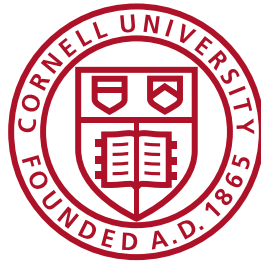


LOW-COST DEPTH SENSING MODULE FOR DEEP-WATER INSTRUMENTS



A Design Project Report Presented to
The School of Electrical and Computer Engineering of Cornell
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Submitted by: Nikolai Nekrutenko
M.Eng. Field Advisor: Dr. V. Hunter Adams, School of Electrical and
Computer Engineering of Cornell University
M.Eng. External Advisor: Jonathan Pfeifer, Woods Hole
Oceanographic Institution
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1 Abstract

Master of Engineering Program

School of Electrical and Computer Engineering

Cornell University

Design Project Report

Project Title: Low-Cost Depth Sensing Module For Deep-Water Instruments

Author: Nikolai Nekrutenko

Abstract: Deep-sea research requires sensors that work at great depths and are cost-effective. Current solutions that work at the required depths are either expensive or are inexpensive and limited in capability. This report presents the design, fabrication, and evaluation of a low-cost (\$50) depth sensor module capable of operating at pressures over 200 bar, equivalent to a depth of 2 km underwater. Developed in collaboration with the Woods Hole Oceanographic Institution, this novel depth sensor integrates a magnetic piston and Hall effect sensing system within a waterproof epoxy-potted chamber, interfaced with a Raspberry Pi Pico microcontroller. The sensor utilizes the compressibility of water to convert pressure changes into piston displacement, which is measured using Hall effect sensors. The prototype survived pressures beyond its 200 bar design target, with observed piston travel following a predictable pattern despite significant error compared to the theoretical values. This project demonstrates the feasibility of affordable modular depth sensors for oceanographic use, laying the foundation for future improvements such as calibration routines, integration with UAVs, and other sensor platforms/packages. This project offered an opportunity to bring physical modeling and engineering skills to a practical use case, allowing Woods Hole Oceanographic Institute (WHOI) research efforts to benefit from a cost-effective and easy-to-integrate depth sensor.

2 Executive Summary

This project presents the design and validation of a low-cost depth sensing module for deep-sea instruments, offering a pressure-tolerant, modular alternative to commercial depth sensors that cost 10–20× more. The system was developed in collaboration with the Woods Hole Oceanographic Institution to meet a 2,000-meter depth requirement while remaining affordable and mechanically simple.

The sensor uses a compressible water-filled cavity and a magnetically tracked piston, converting hydrostatic pressure into linear displacement. This displacement is measured by an array of Hall effect sensors, interfaced with a Raspberry Pi Pico microcontroller, and encapsulated in a waterproof epoxy-potted housing. All critical components were designed to be manufactured with basic tools and consumer-grade 3D printers.

Key accomplishments include: (1) deep-water survivability: the second prototype withstood 230 bar—exceeding the 200 bar design spec by 15%; (2) physical modeling accuracy: magnetic field simulations were fitted to Hall effect sensor data with $R^2 \geq 0.997$; (3) modular design: system components were separated into pressure-tolerant and pressure-equalized zones, simplifying packaging and improving reliability.

As an electrical engineer with a physics background, I applied analytical modeling, magnetic field simulation, and embedded system integration to produce a reliable sensor for real-world oceanographic use. While pressure-to-depth accuracy remains a challenge (with uncalibrated error ranging from –20% to 70%), post-processing routines and hardware refinements are already in development.

This work demonstrates the feasibility of a sub-\$60, reusable, and integrable depth sensor for scientific and autonomous underwater vehicles, with future improvements aimed at full RS-232 compliance, improved calibration, and UAV platform deployment.

Contents

1	Abstract	1
2	Executive Summary	2
3	Acknowledgments	4
4	Background	4
5	Requirements	5
6	Design	6
6.1	Physical Mechanism	6
6.1.1	Gas vs. Liquid-Based Approach	7
6.1.2	Translating Volume Changes into Linear Displacement	10
6.2	Electrical Design	12
6.2.1	Hall Effect Sensors	12
6.2.2	Analog to Digital Converters (ADCs)	16
6.2.3	Raspberry Pi Pico Interfacing	17
6.2.4	Estimated Power Consumption	19
6.3	Mechanical Design	20
6.3.1	Sensor Package	21
6.3.2	Magnetic Piston	22
6.3.3	99% Volume Cavity	23
7	Methods & Results	25
7.1	Fitting Magnet Position to ADC Values	26
7.2	Pressure Testing	28
7.3	Pressure & Depth Results	32
8	Conclusion	37
9	References	39
10	Appendix	40
10.1	Bill of Materials	40
10.2	Derivations	42
10.2.1	Variable Definitions & Constants	42
10.2.2	Pressure-Displacement Relationship Derivation	42
10.2.3	Depth-Displacement Relationship Derivation	43

3 Acknowledgments

I would like to thank Dr. V. Hunter Adams and Jonathan Pfeifer for being excellent mentors in guiding me, transforming this project from a mere idea into a sensor that worked and can be deployed in the field with future prototypes. Additionally, I would like to thank the WHOI building operations director, Justin Ossolinski, for his time and use of facilities to help with the project. Last but not least, thank you to the Cornell Maker Club and the MAE Drone Studio for allowing me to use their 3D printers and materials.

4 Background

Underwater sensing presents complex challenges, from ensuring that instruments are watertight to designing systems that can withstand hydrostatic pressures hundreds of times greater than atmospheric pressure. Woods Hole Oceanographic Institution (WHOI), a leader in marine science research and engineering, frequently operates in deep-ocean environments using a range of underwater vehicles and instruments. Depth measurements are critical for WHOI's work, enabling the collection of depth-resolved oceanographic data and reliable deployment of sensors and payloads [1].

Several commercial depth sensors are currently available, for instance from manufacturers such as Keller, TE Connectivity, and RBR. These devices often rely on piezoresistive or resonant pressure-sensing elements housed in titanium or stainless steel enclosures, and many offer precision on the order of centimeters even at full-scale ranges of 2000 meters or more [2, 3, 4]. However, such high-performance sensors are often priced well above \$1000 per unit, which limits their use in fleet deployments, expendable payloads, or academic settings with constrained budgets. In addition, many of these sensors are closed systems with proprietary communication protocols, making integration with custom UAV platforms more difficult.

On the opposite end of the spectrum, low-cost sensors such as the MS5837 series (by TE) or barometric sensors such as the BMP388 offer easy integration and affordability (under \$50), but are generally limited to shallow water applications (typically less than 30 meters) and lack the mechanical robustness to withstand high pressures encountered in deep-sea environments [5]. This leaves a clear market gap: there is a lack of pressure-tolerant and cost-effective depth sensors with open integration standards suitable for interme-

diate depths (500–2000 meters), which would be valuable for institutions like WHOI and others engaged in distributed or exploratory deployments.

This project aims to address the inexpensive yet great depth sensing gap by developing a pressure-based depth sensor that balances performance, durability, and affordability. The primary motivation is to provide a reliable, cost-effective alternative to expensive commercial solutions by leveraging inexpensive sensing solutions and a microcontroller-based acquisition system. A secondary motivation is to explore the use of a simple physical principle: the relationship between hydrostatic pressure and depth as the foundation for a practical, extremely simple sensing approach. By combining these principles, the resulting depth sensor is intended to be compact, modular, and adaptable for integration into a wide range of submersible platforms, whether as a primary or backup depth sensor. With a target depth rating of 2000 meters and an accuracy on the order of ± 10 meters, the design meets the needs of many operational and research deployments that do not require extreme precision but demand robustness and reliability.

5 Requirements

The following requirements were defined in consultation with advisors Jonathan Pfeifer and Dr. V. Hunter Adams. They represent the target specifications necessary for feasible integration with WHOI instrumentation and underwater autonomous vehicles (UAVs).

Table 1: Sensor requirements

Parameter	Specification
<i>Performance</i>	
Maximum Depth	2,000 m
Pressure Rating	200 bar
Accuracy	± 10 m
<i>Electrical</i>	
Power Input	5–24 V, ≤ 100 mA
Data Protocol	RS-232
<i>Mechanical / Interface</i>	
Physical Size	Soda can to Nalgene bottle
Connector Type	MacArtney SubConn
Mounting Method	Hose clamps, bolts, etc.

As is evident from Table 1 above, the sensor must be capable of operating reliably at depths up to 2,000 meters (200 bar), while accepting a wide input voltage range commonly used across WHOI platforms and consuming no more than 100 mA. It must communicate via the RS-232 protocol, conform to a compact cylindrical form factor (approximately the size of a soda can or Nalgene bottle), and employ a waterproof MacArtney SubConn connector for electrical interfacing. The system should achieve an accuracy of ± 10 m across the full operating range and feature accessible mounting points to support flexible attachment methods, such as bolts, zip-ties, or hose clamps, on a variety of UAVs.

6 Design

The design of the sensor will be broken up into three main parts: The physical mechanism, the electrical, and mechanical design of the sensor.

6.1 Physical Mechanism

For the design of this depth sensor, several physical mechanisms were considered to translate pressure or depth into a measurable signal. These ideas can be broadly categorized as follows:

- **Mechanical Deformation**

- Deflection of a diaphragm, membrane, or beam under pressure.
- Use of a strain gauge or load cell to quantify deformation.
- Angular deflection of a mechanical lever or mirror under stress.

- **Fluid Compression and Response**

- Boyle’s Law-based compression of air in a vertical or sealed tube.
- Measuring volume or diameter changes in a compressible fluid-filled object.
- Monitoring fluid column height in a partially filled cavity.

- **Electrical and Acoustic Properties**

- Changes in resistance of a compressible or conductive fluid.
- Shifts in resonance frequency of piezoelectric or quartz elements.
- Measuring speed of sound through a compressible medium.

- **Optical Techniques**

- Optical distortion of a lens or viewing system under pressure.
- Laser or optical lever displacement measurement.

- **Chemical and Biochemical Responses**

- Change in solubility of salts or gases (e.g., CO_2) tracked via pH or conductivity.
- Gas dissolution in fluid mimicking nitrogen absorption in blood.

6.1.1 Gas vs. Liquid-Based Approach

Ultimately, a design was chosen that leverages one of the simpler yet elegant physical principles considered: the slight compressibility of liquids such as water. This property provides a robust basis for depth sensing.

Initially, we explored the use of air or other gases as the working medium, relying on their high compressibility to produce measurable volume changes

with increasing pressure. Gases follow Boyle's law, which predicts a nonlinear but substantial decrease in volume under pressure:

$$P_1 V_1 = P_0 V_0$$

At a depth of 2000 meters, the pressure increases by approximately 200 bar. This corresponds to:

$$\frac{V_1}{V_0} = \frac{P_0}{P_1} = \frac{1}{200} = 0.005$$

indicating a 99.5% decrease in volume. While highly sensitive at shallow depths, this approach rapidly loses resolution with depth due to the inverse relationship and the second derivative being positive as shown in Figure 1. Additionally, gas-based systems suffer from temperature sensitivity and require perfect sealing, making them less reliable in deep-sea environments.

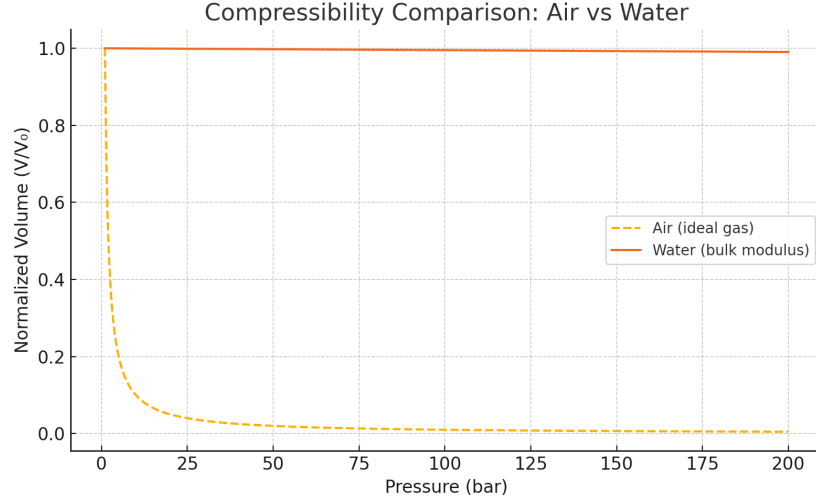


Figure 1: Comparison of volume response to pressure for air (ideal gas) and water (based on bulk modulus). Air compresses significantly at shallow depths, while water compresses very slightly but linearly across the full range.

In contrast, liquids such as water exhibit a low but consistent compressibility governed by the bulk modulus:

$$K = -V \frac{dP}{dV}$$

This relationship implies a linear response to pressure change, which is highly favorable for sensing. Though the total volumetric change is small, it is stable and repeatable. For instance, at a depth of 2000 meters (corresponding to $\Delta P = 2 \times 10^7$ Pa), we calculate:

Distilled Water:

$$\frac{\Delta V}{V_0} = -\frac{\Delta P}{K} = -\frac{2.00 \times 10^7}{2.09 \times 10^9} = -0.0095 \Rightarrow 0.952\% \text{ decrease}$$

Ethyl Alcohol:

$$\frac{\Delta V}{V_0} = -\frac{\Delta P}{K} = -\frac{2.00 \times 10^7}{1.07 \times 10^9} = -0.0186 \Rightarrow 1.86\% \text{ decrease}$$

These values are small, but linearly scale with pressure—offering a reliable physical mechanism for depth sensing. Additionally, since water is already present in the environment, and can be accessed from any water source, this makes the sensor much more accessible and feasible to use.

Table 2: Bulk modulus of several liquids

Liquid	Bulk Modulus (Pa)
Helium-4 (liquid)	2.5×10^7
Methanol	8.23×10^8
Acetone	9.20×10^8
Ethyl Alcohol	1.07×10^9
Water (distilled)	2.09×10^9
Sea Water	2.34×10^9
Mercury	2.85×10^{10}

While other liquids such as ethyl alcohol and methanol offer higher compressibility, their volatility, toxicity, or incompatibility with marine environments made them less practical. Liquid helium, though extremely compressible, is cryogenic and thus infeasible for field deployment. Water offers a favorable balance of linear response, allowing translating volume changes to depth straightforward and feasible. Since water is readily available, and this mechanism is simple, it is well-suited for deployment aboard WHOI's underwater platforms.

6.1.2 Translating Volume Changes into Linear Displacement

Water compresses by approximately 1% at a depth of 2 km (200 bar), based on its bulk modulus. Since my background is in electrical engineering with an undergraduate physics background and not a mechanical engineering, and for the sake of simplicity, an approach that minimizes the number of parts that are pressure-sensitive was followed.

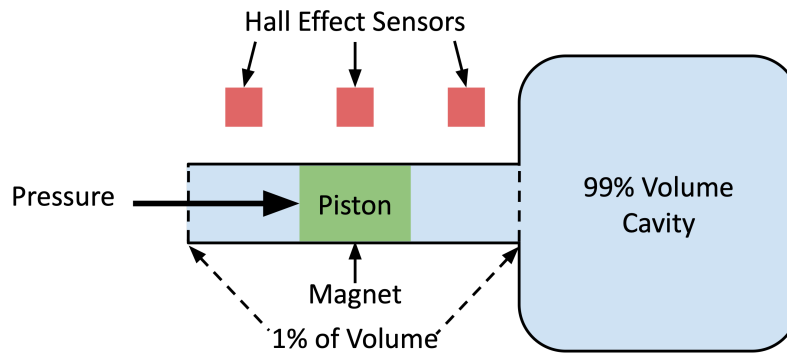


Figure 2: Diagram of physical mechanism. The magnetic piston travels over a 1% volume change

As shown by Figure 2 above, a simplified linear encoder was developed that is sensitive across the 1% pressure difference range. The sensor cavity and cylinder where the piston is located are filled with water. The decrease in volume of water to the right of the piston caused by hydrostatic pressure as a result of the depth acting on the left of the piston creates a measurable linear displacement that linearly correlates to the depth of the sensor. As the piston is magnetic, its position is determined non-invasively by Hall effect sensors.



Figure 3: 4 mm x 12 mm N48 cylindrical magnet as used in the magnetic piston. Penny shown for scale

The first choice that had to be made in this design, then, is the particular kind of magnet used. Since the magnetic field is measured with Hall effect sensors, and the cheapest sensors are usually the least sensitive, the strongest magnet should be used. Thus, neodymium magnets are the only viable choice, in particular a cylindrical magnet with maximum height and minimum diameter. This is vital as it maximizes the linear travel across the entire depth range as the magnetic field changes are detected along the height of the magnet. Ultimately, a 4 mm x 12 mm N48 cylindrical magnet, as shown in Figure 3 was used as this had the best height to diameter ratio that was found on the magnetic market.

The use of Hall effect sensors enables the position of the piston to be measured wirelessly. Only the Hall effect sensors along with the rest of the electronics hardware needs to be placed in a water and pressure-resistant package. The rest of the sensor, while still subjected to pressure, has the pressure equally distributed on the inside and outside since it is equalized from the movement of the piston. Thus, the cavity and cylinder along which the piston travels only need to be designed to survive the pressure difference due to static friction caused by the piston inside the cylinder, which is several orders of magnitude less than the 200 bar environmental pressure. This enables low-cost materials to be used.

6.2 Electrical Design

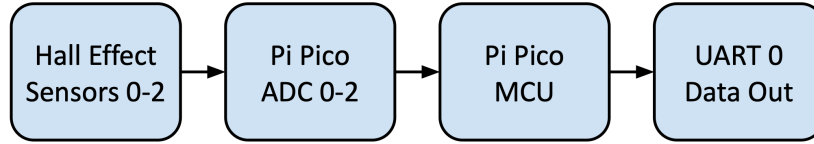


Figure 4: Electrical system diagram

As shown by Figure 4 above, this sensor is made up of Hall effect sensors, the onboard Raspberry Pi Pico analog-to-digital converters (ADCs), and the Pico itself. The Hall effect sensor outputs a voltage proportional to the magnetic field sensed, the ADCs convert the analog voltage from the Hall effect sensors into a digital signal, which is then interpreted and sent by the Pi Pico using the UART 0 port over wires that interface with the MacArtney SubConn connector. Solid-core wires rather than braided wire was used to connect to the MacArtney SubConn connector. Braided wire can act like a candle wick and allow pressurized water to make it to the electronics, bypassing the whole package.

6.2.1 Hall Effect Sensors

Hall effect sensors translate the magnetic field magnitude to an analog voltage as follows: a fixed direct bias current is applied along one axis across a thin metal strip. Sensing electrodes positioned on opposite sides of the Hall element along another axis measure the voltage difference across the axis of the electrodes. The charge carriers of the current are deflected by the Lorentz force in the presence of a magnetic field perpendicular to their direction of motion. The sensing electrodes measure the potential difference (Hall voltage) that is directly proportional to the axial component of the magnetic field that is perpendicular to both the current's axis and the sensing electrode's axis [6].

It is important to note that Hall effect sensors are capable of detecting both static and changing magnetic fields. In the case of this project, the magnetic field is static since the magnet itself is barely moving at any appreciable velocity since the piston travels a few cm over the whole 2 km depth range.

To determine the Hall effect sensor to be used, the magnetic field of the 4 mm diameter by 12 mm high N48 cylindrical magnet was simulated using the magpylib package [7] as shown in Figure 5 below.

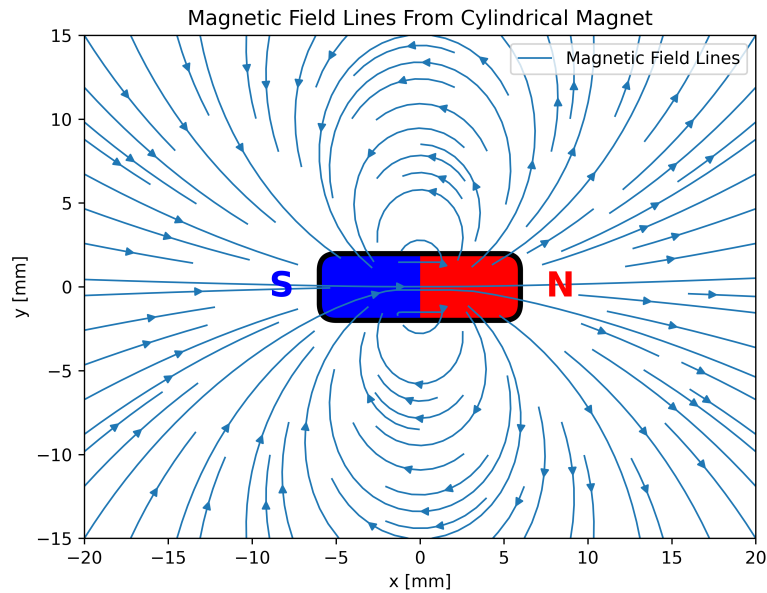


Figure 5: Simulated magnetic field lines from 4 mm diameter by 12 mm high N48 cylindrical magnet using magpylib package

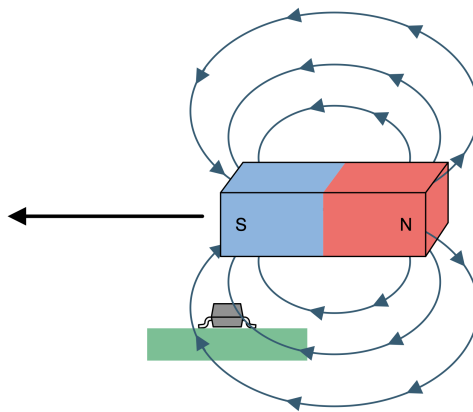


Figure 6: Hall effect sensor use-case

Only the magnetic field strength along the axis normal to the displacement of the magnet is simulated as Hall effect sensors are only sensitive along a single axis. In the figure above, this is the y-axis since the magnet travels along the x-axis. The results of the simulation of B_y while changing the x-axis position of the magnet are shown in Figure 7 below.

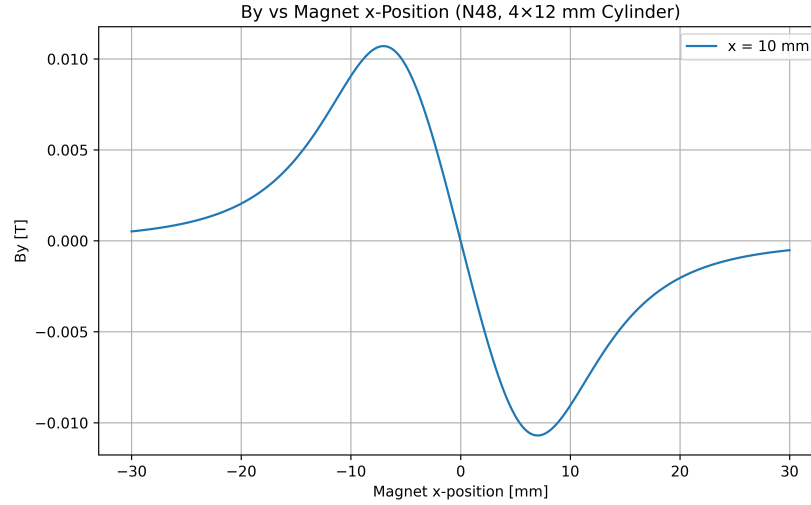


Figure 7: Simulation of B_y (y-axis component of magnetic field) while varying magnet position at a distance of 10 cm from the magnet using the magpylib package

As shown in Figure 7 above, the 10 cm distance between the simulated point and the center of the magnet was used as a realistic benchmark since the piston, cylinder, sensor housing, and epoxy itself will be between the magnet and Hall effect sensor as indicated in the Mechanical Design section.

From the simulation, we see that the magnetic field ranges from approximately 0.010 T at -6 mm to -0.010 T at 6 mm. This works nicely with the DRV5055A1QDBZR Hall effect sensor by Texas Instruments that has a sensitivity of 100mV/mT [8]. This sensor has the following relationship between B (magnetic field in Tesla), 3.3 (power supply voltage), and V_{out} (sensor output voltage):

$$V_{out} = 100B + \frac{3.3}{2}$$

Thus, the sensor output theoretically ranges from 0.6 V to 2.7 V. Al-

though not quite the 0-3.3 V range that the Pi Pico ADC can accept, this covers 60% of that range.

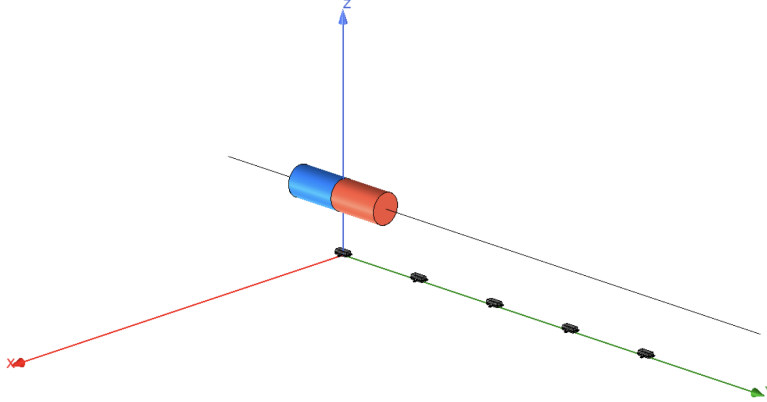


Figure 8: Linear encoder setup [9]

Three of the same model of Hall effect sensors (DRV5055A1QDBZR) in the SOT-23 package were used for the corresponding three integrated ADCs on the Pi Pico to create a linear encoder [9] with the Hall effect sensor being spaced an line, with a magnet distance between each, similar to what is shown in Figure 8. This is done because the largest signal amplitude occurs at both ends of the magnet and the pattern in-between is mostly linear. This spacing produces the following expected result in output signals for each ADC channel in Figure 9 below.

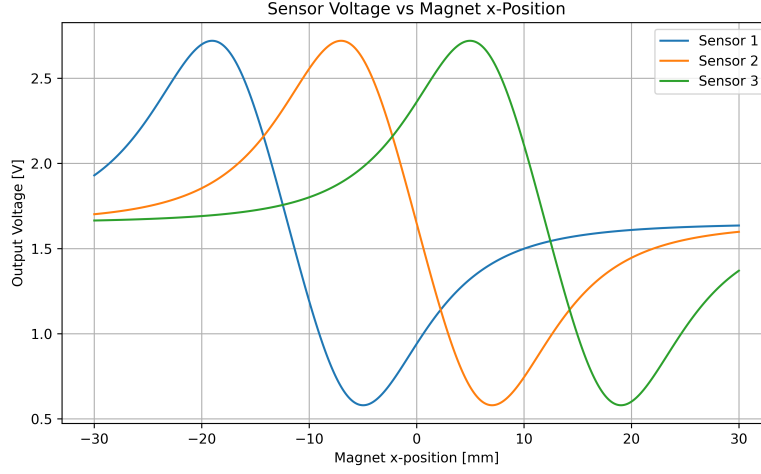


Figure 9: Expected response from three Hall effect sensors across magnet’s range of motion

6.2.2 Analog to Digital Converters (ADCs)

Since the Hall effect sensors output an analog signal (voltage) proportional to the magnetic field, these values need to be converted into digital values to be used with the Pi Pico. This is done with the three integrated ADCs in the Pi Pico.

The Pico ADCs offer 12 bits of resolution, or $2^{12} = 4096$ values from 0 V to 3.3 V. They are far from ideal, suffering from a substantial amount of noise. Specifically, the Pico ADC has an effective resolution of 9 bits, and the lower 3 bits are all noise [10]. However, since the depth sensor will operate under long time scales on the order of hours or days, simple averaging across multiple samples can help recover some of the lost precision by reducing random noise. The effective number of bits (ENOB) increases by half a bit for every quadrupling of the number of averaged samples as shown in Table 3:

$$\text{ENOB}_{\text{avg}} = \text{ENOB}_{\text{raw}} + \frac{1}{2} \log_2(N)$$

Table 3: Effective number of bits (ENOB) with averaging

Samples Averaged	ENOB Gain (bits)	Total ENOB
1	0.00	9.00
4	1.00	10.00
16	2.00	11.00
64	3.00	12.00
256	4.00	13.00
1024	5.00	14.00

Thus, if the sensor is not meeting the accuracy spec with just the 9 effective ADC bits, accuracy can be further improved by implementing averaging. To determine whether or not we need averaging, the resolution of the sensor is computed. At a distance of 10 cm from the Hall effect sensor and the center of the magnet, the voltage ranges from 0.6V to 2.7V, meaning there are this many discrete, effective ADC values:

$$N_{ADC} = 2^9 \cdot \frac{2.7V - 0.6V}{3.3V} = 326 \text{ discrete values per ADC}$$

Since there are 3 ADCs, this equates to:

$$3N_{ADC} = 326 \text{ discrete values per ADC} \cdot 3 = 978 \text{ discrete values}$$

These three ADCs are spaced across the entire range of the 2 km depth spec, thus the resolution in meters can be calculated:

$$\text{Sensor resolution} = \frac{2000\text{m}}{978} \approx 2.04\text{m}$$

This resolution is sufficient as it is an order of magnitude less than the +/- 10m spec. Therefore, averaging ADC values is not necessary for the purpose of improving resolution, but could perhaps be done so every 4 or 16 samples to improve noise if needed.

6.2.3 Raspberry Pi Pico Interfacing

Due to the simple nature of the design and the use of the Pico's onboard ADCs, it was relatively straightforward to wire everything together.

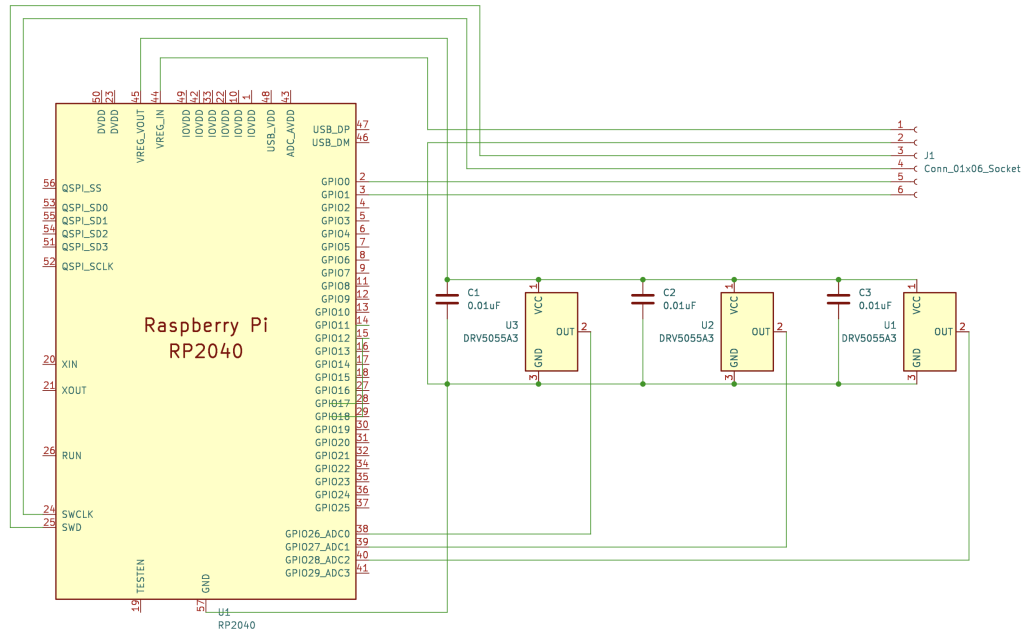
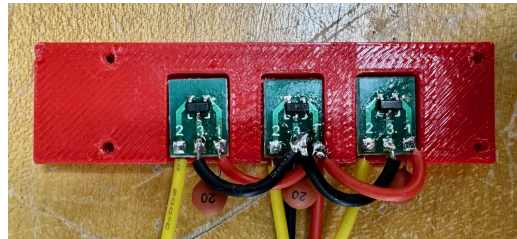


Figure 10: Raspberry Pi Pico wiring schematic

In Figure 10, the socket connector in the upper right corner is the MacArtney subconn connector, which has six wires going to it. Those are UART0 TX (GPIO 0) and UART0 RX (GPIO 1) to send data out of the sensor, VREG_IN and GND to supply the sensor with power, SWCLK and SWD to be able to program and debug the sensor while it is already assembled. For the first iteration, the electronics were soldered onto a 3D printed spacer plate, as shown by Figures 11 and 12:

Figure 11: Soldered Hall effect sensors with 3D printer spacer plate and 0.02 μF ceramic capacitors

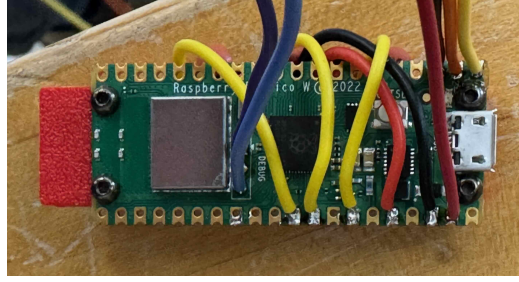


Figure 12: Soldered Pi Pico with wires exiting the image going to the MacArtney Subconn connector

A custom PCB, shown in Figure 13, was developed for future iterations of the sensor to break out the Hall effect sensor outputs and make it easier to connect it to the Pi Pico, while enforcing the 12 mm spacing between sensors due to the magnet used. Additionally, $0.01 \mu\text{F}$ capacitors were used as per the Hall effect sensor datasheet [8].

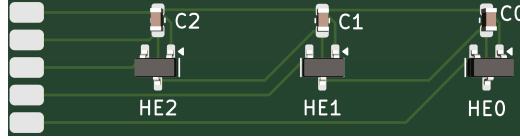


Figure 13: Custom PCB to power and interface with the Hall effect sensors

6.2.4 Estimated Power Consumption

The Pi Pico along with three Hall effect sensors are the only power-consuming components in the design.

In particular, the Pi Pico power draw is approximately 90mA at full load, running a VGA, accessing an SD card, and running an audio board as per an example in the Pi Pico datasheet [11]. Since the only function of the Pi Pico is to poll the ADCs at a relatively low frequency of about 10-100 Hz depending on the test, and send that data over UART, this should be using less than half of the power at full load, or 50 mA conservatively. 10-100 Hz is sufficient and even excessive since the sensor is likely to be deploying in applications involving hour-long timescales.

From the Hall effect sensor data sheet, the max power draw for each Hall effect sensor is 10 mA [8].

Table 4: Estimated power consumption at 5 V

Component	Current Draw (mA)	Power (mW)
Raspberry Pi Pico	50	250
3 $\times$ Hall Effect Sensors	30	150
Total	80	400

As determined in Table 4, the 80 mA combined power draw is safely below the 100 mA limit. Since the Pico is being directly powered, the input voltage needs to be 5 V. To address the input voltage range specification, a simple buck converter can be implemented to maintain the 5 V along the required 5-24 V voltage range with high efficiency of conversion of 80-90%.

6.3 Mechanical Design

With the electronics out of the way, the three main components of the sensor were designed and assembled. They are as follows:

1. Sensor Package: Pressure-resistant and waterproof package for the electronics
2. Magnetic Piston: The piston that moves inside the cylinder in response to pressure changes
3. 99% Volume Cavity: Cavity that holds the remaining 99% of water not in the cylinder

All of the components above were designed to be easily printed on any low-cost modern Fused Deposition Modeling (FDM) 3D printer and assembled with readily available hardware. These parts were successfully printed on both the Prusa MINI+ and Bambu Lab X1C 3D printers using Polycarbonate (PC), chosen for its high durability, Shore hardness, and resistance to deformation under mechanical stress. Unlike materials such as Polylactic Acid (PLA) or Polyethylene Terephthalate Glycol-modified (PETG) typically used for 3D printing, which may absorb moisture or soften under heat and pressure, PC remains dimensionally stable and resists cracking under high load. Its balance of print-ability and mechanical robustness made it an ideal material choice for this design.

6.3.1 Sensor Package

The purpose of the sensor package is to house the electronics in a pressure-resistant and waterproof package. After consulting with Jonathan Pfeifer, it was determined that a good approach is to use epoxy to fill a cavity containing the electronics, while exposing wires for power, data collection, and debugging. Specifically, 3M™ Scotchcast™ Electrical Insulating Resin 4N was used for its electrically insulating properties.

Additionally, the Hall effect sensors in the package need to be perpendicular to and at an optimal distance away from the magnet inside the piston so as not to over-saturate the readings but also to have enough epoxy between them and the external environment for pressure survivability. The design that was ultimately used is shown below in Figure 14.

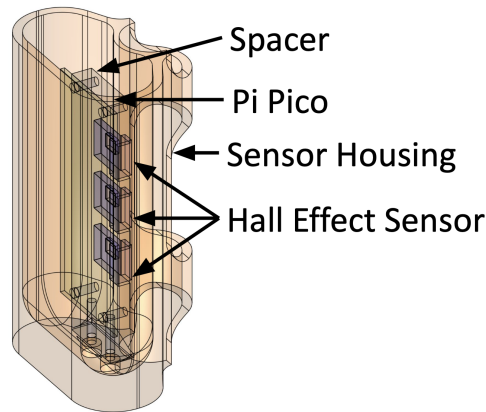


Figure 14: Isometric view of sensor package

The sensor housing, as shown in Figure 14 above, was 3D printed, mounted onto and aligned with the cylinder. The use of the 3D printed spacer allows the Hall effect sensors to be mounted normal to the piston's path of motion and with the use of screws between the bottom of the housing and the spacer itself. The Pi Pico is mounted directly on the other side of the spacer also with screws, allowing for a tidy electronics package ready to be potted in epoxy, the process of which is shown below in Figure 15.

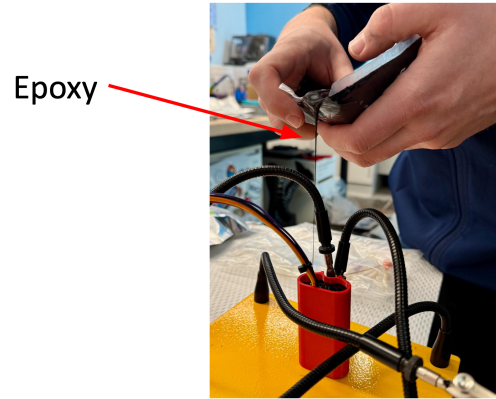


Figure 15: Potting electronics with 4N epoxy

Potting the sensor package in epoxy, as shown in Figure 15 is a straightforward and effective method for ensuring high-pressure survivability and waterproofing. By fully encapsulating the electronics, epoxy protects against water ingress, corrosion, and mechanical damage, while also distributing external pressure evenly across the device.

Compared to constructing a traditional pressure housing—often requiring expensive materials, precision machining, and complex sealing—potting is significantly more cost-effective and easier to implement. It eliminates the need for gaskets or pressure-rated enclosures, making it ideal for this sensor.

6.3.2 Magnetic Piston

The purpose of the magnetic piston is to translate pressure changes due to depth into linear displacement that is then measured by the Hall effect sensors. This needs to be done as smoothly as possible, with minimal static friction between the walls of the cylinder and the piston itself, while being water-tight to accurately translate pressure changes.

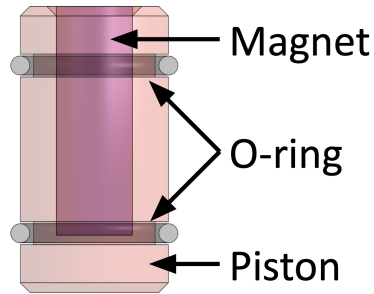


Figure 16: Cross-section view of magnetic piston

The following design shown in Figure 16 above was ultimately used. Note the use of two O-rings to ensure a watertight seal [12]. The piston itself was 3D printed, and the magnet was press-fit into the piston body using a vise. As shown in Figure 17 below, silicone O-ring lubricant was applied to minimize friction inside the cylinder.

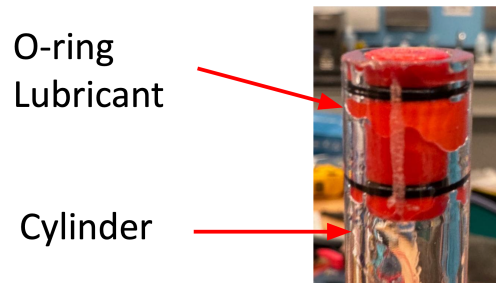


Figure 17: Magnetic piston inside of lubricated cylinder

6.3.3 99% Volume Cavity

The purpose of the 99% volume cavity is to have $99\times$ the volume of the magnetic piston travel over 200 bar. It also must be waterproof so that external water does not get in and water also does not get out, although this is also ensured by the use of rubber O-rings in the magnetic piston. As discussed previously, the pressure difference between the cavity and the environment will be minimal, thus while it does not need to be very pressure-resistant, it also cannot deform as easily as something like a balloon as the pressure delta

caused by friction between the piston's O-rings and the cylinder must not cause the structure to deform. Due to its accessibility at any hardware store and ease of assembly with PVC cement, PVC was used to create the cavity.

The volume of the 99% volume cavity is derived below. Let the volume of the cylinder projected by the inner radius of the cylinder and the piston's travel, that is the 1% in volume, be:

$$V = \pi r^2 d$$

Where:

- $r = 4$ mm is the inner radius of the cylinder—the inner radius of the piece of acrylic tubing that was used
- $d = 48$ mm is the distance that the piston travels over 200 bar—exactly 4 times (N of Hall effect sensors + 1) the length of the magnet that is 12 mm since there are three sensors that have an active region over the entire magnet's length, leading to four magnet lengths that can be measured

We now want a volume 99 times greater that is the 99% volume cavity:

$$V' = 99V = 99\pi r^2 d$$

Plugging in values used in the design:

$$V' = 99\pi(4.00 \cdot 10^{-3} \text{ m})^2(4.80 \cdot 10^{-2} \text{ m}) \approx 1.79 \times 10^{-4} \text{ m}^3 = \boxed{239 \text{ ml}}$$

A quick trip to the hardware store later, and the PVC assembly (a true work of art) shown below in Figure 18 was born. The measured volume of this cavity is 247 ml. This is extremely close to the computed 239 ml.

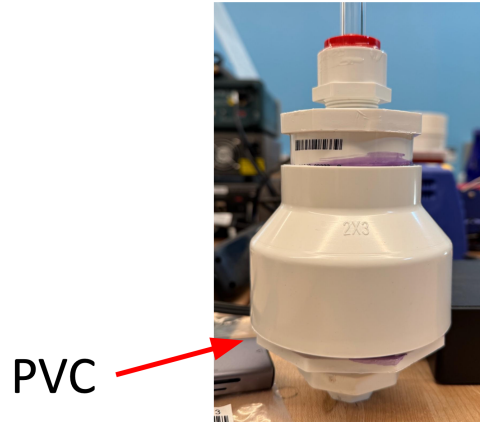


Figure 18: 99% Volume cavity showcasing PVC assembly

Note that there are screw fittings on both ends (the bottom and top of the figure). The one on top was used to directly interface with the acrylic cylinder which utilized a 3D printed adapter and 5 minute epoxy to secure it to the female fitting which then screws into the cavity. The fitting on the bottom is used to provide easy access to fill the sensor with water. A problem with this design, as was determined with testing, is that screwing the fitting back in causes the piston to move as the volume of the internal cavity is decreased. Thus it is necessary to push the piston further into the cylinder and screw in the fitting, ensuring that the piston remains in the cylinder.

This component was ultimately not 3D printed due to time constraints and the tendency of FDM 3D prints to not be ideal for making water-resistant parts due to its nature of stacking layers. With more experimentation and the use of several perimeter layers, this part could be 3D printed for future iterations.

7 Methods & Results

The testing was performed in a pressure chamber at WHOI. Here are the tests done and analyses performed:

1. ADC values were recorded as a function of piston position to characterize sensor response. A physical model of the magnetic field component B_y was fit to the measured ADC values versus piston position.

2. The sensor was submerged in a sealed test chamber to simulate hydrostatic conditions. Chamber pressure was increased in 20 bar intervals until failure, with ADC readings recorded at each step.
3. Pressure was calculated from ADC readings during the pressurization test using the fitted physical model.

Two, almost identical pressure sensors were ultimately built. Since the first was just a prototype tested to see whether or not it would work at all, its data was ultimately not used since the ADC values were not mapped to distance before testing. The second pressure sensor was used for the following analyses. The changes between both sensors will be discussed in the Pressure Testing section and are as follows:

- Sensor 1: Standard Pico W with no modifications, epoxy done under atmospheric pressure
- Sensor 2: Pico W with removed wireless shield; epoxy done under vacuum

7.1 Fitting Magnet Position to ADC Values

Before running any pressurization tests, the position of the magnetic piston was correlated with the corresponding ADC values on each channel to account for any dimensional in-accuracies or errors in simulating the expected sensor magnetic field response.

The magnet was inserted into the cylinder and moved along the active region, that is between the Hall effect sensors, in 2mm increments. ADC values from the sensor were recorded as shown in Figure 19.

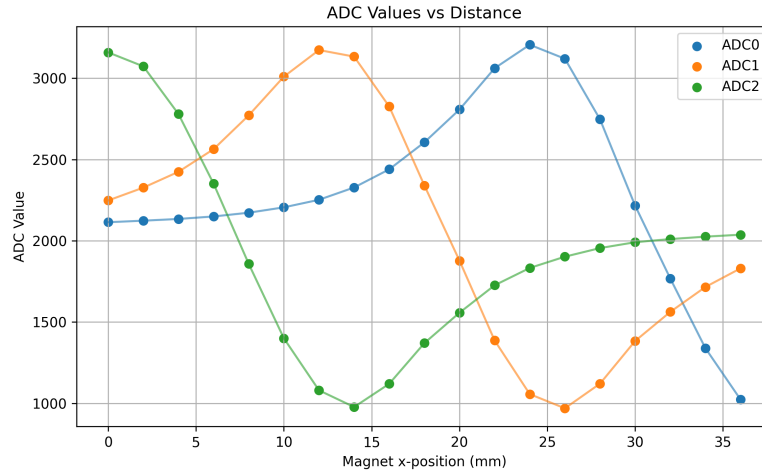


Figure 19: ADC values from each Hall effect sensor vs the x-position of the magnet

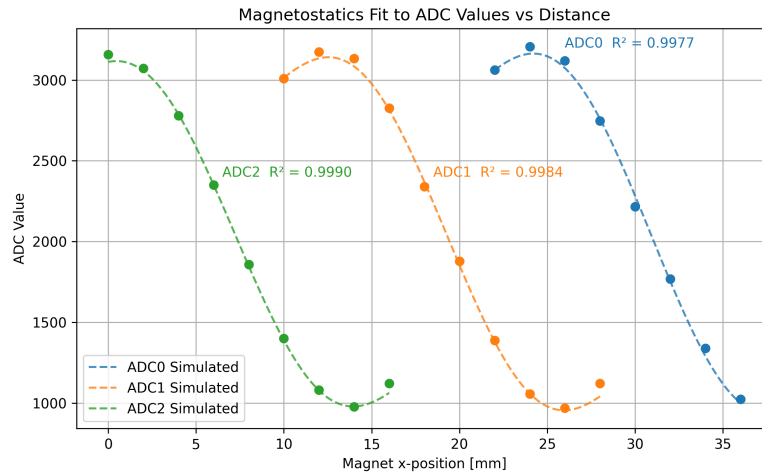


Figure 20: ADC values from each Hall effect sensor vs the x-position of the magnet with overlaid best-fit physical model. Note that the model was only fitted on the s-shaped part of the curve as this will be used to determine the magnet's position

Table 5: Fitted parameters and model accuracy

Channel	y (mm)	x (mm)	R^2
ADC0	10.22	30.88	0.9977
ADC1	10.30	19.25	0.9984
ADC2	10.38	7.21	0.9990
Optimized Magnet Height: 10.74 mm			

Then, from the gathered data, a physical model using magpylib was fit, visualized in Figure 20 to the results over the following variables as in Table 5. The magnet height was optimized as the cylinder had rounded edges, so the whole 12mm are not exactly equally magnetic. The high R^2 values ranging from 0.9977 to 0.9990 indicate a highly statistically significant model, this means the sensor is functioning as intended according to its physical model.

7.2 Pressure Testing

With a physically fitted curve for each of the three Hall effect sensors, they can now be used to back-calculate the position knowing ADC values.



Figure 21: Depth sensor submerged in pressure chamber

The sensor was completely filled with tap water and submerged into the

pressure chamber for testing, as shown in Figure 21. The pressure of the test chamber was increased in increments of 20 bar until the sensor failed. Failure is when the sensor completely stops sending data and communicating with our computer.

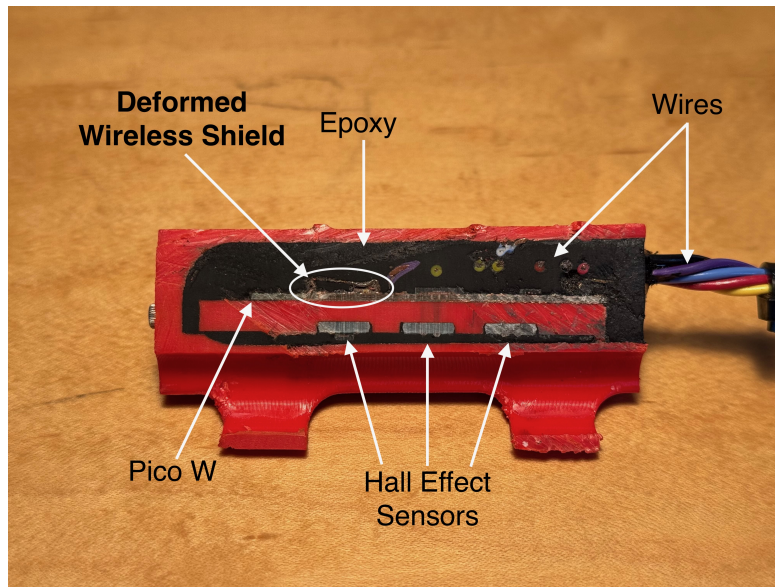


Figure 22: Cross-section of first sensor prototype, showcasing wireless shield collapse failure mode

The first sensor survived up to 120 bar, which informed a slight design change moving forward with the second prototype. In particular, it was noted that epoxy had not made it under the wireless shield of the Pico W, causing the wireless shield to collapse in on itself due to the extreme pressures as shown in Figure 22. It is hypothesized that this created a short or caused structural damage to the PCB that permanently damaged the Pi Pico.

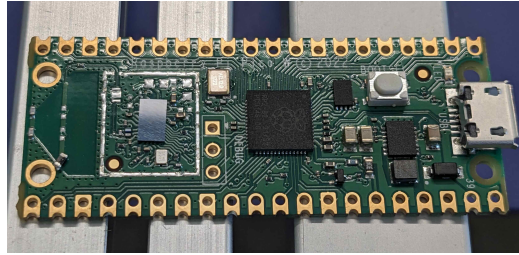


Figure 23: Pico W with wireless shield removed as shown by exposed IC

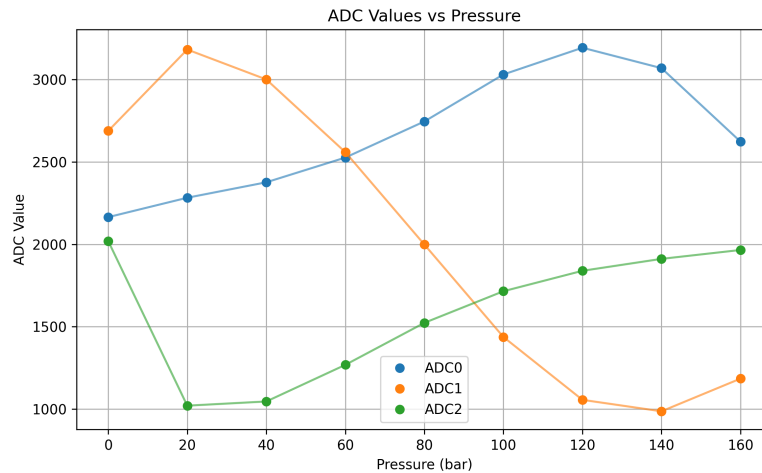


Figure 24: ADC readings vs chamber pressure

The second iteration of the sensor was made possible thanks to Jonathan Pfeifer's help at WHOI removing the wireless shield and running the pressure tests. The second sensor, with the wireless shield removed survived up to 230 bar. The Pico W with the wireless shield removed is shown in Figure 23. The data gathered, as shown in Figure 24 is only up to 160 bar due to a bug in the data logging program.

Table 6: Sensor depth survivability

Sensor	Max Pressure	Depth
1	120 bar	1.2 km
2	230 bar	2.3 km

According to Table 6, removing the Pico W wireless shield and potting the sensor with epoxy under a vacuum to prevent air bubbles nearly doubled the depth capability. The first sensor survived up to 1.2 km, while the second sensor survived up to 2.3 km, exceeding the target spec by 15%.

To make Table 6 more relatable, Table 7 was created, which expresses pressure survivability results in familiar Cornell terms: TCATs and Clocktowers. The TCAT column shows how many fully loaded TCAT buses would need to be stacked on top of the sensor to exert the same pressure as the water does at depth. A typical TCAT bus weighs about 15,000 kg, which corresponds to a downward force of roughly 150,000 N. The Clocktower column converts depth into units of McGraw Tower height. Since McGraw Tower stands 53 m tall, this column indicates how many towers stacked tip-to-base would match the depth the sensor survived underwater.

Table 7: Sensor depth in Cornell units

Sensor	TCAT Pressure	Clocktower Depth
1	0.8	22.6
2	1.5	43.4



Figure 25: Equivalent pressure on sensor package in TCAT weight. 1.5 TCATs could be stacked on sensor 2

7.3 Pressure & Depth Results

With the gathered ADC values from the pressure test, they need to be converted into pressure to compare them against the known pressure of the test chamber, and ultimately into depth as will have to be done in real-field deployments. They are converted according to Figure 26.

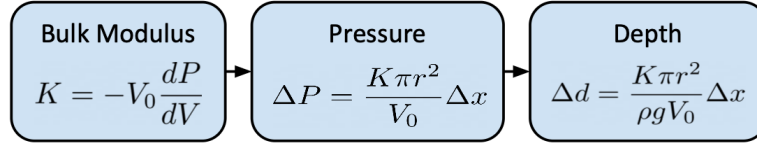


Figure 26: Pressure and depth calculation equation diagram. Where r is the radius of the cylinder wall, V_0 is the initial volume, ρ is the density of seawater and g is the gravitational constant

Since the physical model fit for each Hall effect sensor (ADC channel) was determined, the pressure ADC results are looked up and converted to a piston position as shown in Figure 27. Note that the model was only used across the range of the one-to-one function to ensure each ADC value corresponds to a unique piston position.

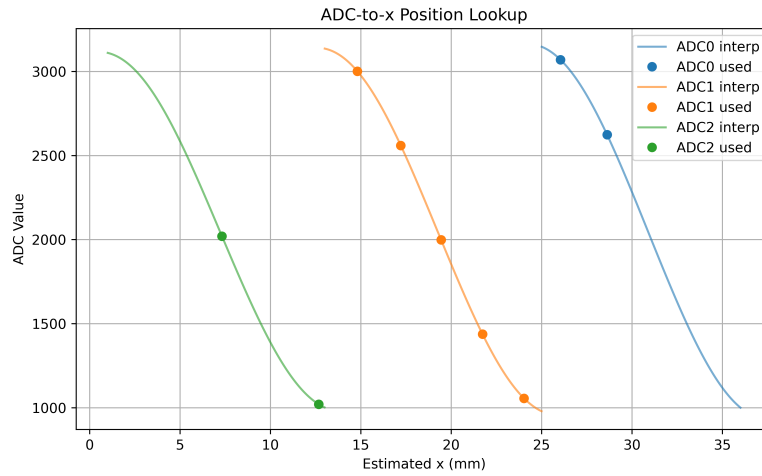


Figure 27: ADC to piston x-position lookup from physical model based on ADC data gathered from pressure testing. The points represent the ADC values for every 20 bar pressure increment and the curves represent the physical model for each Hall effect sensor

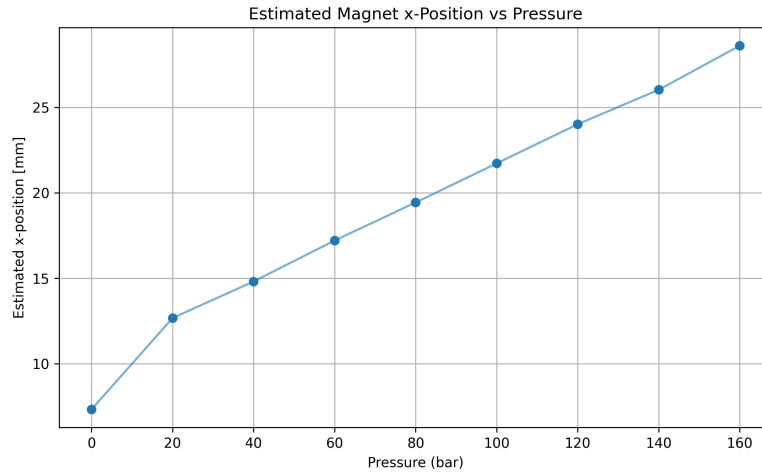


Figure 28: Results of piston x-position lookup vs chamber pressure. Note the sudden increase in x-position from 0 to 20 bar

As can be seen on the plot above in Figure 28, the estimated magnet position increases linearly after 20 bar. The 0-20 bar discontinuity is likely caused by trapped air in the sensor cavity.

With the piston position determined for every corresponding pressure, the relationships between position and pressure [Appendix 10.2.2] and position and depth are determined [Appendix 10.2.3]:

- Relationship between piston position (Δx) and pressure (P):

$$\Delta P = \frac{K\pi r^2}{V_0} \Delta x$$

- Pressure as a function of Δx :

$$\Delta P \approx 4.475 \cdot 10^8 \cdot \Delta x$$

- Relationship between piston position (Δx) and depth (d):

$$\Delta d = \frac{K\pi r^2}{\rho g V_0} \Delta x$$

- Depth as a function of Δx :

$$\Delta d \approx 4.47 \cdot 10^4 \cdot \Delta x$$

From the derived equations, the relationship between the experimental pressure, calculated from the piston displacement, and the actual pressure of the chamber is determined, shown in Figure 29.

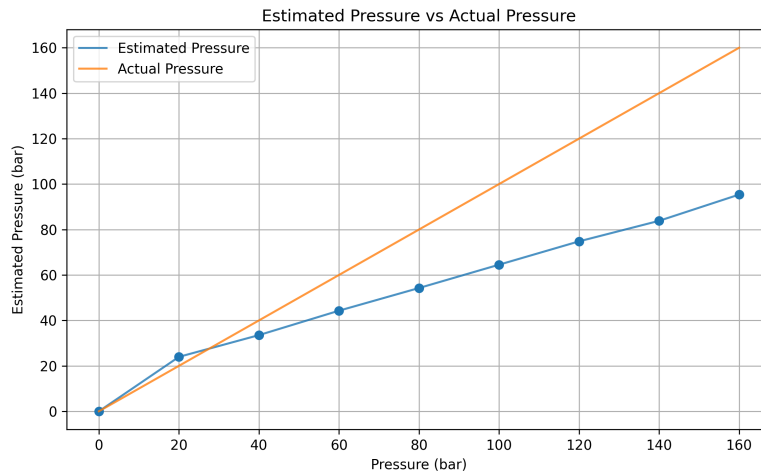


Figure 29: Sensor-determined pressure (blue) compared to actual chamber pressure (orange)

From Figure 29, it is determined that the sensor-determined value lags behind the actual chamber pressure along the y-axis from 20 bar. The good news is that the slope is relatively constant from point to point after 20 bar, meaning the sensor behavior is extremely predictable.

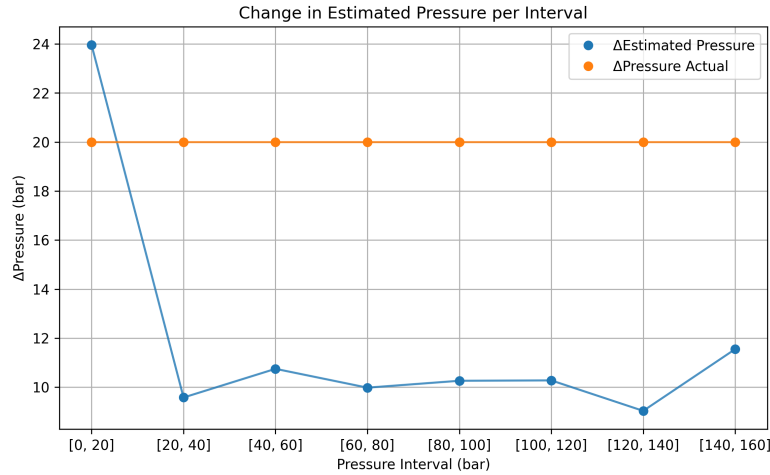


Figure 30: Change in estimated pressure from across 20 bar interval

Further supporting this point, after the 20 bar discontinuity, the change in estimated pressure from interval to interval ranges from approximately 9.5 to 11.5 bar as shown in Figure 30. Due to the highly linear nature of this behavior, a simple calibration routine can be developed to map ADC readings to pressure directly through linear interpolation. This avoids the need for complex models and allows for real-time pressure estimation with minimal computation. Moreover, this linearity suggests that the system maintains stable sensitivity across a broad pressure range.

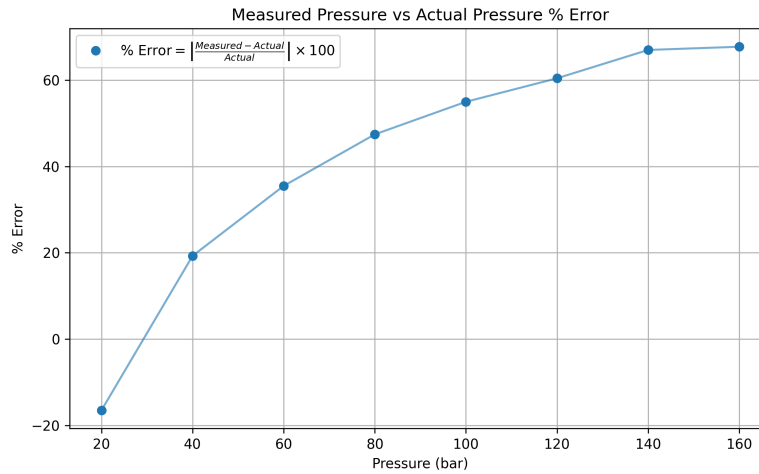


Figure 31: Percent error from sensor-determined pressure compared to actual chamber pressure

The % error is rather significant, ranging from -20% to 70% as indicated in Figure 31. The second derivative of % error is negative, and the error levels out at 70% around 140-160 bar. There is definitely additional work to be done on improving the performance of the sensor, with a calibration routine and through more testing and refining the design to avoid air bubbles which could lead to jump discontinuities.

The relationship with the depth and pressure is shown below in Figure 32. Since depth is just pressure multiplied by a constant, performing an analysis on this data would not inform anything not already learned by the pressure data.

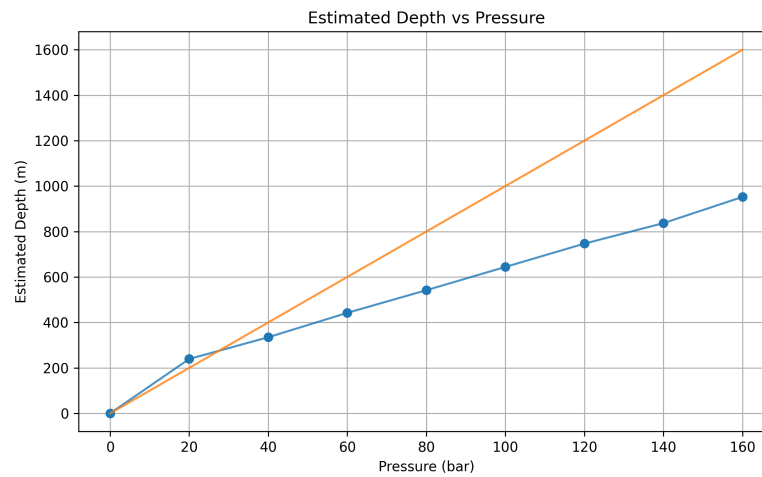


Figure 32: Sensor-determined depth (blue) compared to depth derived from actual chamber pressure (orange)

8 Conclusion



Figure 33: Assembled depth sensor module in front of pressure chamber

The depth sensor, shown in its entirety on Figure 33, survived to a greater depth than expected, exceeding the 200 bar spec by 15% (230 bar). The piston system seemed to be working correctly, due to the extremely linear behavior due with increasing pressure. For approximately \$60 [Appendix 10.1], half of which were the PVC fittings, a functional sensor was constructed with a predictable measurement pattern. Despite the high error, a calibration routine could address this issue. This compares favorably to market sensors typically priced between \$1,000 and \$10,000. A comparison of target and achieved specifications is shown below in Table 8.

Table 8: Sensor module specifications (target vs. achieved)

Parameter	Specification	Achieved
<i>Performance</i>		
Maximum Depth	2,000 m	2,300 m
Pressure Rating	200 bar	230 bar
Accuracy	± 10 m	-20% to 70% error
<i>Electrical</i>		
Power Input	5–24 V, ≤ 100 mA	5 V, 80 mA
Data Protocol	RS-232	UART (RS-232 compatible)
<i>Mechanical / Physical</i>		
Size	Soda can to Nalgene	Nalgene bottle
Connector Type	MacArtney SubConn	MacArtney SubConn
Mounting Method	Hose clamps, bolts, etc.	Not addressed

9 References

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10 Appendix

10.1 Bill of Materials

Table 9: 3D Printed Components: Mass and Cost

Part	Filament Mass (g)	Cost (USD)
Sensor Package	23.56	1.34
PVC Spacer	7.37	0.42
Sensor Spacer	4.62	0.26
Magnetic Piston	0.80	0.05
Total	36.35 g	\$2.07

Filament mass as sliced in PrusaSlicer, taking into account printing with a brim for better bed adhesion, supports for the sensor package, and slight over-extrusion of 3% to ensure waterproof parts. The cost was determined from the mass of the part and the cost of PC filament, specifically Polymaker Polymax Tough PC Filament that sells for \$42.99 per 0.75 kg (\$57.32 / kg).

Table 10: 99% Volume Cavity PVC Components

Part	Quantity	Price (\$)
3/4" Threaded Adapter	1	1.39
3/4" Threaded End Cap	1	1.59
1.5" x 1/2" Bushing	1	3.99
2" x 3" Coupler	1	9.99
2" x 3/4" Bushing	1	4.99
3" x 1.5" Bushing	1	8.59
Total Cost		\$30.54

Table 11: Bill of materials, grouped by category

Item	Qty.	Unit Price (\$)	Total (\$)
<i>Electronics</i>			
Raspberry Pi Pico (RP2040)	1	4.00	4.00
DRV5055 Hall Effect Sensor	3	1.20	3.60
0.01 μ F Capacitor	3	0.10	0.30
<i>Magnetics</i>			
4x12 mm Cylindrical Magnet	1	0.10	0.10
<i>Mechanical / Structural</i>			
Acr. Tube (8 mm ID, 12 mm OD)	1	5.79	5.79
O-ring (6 mm ID, 8 mm OD)	2	0.10	0.20
PVC Fittings	1	30.54	30.54
<i>Materials</i>			
PC Filament	36.4 g	57.32 / kg	2.09
3M TM Scotchcast TM Resin 4N	30.0 mL	0.28 / mL	8.40
Total Cost			\$55.02

The MacArtney SubConn connector was not included in the price calculation, as such connectors are typically already available in marine research laboratories and are often reused across multiple deployments. Additionally, consumables such as PVC cement, superglue, 2mm and 3mm screws, and silicone O-ring lubricant were excluded due to their low cost and incidental use.

10.2 Derivations

10.2.1 Variable Definitions & Constants

Table 12: Variable definitions

Variable	Meaning
P	Pressure
V	Volume of water-filled components
K	Bulk modulus of water
d	Depth
x	Position of piston in sensor
r	Radius of cylinder inner diameter

Table 13: Constants used in pressure and depth calculations

Parameter	Value
Bulk modulus of water, K_{water}	$2.2 \cdot 10^9$ Pa
Sensor piston radius, r	4 mm = $4 \cdot 10^{-3}$ m
Density of seawater, ρ	1022 kg/m ³
Gravitational acceleration, g	9.81 m/s ²
Initial water volume, V_0	247 ml = $2.47 \cdot 10^{-4}$ m ³

Note: K slightly varies with pressure/depth, which should be included in future iterations of these calculations.

10.2.2 Pressure-Displacement Relationship Derivation

Relationship between piston position (Δx) and pressure (P)

Bulk modulus relates pressure and volume:

$$K = -V_0 \frac{dP}{dV} = -V_0 \frac{P_1 - P_0}{V_1 - V_0} \quad (1)$$

Rearranged to solve for P_1 :

$$P_1 = -\frac{K}{V_0}(V_1 - V_0) + P_0 \quad (2)$$

Using the volume of a cylinder:

$$V_{\text{cylinder}} = \pi r^2 h \quad (3)$$

$$V_1 = V_0 - \pi r^2 (x_1 - x_0) \quad (4)$$

$$V_1 = V_0 - \pi r^2 \Delta x \quad (5)$$

Substituting:

$$P_1 = \frac{K}{V_0}(V_0 - V_1) + P_0 \quad (6)$$

$$P_1 = \frac{K}{V_0} (V_0 - (V_0 - \pi r^2 \Delta x)) + P_0 \quad (7)$$

Thus:

$$\boxed{\Delta P = \frac{K \pi r^2}{V_0} \Delta x} \quad (8)$$

Substituting constants to determine pressure P as a function of Δx :

$$\Delta P = \frac{2.2 \cdot 10^9}{2.47 \cdot 10^{-4}} \cdot \pi \cdot (4 \cdot 10^{-3})^2 \cdot \Delta x \quad (9)$$

$$\boxed{\Delta P \approx 4.475 \cdot 10^8 \cdot \Delta x} \quad (10)$$

With the derived equations, the relationship between pressure can be plotted to showcase the accuracy of the sensor.

10.2.3 Depth-Displacement Relationship Derivation

Relationship between piston position (Δx) and depth (d)

From hydrostatics:

$$P_1 = \rho g d + P_{\text{atm}} \quad (11)$$

Equating with bulk modulus expression:

$$\rho g \Delta d + P_{\text{atm}} = -\frac{K}{V_0}(V_1 - V_0) + P_0 \quad (12)$$

$$\rho g \Delta d = \frac{K}{V_0}(V_0 - V_1) \quad (13)$$

$$\Delta d = \frac{K}{\rho g V_0}(V_0 - V_1) \quad (14)$$

$$V_1 = V_0 - \pi r^2 \Delta x \quad (15)$$

$$\boxed{\Delta d = \frac{K \pi r^2}{\rho g V_0} \Delta x} \quad (16)$$

Substituting constants to determine depth d as a function of Δx :

$$d = \frac{2.2 \cdot 10^9 \cdot \pi \cdot (4 \cdot 10^{-3})^2}{1022 \cdot 9.81 \cdot 2.47 \cdot 10^{-4}} \cdot \Delta x \quad (17)$$

$$\boxed{\Delta d \approx 4.47 \cdot 10^4 \cdot \Delta x} \quad (18)$$