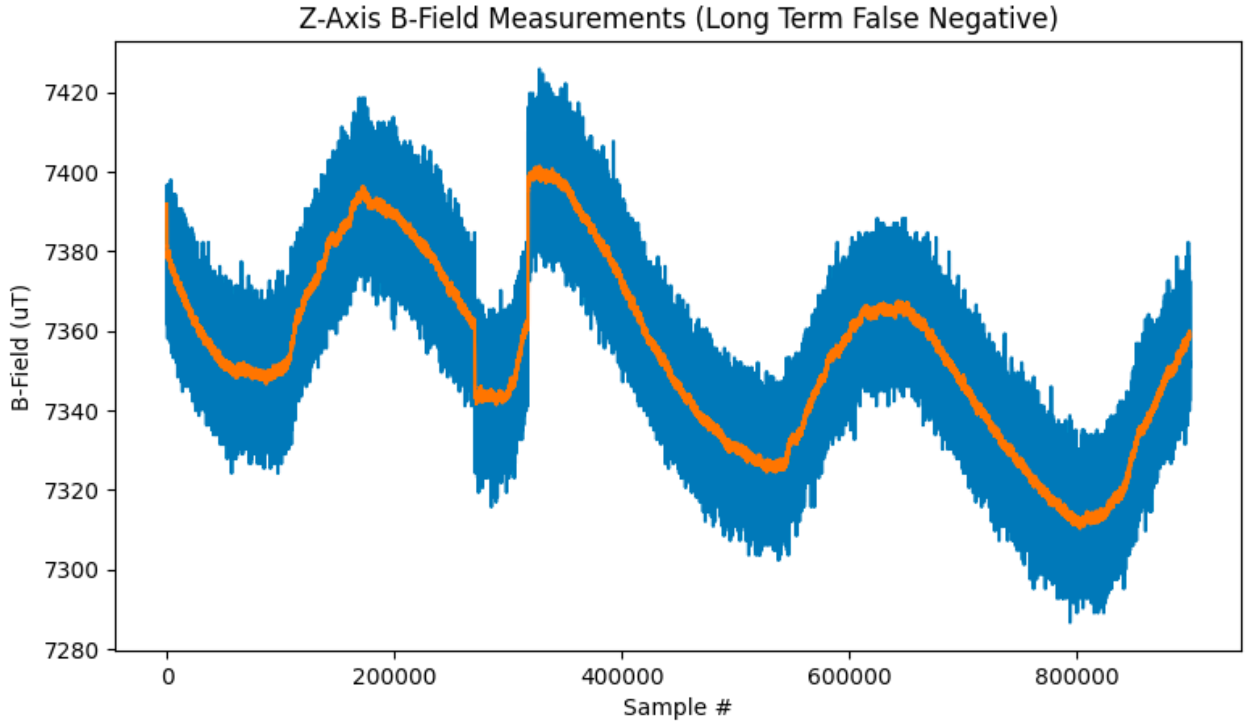
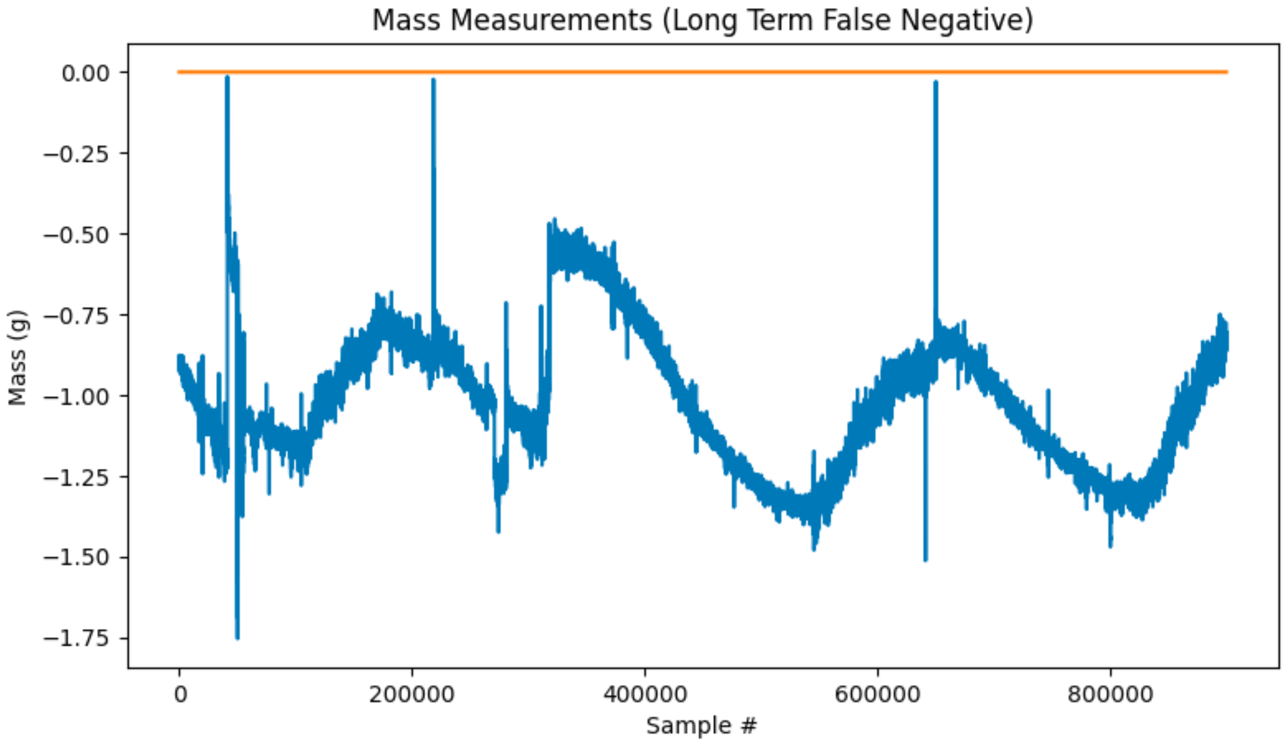
Long Term False Negative Test Results





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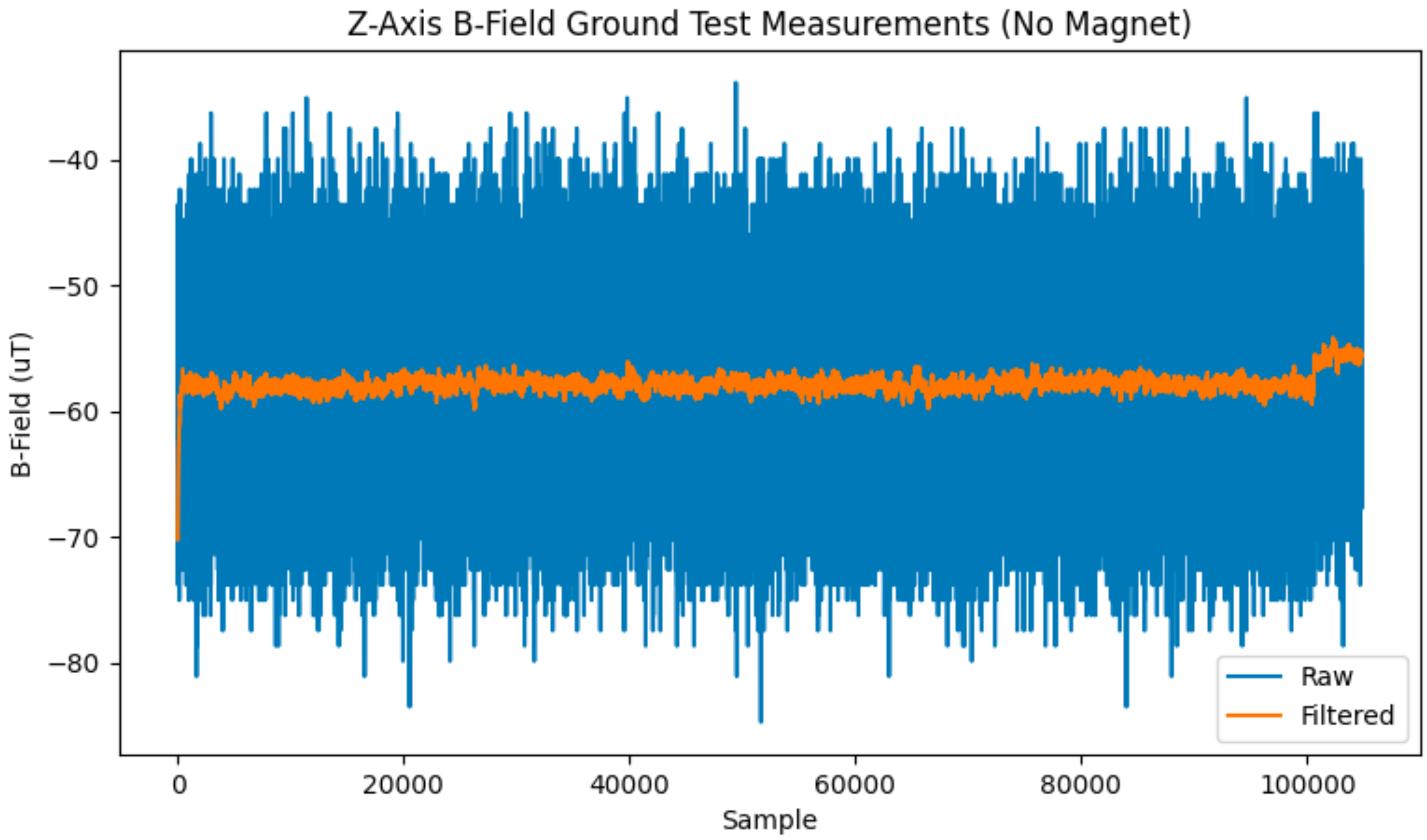
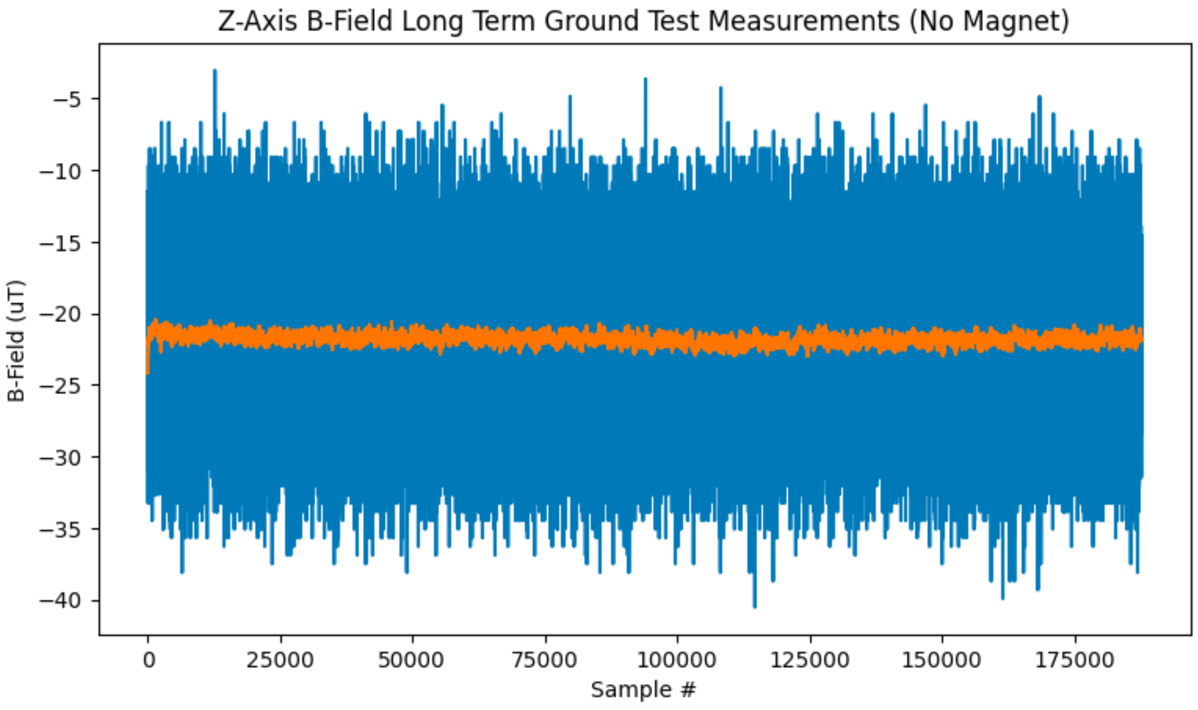
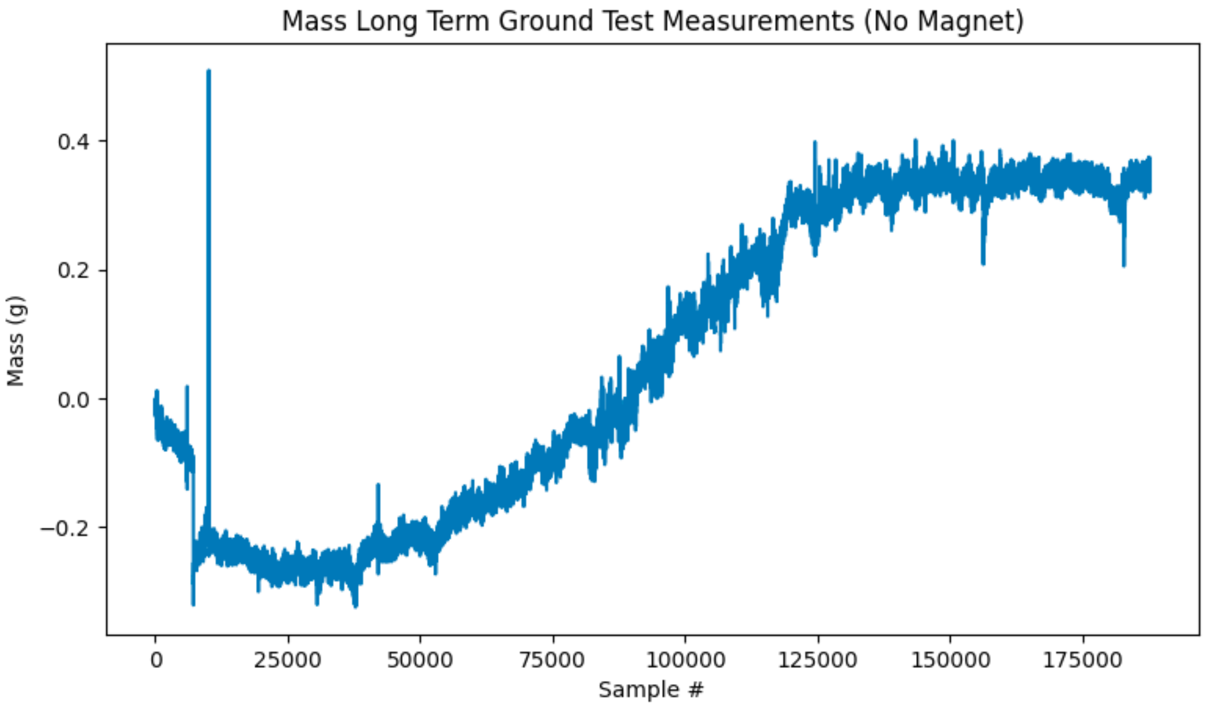
Ground Test Results



Long Term Ground Test Results





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Discussion

A few noteworthy observations I made from this data are:

- The drift is clearly a sinusoidal noise. The source is still to be determined.
- The magnetometer and the load cell drift in the same direction and at the same pace. I hypothesize that this can be addressed using the following:
    - The power from the Arduino might not be stable enough for the sensors. To verify this, redo the tests with a PSU that is reliably steady
    - The wiring might not be stable. To address this, try getting a circuit board printed of my circuit, or try using shorter wires.
    - Use an oscilloscope to determine the noise frequency and develop a filter to remove the noise.
    - Make a case that covers the test apparatus to mitigate any environmental factors such as dust or wind.
- The ground test does not exhibit the same noise as the other tests, indicating that the sensor itself is not faulty.

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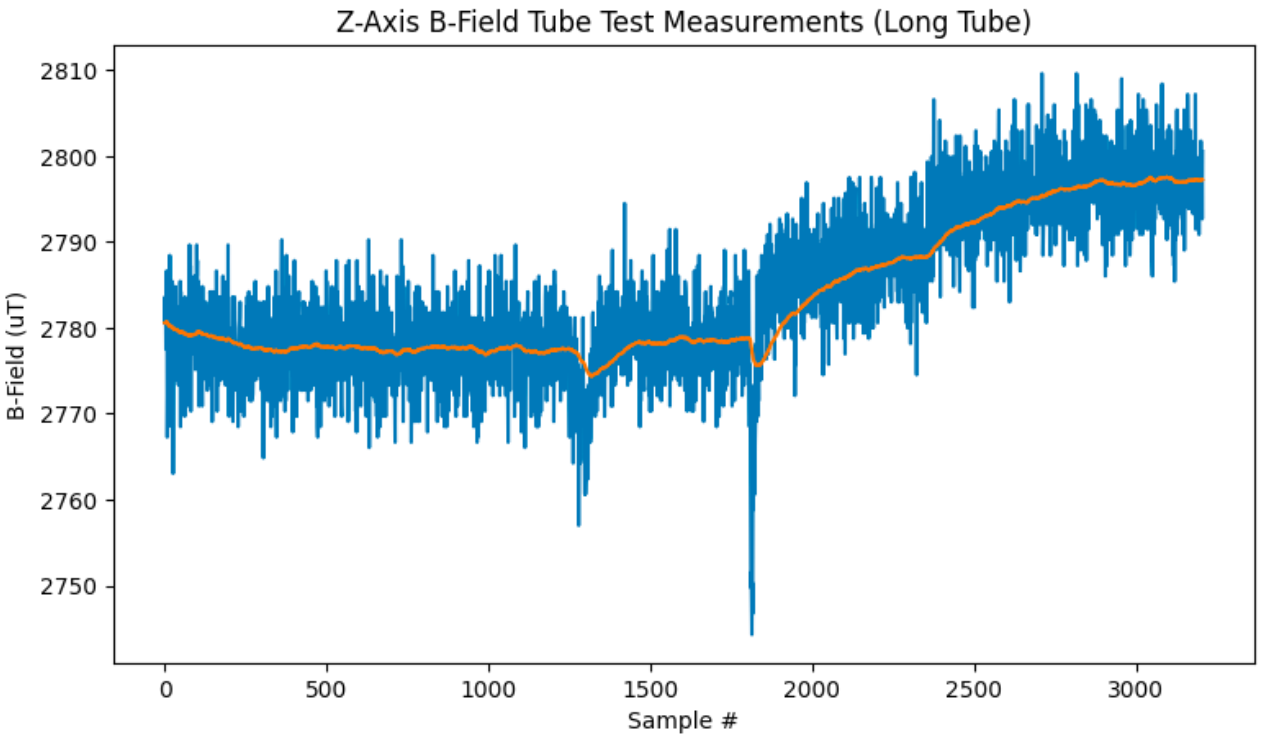
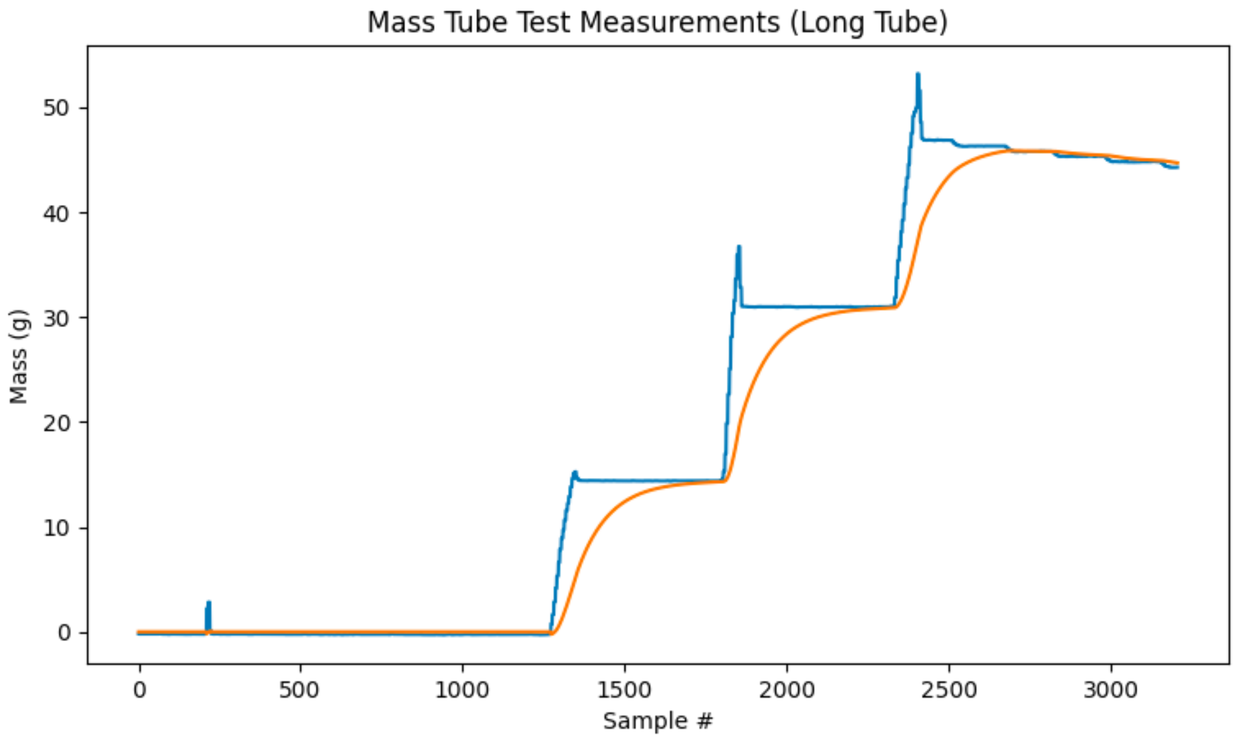
Live Demo Test (Last Day Showcase)





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Conclusions

- The live demo test results are promising due to the following:
  - The b-field values are very clearly changing by a significant magnitude with each injection of a few milliliters of water. This shows that using the smaller magnet and ensuring the load of the water is all coming onto the elastomer
  - The curve appears steady, similar to the ground test data. However, further testing is required to confirm with longer experiments
- It is important to note that the load cell was not calibrated properly during the live demo since I was only trying to show how the test setup works. With a proper test setup, I believe the system can achieve better results

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Prototyping Phase 2

Dynamic Water Testing

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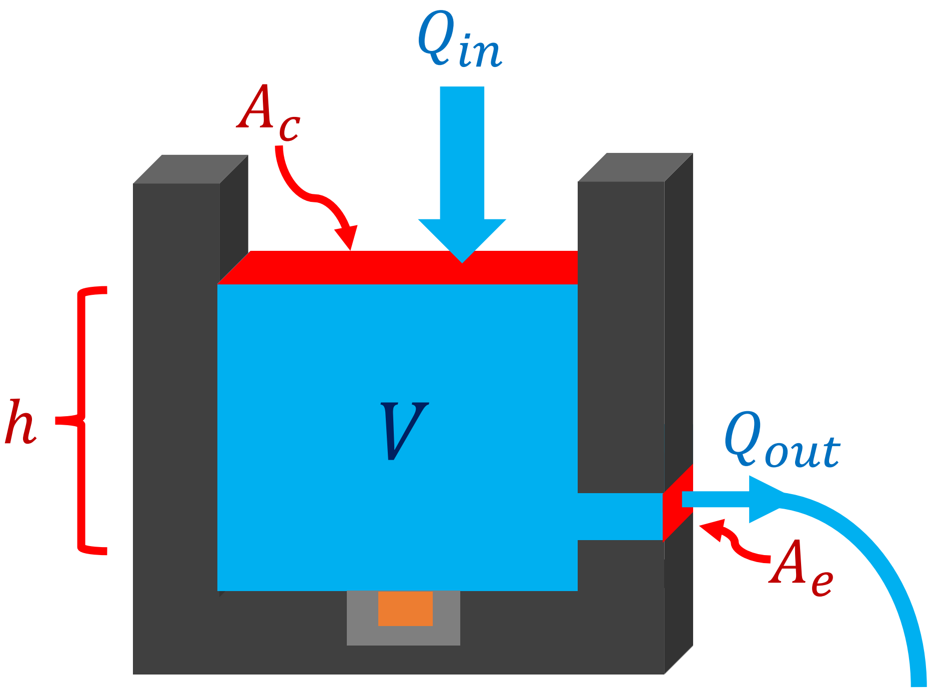
Dynamic Water Derivation



Base Equation

$$\frac{dV}{dt} = Q_{in} - Q_{out}$$

The objective is to solve for the flow rate, which is Q_{in}, so rearranging gives the following:

$$Q_{in} = \frac{dV}{dt} + Q_{out}$$

Variables

$\boldsymbol{h}$ $[\boldsymbol{mm}]$: height of fluid

$\boldsymbol{V}$ $[\boldsymbol{mL}]$: volume of fluid

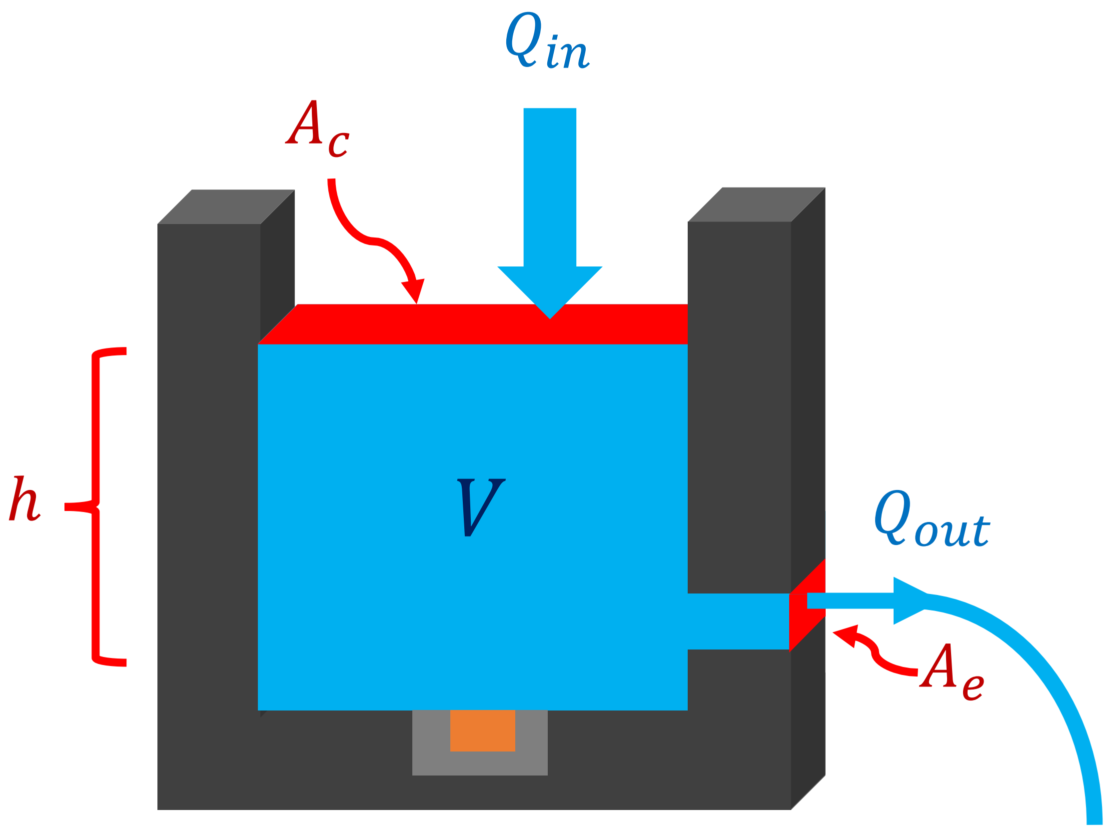
$\boldsymbol{A_c}$ $[\boldsymbol{mm^2}]$: chamber cross-sectional area

$\boldsymbol{A_e}$ $[\boldsymbol{mm^2}]$: exhaust cross-sectional area

$\boldsymbol{Q_{in}}$ $[\boldsymbol{mL/s}]$: volumetric inflow rate of fluid

$\boldsymbol{Q_{out}}$ $[\boldsymbol{mL/s}]$: volumetric outflow rate of fluid

Dynamic Water Derivation



$$Q_{in} = \frac{dV}{dt} + Q_{out}$$

These following physical relationships are important in order to get the equation in terms that can be measured by the sensor:

$$Q_{out} = v_e A_e$$

$$v_e = C_d\sqrt{2gh}$$

$$V = \frac{m}{\rho}$$

$$\frac{dV}{dt} = \lim_{\Delta t \to 0} \frac{V(t+\Delta t) - V(t)}{\Delta t}$$

$\boldsymbol{v_e}$ $[\boldsymbol{m/s}]$: Exhaust velocity of fluid
$\boldsymbol{C_d}$ $[\boldsymbol{unitless}]$: Coefficient of discharge of fluid (experimentally determined)
$\boldsymbol{g}$ $[\boldsymbol{m/s^2}]$: Gravitational acceleration
$\boldsymbol{m}$ $[\boldsymbol{g}]$: Mass of fluid
$\boldsymbol{\rho}$ $[\boldsymbol{g/mL}]$: Density of fluid

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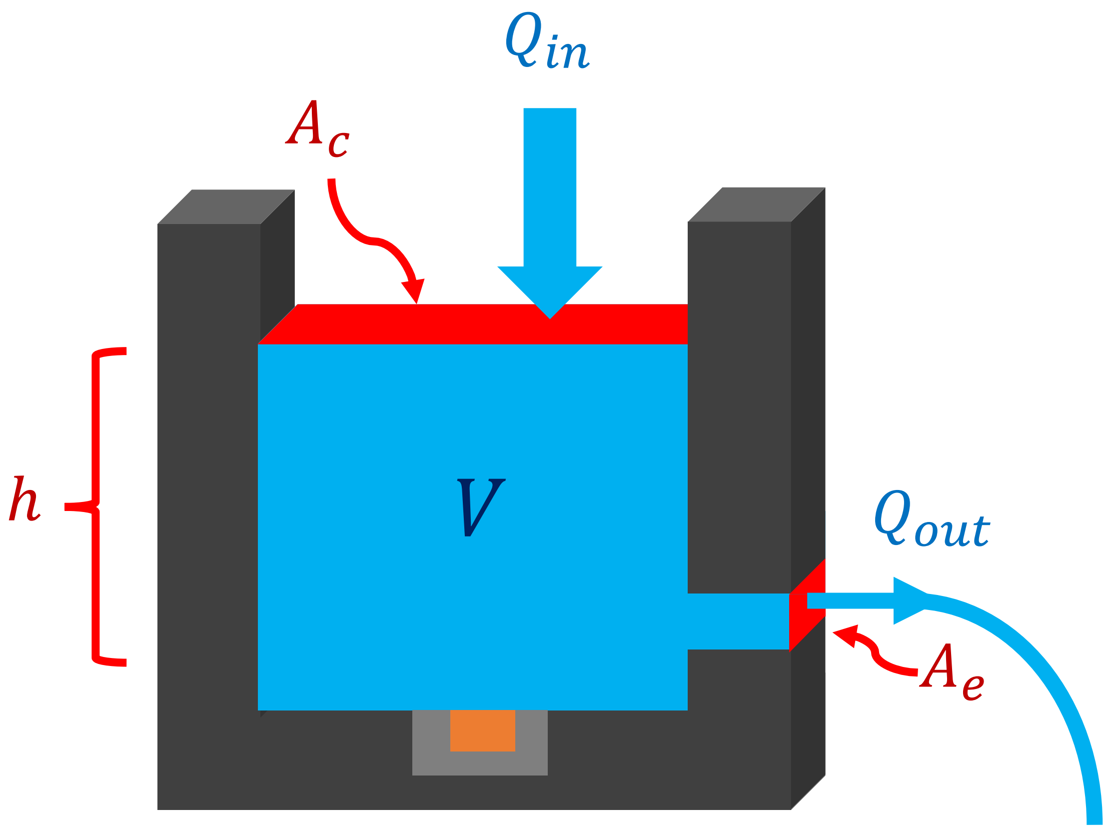
Dynamic Water Derivation



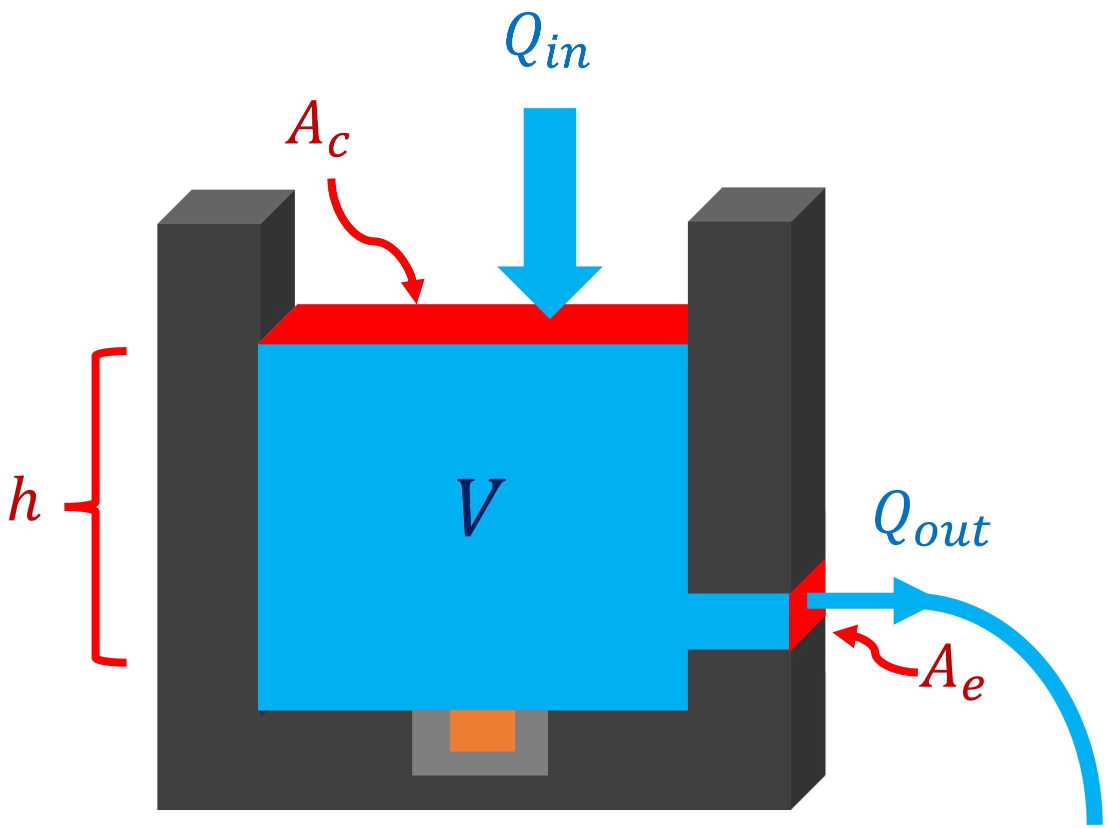
$$Q_{in} = \frac{dV}{dt} + Q_{out}$$

Using the previous definitions, the equation can be rewritten as:

$$Q_{in} = \frac{1}{\rho} \lim_{\Delta t \to 0} \frac{m(t + \Delta t) - m(t)}{\Delta t} + A_e C_d \sqrt{2gh}$$

Now this equation is in terms of variables that can be measured by the magnetometer sensor.

Dynamic Water Derivation



$$Q_{in} = \frac{1}{\rho} \lim_{\Delta t \to 0} \frac{m(t+\Delta t) - m(t)}{\Delta t} + A_e C_d \sqrt{2gh}$$

The magnetometer sensor measures the B-field value x, which is then converted into mass using a calibrated 5th order polynomial regression:

$$m = f(x)$$

where m is mass in grams, x is the B-field in µT, and f is the polynomial evaluation

The height of fluid h therefore can be computed using the following:

$$h = \frac{m}{\rho A_c} = \frac{f(x)}{\rho A_c}$$

To compute the derivative expressed above in the form of a limit, various numerical methods can be implemented. I have derived 6 different equations. Experimentation will help me determine which is the optimal equation.

Numerical Methods

$$Q_{in} = \frac{dV}{dt} + Q_{out} = \frac{1}{\rho}\lim_{\Delta t \to 0}\frac{m(t+\Delta t) - m(t)}{\Delta t} + A_e C_d\sqrt{2gh}$$

Forward Finite Difference *O(h)*

$$Q_{in} = \frac{f(x_{i+1}) - f(x_i)}{\rho\Delta t} + A_e C_d\sqrt{2g\frac{f(x_{i+1})}{\rho A_c}}$$

Backward Finite Difference *O(h²)*

$$Q_{in} = \frac{(3f(x_i) - 4f(x_{i-1}) + f(x_{i-2}))}{2\rho\Delta t} + A_e C_d\sqrt{2g\frac{f(x_i)}{\rho A_c}}$$

Forward Finite Difference *O(h²)*

$$Q_{in} = \frac{4f(x_{i+1}) - f(x_{i+2}) - 3f(x_i)}{2\rho\Delta t} + A_e C_d\sqrt{2g\frac{f(x_{i+2})}{\rho A_c}}$$

Centered Finite Difference *O(h²)*

$$Q_{in} = \frac{f(x_{i+1}) - f(x_{i-1})}{2\rho\Delta t} + A_e C_d\sqrt{2g\frac{f(x_{i+1})}{\rho A_c}}$$

Backward Finite Difference *O(h)*

$$Q_{in} = \frac{f(x_i) - f(x_{i-1})}{\rho\Delta t} + A_e C_d\sqrt{2g\frac{f(x_i)}{\rho A_c}}$$

Centered Finite Difference *O(h⁴)*

$$Q_{in} = \frac{(f(x_{i-2}) + 8f(x_{i+1}) - 8f(x_{i-1}) - f(x_{i+2}))}{12\rho\Delta t} + A_e C_d\sqrt{2g\frac{f(x_{i+2})}{\rho A_c}}$$

Future Steps

1. Solve the noise issues in the static water test in order to acquire accurate calibration curves and fit B-field values to mass values using polynomial regression
2. Once a decent polynomial model is generated, conduct dynamic water testing
3. Analyze dynamic water test results and iterate to fix any issues
4. Once desirable results are achieved, design a new fixture within the UrinDX device or design a new device to contain the magnetometer sensor system and elastomer
5. Conduct simulation testing using the newly designed system

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