ARTIFICIAL REEF: SEEKING LIFE IN UNKNOWN WATERS

A Design Project Report

Presented to the School of Electrical and Computer Engineering of Cornell University

in Partial Fulfillment of the Requirements for the Degree of

Master of Engineering, Electrical and Computer Engineering

Submitted by

Vicky Le and Grace Lo

MEng Field Advisor: Van Hunter Adams

Degree Date: December 2025

Abstract

Master of Engineering Program

School of Electrical and Computer Engineering

Cornell University

Design Project Report

Project Title: Artificial Reef: Seeking Life in Unknown Waters

Author: Vicky Le and Grace Lo

Abstract: The discovery of extraterrestrial life requires reliability, autonomy, and durability to detect life for years after deployment. This project explores how artificial reefs can be constructed to attract and detect small-scale life using low-power embedded systems, including optical beam break and Hall effect magnetic detection, to identify when life is present within the reef. Real-time signal processing and event detection are done for the system to operate autonomously and selectively collect data regarding the presence of life without human interference. Low-power usage is also explored to extend the life of deployment and increase the probability of life detection. With the emphasis on reliability, durability, and extended deployment, a proof-of-concept artificial reef structure was designed, implemented, and tested to show the ability to detect small-scale life

Executive Summary

This project developed and evaluated a proof-of-concept artificial reef sensing platform designed to autonomously detect and validate signs of life in remote environments, where continuous human supervision is infeasible. The artificial reef structure is a passive life attractor based on the assumption that if life exists, it will inhabit structures placed in its environment. Motivated by the challenge of detecting life on extraterrestrial bodies such as Jupiter's moon Europa, the system explores how two levels of embedded sensing can be combined into a durable and low-power platform.

The system successfully implemented an autonomous life detection reef consisting of a first-level beam break and hall effect sensing system to detect organism movement and a second-level camera validation system to capture the organisms. These systems are controlled by a Raspberry Pi Pico and a Raspberry Pi 4, respectively, where a trigger signal from the Pico notifies the Pi to take a picture. Both the beam break and hall effect system demonstrated reliable detection through acrylic and water, and scaled effectively from benchtop testing to reef-length configurations. Integrating a custom PCB-based photoresistor array improved durability, alignment tolerance, and scalability compared to breadboard prototypes.

Three rounds of testing validated system functionality at increasing levels of complexity and environmental conditions. During large-scale integrated testing, the system consumed approximately 2000 mAh of power, corresponding to roughly 10 W average power consumption, which is significantly lower than the power consumption of existing satellites.

Overall, this project demonstrates the feasibility of an autonomous, low-power sensing platform capable of detecting and validating biological activity without human intervention. The results establish a strong proof-of-concept design and identify clear paths for future improvements, including improved sensor integration, mechanical design development, renewable power integration, and enhanced discrimination between biological and non-biological events.

Acknowledgements

We would like to thank Professor Hunter Adams for his guidance, feedback, and support throughout this project and Professor Skovira for providing supplies that were essential to the development process.

Member Contributions

Both members contributed during the formulation phase of the project, each researching and pitching ideas for potential solutions to the problem of detecting life in unknown waters. We came together with our advisor Professor Hunter Adams to discuss the best solution and define the scope of the project for this first proof-of-concept prototype. At that point, the work was divided with Vicky focusing on the Pico-based detection system and Grace focusing on the Pi-based validation system. The division was not rigid and we regularly exchanged ideas and assisted each other with development. In later stages of the project, for example with the PCB design, we each worked on one design to see who would come up with the best solution. Once we reached the integration step, we worked together assembling, testing, and optimizing the system. Both members documented progress throughout the two-semester project and contributed to the final poster and report.

Introduction

The discovery of life beyond Earth would mark a transformative milestone in our understanding of evolution, planetary habitability, and adaptation to extreme environments. It would be a groundbreaking milestone for both science and humanity as it would show the possibility of another body in the solar system to support life and allow for human habitation, potentially for long-term human settlement. Furthermore, this discovery would improve our understanding of biology and evolution by offering insights into the evolution of life and the basic requirements for life to begin and thrive. Scientists have identified several exoplanets and moons that have the potential to host life. The "habitable zone" is the distance from a star at which liquid water can exist and a planet can have the proper conditions for life [1]. There are 70 candidates on the habitable worlds catalog, with varying levels of probability [2]. Within our solar system, Jupiter's moon Europa shows strong evidence of the ingredients needed for life: water, chemistry (carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur), and energy [3]. The instrumentation of an artificial reef aims to explore the possibility of finding extraterrestrial life and give insight into the habitability of new bodies.

This project introduces a proof-of-concept system designed to autonomously search for signs of life in remote environments, with the long-term goal of adapting this technology for use on other planets. Living organisms on Earth tend to inhabit structures placed in their environment (e.g. shipwrecks). If this is a general property of life, offering homes and hiding places can enable the detection of life elsewhere. A small-scale, self-sustaining platform on Earth, modeled after an acrylic artificial reef, can be placed in conditions to simulate the types of habitat and biological interactions that might exist in extraterrestrial settings. The system will operate independently for extended periods, monitoring biological activity without human intervention. This capability is essential for future missions to distant planetary bodies, where continuous human supervision is not possible. In this project, life is defined as any organism or system that can perform essential biological processes, including metabolism, growth, reproduction, and the ability to respond to stimuli, and focus on organisms on the centimeter or larger scale.

Design Problem

It is infeasible to rely on constant human supervision to search for life in remote extraterrestrial environments with harsh and unpredictable conditions, so a device must be created to detect signs of life over long periods of time without human intervention. This system must be designed to be deployed once then continue to self-sustain as it collects data reliably and accurately to detect signs of life. This functionality must last over long periods of time to increase the chance of life detection (on the magnitude of years). To address these requirements, a smaller proof-of-concept system was designed and deployed to operate autonomously and store data for manual retrieval after several hours, thus simulating how this system will behave on extraterrestrial environments. In summary, the system will:

- detect life on the centimeter or larger scale
- validate life detection through capturing pictures
- be durable and autonomous for extended remote deployment

Trade Study

The exploration began with an extended trade study to determine viable solutions for life detection. In particular, ideas include changes in patterns, movement, and environment that indicate the presence of life. The rather obvious answer is to use an underwater camera as the "eyes" of the system [4]. The footage can be reviewed after deployment for confirmation of life. Furthermore, computer vision models can be added to scan for life, but for this application, it would add computational complexity and extra power draw that may not even detect the proper image, since fish on Earth may not look like fish on Europa.

The fishing industry is also trying to locate fish and uses sonar on a much larger scale [5]. Sonar detects objects by transmitting a sound wave and looking for how it is interrupted or reflected. In the context of this project, this can be implemented as a beam break system, where a laser beam is transmitted and interruptions would mean that fish are present. Similarly, hall effect sensors can leverage disturbances caused by a fish's movement to trigger a detection when its corresponding magnet is moved.

Some ideas draw inspiration from animals themselves. Catfish, in particular, can detect slight changes in the water's pH [6], suggesting that chemical sensors (e.g. pH or ammonia) can detect chemical markers associated with organisms. This can potentially also address the challenge of detecting microbial life. Fish also have a “sixth sense” known as lateral line that can detect movement, vibrations, and pressure changes underwater. Ongoing research is being completed at the Ocean University of China for lateral line imitation using piezoelectric flow sensors and MEMs-based technology to detect differences in water pressure [7]. Given that the lateral line technology is still in the research phase, it is interesting to explore as a future feature of the artificial reef, but was not chosen for the initial proof-of-concept design.

Life attraction systems were also considered to augment the system and increase the likelihood of life detection. Artificial reefs are manmade structures placed in oceans to create complex habitats to host life. These passive systems attract life by providing shelter to marine organisms [8]. Active attraction systems include light and low-frequency sounds. Some research has found that green light [9] and low-frequency sounds (<20 Hz) [10] can attract marine life. Given the many unknowns of extraterrestrial bodies, it is not obvious which exact sensor or would best detect organisms, so a collection of systems is likely the best choice to increase the likelihood of detection. Furthermore, these sensor systems alone can neither confirm nor deny life, but in combination may provide strong enough confidence to conclude the existence of life. So exploring life detection in conjunction with life attraction enables the development of a robust system that attracts and captures life.

The focus of the first prototype is on passive life attraction in the form of an artificial reef and a two-level life detection system. The first-level is a cheap and low-power sensing system that continuously monitors the artificial reef’s surroundings. Motion detection is achieved via beam break and hall effect sensor, which are low-power analog devices with low computational requirements, lending well to autonomous deployment for extended periods of time. Their simplicity reduces potential electronic failures and with sufficient redundancy, the system is tolerant to individual sensor failures. Unlike chemical sensors, they do not need calibration, which makes them well-suited for unknown environments. Both sensors are also paired with a second-level camera system for validation. The second-level is more expensive and consumes more power, but provides higher confidence in the system’s life detection. To mitigate the cost and power impact from the second-level, the camera is only turned on when triggered by a first-level sensor. The hierarchical approach balances confidence in detection with cost and power.

Design

Reef System Design

In order to attract and detect life, the system contains 2 main components: the mechanical reef structure and the life detection systems. These components work together to provide a physical shelter/structure for life to inhabit and also an autonomous sensing platform to document the presence of small life forms. Figure 1 is the concept design of the reef system. The reef structure (gray) is submerged in the water (blue) with cutouts filled with water as cavities for fish to swim through. Various sensing systems, including hall effect, photo receiver, and camera, are also labeled, showing the instrumentation of the artificial reef.

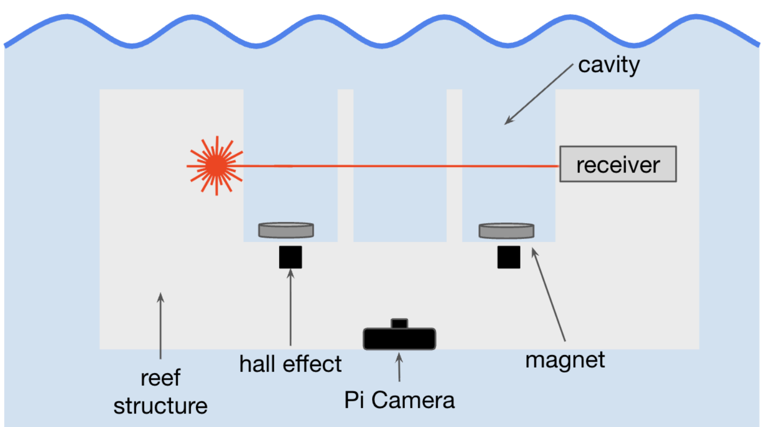

Figure 1: Reef Structure Containing Life Detection System

Mechanical Structure

The mechanical reef structure is a stacked design consisting of laser-cut clear acrylic and is based on the monolith from the 2001 film *A Space Odyssey*. It provides a physical structure to attract life and house all onboard sensors. Each acrylic sheet contains laser cut openings of varying sizes as seen in Figure 2, and these sheets are vertically stacked and bonded using acrylic solvent cement to create cavities of varying sizes as shelter for life to inhabit and to hold the life detection system.

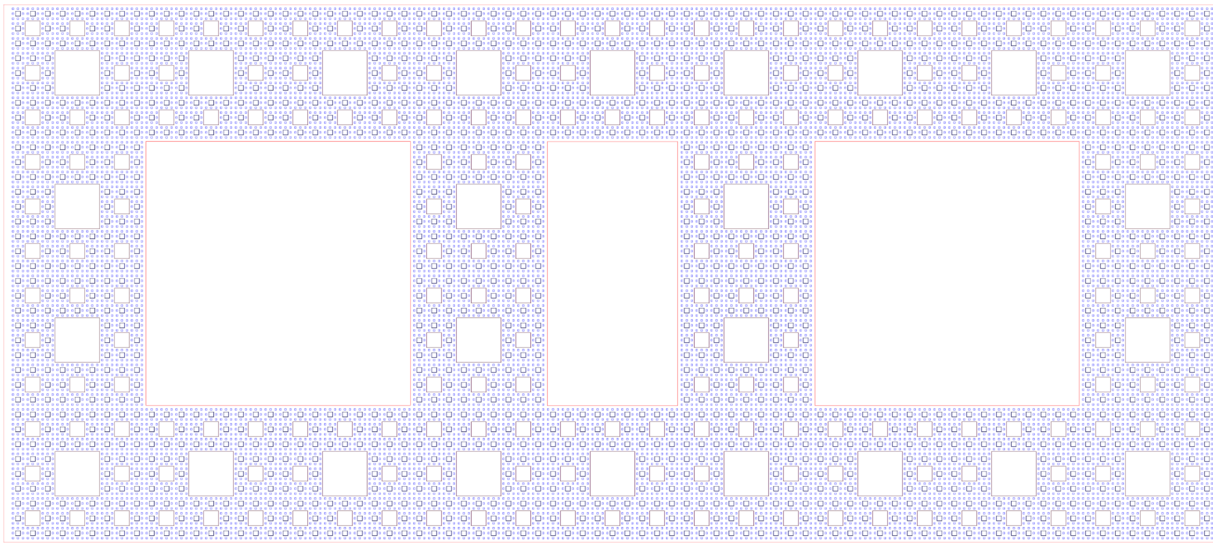

Figure 2. Cross-Section of Acrylic Sheet

These cavities are arranged symmetrically so sensing elements, such as the beam break system, can be mounted on one side of the reef and the receiver is on the other for laser beams that span the length of the reef. The use of clear acrylic also allows the laser beam to freely pass through cavities and be received on the other side of the reef, meaning that one transmitter/receiver pair can monitor multiple cavities across the whole length of the reef.

Additionally, cavities are used to arrange magnets for the magnetic sensing system, where magnets are placed in cavities directly above the hall effect sensor. These cavities are spaced further apart such that there is no interference between cavities so hall effect sensors are only detecting the effects of the magnet in the cavity directly above it.

The stacked design of the structure also acts as a shield to water turbulence and assists in isolating detection to that of living organisms rather than turbulence of the surrounding waters. Furthermore, the geometry with various cavities and overhangs mimics natural reef structures to attract life.

Implementation

Life Detection Systems

Two main detection systems were designed to autonomously detect the presence and movement of small forms of life within the reef, while minimizing power consumption and unnecessary data collection. Figure 3 presents a system diagram with a Raspberry Pi Pico and a Raspberry Pi 4 used to control the detection and validation systems, respectively. The Raspberry Pi Pico acts as the controller for life detection and contains the beam break system and the hall effect magnetic sensing system, while the Raspberry Pi 4 is used for validation, such that a picture is captured upon a trigger signal sent from the Pico. The communication between the Pico and Pi 4 is through general-purpose input/output (GPIO) pins connected via a jumper wire. When the Pico detection system sets the GPIO high, the Pi 4 receives the signal as if a button was pressed and will momentarily turn on the camera to snap a photo.

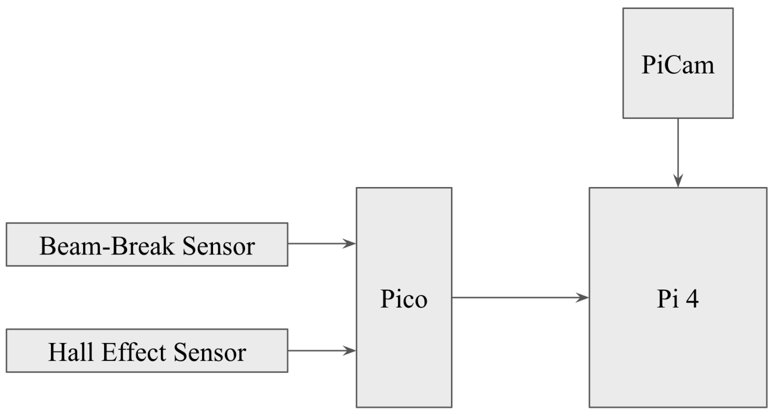

Figure 3: System Diagram

Hall Effect System

The magnetic sensing system is implemented through the use of hall effect sensors that detect variation in magnetic fields. During the implementation of this system, 2 different hall effect sensors were used. Initial testing was done with a A3144 digital hall effect sensor which outputs a boolean signal upon detection of a larger deviation in the magnetic field, however since even small deviations in the magnetic field correspond to movement that could be due to life an analog hall effect sensor was explored. The SS49E hall effect sensor provides fine-grained output readings to detect smaller changes in magnet movement. This finer-grain control also allowed for testing to determine if there is movement due to water turbulence or due to movement from an organism.

To test the hall effect system various experiments were done to determine the best magnets for the system and distances needed between sensors to prevent detection of multiple magnetic fields. From this testing it was determined that having larger deviations in the readings from the hall effect sensors is proportional to the magnet strength and size as a result the best magnets were neodymium magnets that are with ⅛” radius so that they are small enough to be able to fit into the cavities of the reef and strong enough to provide stable readings to the hall effect sensor through the acrylic. From this, a maximum detection radius of 3” from the location of the hall effect sensor, meaning magnets and hall effect sensors should be placed in cavities approximately this far apart.

Due to mechanical limitations of not having a full, stacked reef design and not having a method to secure the magnets, the hall effect system was not implemented into the final designed system.

Beam Break System

For the detection of the presence of life, a beam break system consisting of a low-power laser diode mounted on one side of the reef structure and an optical receiver is positioned directly opposite. For the optical receiver side, an array of photoresistors is used where the laser beam constantly shines on the photoresistors. The NSL-6112 photoresistor was chosen for its ideal reading ~620 nm, which is fit for red light wavelengths ranging from ~620 to 750 nm. Figure 4 shows the wiring diagram for a photoresistor, which is set up in a voltage divider with a 10 kΩ resistor to provide more stable readings and better detect variation in light intensity in comparison to direct reading of the photoresistor. The original system alone was able to detect laser beam interruptions from up to 18.5 feet apart in open air

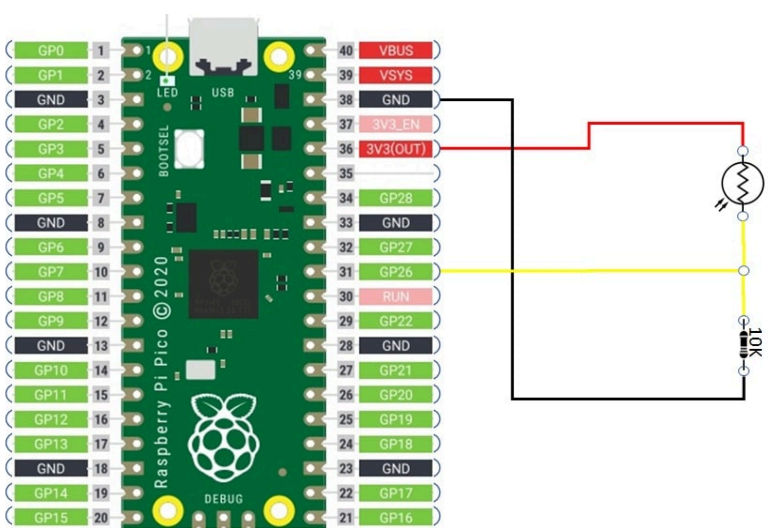

Figure 4: Photoresistor Wiring Diagram

Additionally, a printed circuit board (PCB) was created to increase the durability and reliability of the system in comparison to original breadboard prototyping. It also increases the scalability of the design by simplifying assembly to soldering electronic components. This array is created on a 66 mm x 60 mm 4-layer PCB, as seen in Figure 5, to create a larger area for the laser beam to target in case of laser attenuation. The 4 layers of the PCB have full ground and power planes for stable voltage distribution and allow for easy routing within the compact array. Additionally, 2 signal planes are used for easier routing and avoiding the criss-cross of wires, and to allow for closer placement of components.

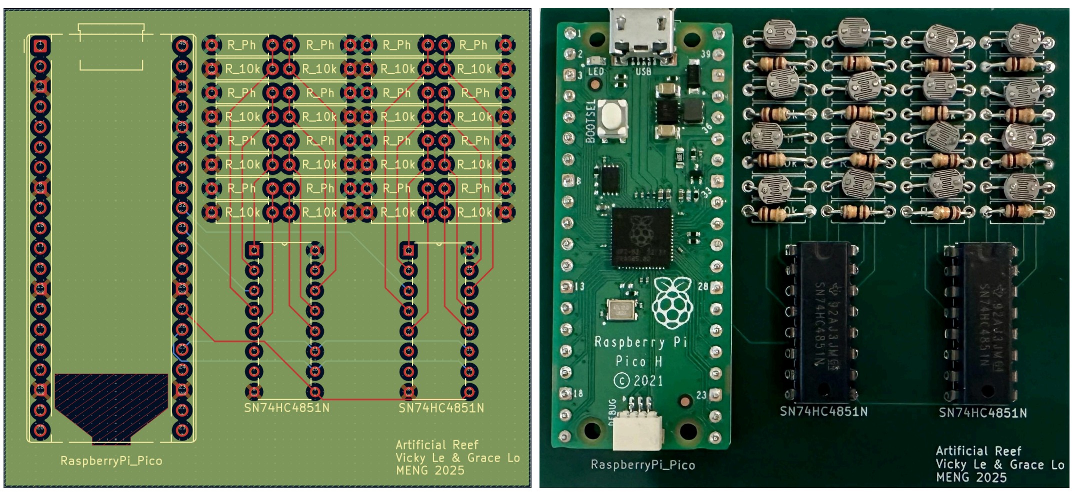

Figure 5: PCB for Photoresistor Array

The beam break system went through several iterations before arriving at this final setup. Initially, the analog values were directly read from the photoresistor. However, the Pico analog-to-digital (ADC) converter pin can only read analog voltages, so the photoresistor was integrated into a voltage divider for the resistance to voltage conversion and also to provide a stable reference. A 10 kΩ resistor was chosen to maximize resolution over the useful range based on the minimum and maximum resistance of the photoresistor. Beam break triggers are determined when the difference in light readings exceed a certain threshold. Testing also shows that there is an issue where readings from photoresistors are very noisy, which leads to false detections. To resolve this issue, a software low-pass filter was implemented to filter out the noise from the read signal. Additionally, testing also showed that upon powering on of the device there is a short period of time where values are very unstable so a short sleep is embedded into the code to account for this settle time. Double detections were observed because there would be a large reading difference when the laser beam is blocked and restored. This was resolved by properly calibrating the system to a sufficient threshold value and using only falling edge detections to cause a trigger.

Mux

Since the Raspberry Pi Pico is limited to 3 ADC converter pins, SN74HC4851N 8-to-1 muxes were used to expand the number of available analog pins. These muxes work by connecting the input pin on the mux to an ADC pin on the Pico and internally the mux flips which mux input to read to effectively expand the number of analog pins. In terms of software, each of the 8 channels has an address. So by changing the read address, each of the 8 channels can be read individually.

Within the PCB, the muxes are used to create a 4x4 photoresistor array since the hall effect system was not implemented due to mechanical limitations. In the future, one mux can be used for photoresistors and the other for hall effect sensors.

Camera

For validation that life was successfully detected, a Pi camera 3 was connected to the Raspberry Pi 4 to capture images for post analysis to determine whether it was a true or false detection of life. The images are named using the current date and time for better organization and easier analysis across a longer time domain. The camera is mounted to the side of one of the cavities to capture images of organisms interacting with or moving through the reef. Particularly, the Pi camera 3 has an autofocus feature to improve clarity of images. Due to storage and power limitations, the camera only captures after receiving a trigger signal from one of the life detection systems.

The power consumption of the Pi and camera system was also characterized in Table 1, using Nordic Semiconductor's Power Profiler Kit II, to determine the ideal setup. Given that $P = IV$ and V is a constant 5 V supplied through the Pi's power cable, power is proportional to current. Thus the average current measured can be compared for relative power differences. The baseline design uses the Bullseye Full operating system (OS) with the graphical desktop to ease design and testing of the camera system. Next, a headless system running off of SSH led to a ~30 mA decrease because peripherals (e.g. keyboard, mouse, and monitor) do not need to be powered. Luckily, this will be the system used in the final design since there are no monitors on Europa anyways. Disabling peripheral ports (e.g. USB and HDMI) was also explored, but its 2mA difference was negligible and likely picked up measurement noise. Finally, the Raspberry Pi OS was changed to a Lite version deploying a minimal command line to see if there were any differences. Over the course of the project, Raspberry Pi came out with a new Trixie OS, making Bookworm the new legacy version instead of Bullseye. So in addition to the change to the Lite version, the OS was also upgraded to Bookworm. The Bookworm Lite version had similar results to Bullseye Full, however the lite version uses less RAM and storage space, leaving more SD card space for photo capture. In conclusion, the final ideal setup is a Raspberry Pi 4 running the Bookworm Lite OS on a headless system that only accesses the Pi via SSH.

Condition	Average Current (mA)	P = IV (W)
Bullseye Full (Running off of Desktop)	480.57	2.40285
Headless via SSH	452.85	2.26425
Headless + Disabling USB	454.02	2.27010
Bookworm Lite	488.47	2.44235

Table 1: Power Profile of Various Pi + Camera Setups

Testing & Results

Three rounds of testing were conducted to confirm the functionality of the integrated system, each targeting different goals. The first round of testing aimed to determine the effectiveness of the sensing systems through acrylic and water. The second round of testing was composed of a larger scale test utilizing the detection systems when fully submerging two electronic enclosures containing transmitters and receivers. The third round of testing focused on the effectiveness of the system over a longer time duration and under varying conditions.

Acrylic and Water Transmission Test? (spoon fish)

This test focused on validating the operation of detection systems through acrylic and water. For the beam-break system, the laser transmitter was placed inside a watertight electronic enclosure which was submerged within a 10” x 10” x 10” acrylic box filled with water, and the receiver side was placed opposite this enclosure on the side of the acrylic box. The hall effect sensors were placed beneath the acrylic box to test the effectiveness of the system. Figure 6 shows the setup of this acrylic box, transmitter, and receiver.

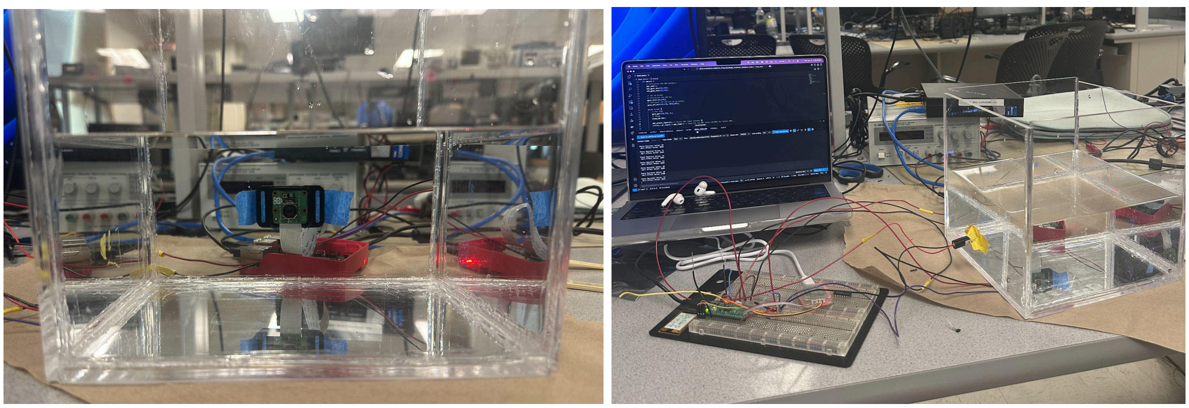

Figure 6: Acrylic and Water Transmission Testing Setup

Within the electronic enclosure was an AA 2 battery holder to power the laser diode to provide a stable laser beam. One issue that was encountered during the testing process was due to the not filling the enclosure entirely and having a large amount of air trapped. The enclosure had the tendency to float, so for this experiment, external weights were placed on top of the enclosure. This issue also led to future design changes to include weights to keep the structure stationary and submerged.

Outside of the acrylic box was the receiver side, where the photoresistor was manually lined up with the laser beam and then a plastic spoon was used to manually block the laser beam. Figure 7 shows the successful detection of beam interruption, demonstrated through manual testing of blocking the laser beam and then validating that a picture was captured upon detection of the beam breaking system.

Similarly, hall effect sensors were evaluated by placing magnets underneath the acrylic box and submerging the magnets to verify that the magnetic field variations remained detectable despite the presence of acrylic and water. To verify the effectiveness of the hall effect system, an oscilloscope was used to probe the read signal of the hall effect sensor and observe the variations in the analog signal resulting from the movement of the magnet within the acrylic box. Following analyzing the steady state readings of the hall effect sensor, detection code was written such that when there was a large enough deviation from typical readings, an LED was toggled to be on, indicating detection. For this test, the camera was not triggered due to the camera not being in a position to capture the cause of detection.

These tests confirmed that neither the structural material nor the aquatic environment significantly attenuated sensor signals, establishing the effectiveness of these detection systems for use in an underwater environment.

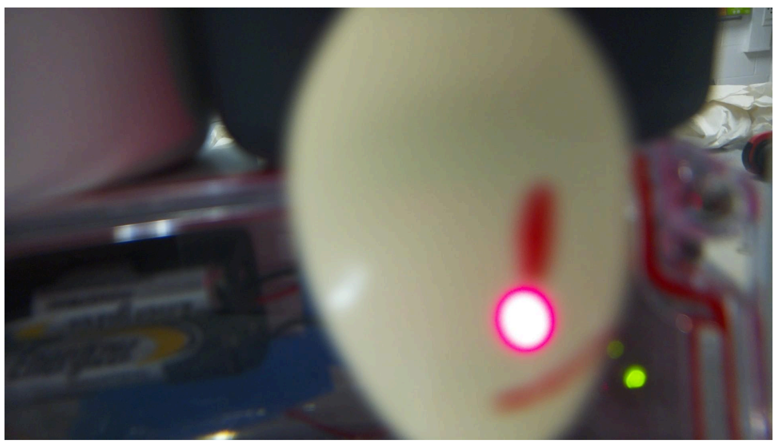

Figure 7: Spoon Fish Detected

Submerged System Test? (Cardboard Fish)

The second round of testing focused on sensor performance at a larger scale more representative of the full reef length. A breadboard-based prototype, in Figure 8, was constructed to replicate the relative placement of sensors, laser transmitter, and receiver across the anticipated distance within the reef structure. The Raspberry Pi Pico communicates to the Raspberry Pi 4 via a single jumper wire to take a photo.

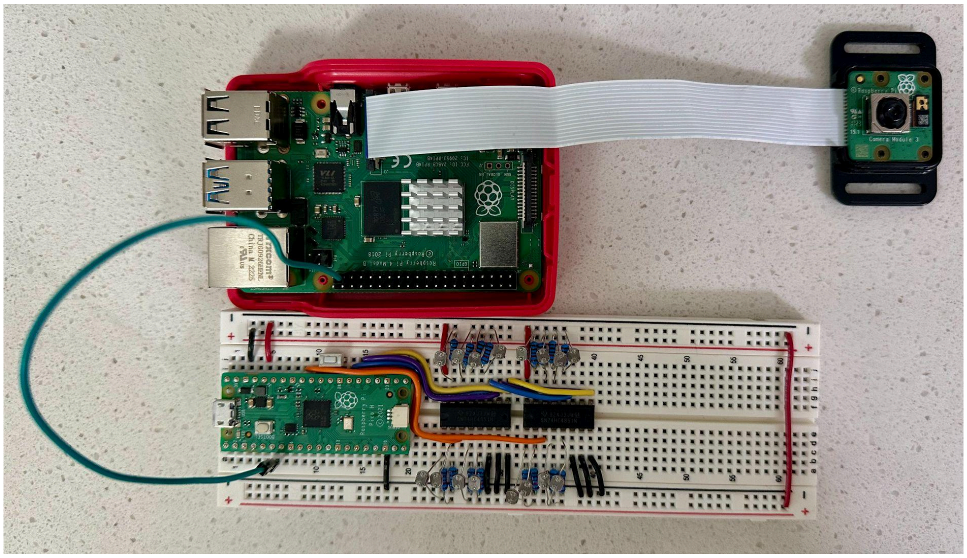

Figure 8: Breadboard Prototype with Raspberry Pi Pico and Pi 4

Figure 9 shows the testing setup with two electronic enclosures used to protect the electronics. The enclosure on the left holds a red laser diode and a 2 x AA battery holder. The diode is rated for 2.8 - 5.2 V DC voltage input, so two AA batteries satisfy the minimum and provide a longer battery life. The enclosure on the right holds the breadboard prototype powered by a 10,000 mAh portable charger with built-in USB-C and micro-USB cables. The use of a portable charger streamlines the power system since the Pico is powered through a micro-USB cable and the Pi 4 is powered through a USB-C cable. Note that this configuration works because the Pi 4 is a single board computer and draws sufficient current to keep the portable charger on. If the system consisted of a Pico alone, it would not draw enough current to keep the portable charger on and a different power source that remains always-on would have to be used. Finally, the enclosures are aligned so that the laser diode aims for the photoresistors.

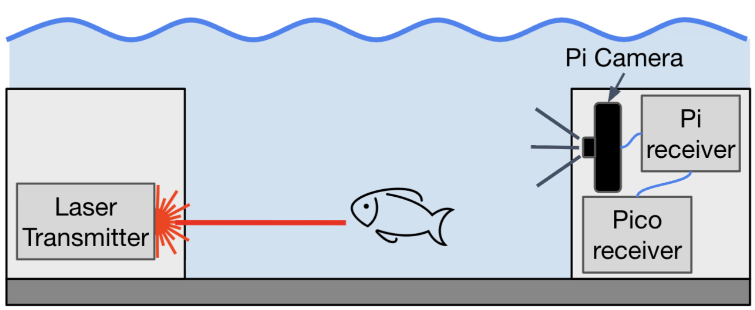

Figure 9: Testing Setup

This configuration evaluated signal integrity, alignment tolerance, and detection reliability over extended distances. The beam-break system was tested to ensure the laser could consistently reach the receiver across the full span while remaining sensitive to partial and complete occlusions. Figure 10 shows the successful detection by manually blocking the laser beam with a model fish. Hall effect sensing was also evaluated at increased spacing to examine magnetic field strength decay and potential coupling effects. This stage validated that the sensing concepts scaled beyond benchtop distances and informed design parameters for the final mechanical layout.

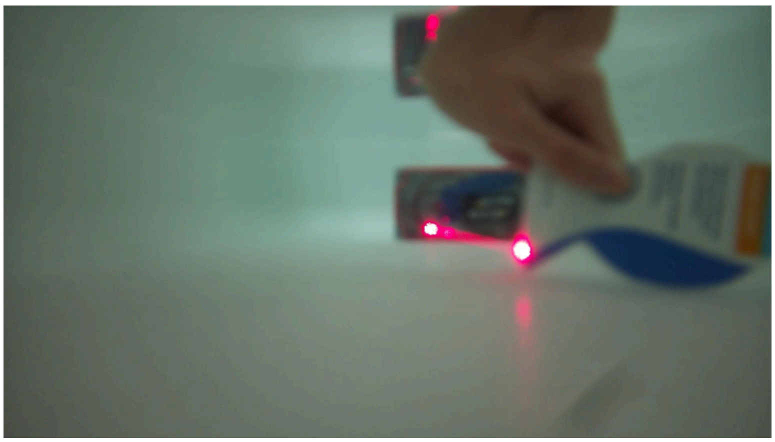

Figure 10: Cardboard Fish Detected

Extended Period Testing Under Varying Environmental Conditions

The final round of testing evaluated the long-term durability, stability, and environmental robustness of the integrated sensing system. Unlike previous rounds—focused primarily on validating signal transmission through acrylic, water, and across reef-length distances—this test assessed how the system performs over extended deployment periods under dynamic, variable conditions representative of real aquatic environments. A PCB-based prototype was assembled to test the effectiveness of the photoresistor array in various conditions. These conditions include high levels of light, low levels of light, and turbulent water conditions. For the setup of this test, the electronic enclosures were secured to a single acrylic reef sheet (4’ apart) to demonstrate the ability of the system to withstand longer periods of deployment and to ensure that there is no drift of equipment or the laser beam following deployment. Within the electronic enclosures, the equipment remains the same for the laser transmitter side, however, on the receiver side, the designed photoresistor array PCB was used for sensing rather than the breadboard prototype. Testing in this round is set up as shown in Figure 11, where the electronic enclosures are secured to the acrylic reef sheet with 2 robotic fish Nemo and Dory swimming in the water. Nemo and Dory move autonomously to simulate living organisms in the environment.

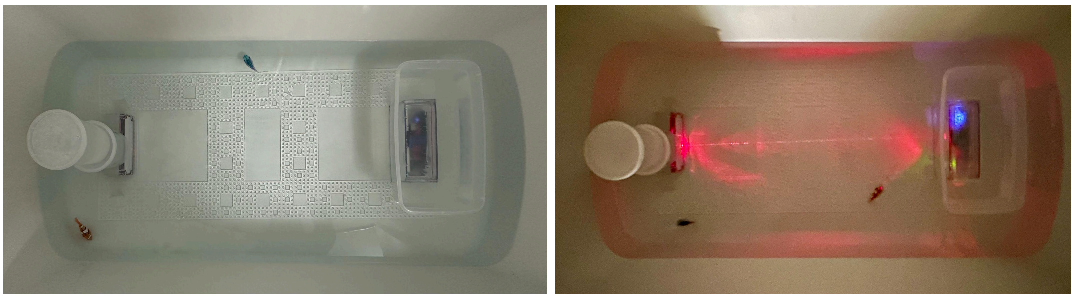

Figure 11: Testing Setup in Light (left) and Dark (right) Conditions

The system was set to run for three hours, with the first half in light and the second half in the dark. Figure 12 shows image captures of the fish in light and dark conditions. The laser beam appears much brighter in the dark condition as compared to the light condition, suggesting that the range of detection would be better and more sensitive for dark conditions.

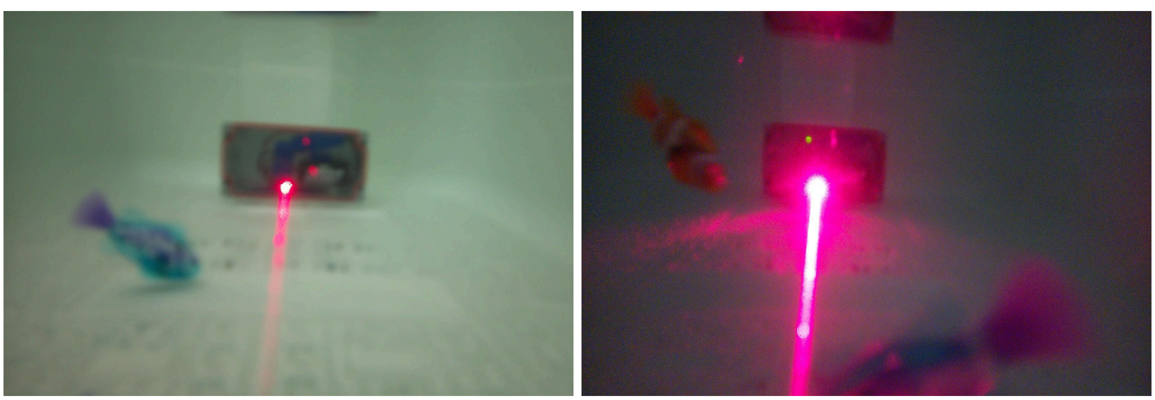

Figure 12: Robot Fish Detected in Light (left) and Dark (right) Conditions

Separate turbulence tests were completed by splashing the surface of the water. The artificial reef submerged in a shallow area is more sensitive to turbulence than one submerged in a deeper area. This is because the surface water reflection is more pronounced and the waves cause more light reflection. This issue can easily be fixed by submerging the reef in a deeper area.

Additionally, power consumption was analyzed for this test to determine the current length of deployment. The entire system consumed approximately 2000 mAh of power over the course of the three hour test, which means with the current portable charger, the total run time of the system is 15 hours. This translates to approximately 10W in comparison to 40W average power consumption of current satellites [11].

Bill of Materials

Item	Quantity	Price	Notes
Printed Circuit Board	1	$1.40	Username: Artificial_Reef Password: ArtificialReef2025
Raspberry Pi Pico RP2040	1	$4.00	
SN74HC4851N 8:1 Mux	2	$1.18	
NSL-6112 Photoresistor	16	$22.56	
10kΩ Resistor	16	$0.32	
2 x AA Battery Holder	1	$1.30	
AA Battery	2	$2.00	
Red Laser Diode	1	$5.95	
Raspberry Pi 4 Model B - 1 GB RAM	1	$38.50	
Aluminum Heat Sink - 15 x 15 x 15mm	1	$1.95	
Raspberry Pi Camera Module 3 Standard - 12MP Autofocus	1	$29.25	
10000mAh Portable Charger with Built-in USB-C & Micro-USB Cables	1	$10.00	
Serpac RB63 Electronic Enclosure	1	$20.90	Top: Clear Bottom: Clear Top Height: 15 mm Bottom Height: 40 mm
Serpac RB85 Electronic Enclosure	1	$31.66	Top: Clear Bottom: Clear Top Height: 15 mm Bottom Height: 60 mm
Total		$170.97	

Conclusion and Future Work

After multiple rounds of testing, the proposed structure and detection methods have the potential to accurately detect life autonomously, reliably, and for extended periods of time. Life detection methods such as beam breaking and magnetic sensing have been proven to detect both the presence and movement from organisms under different environmental conditions, giving confidence in the system's ability to autonomously identify and record potential biological interactions.

Despite these successes, several limitations were identified. While the system could detect movement within the reef, distinguishing living organisms from non-biological debris such as drifting particles or transient disturbances remains a challenge. Furthermore, there are many opportunities and directions to explore and expand upon the reef, including adding redundancy for reliability and increasing probability of detection, implementing self-sustaining energy sources, integrating life attractor systems, developing long-distance communication, and expanding detection capabilities to expand the scale of life detected from the mm scale to microbial level.

With base instrumentation for detection systems done, it is important to add redundancy into the system because, for remote deployment, it is important to have backups in the case that the detection system goes down. Adding redundancy, such as additional optical and magnetic sensing systems across the reef to allow for detections, both increase the probability of detection, but also increase failure tolerance. In addition to adding redundancy, the mechanical structure of the reef will be fully constructed to include chambers for the hall effect sensors, internal cavities to hold sensing equipment, and adding in cavities that are partially covered and holes to better model a reef structure and provide shelter for potential life.

Life attractor systems in the forms of light and low-frequency sounds will also be added to the system which can be turned on or off for certain periods of time to attract life through providing different stimuli. Additionally, different sensors could be used to detect life on different scales, such as microbial life forms through use of chemical sensors measuring changes in pH or concentrations of essential elements like oxygen or nitrogen. Furthermore, sensors to detect life with translucent bodies will need to be explored.

For deployment in remote places over extended periods of time, the system must also be self-sustainable, so power generation through solar or tidal could be explored as energy sources to maintain the system's operation for extended deployments. Communication and the ability to extract data from the system is another important design aspect. For the current goal of deployment on Europa, the surface of the water is relatively still, which allows for communication via creating wave patterns on the surface of the ocean detected by a satellite. Overall, there are many directions of exploration before the system is ready for deployment on extraterrestrial bodies, but even at its current state, the system demonstrates the ability to detect life in a reliable manner while maintaining a low power profile.

References

[1] “The habitable zone - NASA science,” NASA, https://science.nasa.gov/exoplanets/habitable-zone/ (accessed Apr. 20, 2025).

[2] PHL @ UPR Arecibo - Habitable Worlds Catalog, https://phl.upr.edu/hwc (accessed Apr. 20, 2025).

[3] “Ingredients for life,” NASA, https://europa.nasa.gov/why-europa/ingredients-for-life/ (accessed Apr. 20, 2025).

[4] A. Whittaker, “Watch your fish with a Raspberry Pi camera - Raspberry Pi,” Raspberry Pi, Jan. 23, 2023. https://www.raspberrypi.com/news/watch-your-fish-with-a-raspberry-pi-camera/ (accessed Dec. 08, 2025).

[5] C. Knowlton, “How is sound used to locate fish?,” Discovery of Sound in the Sea, Jan. 02, 2019. https://dosits.org/people-and-sound/fishing/how-is-sound-used-to-locate-fish/

[6] Louisiana State University, “Biologists identify unique way catfish locate prey,” Phys.org, Jun. 05, 2014. https://phys.org/news/2014-06-biologists-unique-catfish-prey.html (accessed Dec. 09, 2025).

[7] G. Liu, A. Wang, X. Wang, and P. Liu, “A Review of Artificial Lateral Line in Sensor Fabrication and Bionic Applications for Robot Fish,” Applied Bionics and Biomechanics, vol. 2016, p. 4732703, 2016, doi: https://doi.org/10.1155/2016/4732703.

[8] “Artificial Reefs,” Department of Environmental Conservation, 2024. https://dec.ny.gov/things-to-do/saltwater-fishing/artificial-reefs

[9] A. S. Afonso, A. Fontes, D. M. Silva, and F. Hazin, "The effect of light attractor color in pelagic longline fisheries," Fisheries Research, vol. 239, p. 105924, 2021, doi: 10.1016/j.fishres.2021.105924.

[10] J. D. Richard, “Fish Attraction with Pulsed Low-Frequency Sound,” Journal of the Fisheries Research Board of Canada, vol. 25, no. 7, pp. 1441–1452, Jul. 1968, doi: https://doi.org/10.1139/f68-125.

[11] A. Mahmood, A. M. Abdallah, Bazilah Binti Baharom, and A. Habila, “Ensuring Satellite Operational Integrity: A Power Budget Analysis for Next Generation Satellites,” IEEE Access, vol. 13, pp. 44901–44911, Jan. 2025, doi: https://doi.org/10.1109/access.2025.3547826.

Appendix

Beam Break Code

To set up detection of life on the reef flash the code onto the Raspberry Pico. Hold the reset button of the Pico down and unplug and replug the power cable. Release the reset button, and the pico is now in BOOTSEL mode and is ready for code to be flashed on. Import the following to a C/C++ Pico project and copy the following code into the main C file. Next, hit run to compile and flash the code onto the Pico.

```
#include <stdio.h>
#include <stdlib.h>
#include "pico/stdlib.h"
#include "hardware/adc.h"
#include "hardware/gpio.h"
// Data sheet for CD4051: https://www.mouser.com/datasheet/2/308/4051BC-1190287.pdf

// MUX select lines
#define S0_PIN 21  // A (LSB)
#define S1_PIN 20  // B
#define S2_PIN 19  // C (MSB)

// set inhibitor pin to 0, alternatively ground pin
#define MUX_EN_PIN 22
#define MUX_ADC0_GPIO 26
#define MUX_ADC1_GPIO 27
#define MUX_ADC2_GPIO 28

#define MUX_ADC0_CHANNEL 0
#define MUX_ADC1_CHANNEL 1
#define MUX_ADC2_CHANNEL 2

// define detection GPIO
#define DETECT_LED 25
#define DETECT_PIN 4

uint16_t pr_prev[8] = {0,0,0,0,0,0,0,0};
int detected = 0;
const uint8_t mux_addresses[8][3] = {
   {0,0,0}, // PR 0
   {1,0,0}, // PR 1
   {0,1,0}, // PR 2
   {1,1,0}, // PR 3
   {0,0,1}, // HE 4
   {1,0,1}, // HE 5
   {0,1,1}, // HE 6
   {1,1,1}  // HE 7
};

void set_mux_channel( uint8_t index) {
    gpio_put(S0_PIN, mux_addresses[index][0]);
    gpio_put(S1_PIN, mux_addresses[index][1]);
    gpio_put(S2_PIN, mux_addresses[index][2]);
}
```

```c
int main() {
   stdio_init_all();

   // Initialize GPIOs
   gpio_init(S0_PIN); gpio_set_dir(S0_PIN, GPIO_OUT);
   gpio_init(S1_PIN); gpio_set_dir(S1_PIN, GPIO_OUT);
   gpio_init(S2_PIN); gpio_set_dir(S2_PIN, GPIO_OUT);

   // Enable pin (optional)
   gpio_init(MUX_EN_PIN); gpio_set_dir(MUX_EN_PIN, GPIO_OUT);
   gpio_put(MUX_EN_PIN, 0); // Active LOW → 0

   // Initialize Detection pin
   gpio_init(DETECT_PIN); gpio_set_dir(DETECT_PIN, GPIO_OUT);
   gpio_put(DETECT_PIN, 0);

   gpio_init(DETECT_LED); gpio_set_dir(DETECT_LED, GPIO_OUT);
   gpio_put(DETECT_LED, 0);

   // Initialize ADC
   adc_init();
   adc_gpio_init(MUX_ADC0_GPIO);
   adc_gpio_init(MUX_ADC1_GPIO);
   adc_gpio_init(MUX_ADC2_GPIO);

   sleep_ms(1000); // Let things settle
   while (1) {
       for (int adc = 0; adc < 2; adc++){
           adc_select_input(adc);
           printf("\n\nADC: %d:", adc);
           for (int ch = 0; ch < 8; ch++)
           {
               set_mux_channel(ch);
               sleep_us(100); // Let mux settle
               uint16_t val = adc_read(); // 12-bit ADC (0-4095)
               printf("\nPR Channel %d: %u\t", ch, val);
               int diff = (int) pr_prev[ch] - (int) val;
               pr_prev[ch] = val;
               if (diff > 200)
               {
                   printf("detected on channel: %d\t", ch);
                   detected = 1;
               }
           }
       }
       if (detected == 1){
           gpio_put(DETECT_PIN, 1);
           gpio_put(DETECT_LED, 1);
           detected = 0;
           printf("detected sleep");
           sleep_ms(5000);
       }
       sleep_ms(500); // time between readings can be decreased
       gpio_put(DETECT_PIN, 0);
       gpio_put(DETECT_LED, 0);
   }
   return 0;
}
```

Camera Code

The camera code lives on the Raspberry Pi 4. After flashing the Bookworm Lite OS, copy this python script into the file system and run it using:

```
python /home/pi/[*path to python script*]/camera_on_trigger.py
```

```python
import RPi.GPIO as GPIO
from picamera2 import Picamera2
from picamera2.encoders import H264Encoder
from libcamera import controls
from datetime import datetime
import time

########################################
### Picam
########################################
# configure settings
picam2 = Picamera2()
picam2.set_controls({"AfMode": controls.AfModeEnum.Continuous})
photo_config = picam2.create_still_configuration(main={"size": (1920, 1080)},
                                                 lores={"size": (640, 480)},
                                                 display="lores")
picam2.configure(photo_config)

########################################
### GPIO
########################################
# Set up GPIO's
GPIO.setmode(GPIO.BCM)
GPIO.setup(21, GPIO.IN, pull_up_down=GPIO.PUD_UP)
GPIO.setup(26, GPIO.IN, pull_up_down=GPIO.PUD_UP)

print("Waiting for trigger...")

def GPIO21_quit_callback(channel):
   global code_run
   code_run = False

def GPIO26_callback(channel):
   print("Movement detected!")

   # capture
   picam2.start()
   picam2.capture_file('/home/pi/artificial_reef/capture/%s.jpg' %
                       datetime.now().isoformat())

   print("Waiting for trigger...")

# initialize interrupt detection
GPIO.add_event_detect(21, GPIO.FALLING, callback=GPIO21_quit_callback, bouncetime=300)
GPIO.add_event_detect(26, GPIO.FALLING, callback=GPIO26_callback, bouncetime=300)

code_run = True
while code_run:
   time.sleep(0.2)

# cleanly exit
GPIO.cleanup()
```