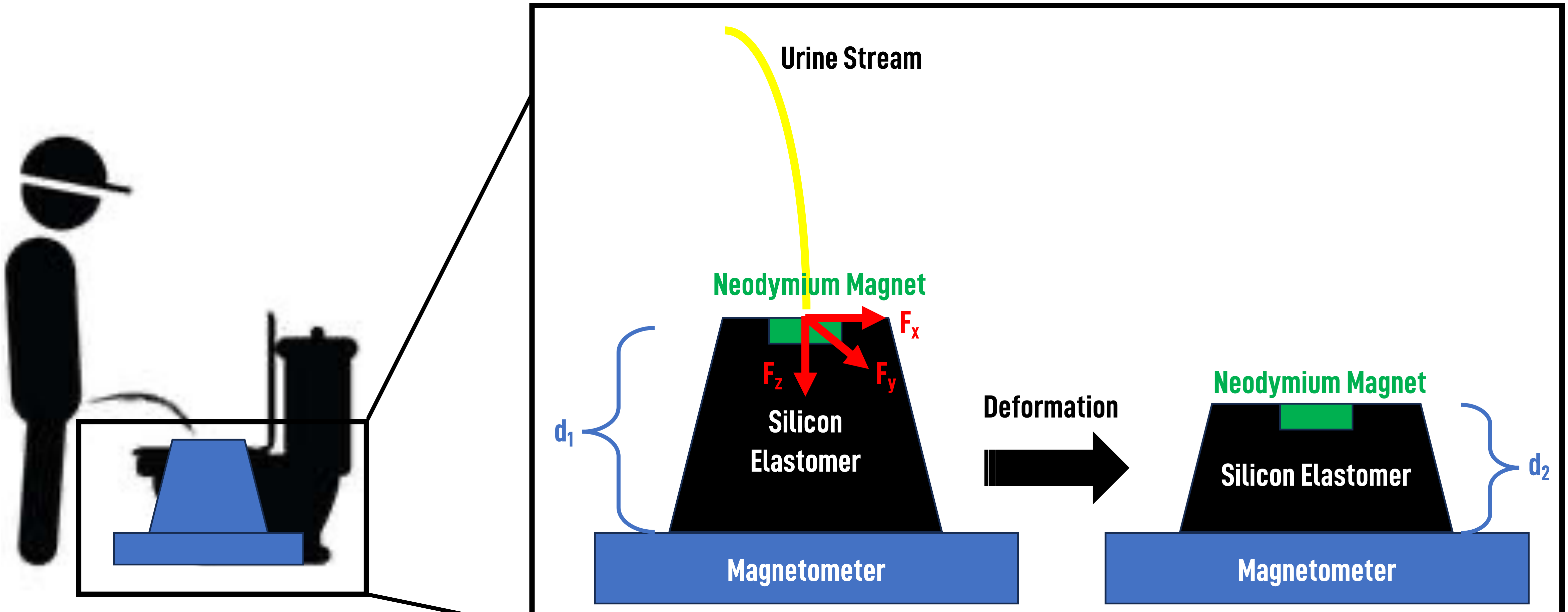
Introduction

- 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)

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

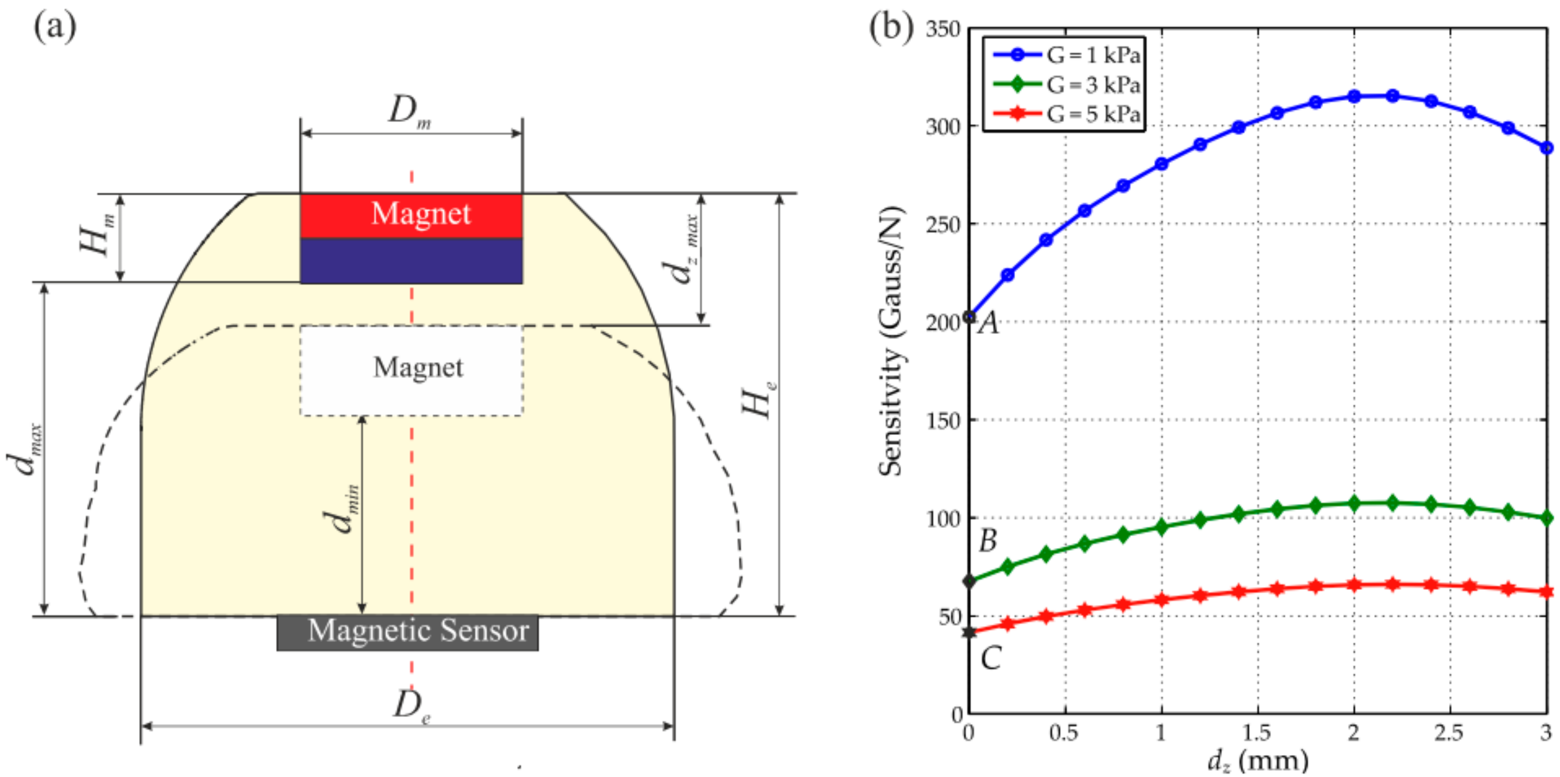


Figure 7. (**a**) The design parameters of the tactile sensor; (**b**) The sensitivity of the tactile sensor with different material properties (shear modulus G = 1, 3, 5 kPa). Points A–C indicate the point of lowest sensitivity for each material.

Manufacturing Process

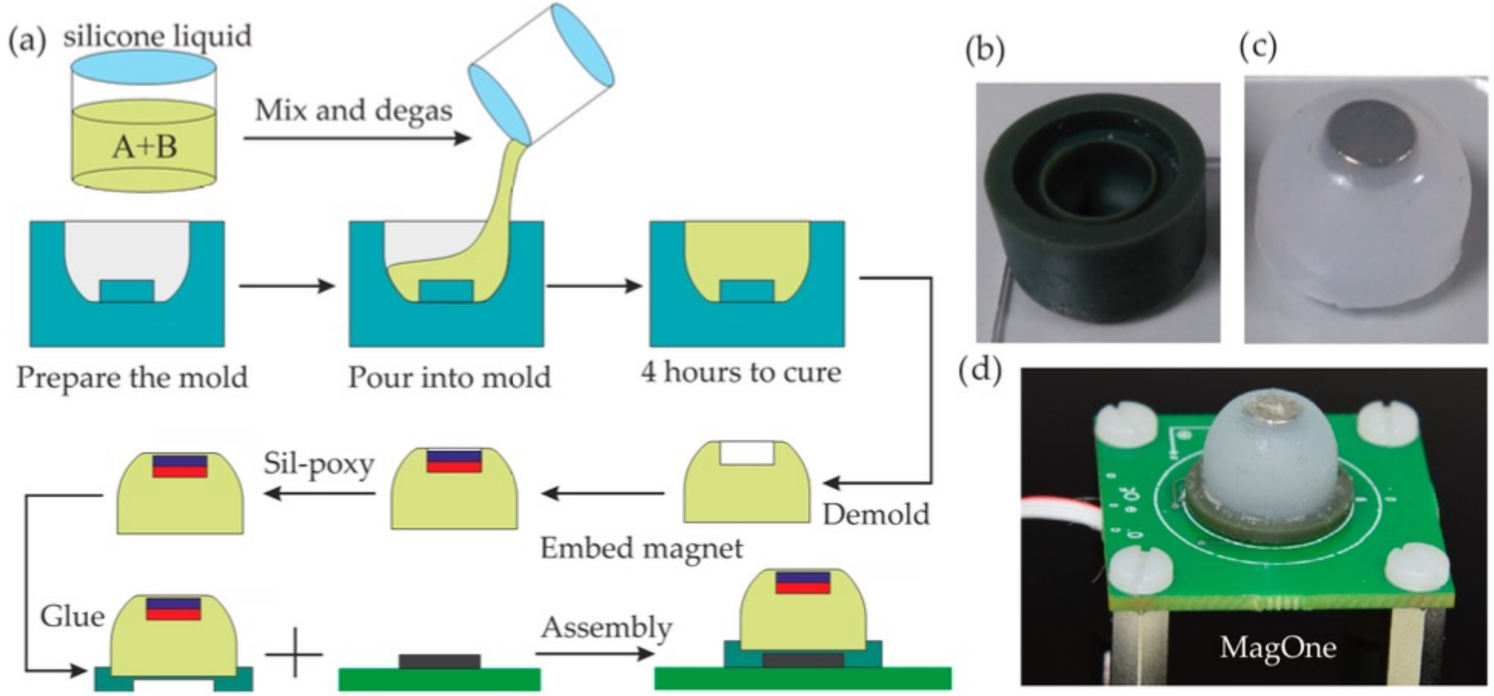
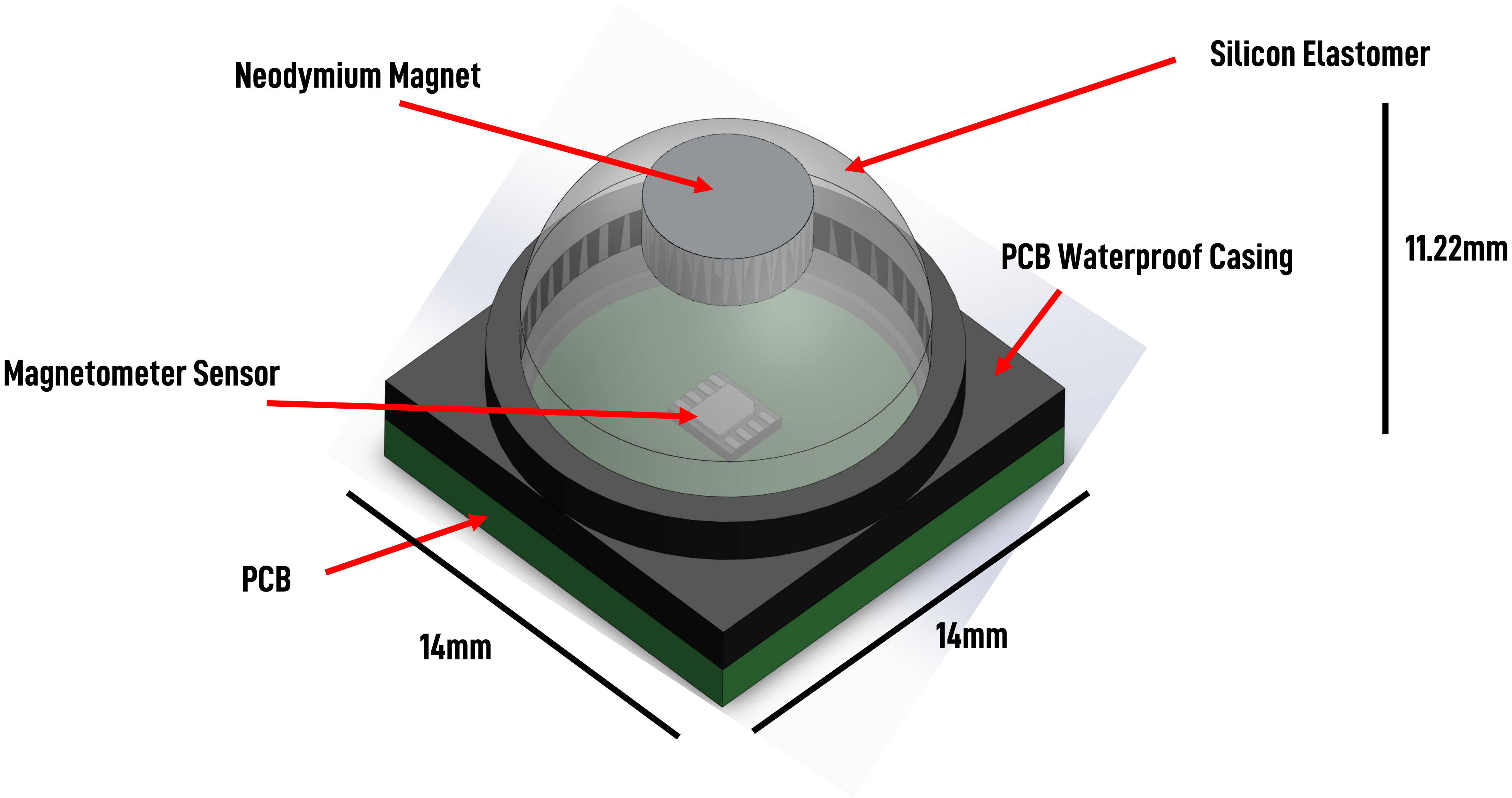


Figure 9. (**a**) Schematic of the fabrication process; (**b**) Photograph of the mould; (**c**) Photograph of the fabricated elastomer; (**d**) Photograph of the MagOne prototype.

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

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)

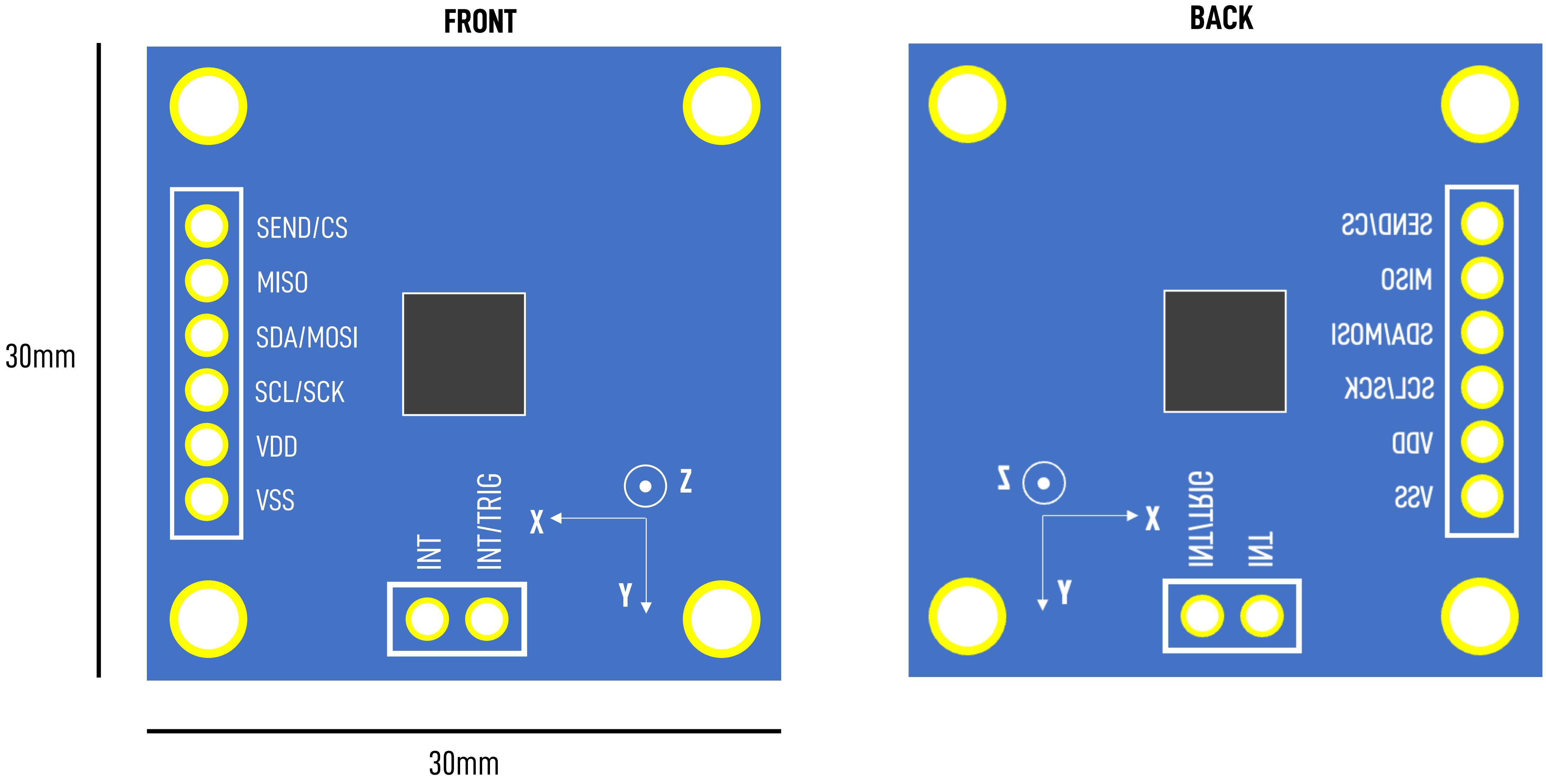
- Tilting of magnet can cause inaccuracies – can be mitigated with IMU MEMS sensor

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

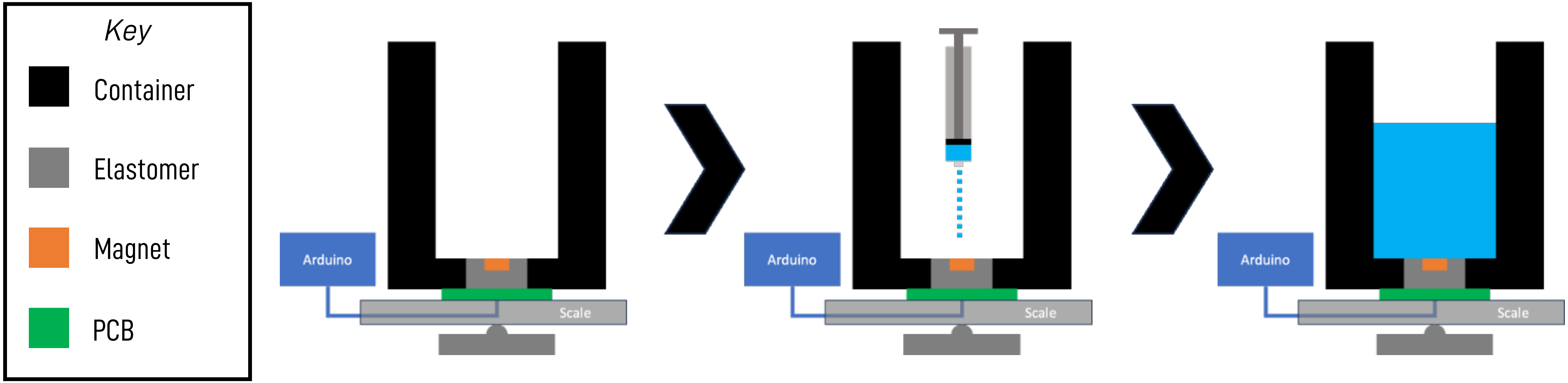
Total Cost of Materials: $74.80

Sensor Pinout



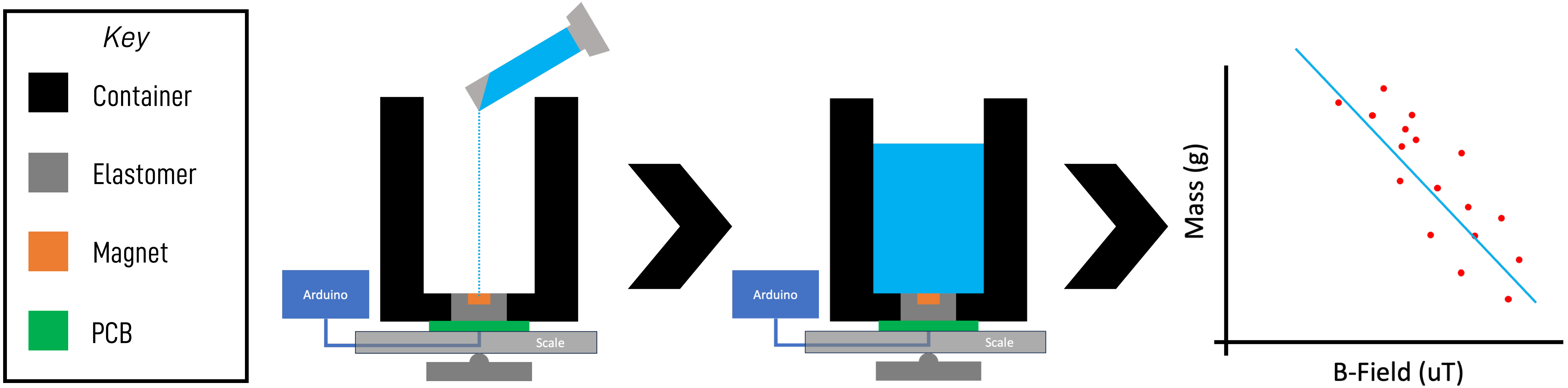
Static Water Calibration Procedure

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



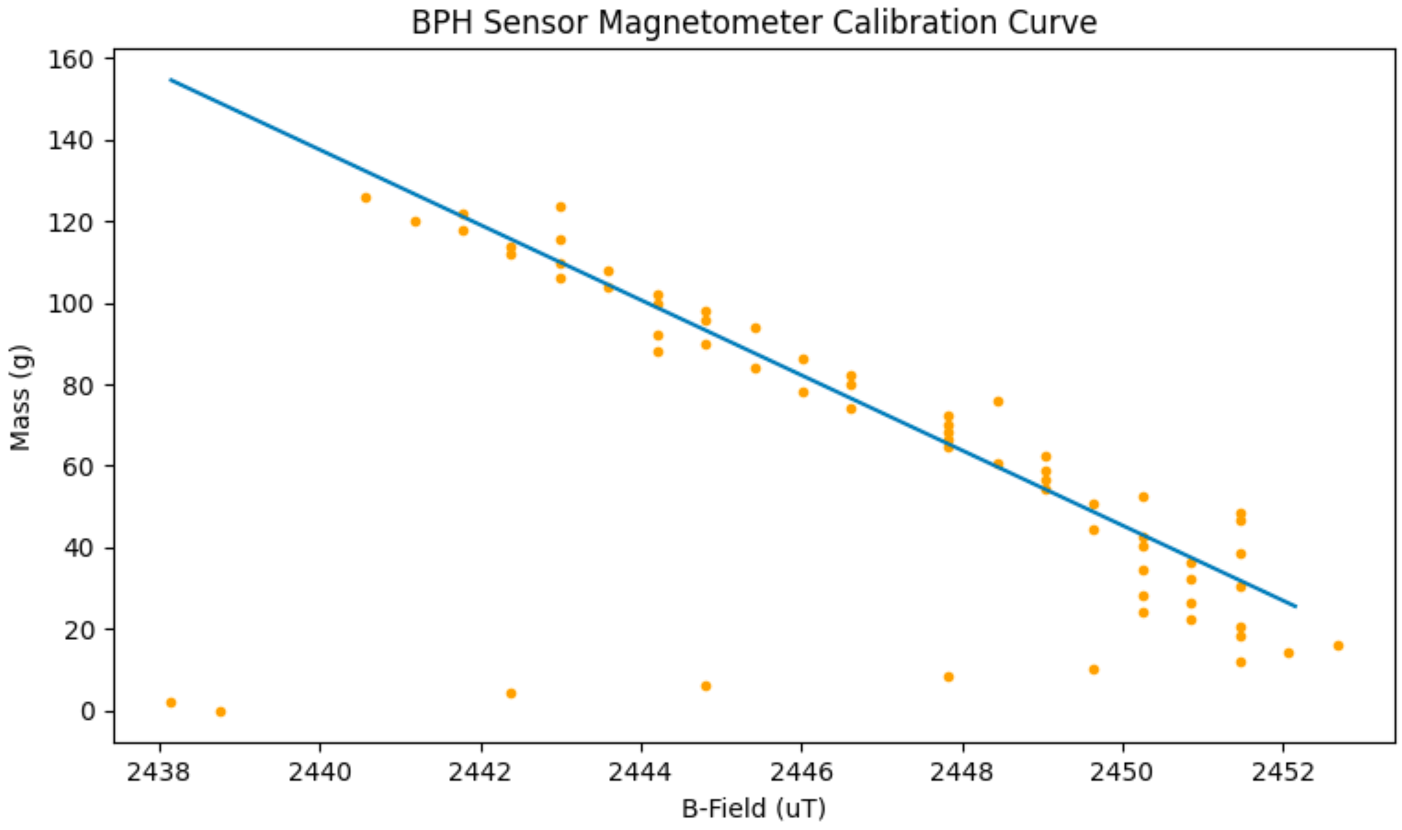
Static Water Test Procedure

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

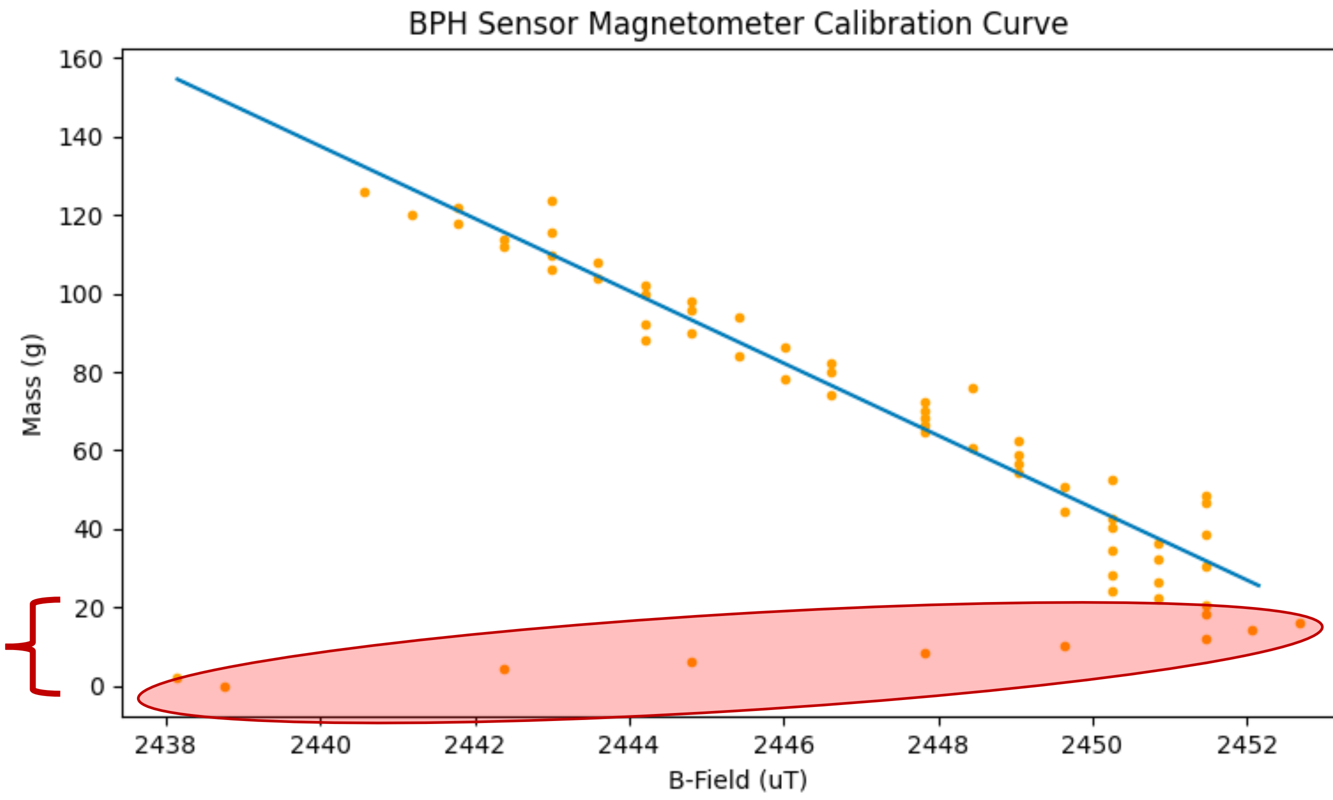
Calibration Results



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

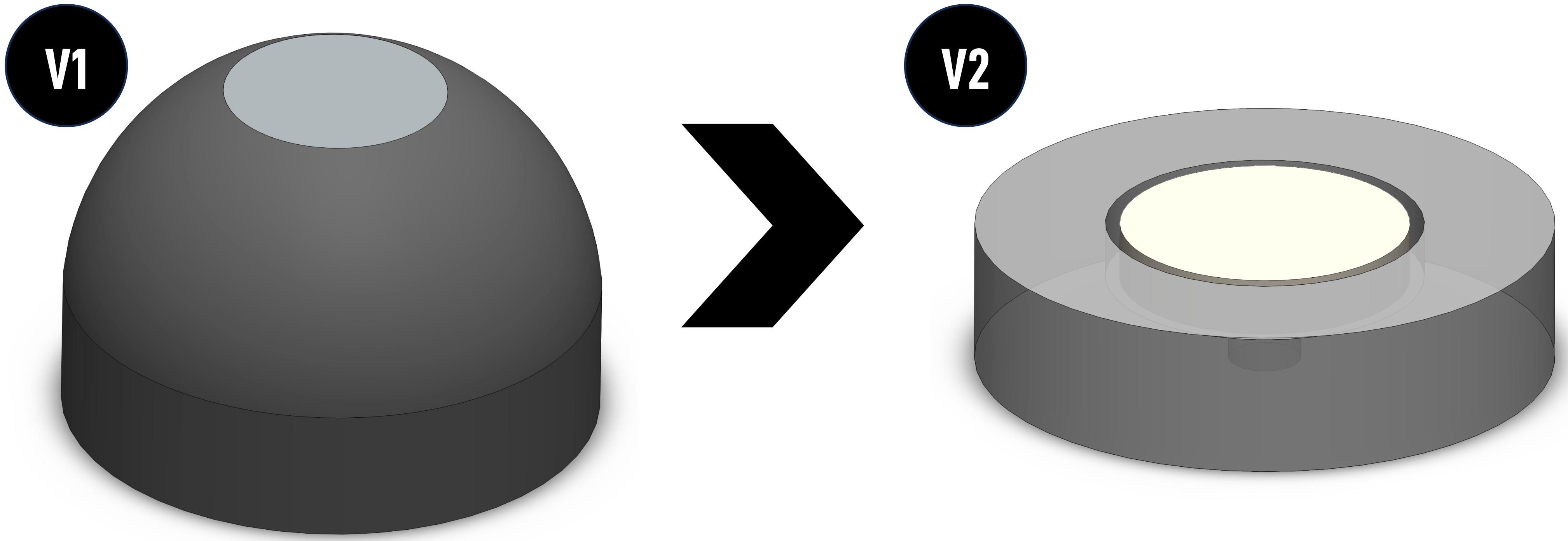
Discussion

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.



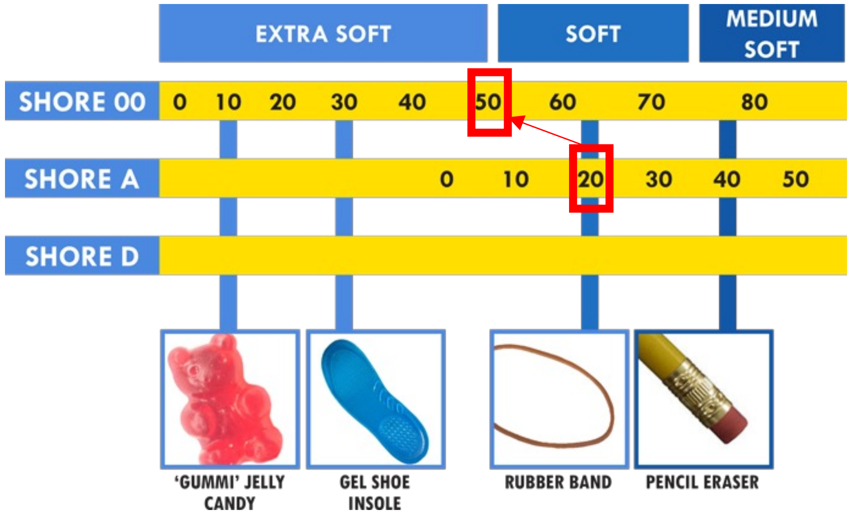
Discussion

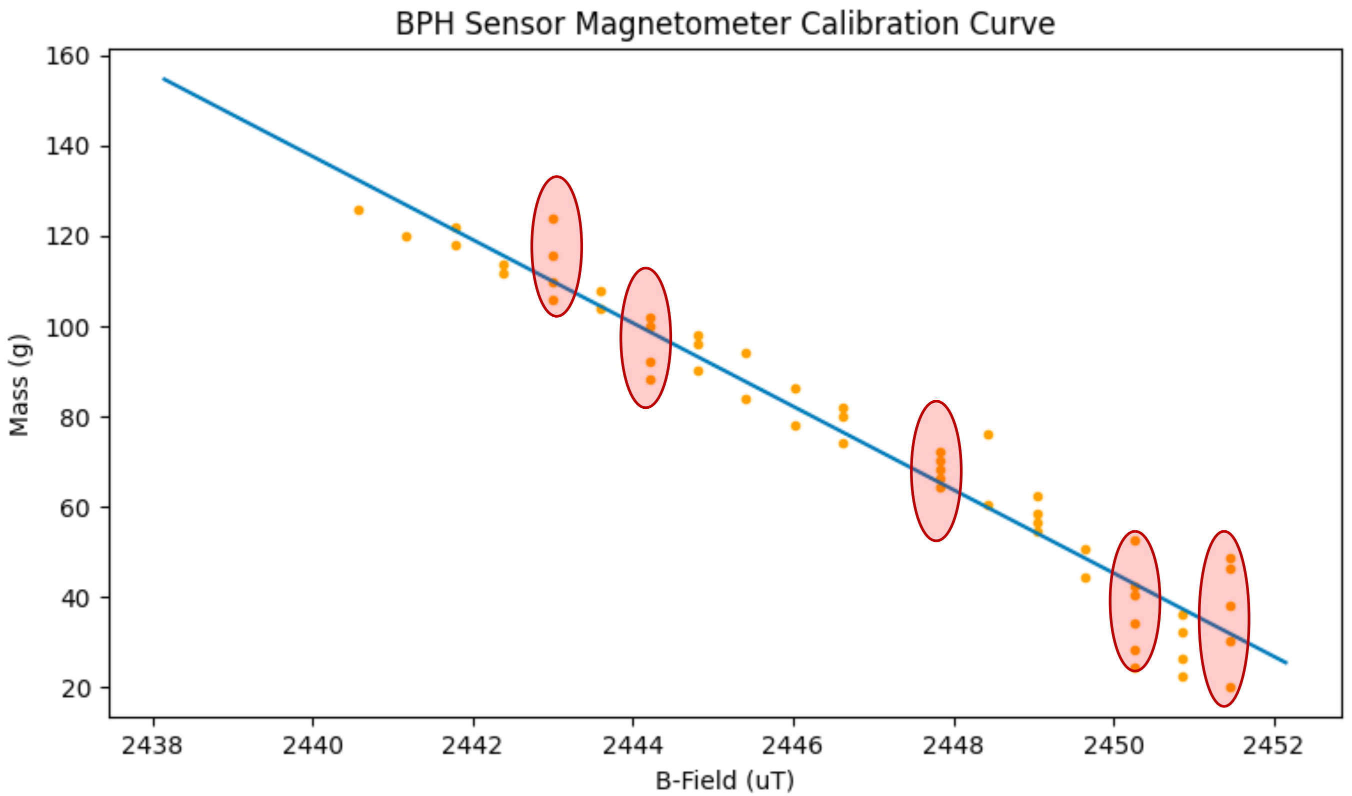
To solve this, I redesigned the elastomer geometry to be flush with the surface of the container.



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).

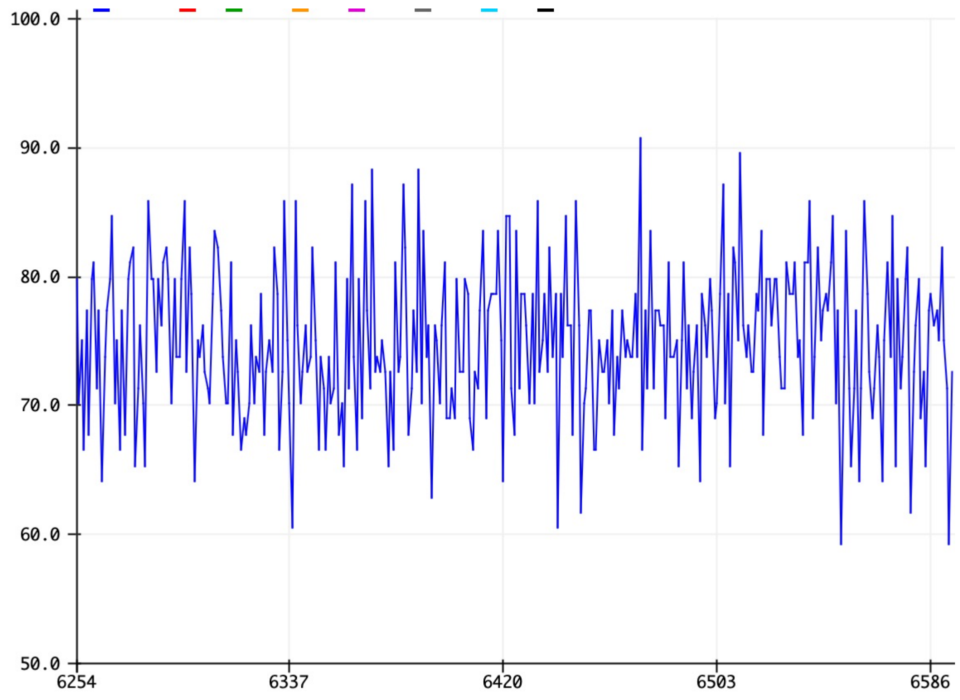




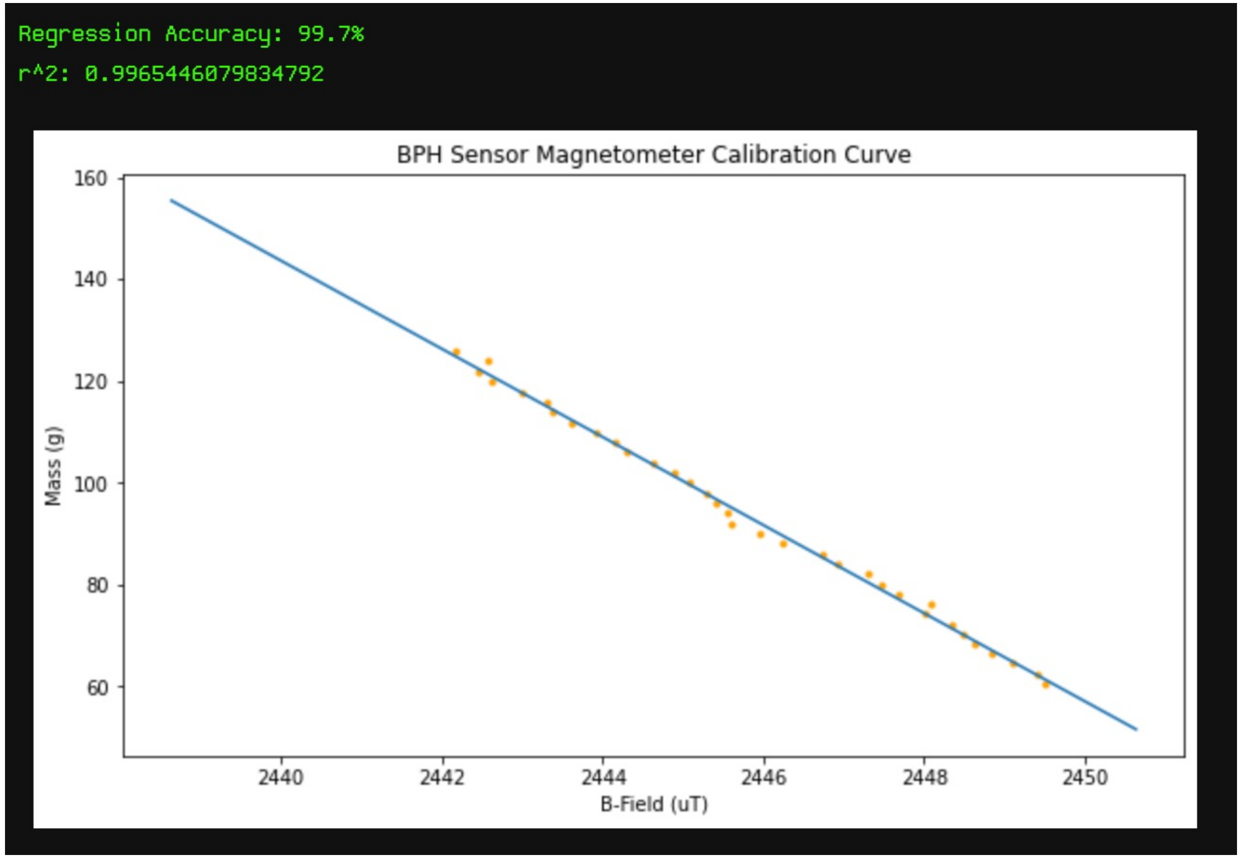
Discussion

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

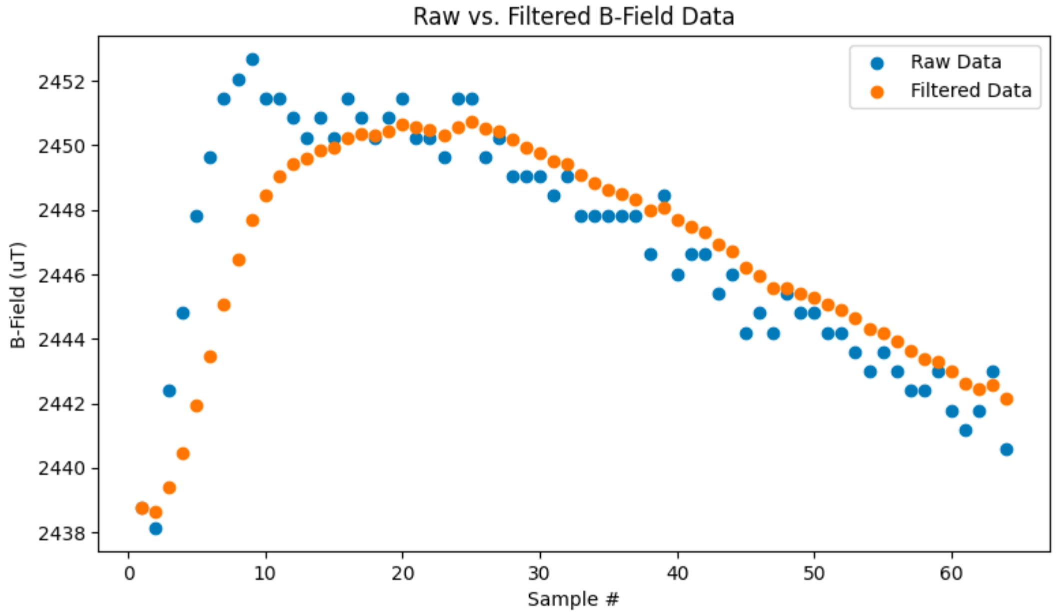


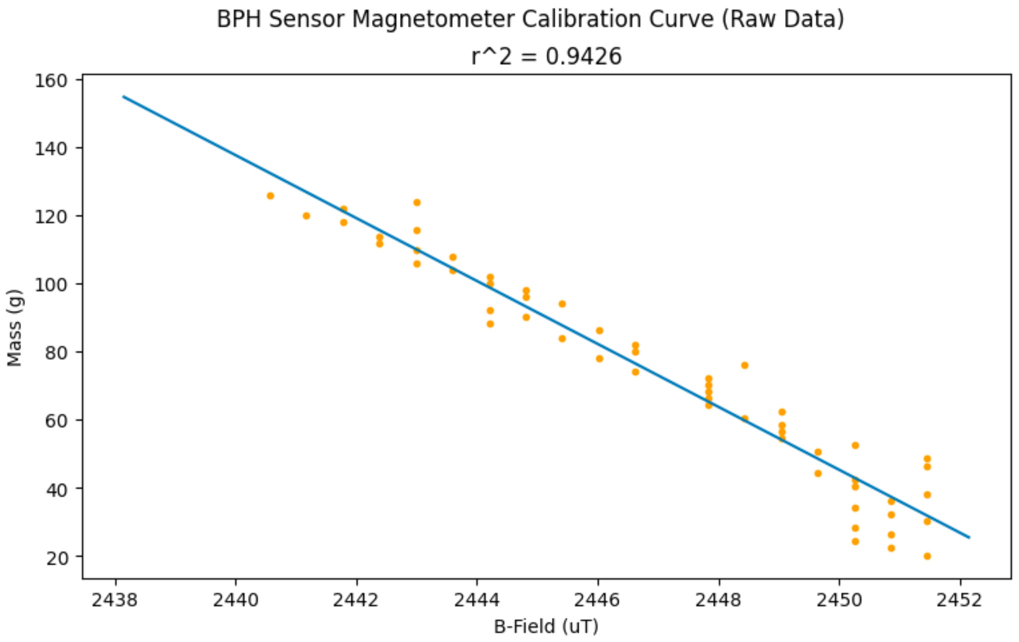
Cleaned Data

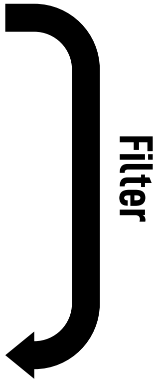


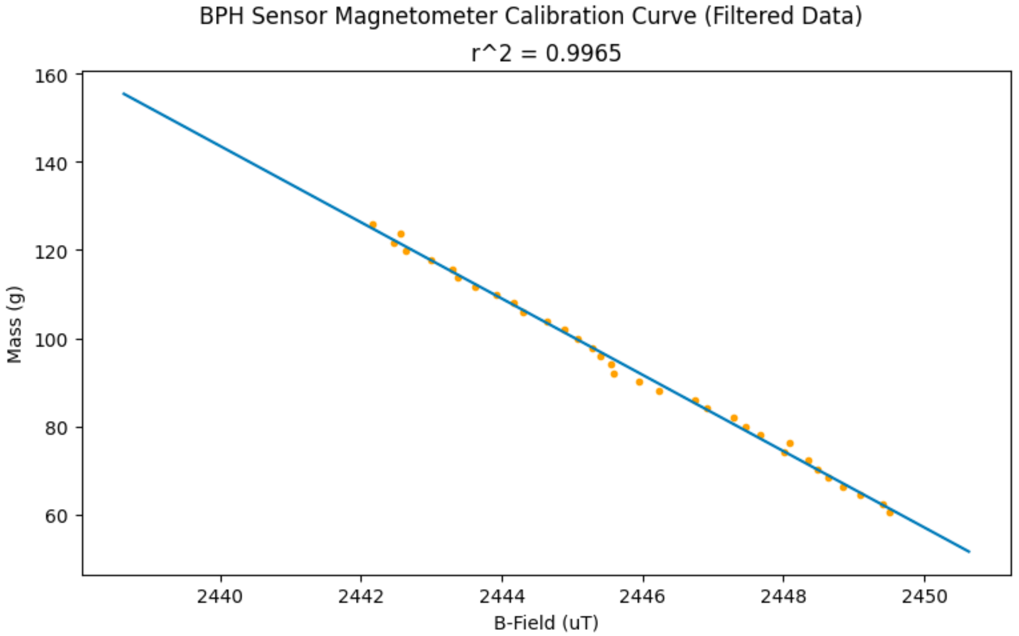
Exponential Moving Average Algorithm

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

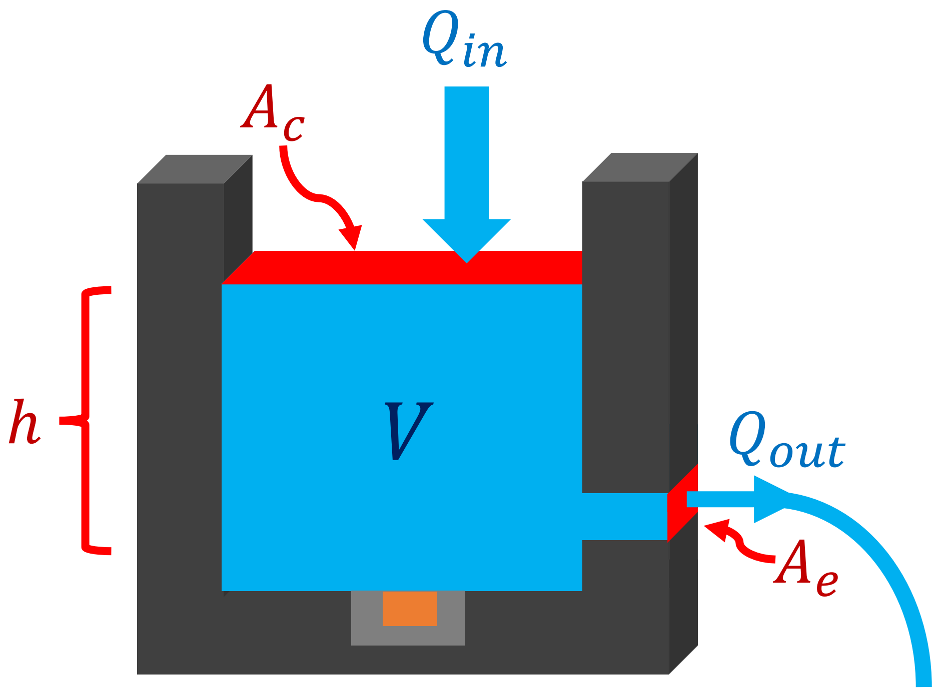








Dynamic Water Derivation



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

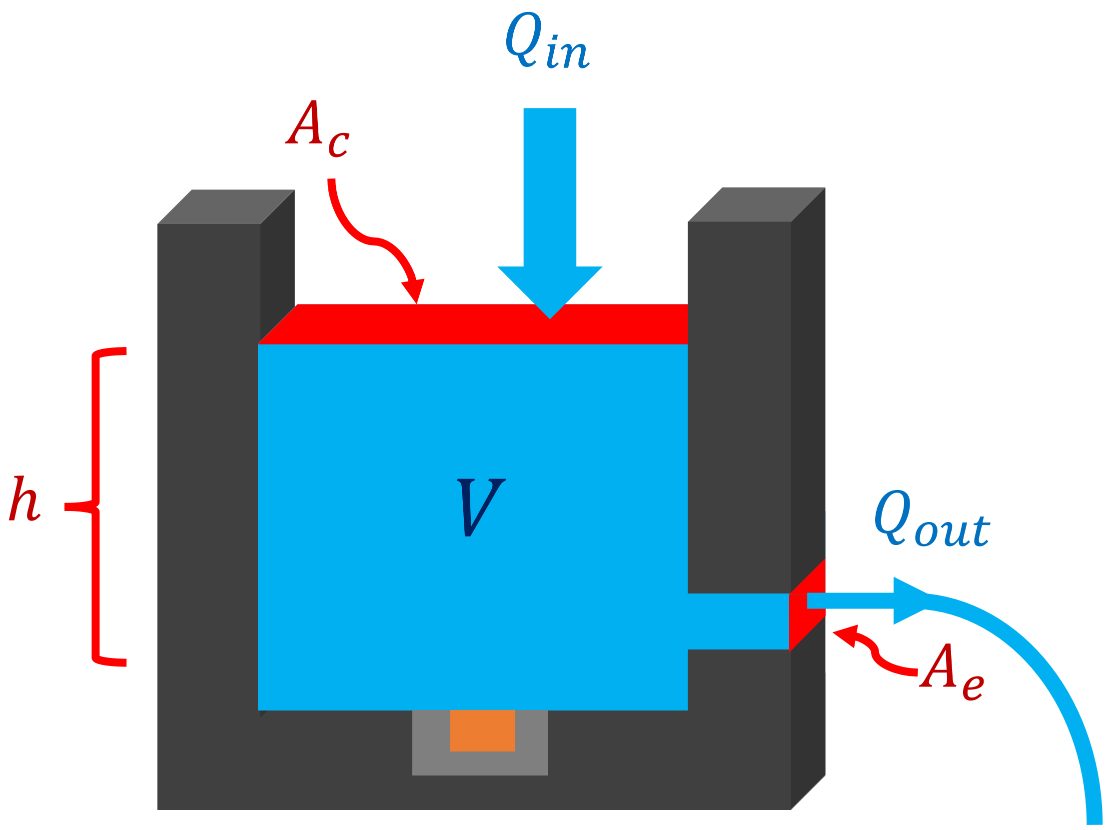
$\boldsymbol{A_c}$ $[\boldsymbol{mm^2}]$: chamber cross-sectional area

$\boldsymbol{A_e}$ $[\boldsymbol{mm^2}]$: 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:

$$Q_{out} = v_e A_e$$

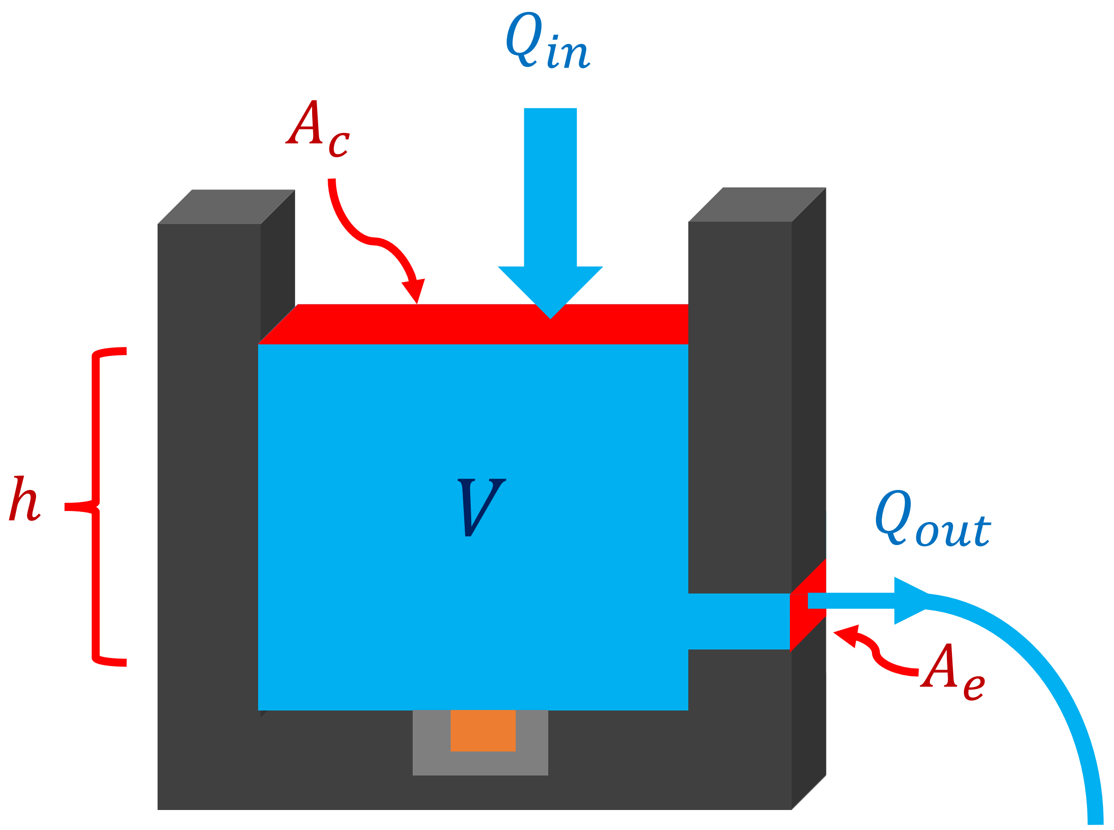
$$v_e = C_d\sqrt{2gh}$$

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

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

$\boldsymbol{v_e}$ $[\boldsymbol{m/s}]$: 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

Dynamic Water Derivation



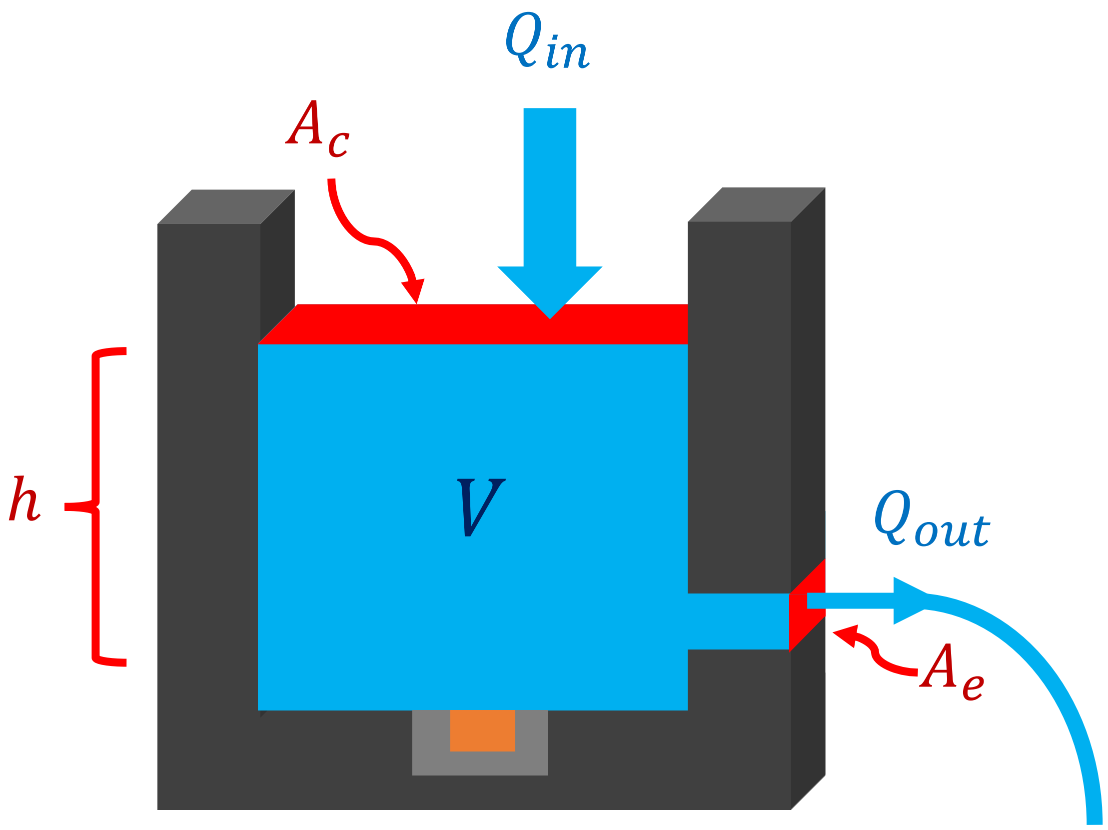
$$Q_{in} = \frac{dV}{dt} + Q_{out}$$

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 linear regression:

$$m = \alpha x + \beta$$

where m is mass in grams and x is the B-field in µT

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

$$h = \frac{m}{\rho A_c} = \frac{\alpha x + \beta}{\rho A_c}$$

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

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

Forward Finite Difference *O(h)*

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

Forward Finite Difference *O(h²)*

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

Backward Finite Difference *O(h)*

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

Backward Finite Difference *O(h²)*

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

Centered Finite Difference *O(h²)*

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

Centered Finite Difference *O(h⁴)*

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