

Using Geostrophic Flow and Magnetometer Readings to Map and Source Seafloor Debris

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Abstract—This paper presents the design of an autonomous underwater vehicle and an experimental procedure using pressure, temperature, and magnetic flux density readings to calculate geostrophic flow and map seafloor debris, then reconstruct their surface entry points. Autonomous deployments to collect this data were conducted at pHake Lake and Dana Point Pier with the goal of performing these calculations and mappings. The collected pressure data was most reliable. The sensor output indicated readings of 96.03-97.57kPa at the surface, which closely matched barometer measurements of 101.7kPa. The depth control algorithm was also effective. The recorded depth when the vehicle was stationary only fluctuated by at most 0.032m, and the largest overshoot when moving to a new waypoint was only 0.048m. Temperature data was not successfully recorded as the sensor railed out and produced readings of 28.0545°C in the ocean as opposed to probed measurements of 18.4-18.7°C. The recorded magnetic flux density predictably fluctuated between 50.25-50.6μT in the air, but the sensor's readings flatlined in the water, likely due to electromagnetic interference. Thus, calculating geostrophic flow and mapping seafloor debris using these three quantities is likely feasible, but requires further investigation into improving the sensor's functionality underwater during deployment to confirm the effectiveness of this method.

I. INTRODUCTION

The goal of this project was to explore the potential of using an autonomous underwater vehicle (AUV) to map seafloor debris and determine their water surface entry point. The United Nations Educational, Scientific, and Cultural Organization estimates there are three million shipwrecks worldwide, among other catastrophe-induced ocean debris. These wreckages are artifacts of human behaviour and are investigated to inform historical and cultural accounts [1]. However, these investigations have historically been difficult because current methods to locate wreckages are complex and inefficient. These methods can be improved by detecting magnetic anomalies that indicate metal wreck pieces due to their material composition underwater and reconstructing their points of entry into the water [2].

An AUV was constructed to collect pressure, temperature, and magnetic flux density data at Dana Point Pier with a sample rate of 10Hz. Pressure and temperature data can be used to create a 3D vector field map of currents in the ocean. The magnetic flux density data can be used to form a contour plot of the magnetic flux density across the ocean floor. These two plots would enable conclusions to be drawn about ferromagnetic materials, which include most metals, on the seafloor and their possible points of entry on the ocean

surface through approximating their trajectory along currents while falling downwards.

The remainder of this report will present the chosen sensors and necessary modifications made to them, mechanical design choices for the AUV, and the methods used to collect and process data. The results and analysis section will present the data collected and compare results with expected values. The report will conclude by addressing the limitations of this experimental method and the sensors used regarding mapping and sourcing seafloor debris, and suggesting potential areas for future work.

II. SENSOR SELECTION

A. Pressure

A pressure sensor was used for the AUV's autonomous navigation to preset depths while recording pressure measurements. The MPX5700 sensor was chosen because of its large operating absolute pressure range (15-700kPa), linear relationship between output voltage and pressure, and easy integration with the AUV [3].

B. Temperature

A thermistor was used to collect temperature readings during deployment. A thermistor was chosen because of its fast response time (0.12-10 seconds), higher sensitivity than other temperature sensors, very low effect of lead resistance on accuracy, and ease of linearising its non-linear relationship between output resistance and temperature. Thermistors change their resistance based on the temperature they are in contact with [4]. The NXFT15XH103FEAB035 thermistor was chosen to collect temperature data because of its large operating temperature range (-40-125°C), high accuracy ($\pm 1\%$ resistance), and easy integration with the AUV. This thermistor has a negative temperature coefficient, so its resistance decreases at higher temperatures [5].

C. Importance of Pressure and Temperature Readings

Geostrophic balance describes the state of fluid flow (currents) in the ocean based on a steady-state force balance between the pressure gradient in the ocean (which is influenced by factors such as surface winds) and the apparent force on particles moving in the water relative to the Earth's rotating reference frame. The velocity of fluid particles along the Cartesian x and y axes is related to the fluid density, Earth's

rotation rate, and the latitude of the particle. Flows in the ocean occur along lines of equal pressure, so there would be a different set of current vectors at each measured depth [6].

The density of seawater changes throughout the ocean based on the One Atmosphere International Equation of State of Seawater, which is dependent on temperature and salinity [7]. Salinity of ocean water is roughly constant over 10-100m of depth and along the ocean surface [8]. However, temperature in the ocean changes rapidly (10-20°C fluctuation) over the first 400m deep into the ocean, especially in mid-latitude regions (including California) [9]. Thus, to characterize oceanic currents according to the above, pressure and temperature readings were collected at various points in the ocean.

D. Magnetic Flux Density

A magnetometer was used to collect magnetic flux density readings on the ocean floor. Magnetic flux density, measured in T, is a quantity that describes the magnitude of a magnetic field [10]. Ferromagnetic materials induce magnetism and change the magnetic field around them when they are placed in an external magnetic field. The Earth has a magnetic field that is downward-angled in the northern hemisphere (which includes the deployment site: Dana Point, CA). Thus, ferromagnetic materials in the deployment area would increase the magnetic flux density around them [11], [12]. This change in magnetic field decreases according to the inverse cube of distance [12]. Magnetic flux density is highly dependent on material composition and object size, and these quantities of the underwater debris were unknown [10]. Therefore, the PNI RM3100 sensor, which converts changes in sensor inductance to magnetic flux density readings, was chosen to detect ferromagnetic materials because of its large range (-800 to 800μT), low noise (15nT), and high sensitivity [13].

III. CIRCUIT DESIGN

A. Pressure Sensor

The MPX5700 outputs voltages that are linearly related to absolute pressure. It was expected that the pressure sensor would output voltages of 0.85-1.04V corresponding to depths of 0-3m below the ocean's surface [3]. The 0-3m range was chosen because Dana Point Harbour has depths between 6-15ft (1.83-4.57m), and the deployment locations were in shallower regions with a 0-3m range [14]. As shown in Figure 1, an offset amplifier (U3) was used to scale this output to nearly fill the 0-3.3V input range of the Teensy 4.0 microcontroller to maximize data resolution. A unity gain buffer (U2) was placed between the pressure sensor and offset amplifier to prevent loading effects.

The offset amplifier was designed with an offset of 14.56V and a gain of -14, calculated using (1). The variable values in (1) for this circuit are as depicted in Figure 1. This resulted in theoretical output voltages of 0.01-2.73V for depths 3-0m, which is within the desired range. A small voltage buffer was left on each side of the output to ensure fluctuations from noise and unanticipated depths slightly outside the expected range would not cause the circuit to rail out.

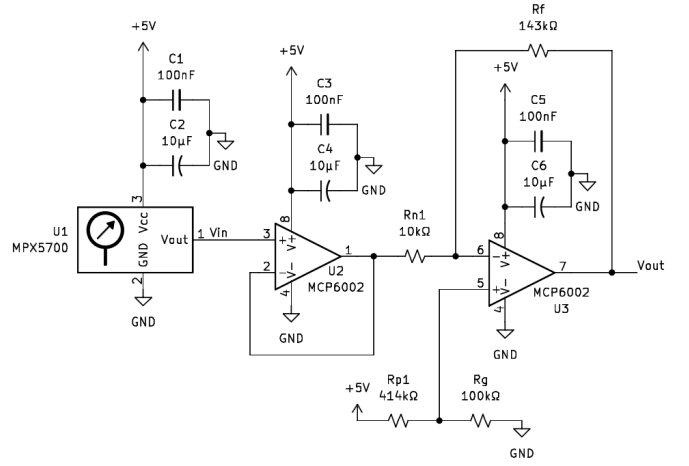


Fig. 1. Pressure sensor interface circuit. All 5V and GND rails are shared.

$$V_{out} = 5 \left(1 + \frac{R_f}{R_{n1}} \right) \left(\frac{R_g}{R_{p1} + R_g} \right) - \frac{V_{in} R_f}{R_{n1}} \quad (1)$$

The output of the pressure sensor is DC voltage, so the default 10Hz sampling frequency in the code was sufficient. However, as described in section VIA, the depth control algorithm was modified to allow the AUV to autonomously determine if it had reached the seafloor to isolate magnetometer readings at the bottom of the ocean.

The sensor was calibrated to derive an equation relating the output voltage to depth by taping a pressure tube connected to the pressure sensor to a meterstick. The output voltage of the circuit was recorded while holding the end of the tube at depths from 0-0.4m in increments of 0.05m in a graduated cylinder filled with seawater. Figure 2 shows the resultant calibration curve with 95% confidence level upper and lower observational and functional bounds. The R^2 value for the fit was 0.996. After calibration, it was noted that the maximum depth that could be recorded was 3.76m under the surface of the water, which was outside the planned 0-3m range.

B. Thermistor

The NXFT15XH103FEAB035 changes its resistance based on its contact temperature. From its datasheet, thermistor resistances of 95420-47000Ω were expected for temperatures of 10-25°C, which is the approximate ocean temperature at Dana Point in April with a 2-5°C buffer on each side [5], [15]. As shown in Figure 3, a voltage divider was created with the thermistor to convert this output resistance to an output voltage. A unity gain buffer and offset amplifier were then used to scale this output to 0-3.3V in the same way as the pressure sensor. The voltage divider equation is shown in (2), with the variable values as depicted in Figure 3.

$$V_{in} = \frac{5R_{div}}{R_t + R_{div}} \quad (2)$$

The offset amplifier was designed with an offset of 12.13V and a gain of -3 according to (1). The variable values in (1)

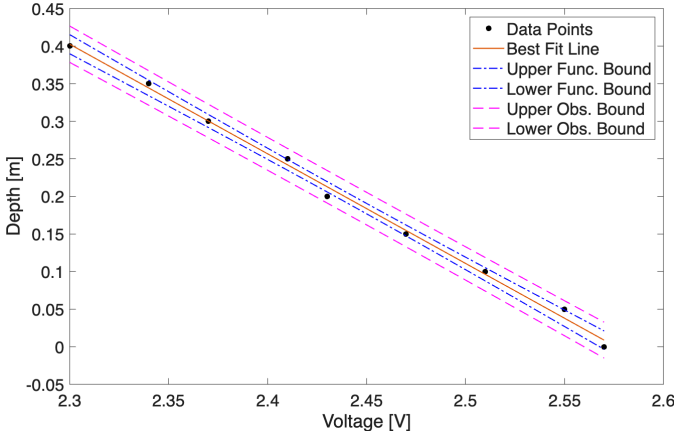


Fig. 2. Calibration curve with 95% confidence level upper and lower functional and observational bounds relating recorded depths and output voltage readings.

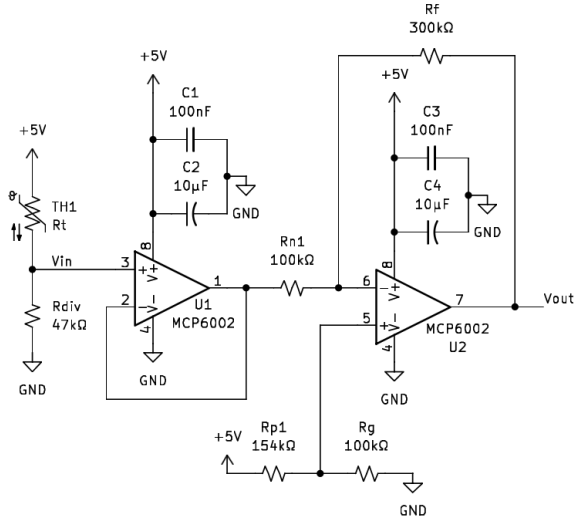


Fig. 3. Thermistor interface circuit. R_t is the thermistor's resistance. All 5V and GND rails are shared.

for this circuit are as depicted in Figure 3. This resulted in theoretical output voltages of 0.37-2.95V for temperatures 25-10°C, which is within the desired range. Like the pressure sensor, the voltage buffer on each side of the output prevents railing out during deployment.

The output of the thermistor interface circuit is DC voltage, so the default 10Hz sampling frequency in the code was sufficient, and no software modifications were made.

The thermistor resistance is related to temperature based on the Steinhart-Hart equation (3), where T is the temperature in K, R is the thermistor resistance in Ω , and A , B , C , and D are unitless Steinhart-Hart coefficients. As shown in Figure 4, the thermistor was calibrated by measuring output voltages when placing the thermistor in 10-25°C water baths, calculating the thermistor resistance using (1), and finding the Steinhart-Hart coefficients. The coefficients with 95% confidence bounds were found to be $A=0.02348$ (-0.1563, 0.2032), $B=-0.005701$

$(-0.05414, 0.04274)$, $C=5.159 \times 10^{-4}$ $(-0.003816, 0.004848)$, and $D=-1.487 \times 10^{-5}$ $(-1.424 \times 10^{-4}, 1.127 \times 10^{-4})$. Combining (1) and (3) was used to determine the relationship between output voltage and temperature.

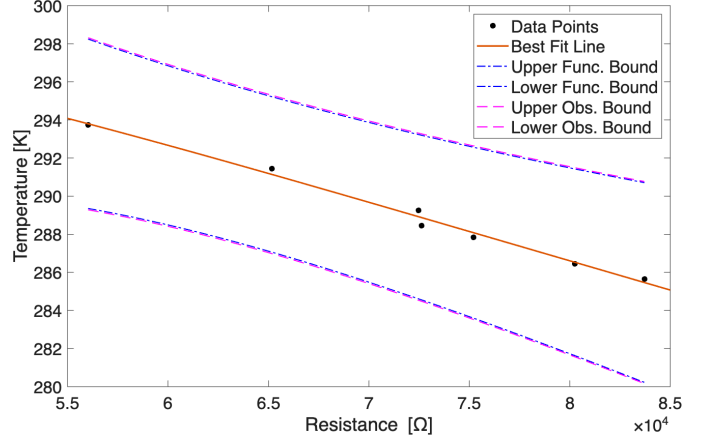


Fig. 4. Steinhart-Hart fit with 95% confidence level upper and lower functional and observational bounds relating thermistor resistance and contact temperature.

$$\frac{1}{T} = A + B \ln(R) + C \ln^2(R) + D \ln^3(R) \quad (3)$$

C. Magnetometer

The RM3100 is an I²C sensor with three output lines: Serial Clock (SCL), Serial Data (SDA), and Data Ready (DRDY), which goes HIGH when a measurement is complete [13]. As shown in Figure 5, these outputs were connected to Teensy 4.0 pins A2, A3, and A10, respectively, and relevant pins were supplied with 3.3V and ground connections.

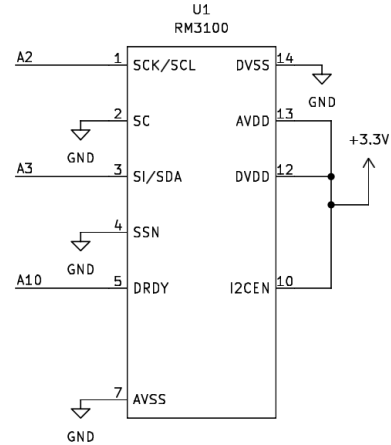


Fig. 5. Magnetometer power and ground connections, and connections to Teensy 4.0 pins.

The default 10Hz sampling frequency in the code was sufficient for the magnetometer readings. The magnetic flux density was expected to be a roughly constant value at each position, and not a periodic signal, so the sampling frequency

producing aliasing was not a concern. Separately, the RM3100 has a data update rate of 37Hz, meaning it would complete a measurement and flag DRDY every 0.027s [13]. If the sampling frequency were more than 37Hz, the Teensy 4.0 could attempt to read data when there is no real output, producing gaps or anomalous values in the recorded data.

Modifications to the code were made in the form of writing C++ functions and constants necessary for the magnetometer to collect and save separate-axis and total magnitude magnetic flux density readings in μT .

The sensor was validated by using it to collect data in open air and away from any ferromagnetic objects (apart from data collection hardware) for around 10 minutes. Figure 6 shows the results of this data collection, where readings fluctuated between around 50.25-50.6 μT , which falls within the expected range of 22-67 μT on the Earth's surface [11].

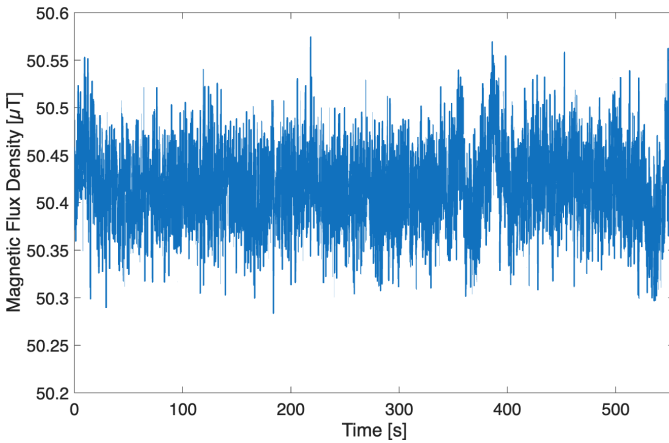


Fig. 6. Magnetic flux density readings collected in open air over 10 minutes.

IV. MECHANICAL DESIGN

The AUV was designed to be a diving and surface robot which would autonomously use P-control to travel to a selected waypoint on the surface of the water located through a GPS. It would then use P-control to dive to selected depth waypoints, stopping at each one for five seconds to take measurements of temperature and magnetic flux density until it either reached the maximum set depth of 3.5m or the sea floor. It would then surface and navigate to a set location for collection.

As shown in Figure 7, the AUV was shaped as a rectangular prism with two z-direction motors for diving and two xy-direction motors for surface navigation attached along the center horizontal axis. A waterproof box enclosing a Teensy 4.0, Inertial Measurement Unit (IMU), Global Positioning System unit (GPS), motor drivers, a microSD card with a reader, and the sensor circuits was placed on the top of the AUV. The magnetometer sensor was enclosed in a separate waterproof box at the bottom of the AUV. This was done to maximize the distance between the motors, the magnetometer sensor at the bottom of the AUV, and the magnetometer integrated in the IMU at the top of the AUV, such that the motors have limited interference with each of the magnetometer's readings.

The pressure sensor tube was fixed along the side of the AUV such that it ended at a point level with the motors, so that when the z-direction motors drove upwards at maximum speed, the pressure tube would end at the surface of the water. The thermistor was fixed along the other side of the AUV such that its head was at the same level as the pressure sensor tube end to take measurements at the same depth.

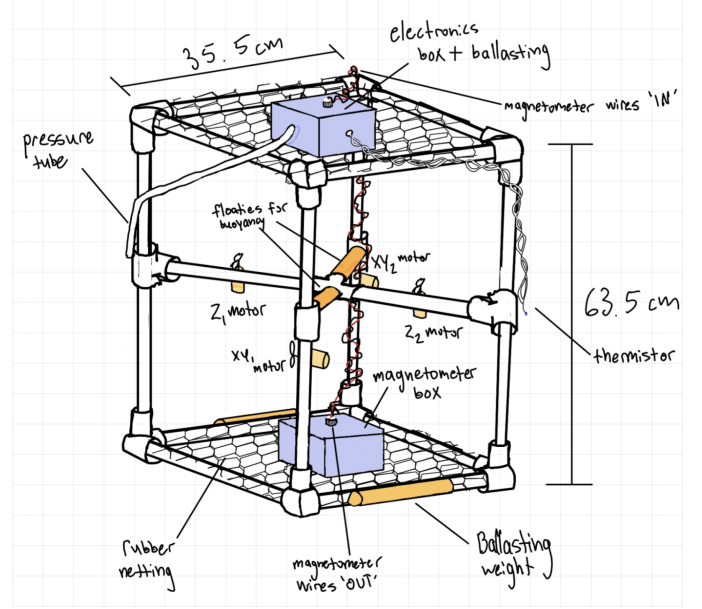


Fig. 7. Annotated isometric view of the AUV.

The waterproof boxes were adapted to fit all wires and the pressure tube using penetrator bolts coated with marine epoxy. The top box had five penetrator bolts to hold the pressure tube, 2 wires for the thermistor, 2 wires for each of the 4 motors, and 6 wires for the magnetometer ground, power, and data lines. The bottom box had two penetrator bolts to hold the 6 magnetometer wires, and the ground and power wires were later split to accommodate the necessary pins. All sensors were waterproofed to prevent shorts in the water by heat-shrinking any exposed solder connections.

The AUV was designed to be approximately neutrally buoyant so that the z-direction motors could generate enough thrust for both descending and ascending in the water. The AUV had a total mass of 2.45kg. Using the equation for buoyancy force (4), where F_b is the buoyancy force of an object in N, ρ is the density of fluid the object is in in kgm^{-3} , V is the object volume in m^3 , and g is the gravitational acceleration in ms^{-2} , the total buoyancy force from all components such as the waterproof boxes, pool noodles, and motors on the AUV was 41.80N.

$$F_b = \rho V g \quad (4)$$

To make the AUV neutrally buoyant, the force of gravity had to be roughly equal to the buoyancy force. The mass of ballast that needed to be added to the AUV to achieve this was calculated using (5), where m_{ballast} is the required mass of

ballast in kg, F_b is the total buoyancy force on the AUV in N, g is the gravitational acceleration in ms^{-2} , and m_{AUV} is the total mass of the AUV in kg. By calculation, ballast weighing around 1.8kg was needed. However, after adding this, the AUV was slightly positively buoyant at pHake Lake, so a total of around 2kg of ballast was used. After this addition, the AUV was also positively buoyant at Dana Point due to the higher density of saltwater versus freshwater, so a total ballasting weight of 2.4977kg was used.

$$m_{ballast} = \frac{F_b}{g} - m_{AUV} \quad (5)$$

By symmetry, the center of buoyancy and mass of the AUV were along its center z-axis. Due to last-minute changes to the AUV, the center of buoyancy was 30.48cm from the top of the AUV, and the center of mass was 18.43cm from the top of the AUV. Since the center of buoyancy was below the center of mass, the AUV was not stable in the water. However, it still had a limited risk of tipping over because the waves at Dana Point were not strong enough to push the AUV past its restorative balancing point.

V. DEPLOYMENT DETAILS

A. Deployment Procedure

A deployment was conducted at pHake Lake, but no usable data was collected due to the Teensy 4.0 combusting from an internal short and a bug in the Arduino IDE code that caused a replacement Teensy 4.0 to reset every 5 seconds.

Deployments at Dana Point were conducted in the early morning to minimize human activity that could interfere with the AUV's position while diving. Initially, it was planned that both surface and depth control would be used to deploy the AUV autonomously. However, the GPS readings were too unreliable to use surface control, as the readings would fluctuate on a scale of 5m, and the AUV refused to move past the first waypoint. Additionally, the GPS lock would be lost after diving and would take over 10 minutes to reconnect to satellites, so it would not be able to return to shore reliably. Only depth control was used for data collection.

At Dana Point, the pressure sensor was recalibrated as described in section IIIA, obtaining the calibration curve in Figure 2. The resultant calibration equation was entered in the Arduino IDE to ensure accurate depth readings during deployment. The voltage output of the pressure sensor interface circuit indicated surface pressures of 96.03-97.57kPa, which was close to the 101.7kPa measured with a phone barometer app. The thermistor and magnetometer were not formally recalibrated or revalidated at Dana Point, but magnetic flux density readings from the magnetometer in the air were 30.15-46.58 μT , which aligned with the expected range, and the voltage output of the thermistor interface circuit indicated air temperatures of 13.14-13.18 $^{\circ}\text{C}$, which was within range of the probed measurements of around 12-14 $^{\circ}\text{C}$.

In each deployment, 8 depth waypoints from 0 to 3.5m in increments of 0.5m were entered through Arduino IDE. The microSD card was placed in its reader, the Teensy 4.0 was

then connected to a laptop through a USB cable, and the code was uploaded through Arduino IDE. After confirming data was being logged and that reasonable outputs from the magnetometer were displayed on the serial monitor, the Teensy 4.0 was disconnected, the waterproof boxes were sealed and strapped to the AUV with velcro strips, and the AUV was dropped in the ocean upright. The approximate latitude and longitude of the deployment point were recorded by dropping a pin on Google Maps. After the AUV resurfaced, it was removed from the water by pulling on an attached tether. It was dried off with a towel, and the microSD card was removed so that its logged data could be taken and analyzed using MATLAB.

To collect experimental data, the AUV was deployed along the edge of Dana Point Pier in increments of about 1.5m away from each previous trial. This location was chosen for the easy monitoring and retrieval of the AUV, and the ability to deploy the AUV in a gridlike path to collect magnetic flux density readings at approximated locations, without using surface control or the unreliable AUV GPS readings. Figure 8 shows the deployment locations as red dots on a map of Dana Point Pier. The plotted points may not be accurate because the latitude and longitude of deployment locations and image cropping bounds were approximated on Google Maps.



Fig. 8. Deployment locations at Dana Point Pier. Positions are with reference to the set origin of (34.1226883, -117.7650364).

Data was processed by plotting the collected pressure, temperature, and magnetic flux density readings in each deployment over time as separate plots in MATLAB. Since pressure and temperature values were recorded using an Analog to Digital Converter (ADC), the values were converted to voltages using (6), where $V_{circuit}$ is the output voltage of the circuit in V and D is the unitless digital output recorded by the ADC. Afterwards, they were converted to depth and temperature using the relevant calibration curves. Deployments which resulted in data that did not match expected values were flagged for further analysis. However, the collected data from each sensor was fairly consistent between all deployments, and these results are described in Section VI.

$$V_{circuit} = 0.0032D \quad (6)$$

B. Deployment Safety

To prevent environmental waste, a tether was tied to the AUV and held onto during deployments so that if the motors failed, it could be brought back to a retrievable location easily. Parts that could easily disconnect from the AUV, such as pool noodles, motors, and ballasting weights, were taped and zip-tied to the frame to prevent them from being lost in the water.

To ensure personal safety, both boxes were checked to be sealed with no protruding wires before deployment to prevent the electronics from getting wet and producing hazardous shorts that deployment personnel could touch. Unexpected occurrences, such as the hardware sparking and foaming, were immediately reported to on-site faculty and staff, and relevant hardware was replaced before redeployment as needed.

VI. RESULTS AND ANALYSIS

A. Pressure Sensor and Autonomous Navigation

During each deployment, the AUV recorded depth continuously while performing P-control. Figure 9 shows the depth tracked during one deployment. The pressure sensor collected very accurate depth measurements, as the recorded depth fluctuated by at most $\pm 0.032\text{m}$ when the AUV was at the surface or bottom of the ocean. Furthermore, the R^2 value of the calibration curve was 0.996 (see Section IIIA), suggesting the calibration curve equation used can predict depth based on output voltage very accurately.

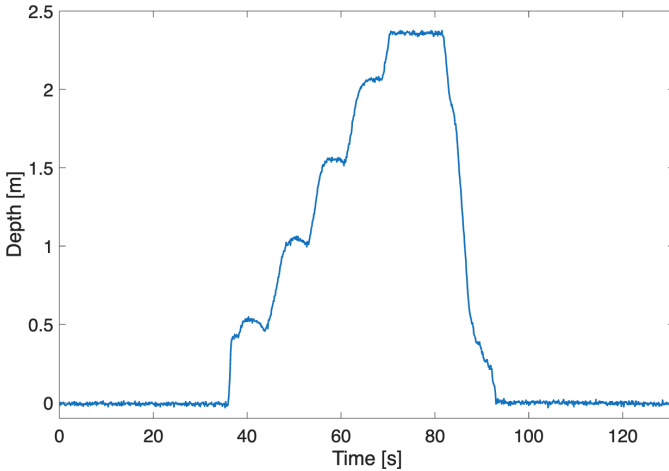


Fig. 9. Recorded depth data from the AUV diving to and hovering at waypoints 0.5, 1, 1.5, and 2m below the ocean surface, and at the ocean floor at Dana Point Pier.

The P-control was successful in holding the AUV's position at each waypoint, as over the 5 seconds it had to hold its position for, the largest overshoot was by 0.048m when the AUV attempted to reach the first waypoint at 0.5m. After the overshoot, the AUV almost immediately corrected itself and held its value within $\pm 0.02\text{m}$ before moving to the next waypoint. These depth variations are negligible compared to

the deepest deployment of 3m in one trial. The depth control algorithm as a whole was also successful, as the AUV was able to determine it had reached the seafloor at around 2.35m below the ocean surface and autonomously came up. The time it took for the AUV to determine it had reached the seafloor varied greatly between trials. In one trial, the AUV ran the depth control algorithm for around 10 minutes before resurfacing. This is because the algorithm determines if the AUV has reached the seafloor when the difference between maximum and minimum output voltages in a range of about 20 seconds is less than 0.05V. Environmental factors, such as other AUVs being simultaneously deployed, could have shifted the AUV underwater in this time frame and changed the output voltage, thus increasing the time spent on the seafloor.

B. Thermistor

The AUV also collected temperature measurements continuously. As shown in Figure 10, the collected temperature readings of a near-constant 28.0545°C were significantly higher than the obtained ground truth measurement of $18.4\text{--}18.7^\circ\text{C}$ from probing the seawater at the surface with a thermometer. Upon further analysis, these readings indicated that either the op-amps or the Teensy 4.0 likely railed out, because an output voltage of 0V from the thermistor interface circuit would result in this exact temperature value according to (1) and (3). Even for the non-constant values, such as the two sharp peaks in Figure 10, the temperature is significantly higher than the expected value.

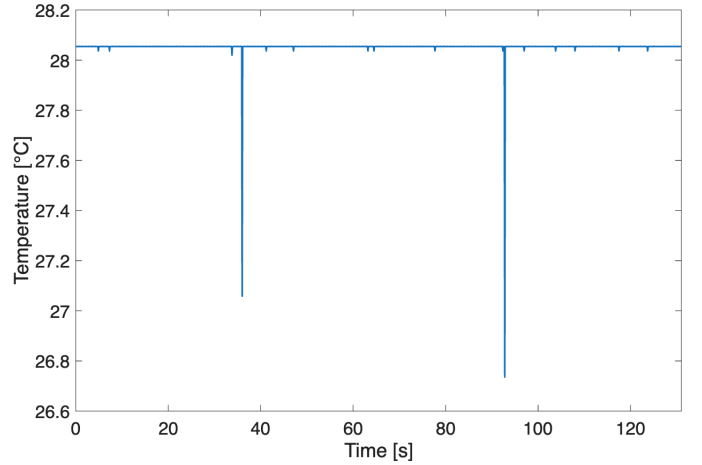


Fig. 10. Thermistor data collected during deployment at Dana Point Pier.

It was first hypothesized that the motors running drew too much current, and this could have prevented the thermistor interface circuit from working properly. However, data from the thermistor was collected in the air and with the motors running, and the thermistor read reasonable values similar to those mentioned in Section VA. It was then hypothesized that because the thermistor had reasonable readings in air and only railed out in the water, part of the thermistor was shorting in the water. The ends of the heat-shrunk areas of the thermistor were probable entry points for seawater, so they were dried

and then wrapped with parafilm in an attempt to waterproof them. However, this produced the same issue of railing out. The thermistor was then detached from the AUV, and its wire was slowly dropped deeper into the water. When only the head of the thermistor was in the water, output voltages indicated a temperature of around 12°C, but when more of the wire was put into the water, the circuit railed out. This means there was likely a nick somewhere along the wire insulation, and this caused the thermistor to short and effectively make its resistance negligible in seawater. The exact location of this hypothetical nick could not be determined. The obtained 12°C temperature is still significantly different from the ground truth measurement, indicating a separate issue with the thermistor interface circuit. One possible explanation for this issue is that, since resistors were desoldered and replaced to debug the thermistor interface circuit at Dana Point, the individual resistor values could have changed due to soldering at high temperatures of around 700°F.

C. Magnetometer

The magnetometer also behaved strangely in the water. As shown in Figure 11, when the AUV started descending in the ocean, the magnetic flux density reading would spike to an invalid value (874.733μT is out of the range of the RM3100's readings) and then read a constant value for the rest of the deployment.

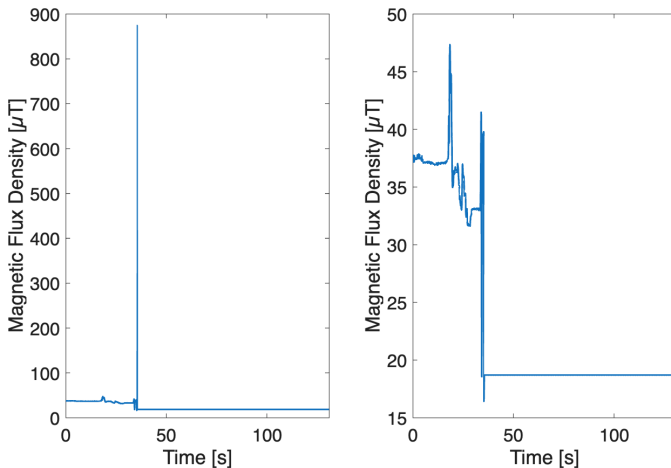


Fig. 11. Magnetic flux density during Dana Point Pier deployment with all data points (left) and with the peak value removed (right).

It was hypothesized that the motors produced electromagnetic interference (EMI), which interfered with the I²C data transmission. EMI can produce three types of errors in I²C sensors: no communication, erroneous values, and permanent values from the sensor [16]. This aligns with the collected data, in that the large spike is an erroneous value, and the constant value indicates either no communication or a permanent value being transmitted. To confirm this theory that motors producing EMI interfered with the magnetometer's I²C communication, a recreation of this spike and flatline pattern was attempted by taping a motor to a waterproof box with the

magnetometer and circuitry, running the code used at Dana Point on the same hardware, and dropping this setup in a tank of freshwater. With this setup, the magnetometer produced steady readings similar to those seen in Figure 6, without any anomalous peaks or flatlines. The magnetometer was then taken out of the box and pressed directly against the running motor. This produced the peak and flatline pattern. Upon further investigation with an oscilloscope, it was found that the DRDY pin output a constant HIGH signal when pressed against the running motor, meaning new data was never being pushed to the relevant registers. Because this pattern only occurred when the magnetometer and motors were far apart in seawater and not in freshwater, it is hypothesized that the seawater amplified the EMI more than freshwater, causing interference only in the Dana Point deployments.

VII. CONCLUSION

A. Summary of Results

This project aimed to determine the effectiveness of calculating geostrophic flow through pressure and temperature measurements and mapping seafloor debris through magnetometry.

The pressure sensor was the most successful sensor used. Its calibration curve had an extremely high R^2 value of 0.996, meaning its output voltages were well correlated with depth, even after amplification from the circuit. Additionally, it worked well with the depth control algorithm, in that the AUV correctly held itself at each waypoint within ± 0.02 m, correctly determined it had reached the sea floor with readings fluctuating by only ± 0.032 m, and surfaced on its own.

The thermistor did not produce any reliable readings underwater. It railed out at around 28°C in each trial. However, from testing, this was likely due to a break along the wire, which would have caused the sensor to short, and this is easily fixable through additional heatshrink or coating the wires with some waterproof material. The narrow 95% confidence intervals for the Steinhart-Hart coefficients from calibrating the thermistor imply that it was well calibrated and had high precision, and fixing this issue would have produced very accurate sensor readings.

The magnetometer did not produce sufficient data to locate seafloor debris at Dana Point. Although it failed to produce reliable readings at Dana Point, readings in the air fell within the expected range. Thus, further development and exploration into its behaviour with EMI from motors in seawater could improve the reliability of this sensor in the ocean, so that it could be used in a similar AUV.

Due to the inadequate temperature and magnetic flux density data, geostrophic flow was not calculated, and a map of seafloor debris was not obtained.

B. Recommendations for Future Work

As discussed in Section VI, the measured temperature from the thermistor circuit had serious discrepancies with the probed measurement, and the magnetometer readings could not be reasonably correlated with the true magnetic flux density

underwater. Future exploration would benefit from finding a better method to waterproof the thermistor and prevent shorts along its path, and exploration into preventing EMI from disrupting I²C sensor readings. After resolving these issues, attempting to characterize geostrophic flow and locating ferromagnetic debris on the seafloor using the collected data would confirm whether utilizing pressure, temperature, and magnetic flux density is a feasible method for accurately locating ocean wreckages.

As a proof of concept, Figure 12 shows a contour plot of magnetic flux density collected by scattering neodymium magnets on the floor outside of Parsons Engineering Building in Claremont, CA, and plotting collected magnetic flux density readings from the magnetometer corresponding to GPS-obtained positions. The peak value at around (4833, -1817) and other elevated values at (4846, -1813) and (4839, -1815) roughly correspond to the magnet locations. Assuming more reasonable magnetic flux density readings can be obtained in the ocean, a similar plot outlining the location of ferromagnetic materials on the seafloor could be acquired.

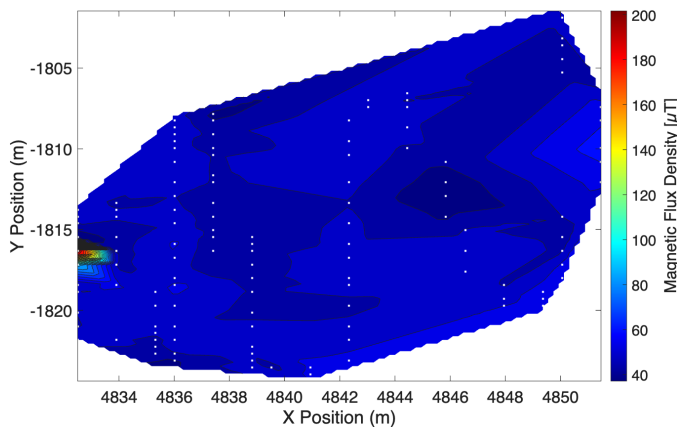


Fig. 12. Contour plot of magnetic flux density collected outside Parsons Engineering Building, Claremont, CA. Positions are with reference to the set origin of (34.1226883, -117.7650364).

Besides improving the method outlined in this paper, work using other sensors that would encompass a more comprehensive view of seafloor debris should be considered. Sensors such as high-resolution side-scan sonar could be used to confirm if detected ferromagnetic materials on the seafloor are actually relevant debris or just part of the ocean's natural ecosystem. In addition, the high error in the GPS made surface control at Dana Point very unreliable and unusable. Using a more accurate GPS module would increase the accuracy of plotted values in the contour plot and enable the AUV to traverse to various surface waypoints and start depth control at remote locations autonomously.

ACKNOWLEDGMENT

Thanks to Xavier Walter for helping to integrate the magnetometer with the E80 codebase and providing an additional sensor when the initial one burned out, Lynn Kim for helping with circuit and hardware debugging and providing moral

support, and all the E80 Professors and Proctors for their help, support, and encouragement throughout the project. Additional thanks to Faviola Salazar and Karis Peebles for providing a pool testing location and transportation, Jessica Li for providing a ground truth pressure reading, and Freja Johnson and Amy Enayati for peer reviewing this report. The author also acknowledges the members of Team 25: Rebecca Kong, Osiel Salazar, and Cian Bryant, who made this project possible.

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