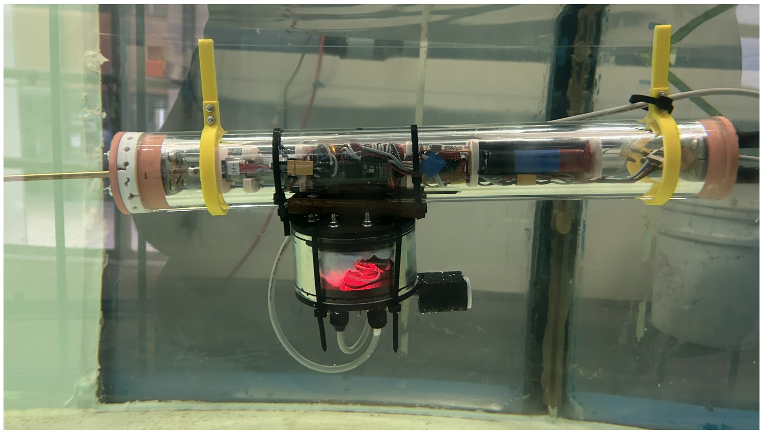
Development and Evaluation of a Non-Visual Perception System for Obstacle Detection on an Experimental AUV in a Flume Environment

Clément Dunot

Supervisor:
Eric Fusil
Eugene Lamnek

Second Year Internship Report

clement.dunot@ensta.fr
clement.dunot@adelaide.edu.au



Executive Summary

This project aims to design and test a non-visual obstacle detection system for a small autonomous underwater vehicle within a flume environment. Developed as part of the Harmonia project, a research initiative led by the University of Adelaide, it focuses on integrating compact, affordable sensors that can provide reliable perception in environments where traditional vision systems struggle, such as shallow or turbid waters.

The approach centres around the use of a forward-facing sonar to detect obstacles and estimate distances in real time. The system will be embedded in a watertight housing and mounted on an experimental submarine.

The work is structured around four key goals: sensor integration, experimental validation in the flume, data preparation for future control logic and a simple autonomy test in which the submarine, mounted on a guided zipline, stops its propulsion when an obstacle is detected. While full autonomy is beyond the current scope, this project lays the groundwork for future developments in that direction.

By focusing on hands-on integration, controlled experimentation and practical evaluation, this project contributes to improving perception capabilities on compact underwater platforms. It also supports the broader ambition of the Harmonia project: to create modular, testable systems that bridge physical prototyping and digital modelling in underwater robotics.

Résumé

Ce projet vise à concevoir et à tester un système de détection d'obstacles non visuel pour un petit véhicule sous-marin autonome dans une veine fluide. Développé dans le cadre du projet Harmonia, une initiative de recherche et développement menée par l'université d'Adélaïde, il se concentre sur l'intégration de capteurs compacts et abordables capables de fournir une perception fiable dans des environnements où les systèmes de vision traditionnels rencontrent des difficultés, tels que les eaux peu profondes ou troubles.

L'approche repose sur l'utilisation d'un sonar orienté vers l'avant pour détecter les obstacles et estimer les distances par rapport aux obstacles en temps réel. Le système sera intégré dans un boîtier étanche et monté sur un sous-marin expérimental.

Le travail s'articule autour de quatre objectifs clés : l'intégration des capteurs, la validation expérimentale dans le canal d'essai, la préparation des données pour la future logique de contrôle et un test d'autonomie simple dans lequel le sous-marin, monté sur une tyrolienne immergée, arrête sa propulsion lorsqu'un obstacle est détecté. Bien que l'autonomie totale dépasse le cadre actuel, ce projet jette les bases de futurs développements dans cette direction.

En mettant l'accent sur l'intégration pratique, l'expérimentation contrôlée et l'évaluation pratique, ce projet contribue à améliorer les capacités de perception des plateformes sous-marines compactes. Il soutient également l'ambition plus large du projet Harmonia : créer des systèmes modulaires et testables qui font le lien entre le prototypage physique et la modélisation numérique dans le domaine de la robotique sous-marine.

Contents

Introduction

0.1 Background and motivation

The internship took place at the University of Adelaide, within the SHIELD (Shipbuilding Hub for Integrated Engineering and Local Design). SHIELD is a research centre focused on naval engineering and the development of experimental miniature submarines to test underwater technologies at scale.

The Harmonia Project is a research and training initiative in close collaboration with *Dassault Systèmes*, aimed at developing experimental miniature submarines equipped with a digital twin. Designed as a scalable test platform, Harmonia integrates physical testing in a controlled flume environment with advanced simulation capabilities to explore underwater navigation, control and system modelling. It enables students and researchers to implement and validate real-time control algorithms (heading, depth, pitch), integrate complex sensors such as IMUs, DVLs and Hall effect sensors and compare experimental data with simulations using Dassault's 3DExperience platform. The development of these submarines serves as a concrete example of digital maritime engineering, bridging hands-on prototyping with virtual system development. Beyond its technical ambition, Harmonia plays a strong educational role, offering a foundation for student internships, collaborative research and future applications in defence-oriented underwater robotics and autonomy.

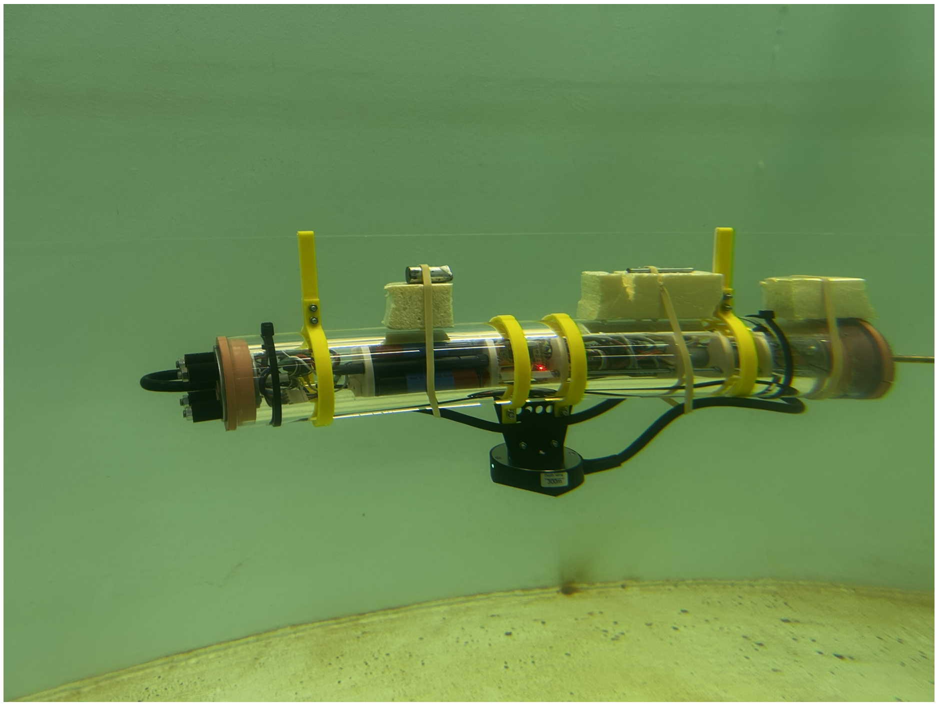


Figure 1 Picture of HermittCrab during DVL tests

Moreover, the HermittCrab module, illustrated above, is a self-propelled miniature submarine designed as an experimental platform for studying underwater propulsion dynamics. Developed as part of research work at the University of Adelaide, it is a free-running model (FRM) capable of moving autonomously in a test tank. Its architecture combines a hull inspired by the geometry of experimental submarines, an electric motor driving a propeller and a set of on-board sensors (IMU, speed sensors, possibly a Doppler Velocity

Log) connected to a microcontroller. The objective of HermittCrab is to experimentally characterise the dynamic response of a submarine during acceleration and braking manoeuvres, particularly in the so-called four quadrant acceleration (FQA) regime, which includes critical situations such as crash-back (emergency stop by reverse thrust). Designed as a flexible and modular tool, it allows different engine and control surface configurations to be tested in order to model the influence of propulsion on the overall performance of a submarine. Through this approach, HermittCrab acts as a physical test bench and modelling support, paving the way for better prediction of real-world behaviour when propulsion systems are modified.

It is within this framework that the present study aims to explore the integration of non-visual sensors onto the Harmonia submarine, with the goal of enhancing the vehicle's situational awareness capabilities in underwater environments. Unlike traditional vision-based systems, which are often limited by turbidity or poor lighting, non-visual sensors such as acoustic, laser-based or electromagnetic solutions offer promising alternatives for detecting and avoiding obstacles. This work builds upon previous developments of the Harmonia submarine by introducing a new perception layer that can support autonomous navigation tasks in confined or visibility-challenged settings such as flume environment. The motivation for this research lies not only in the technological potential of diversifying sensor modalities for underwater autonomy, but also in its practical impact on safety, robustness and applicability of miniature AUVs in real-world missions, where environmental uncertainty remains a key challenge.

0.2 Project aims and scope

The aim of this project is to integrate and evaluate non-visual sensors for underwater obstacle detection in a flume environment, using a FRM as a testbed, with a view to future integration into the Harmonia submarine, although this integration is beyond the scope of the current work. Specifically, the project will:

- Select and integrate a candidate sonar sensor suited to short-range detection in shallow, enclosed environments.
- Design and implement a basic perception module capable of detecting obstacles.
- Test the sensor experimentally in a controlled flume.
- Analyse the results to assess detection reliability and suitability for future autonomous applications.

The project primarily focuses on the integration and evaluation of non-visual sensors for obstacle detection, with an emphasis on perception and data analysis. While real-time autonomous navigation is not within the main scope, a simple closed-loop control on the propulsion system may be implemented toward the end of the project to support basic motion during experimental tests. The vehicle will therefore not perform autonomous avoidance or path planning but may respond to sensor inputs with low-level motor control in a controlled environment.

0.3 Document overview

The present report is organised in a way that follows the logical progression of the internship, from theoretical context to practical implementation and final reflections.

Chapter 1 introduces a literature review of non-visual perception technologies for underwater robotics. It examines three main approaches relevant to obstacle detection in aquatic environments: acoustic sensors, optical Time-of-Flight devices and electrosense. This review situates the project within existing research, highlights the strengths and weaknesses of each method and provides justification for focusing on acoustic sonar as the most suitable solution for this work.

Chapter 2 defines the project objectives and scope. It outlines the expected outcomes of the internship, from the integration of a sonar module into a watertight housing to experimental testing in a controlled flume. The objectives are presented in a structured way, showing how each stage contributes to building a complete perception chain for obstacle detection on a miniature AUV platform.

Chapter 3 constitutes the core of the report and is divided into several subsections. The first part details the implementation of the sonar module, including the selection of sensors, the mechanical design and sealing of the housing, the electronics and wiring, the embedded software and the interface with the HermittCrab control board. It then describes the experimental campaigns carried out in the flume, including the setup, the procedure followed and the data acquisition process. The chapter continues with the analysis of the collected data, an evaluation of sensor performance and a dedicated discussion on dynamic sonar testing. Finally, it identifies the main limitations encountered and proposes improvements for future work.

Chapter 4 presents the conclusion of the internship. It summarises the achievements and contributions of the work, reflects on the challenges faced and places the results within the broader perspective of the Harmonia project. This chapter also highlights the personal and professional skills developed during the internship and outlines possible directions for further development of the perception system.

The annexes provide complementary information supporting the main body of the report. These include a detailed overview of the budget and resources used, as well as a risk assessment identifying potential technical and experimental challenges encountered during the project.

1 Literature review

Remotely Operated Vehicles (ROVs) have significantly popularized visual sensors for underwater navigation and obstacle detection. However, when it comes to Autonomous Underwater Vehicles (AUVs), visual sensors often struggle, since their performance heavily depends on clear water conditions. In real-world scenarios, turbidity or poor lighting conditions can make these sensors ineffective. As a result, exploring alternative solutions like non-visual sensors becomes essential, offering enhanced reliability and robustness in obstacle detection and situation awareness.

In this context, the goal of this project is to explore and develop non-visual sensors but in a specific, controlled setting: a flume environment. Although the controlled nature of a flume is advantageous for systematic testing, it also introduces unique challenges, as a closed environment. Nevertheless, the realm of non-visual sensors is diverse, spanning acoustic, electromagnetic, electric, hydrodynamic and mechanical approaches. Each type offers its unique strengths.

This literature review explores three primary categories of non-visual sensors relevant to AUV applications: acoustic sonar systems, optical Time-of-Flight (ToF) sensors and electric field-based electrosense. Their respective principles, integration challenges and performances in constrained environments such as flumes are examined to inform the selection and implementation process.

1.1 Acoustic sensor

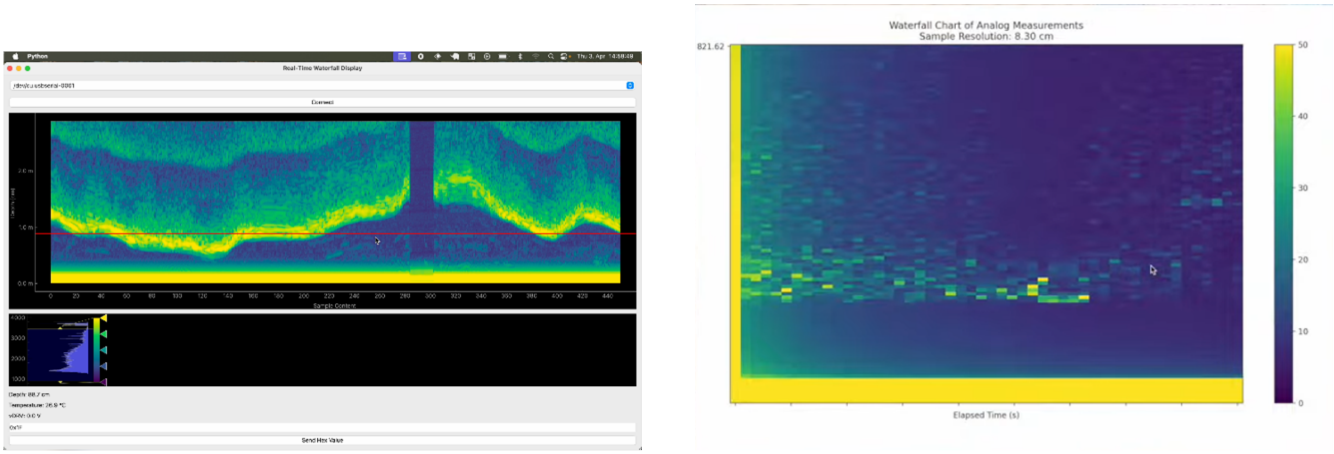
In underwater environments, sound remains the most reliable way for AUVs to detect obstacles. That's why acoustic sensors, especially forward-looking sonar (FLS), side-scan sonar (SSS) and multibeam echosounders (MBES), are commonly used on AUVs. These systems work by sending out short acoustic pulses and listening for the echoes that bounce off objects, using the time delay and signal intensity to reconstruct a map of the surrounding environment.

One particularly interesting use of this technology comes from a Bluefin 12 AUV with a vertically-mounted BlueView P450 sonar [1]. This setup was designed for missions that require the AUV to follow the seabed in a straight line, during sonar surveys for instance. The sonar provided detailed acoustic imagery of the seafloor ahead. What made their system stand out was the use of real-time onboard processing with an FPGA to handle complex image filtering and segment the sonar images. As soon as an obstacle was detected, the vehicle could adjust its altitude and avoid collisions, all without human intervention.

Other AUV platforms make use of side-scan sonars, which are better suited for scanning large areas of the seafloor. For instance, the REMUS 100 AUV uses SSS to locate mines or wrecks in coastal zones. These systems produce wide swaths of high-resolution imagery that can be reviewed later for object identification. In contrast, multibeam echosounders (MBES), like those found on the Iver3 AUV, are used when precise depth measurements are needed, such as when mapping underwater terrain. These sonars send out many narrow beams across the width of the AUV's path and return dense 3D bathymetric data, which is helpful when navigating near complex bottom features.

Another common approach, especially in narrow or cluttered areas, involves mechanically scanning sonars (MSS). These rotate their beam step-by-step, producing a highly detailed image of the surrounding space. Working with sonar data have its challenges. Signals can bounce off multiple surfaces, interfere with each other or get lost in background noise. That's why a lot of effort goes into filtering the data and separating real obstacles from false echoes. Techniques like median filtering, morphological operations and more recently deep learning are being used to improve sonar image clarity and automate detection [2]. Karabchevsky's system, for example, used local histogram entropy to highlight areas of high acoustic complexity, which is often a good clue that an object is present. Meanwhile, Kot's review points out that while AI methods are promising, their real-time use onboard AUVs is still limited by computing constraints.

On a more accessible level, the OpenEcho project is a great example of how these principles can be explored through DIY experimentation [3]. Built around a JSN-SR04T waterproof ultrasonic transducer and a Arduino Uno, OpenEcho provides a simple echolocation system that can estimate distances underwater. The project is fully open source and comes with Python codes and a compact design for the Arduino shield board. While its range and resolution are limited (5 meters, with about 0.5 cm accuracy), it's more than enough for prototyping basic obstacle detection systems or running experiments in a flume.



/dev/cu.usbserial-0001

Depth: 88.7 cm

Temperature: 26.9 °C

vDRV: 0.0 V

0x1F

(a) The interface which allows control of Open Echo boards, live data visualization and board settings

(b) Results of a test conducted in a port

Figure 2 Examples of sonar data visualization using the Open Echo software and custom Python interface

While simple in design, the OpenEcho system offers multiple opportunities for deeper experimentation and improved performance. The open-source nature of the project allows users to modify both the code and the setup to adapt for a new study environment.

Despite its limited range, the system's performance can be significantly enhanced by fine-tuning key parameters. When equipped with an analog-to-digital converter (ADC), users can capture raw echoes and apply post-processing techniques such as median or moving average filters, envelope detection or even Fourier-based analysis to resolve weaker or multiple returns. Environmental factors like temperature and salinity, which affect the speed of sound, can also be compensated for in distance calculations to enhance precision. Altogether, these features make OpenEcho a modular, educational platform for hands-on exploration of underwater acoustic sensing, especially in flume-like environments.

1.2 Time-of-Flight sensors

Advances in laser sensing technologies have enabled effective obstacle detection and depth measurement in shallow underwater environments. Research has demonstrated the technical feasibility of compact green laser LiDAR systems capable of generating accurate 3D imagery several meters below the surface, precisely where traditional sonar tends to lack resolution [4].

A wide range of solutions has emerged, including pulsed LiDAR scanners [4], ultra-sensitive single-photon detectors [5], structured-light triangulation systems [6] and gated imaging cameras developed through projects like UTOFIA [7]. These technologies share several key design principles: using optimal blue-green wavelengths, gating techniques to eliminate backscatter, algorithms to mitigate optical fog and photon-level sensitivity [8][9].

A particularly interesting application demonstrating a low-cost approach involves the use of compact Time-of-Flight sensors (ToF) for basic underwater tasks on small robots. In 2022, a hobbyist integrated a laser sensor (TFMini-S) into a LEGO submarine with an effective range to 30–50 cm in clear water [10].

Experimental deployments in pools and lakes have highlighted the potential for integration into small AUVs, offering short to mid-range obstacle perception capabilities in real time.

However, these studies also underline certain limitations, particularly in turbid or low-light conditions, where effective range drops to just a few meters. In addition, sunlight interference can affect sensitive sensors. While optical filtering and spectral windowing offer promising mitigation strategies, the controlled flume environment of our study allows us to largely bypass these issues, providing ideal conditions for laser-based detection experiments [9]).

The demonstration of the Brick Experiment Channel about ToF sensor integration in a small underwater platform aligns closely with the scope and constraints of our project. The author embedded commercially available modules such as the VL53L0X (infrared, 940 nm) and later the TFMini-S (infrared, 850 nm). These sensors rely on direct time-of-flight measurements via a vertical-cavity surface-emitting laser and single-photon avalanche diodes for detection. Communication with the microcontroller was handled over I^2C and the system operated with minimal power requirements, making it well-suited for small battery-powered robots. In air, the VL53L0X can measure up to 2 m, but underwater, its effective range dropped to about 12 cm due to infrared absorption by water. The TFMini-S, using a longer optical baseline and stronger emitter, achieved a better range of 30 to 50 cm in clear freshwater. Importantly, the integration required only minimal signal processing, data were used for reactive vertical control. Such results suggest that, under controlled conditions, lightweight ToF modules with proper optical isolation (e.g. acrylic tubes) can support basic obstacle detection at short range, making them highly attractive for compact AUV designs where sonar would be oversized or cost-prohibitive. Finally, having the sensor inside the hull reduces the risk of water leaks.

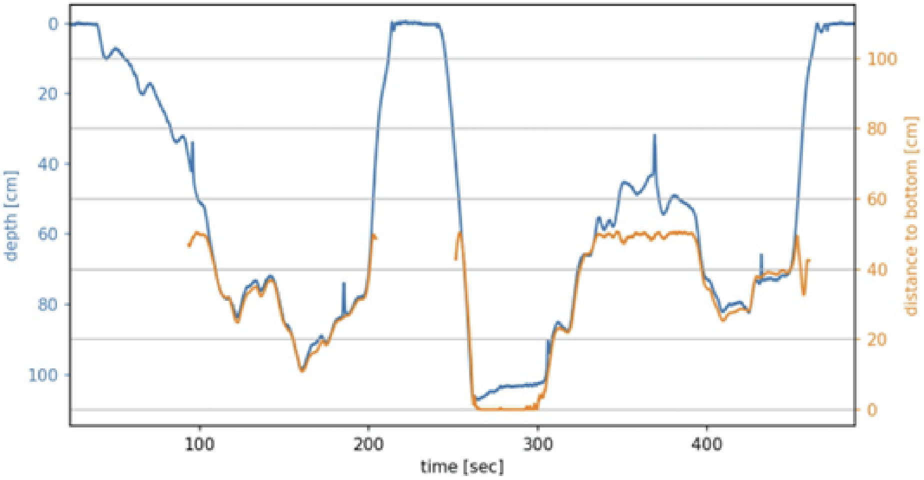


Figure 3 Results from the Brick Experiment channel experimentation with a TFMini-S sensor in a pool

1.3 Electrosense

As mentioned above, conventional visual sensors are less effective in turbid water. Faced with these limitations, interest is turning to alternative sensory modalities, including active electrosensitivity inspired by electric fish. Some species of freshwater fish generate and perceive an electric field to navigate and locate objects in turbid water. Like echolocation, this biological electrolocation enables short-range, light-independent perception, sparking strong interest in equivalent bio-inspired sensors for underwater robotics. Active electrosensitivity thus appears to be a promising method for providing underwater robots with reliable obstacle detection capability in turbid waters.

These ‘electric fish’ emit weak electrical discharges via a specialised electrical organ which generates an electrical field in the water around their body. They can detect disturbances in this field caused by the presence of objects with different electrical properties to the surrounding water (conductivity, permittivity, etc). This is referred to as active electro-location as opposed to passive electro-reception (detection of external electric fields): in this case the fish is both transmitter and receiver of its own field, in the manner of a self-echolocating sonar.

In terms of technical implementation, the principle of active electrolocation can be artificially reproduced using a transmitter dipole and electromagnetic sensors. In practical terms, a generator (often controlled by a microcontroller) powers a pair of transmitter electrodes creating an oscillating electric field in the water, while receiver electrodes positioned around the device measure the resulting potential differences. In the presence of an object, the field is disturbed and the sensors detect variations in the amplitude or phase of the signal compared with the situation in free space. Thanks to this bio-inspired device, it is now possible for an underwater robot to sense its immediate environment without vision, by actively detecting nearby objects based on the electrical disturbances they induce.

Chen et al. [11] conducted a comprehensive study on electrocommunication-based object detection for underwater robots, using both simulations and controlled experiments. They examined several obstacle configurations varying by material, size, geometry and position relative to the electrodes. Results showed that these factors significantly affect electric field propagation, with conductive objects near the transmitter having the strongest impact. The team demonstrated that by analysing the electric signal distortions, it is possible not only to detect obstacles but also to classify them (e.g., conductor vs insulator). This bio-inspired approach provides a promising, low-power alternative for short-range obstacle detection in turbid waters.

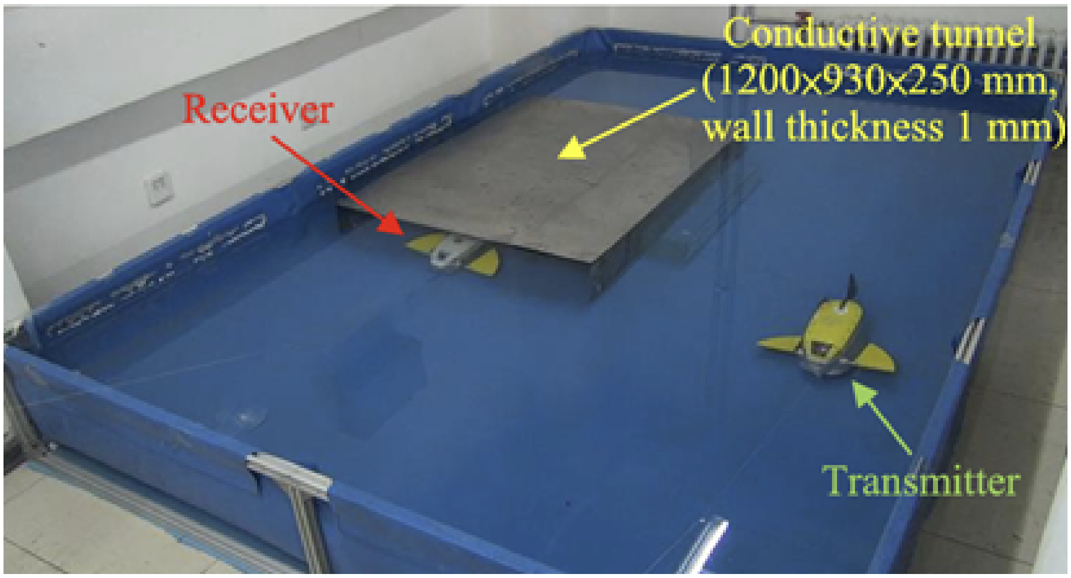


Figure 4 Trial by Chen et al. with the receiving robot passing through a conductive tunnel.

Despite its promise in turbid environments, integrating active electrosense technology into an AUV prototype presents several challenges [12]. First, the detection range is inherently limited to a few tens of centimetres, restricting its use to very local navigation tasks or reactive obstacle avoidance. Additionally, the system's performance is highly sensitive to changes in water conductivity (due to temperature or salinity), which can degrade measurement reliability and require frequent calibration. On the hardware side, the received signals are often in the microvolt range, demanding extremely low-noise analog electronics, which is difficult to maintain in electrically noisy underwater environments. The disturbed field patterns are also heavily influenced by the AUV's geometry and the placement of electrodes, making signal interpretation complex and platform-dependent. Moreover, in some implementations, especially those using electrocommunication principles, a second unit (i.e., another robot or a stationary receiver) may be needed to close the sensing loop, which complicates deployment and limits standalone functionality. Finally, the lack of standardized protocols for detection and signal processing still limits reproducibility and ease of integration across different robotic platforms [13].

2 Project Objectives

The overall aim of this project is to study, integrate and evaluate non-visual sensors for underwater obstacle detection on a miniature FRM operating in a flume environment, with the broader goal of enabling future automation and a closed-loop control into the Harmonia submarine. The project is organised in iterative agile sprints, allowing continuous testing and progressive integration of both hardware and software components. Four main objectives have been identified:

***Objective 1*: Integration of non-visual sensors into a waterproof perception module**

Design and assemble a compact, watertight housing containing a forward-facing sonar, with associated electronics, to be mounted on the HermittCrab experimental submarine.

***Objective 2*: Experimental validation of sensor performance in the flume**

Conduct a series of controlled tests in the flume to evaluate the behaviour and accuracy of the sensors in detecting known obstacles and lateral boundaries.

***Objective 3*: Preparing sensor data for integration with future control logic**

Process raw sensor data into structured, usable form interpretable by a control system.

***Objective 4*: Demonstrate a basic autonomous response to obstacle detection**

Conduct a proof-of-concept where the HermittCrab submarine stops before collision based on sonar input, on a zipline guide system.

3 Implementation and Results

After presenting the objectives and theoretical framework of the project, this section describes the practical implementation of the underwater perception system developed during the internship.

The objective was to assess the feasibility of using non-visual sensors, particularly acoustic sensors, to detect obstacles in an underwater environment where conventional vision-based approaches can be limited. The work focused on the design, integration and experimental validation of a sonar-based perception module mounted on HermittCrab operating in a flume.

The implementation took place in several stages: selection of a suitable sensor, mechanical and electronic integration on a watertight platform, data acquisition during controlled experiments and post-processing of the results using Python scripts. The ultimate goal was not to immediately integrate the system into the Harmonia AUV, but to test its relevance and performance in a simplified setting, with a view to subsequent integration.

This chapter presents the design process for the perception module, the test campaigns carried out under different conditions and the analysis of the results obtained.

3.1 Sensor Integration

The module was designed to allow for the clean and watertight integration of sensors and on-board electronics, while ensuring mechanical compatibility with the HermittCrab platform. The first step in developing an obstacle detection system was to select sensors that met the requirements of an underwater experimental environment.

3.1.1 The choice of the sensors

The choice of sensor for obstacle detection naturally fell on a JSN-SR04T ultrasonic sensor, cited in the literature review, for frontal detection. This offers a complete 1D embedded acoustic perception solution, including Python visualisation scripts.

One of the factors that influenced this choice was the acquisition of all the recommended equipment from the OpenEcho git repository by the University of Adelaide prior to the start date of the internship. This included the JSN-SR04T transducer, the Arduino Uno and the PCB with the soldered analogue-to-digital converter for capturing the raw echo signal. The immediate availability of the equipment reduced delivery times and allowed for rapid experimentation without incurring additional costs.

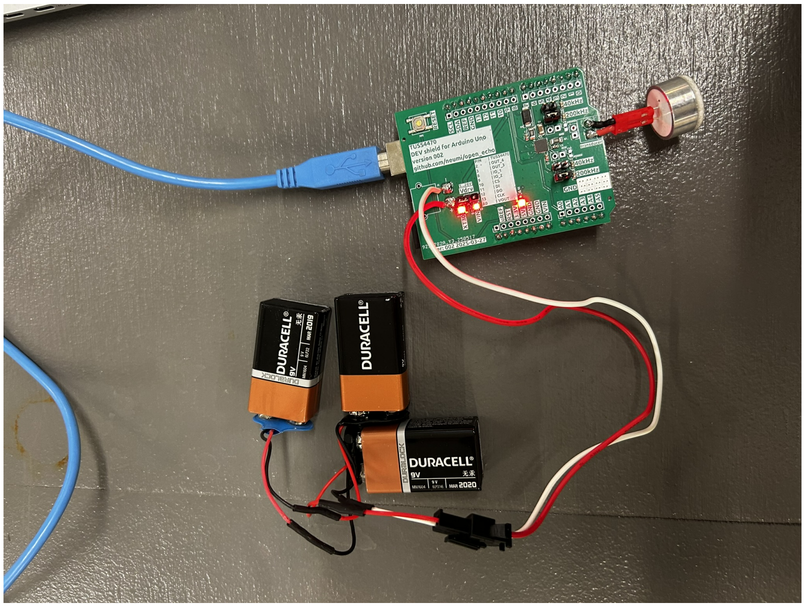


Figure 5 Prototype of the sonar module powered by three 9V batteries

According to the author of the git, the sonar has a nominal range of close to 1 m in air and several metres in water. Its ease of integration and sufficient resolution for short-range obstacle detection applications made it a logical choice for the experimental scenarios envisaged in a flume environment.

The project therefore focused on this front sensor, although two time-of-flight sensors were initially planned for distance measurement on the sides of the submarine to aid in visualising the surrounding space. However, this idea was abandoned due to concerns about hardware integration and relevance and in order to concentrate efforts on a simple, modular system.

3.1.2 Mechanical conception

The mechanical design of the obstacle detection module, based on the selected sensor, was guided by three requirements: to create a compact architecture to house the necessary obstacle detection equipment, to ensure the module was watertight and to enable simple integration into the HermittCrab platform. As a result, the module's geometry is simple and ensures that the transducer is properly exposed to the external environment without mechanical interference.

The module was initially designed to accommodate three LiPo cells, the Arduino Uno and its shield board. The entire module was designed to be 3D printed. A cross-section is shown in Figure 6 to illustrate the internal layout of the components. Waterproofing is ensured by two 3D-printed caps with a density of 100% and O-rings. Each cap is composed of two parts that compress the O-ring (pink parts in the cross-section except the tube).

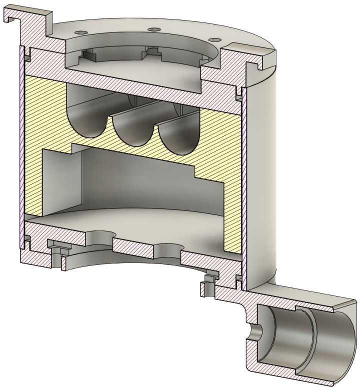


Figure 6 Cross-sectional view of the waterproof sonar module

However, during the development of the module, a more compact version was preferred, omitting the part containing the cells for direct power supply via the HermittCrab battery. The connectors will be detailed in a later section.

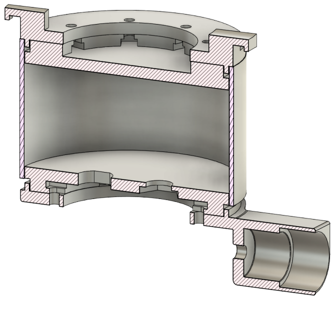


Figure 7 Cross-sectional view of the waterproof sonar module wihtout any batteries

3.1.3 Electronics and wiring

The onboard electronics were designed to ensure the operation of the sonar sensor and the communication of data associated with the HermittCrab control board, a Teensy 4.1. The module is based on an

Arduino Uno, chosen for its compatibility with OpenEcho git resources and its compact size.

The JSN-SR04T sensor is controlled and read by the Arduino, which acquires the echo signal via an analogue-to-digital converter (ADC). The processed data is then sent to the control board via an I^2C link.

The entire module is powered by HermittCrab's battery, which consists of three 3.7V LiPo cells in series, providing a nominal voltage of 11.1V (12.6V when fully charged). In addition, the Arduino Uno is powered via the barrel jack connector pins, which allows for tolerance in the supply voltage range (7-12V, up to 20V but not recommended) and protects against polarity reversal using a diode. Because it is powered by the HermittCrab battery, the module does not need to be dismantled to turn the power on or off.

Before its integration into the submarine, dry running tests were carried out to verify proper signal acquisition and stable communication with the control board.

The internal electronic diagram of the module is shown in the following figure. It shows all the connections between the main components: the Arduino Uno with the shield board, the transducer and the I^2C connection to the HermittCrab control board. This diagram highlights the simple but functional organisation of the circuit, designed to limit the number of external connections while ensuring the readability, accessibility and reliability of the embedded system.

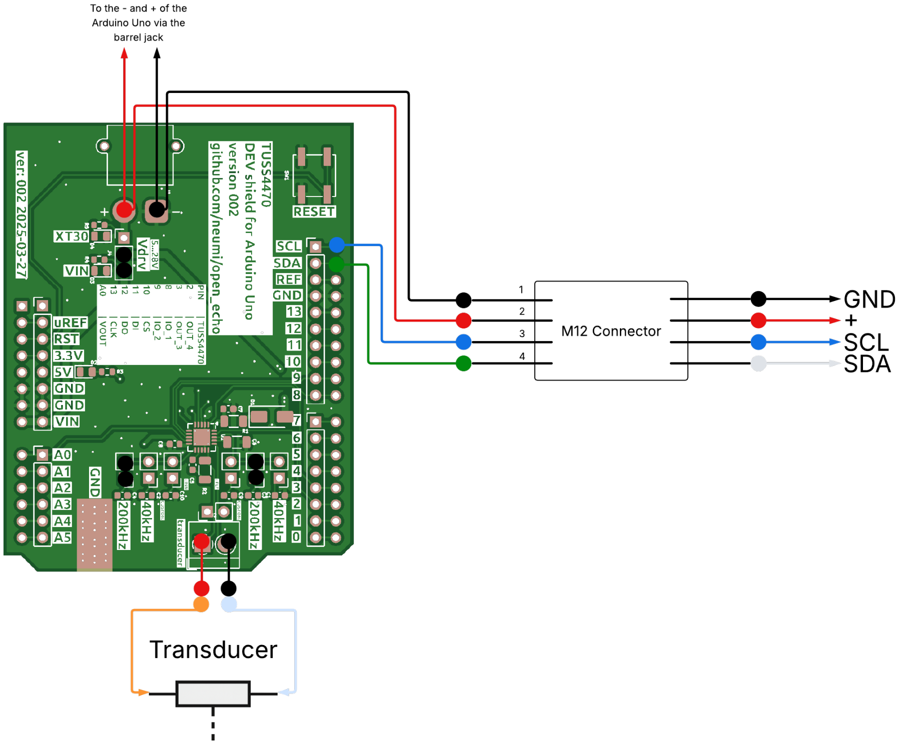


Figure 8 Diagram of the internal electronic circuitry of the sonar module

3.1.4 Software

The module operates using embedded code executed on the Arduino Uno. This programme was developed based on resources available on git OpenEcho and adapted to meet the project's requirements. The code initialises the JSN-SR04T ultrasonic sensor, triggers the emission of an ultrasonic pulse and then acquires the echo signal to detect an obstacle. The detection method used is threshold detection. The threshold used comes from the *Constant False Alarm Rate* theory, which allows threshold detection in a noisy environment. The formula used is:

$$\text{Threshold} = \mu + \text{thr\_factor} \cdot \sigma, \quad \text{with thr\_factor} \in R$$

Thus, the code identifies the presence of an obstacle when a defined number of consecutive samples have an intensity value above the threshold calculated from the noise statistics data calculated at the start of the test. The code has been optimised to work with limited memory due to the use of the Arduino Uno.

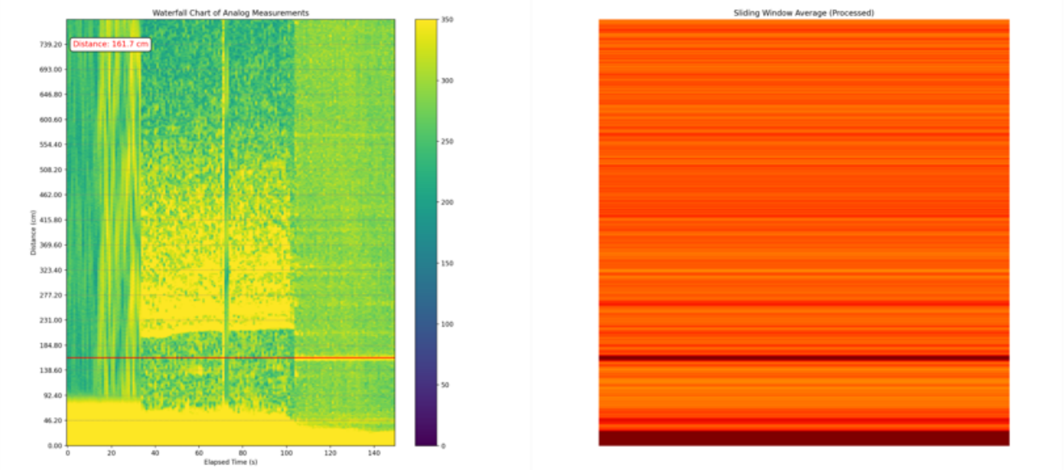


Figure 9 Waterfall visualization of raw analog measurements using serial communication (left) and corresponding processed output using sliding window averaging (right). The sonar module was powered a 20V voltage generator.

3.1.5 Interface with the control board

Communication between the sonar module and the submarine's control board is carried out via an I^2C connection. This communication protocol was chosen for several reasons: it requires only two wires (SCL and SDA) because the two boards are powered by the same battery and thus share the same ground, it is easy to integrate and it is reliable for short distances in a constrained environment, such as between the module and HermittCrab.

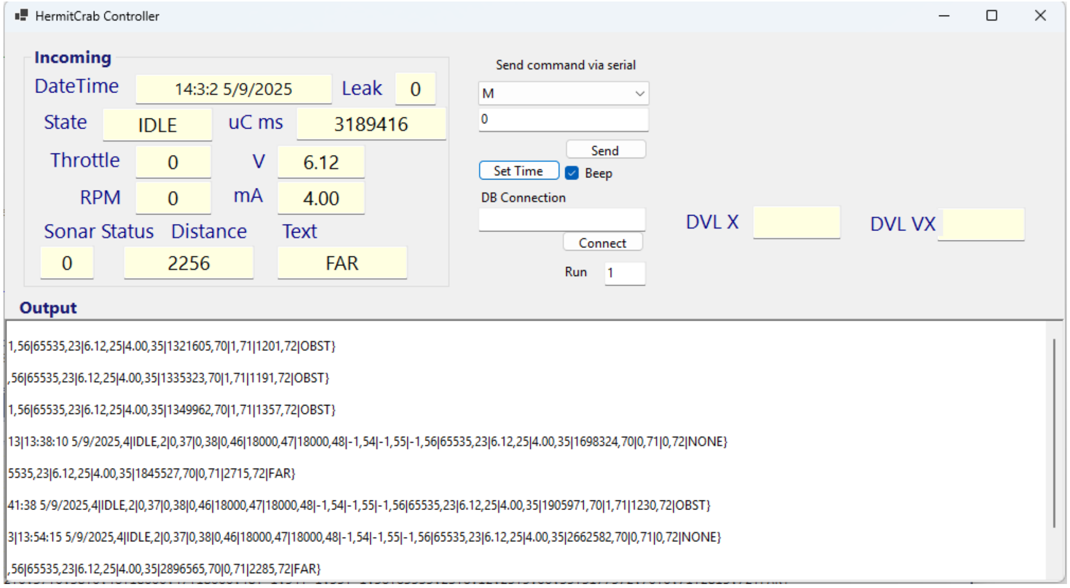
The sonar module acts as an I^2C slave device. When a request is received from the master card (the HermittCrab controller), a data structure is transmitted, containing the following information:

- an integer representing the module status (initialisation, acquisition, error, etc.)
- the distance measured by the sonar (in millimetres)

- a short text field (5 characters) to indicate a status or keyword such as ‘`NONE`’ (No Echo)
- 9-byte padding to ensure compatibility of the structure size.

Transmission is carried out using a function, which is called automatically when a request is made by the master I^{2}C. The contents of the structure that groups together the data to be transmitted, are sent via the `Wire.write()` method in binary form, ensuring fast and compact communication.

In order to limit outgoing cables and electrical noise interference, communication is strictly unidirectional: only the master controller sends requests and the sonar module simply responds without initiating any exchange. Since HermittCrab must be turned on by activating the switch enclosed within it, the sonar module will initially be calibrated in the air. So for experimental purposes, the module will recalibrate itself every 60 seconds. However, an alternative version has been developed but not tested that allows a request to be sent from HermittCrab's control board to the module to indicate when to calibrate the module.



Incoming
DateTime 14:3:2 5/9/2025
Leak 0
State IDLE
uC ms 3189416
Throttle 0
V 6.12
RPM 0
mA 4.00
Sonar Status 0
Distance 2256
Text FAR

M
0
☑ Beep
DB Connection
Run 1
DVL X
DVL VX

```
1,56|65535,23|6.12,25|4.00,35|1321605,70|1,71|1201,72|OBST}
,56|65535,23|6.12,25|4.00,35|1335323,70|1,71|1191,72|OBST}
1,56|65535,23|6.12,25|4.00,35|1349962,70|1,71|1357,72|OBST}
13|13:38:10 5/9/2025,4|IDLE,2|0,37|0,38|0,46|18000,47|18000,48|-1,54|-1,55|-1,56|65535,23|6.12,25|4.00,35|1698324,70|0,71|0,72|NONE}
5535,23|6.12,25|4.00,35|1845527,70|0,71|2715,72|FAR}
41:38 5/9/2025,4|IDLE,2|0,37|0,38|0,46|18000,47|18000,48|-1,54|-1,55|-1,56|65535,23|6.12,25|4.00,35|1905971,70|1,71|1230,72|OBST}
3|13:54:15 5/9/2025,4|IDLE,2|0,37|0,38|0,46|18000,47|18000,48|-1,54|-1,55|-1,56|65535,23|6.12,25|4.00,35|2662582,70|0,71|0,72|NONE}
,56|65535,23|6.12,25|4.00,35|2896565,70|0,71|2285,72|FAR}
```

Figure 10 HermittCrab controller interface used during experiments, showing real-time sonar status, distance measurements and serial communication output.

3.1.6 Mounting on the self-propelled underwater module

The waterproof sonar module was installed at the front of the HermittCrab experimental submarine. This position was chosen to give the front sensor a clear field of vision, while keeping the module aligned with the drone's main axis.

It was secured using an adjustment on the 3D-printed cap that fits the shape of the hull, supplemented by clamps around the submarine's acrylic tube. This simple solution provided robust integration while facilitating quick disassembly of the module between test series.

The cable exiting the module was routed to the front of the self-propelled module and connected to HermittCrab's internal electronics using a compressible rubber plug to ensure watertightness.

Figure 11 Prototype of the sealed sonar module

This mounting solution proved effective during tank tests, ensuring mechanical stability, correct sensor orientation and good water resistance of the system despite multiple manipulations.

3.1.7 Preliminary tests out of the water

Before being integrated into the submarine and tested in an aquatic environment, the sonar module was first evaluated in dry conditions, in the air, to validate its overall functioning. The purpose of these tests was to verify signal transmission and reception, data processing on the Arduino Uno and the correct transmission of results to the control board.

The sonar was placed at different distances from a rigid flat obstacle. The distance measurements obtained, visualised in real time using a Python programme, were consistent with the expected values. Visualisation of the raw signal also confirmed the proper functioning of the threshold detection algorithm, with a clear intensity at the sample corresponding to the main echo.

The power supply system was tested and validated, ensuring automatic activation of the module when connected to the control board. This setup made it possible to simulate on/off cycles, with good stability of the electronics each time the power was turned on.

No transmission instability was observed during these tests, as the I^2C link used to communicate with the control card proved to be stable and free from electromagnetic interference despite its proximity to the module's power cables.

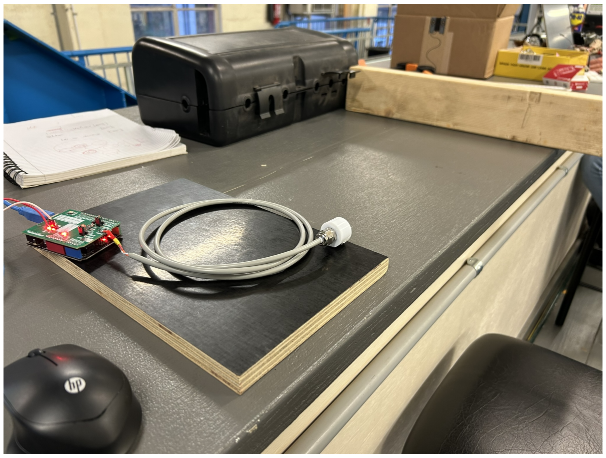


Figure 12 Dry tests of the sonar

3.2 Experimental testing in the flume

3.2.1 Test environment and Setup

The experiments are conducted in flumes located at the University of Adelaide. This infrastructure provides a controlled, stable and repeatable environment suitable for short-range underwater detection testing. The main test tank is approximately 30 metres long, 1.2 metres wide and has a constant depth of 0.9 metres. The smaller secondary tank is 10 metres long, 1.2 metres wide and has a constant depth of 0.7 metres. The water is kept clear and free of currents.

The aim of this project is to verify the proper functioning of the module on the self-propelled submarine, which would be kept on a linear trajectory using a zipline-type guidance system stretched across the water. This solution allows the drone to move forward in a stable and controlled manner without having to maintain its orientation in space. The sonar module is attached to the front of the vehicle, submerged and oriented along the longitudinal axis of the flume. Once started, obstacles would be placed in front of the drone, generating alerts for HermittCrab, which would then stop its propulsion.

Communication with a computer is provided by a radio module connected to the control board. This module establishes a wireless serial link between the on-board system and a computer, particularly for debugging, sending status instructions or the desired throttle value.

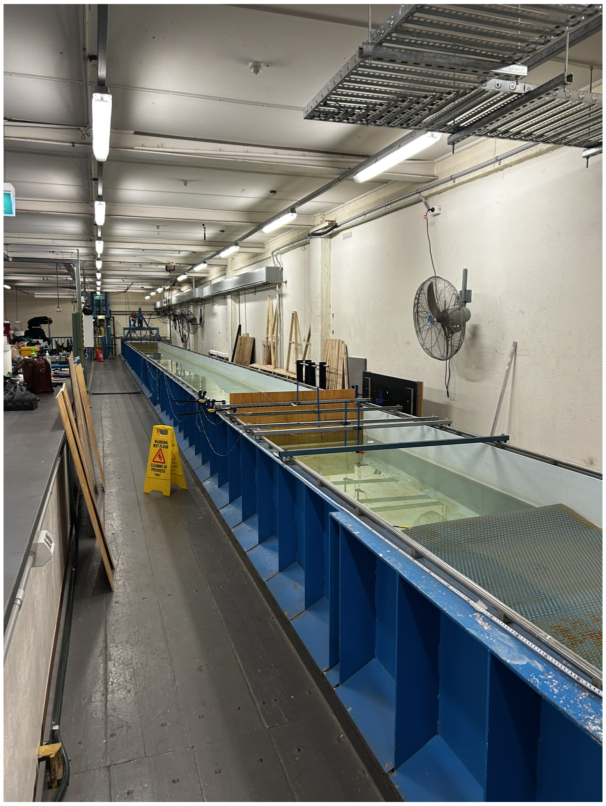


Figure 13 Picture of the large flume at the University of Adelaide

3.2.2 Experimental procedure

The experiment was conducted in two major stages in order to assess the sonar module's ability to detect obstacles in a controlled environment.

Firstly, an experimental campaign was conducted to characterise the behaviour of the 200 kHz sonar module based on two key parameters: the supply voltage and the threshold factor `thr_factor` used in the detection algorithm. The aim of this approach was to identify the optimal operating conditions for the sensor in a constrained embedded environment. To this end, numerous measurements were taken for different distances and supply voltage values.

Based on the results obtained during the static characterisation phase, the sensor's operating parameters were set in order to move on to the dynamic testing campaign mentioned above. The aim of this campaign was to evaluate the module's detection capabilities in a real-life movement situation. A wooden plate was therefore installed at the end of the pool on the zipline's trajectory.

3.2.3 Data acquisition

The transducer data is processed locally by the Arduino Uno, which only returns the distance and the keywords seen previously corresponding to propulsion commands directly to the Teensy 4.1. This data is shared with the computer but also saved every second on an onboard SD card along with all other functional information about the submarine (DVL, throttle, etc).

3.3 Results and Data Interpretation

3.3.1 Collected data

In order to study the sensor's performance in detail, a recording campaign was conducted by creating a multitude of *logs* (each lasting approximately thirty seconds) at different target distances and supply voltages. Each log corresponds to a time sequence of pings captured in the form of a `.csv` file, which allows the complete evolution of the return signal to be preserved. This raw data was also post-processed in Python using a specially developed script, enabling the automatic extraction of sensor performance indicators: average and standard deviation of the measured distance, detection rate, SNR (Signal Noise Ratio), average amplitude, etc. The results of this processing were centralised in a `.json` file, facilitating their reuse for subsequent visualisations and comparative analysis.

For better interpretation, this data can then be visualised in the form of a *heatmap* (waterfall), where each column represents a ping and each row a signal sample. The signal intensity is translated into a colour scale. This allows the evolution of the main echo to be visually tracked over time and areas of significant response to be easily detected.

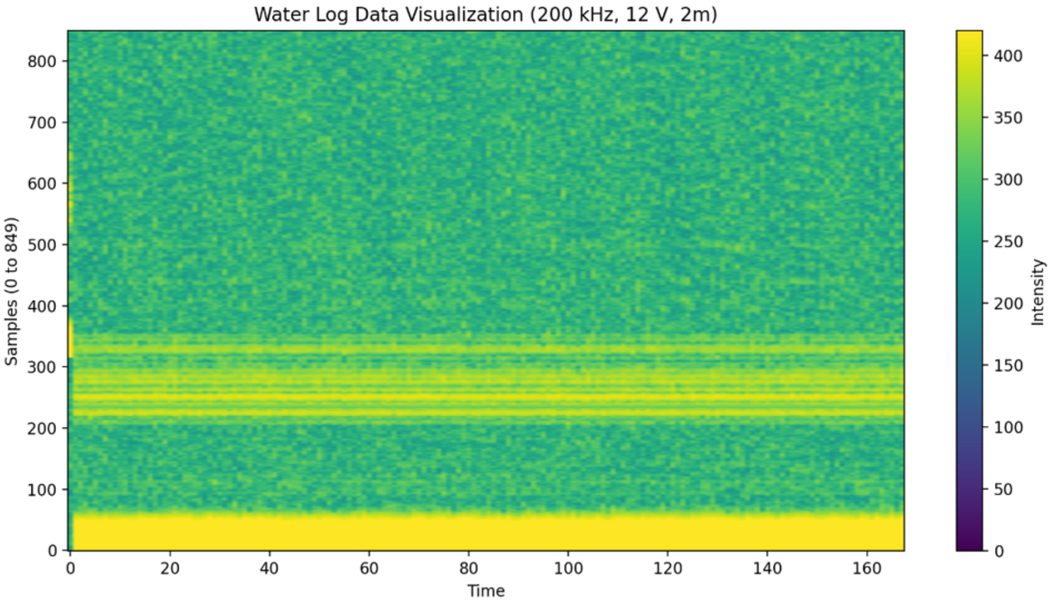


Figure 14 Heatmap visualization of sonar echo intensity (200 kHz, 12V) recorded during a stationary test in the large flume at 2m from the obstacle

This representation shows a clear band corresponding to the main echo, whose position varies depending on the distance to the obstacle. The vertical evolution of this band makes it possible to identify the movements of the sensor or objects in the measurement field.

The distance values estimated by the system are obtained automatically using a threshold detection criterion based on the relative intensity of the samples. This criterion can be adjusted according to ambient noise and has been validated in several dry test cases.

3.3.2 Sensor Performance Analysis

The analysis of the results of the campaign to characterise the optimal parameters revealed a significant influence of the supply voltage on signal quality and measurement reliability. Below 9 V, the detection rate drops significantly beyond 1.5 m, with a deterioration in the signal-to-noise ratio (SNR) and measurement instability. On the other hand, for voltages between 12 and 15 V, performance improves significantly: the average SNR remains stable (around 24-28 dB), reliability exceeds 90 % and measurement error remains within a margin of less than 5 cm up to approximately 2.5 m. Increasing the voltage above 18 V does not provide any significant additional gain and can sometimes even lead to a slight deterioration in performance. Thus, a voltage of 12 to 15 V appeared to be the optimal compromise between measurement quality and energy consumption.

At the same time, an exploration of the parameter `thr_factor`, corresponding to the multiplicative coefficient applied to signal detection, showed that a setting between 2.8 and 3.0 achieved a good balance. Below this threshold, ambient noise is too often interpreted as a valid echo, which degrades accuracy. Conversely, values above 3.2 can lead to the non-detection of legitimate echoes, particularly in cases of weak reflection (long distance or diffuse obstacles).

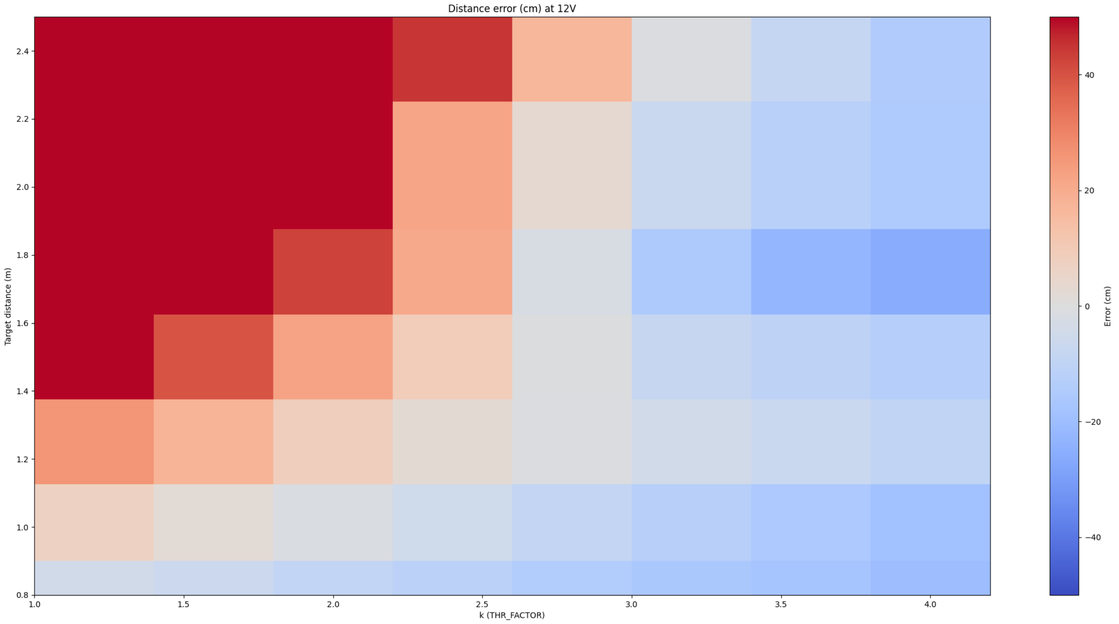


Figure 15 Distance error (cm) as a function of voltage and threshold factor k at 12 V

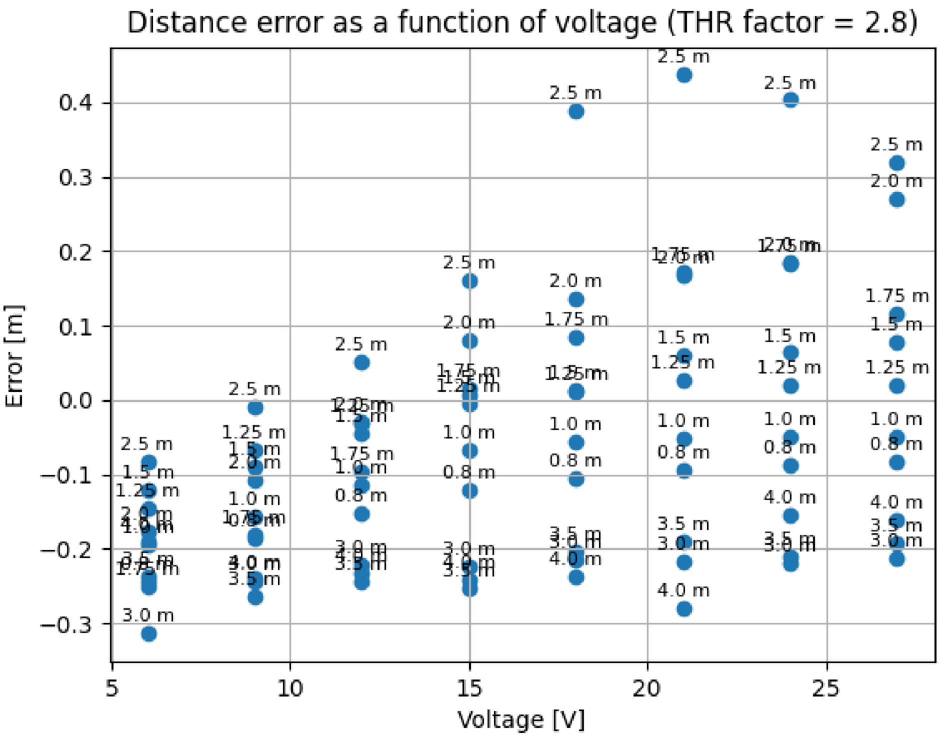


Figure 16 Distance error (cm) as a function of voltage and the true distance

Finally, cross-plots of absolute error versus SNR or actual distance confirmed that SNR is a reliable indicator of sonar measurement quality, with the majority of high errors correlating with SNRs below 25 dB.

In summary, this exploratory study has made it possible to define an initial recommended operating window for the sonar in the context under consideration:

- Supply voltage: 12 to 15 V
- Threshold factor (`thr_factor`): between 2.8 and 3.0

These parameters will be used as a basis for future real-world testing and integration of the sensor into the autonomous vehicle. This phase relied on a serial connection to access information that could not be communicated through I^2C.

3.3.3 Dynamic sonar testing

Dynamic tests were carried out to assess the sonar module's ability to detect obstacles in real-life movement situations. Despite numerous tests and precautions taken when aligning the sensor and calibrating the detection threshold, the results proved to be mixed and sometimes inconsistent.

Due to the limited time available at this stage of the internship, as soon as the static tests showed satisfactory behaviour, the focus was immediately shifted towards dynamic tests. The static trials although not fully representative of real scenarios, demonstrated that the sonar could detect the presence of an obstacle in around 75% of cases, usually with an accuracy of ±20 cm. Encouraged by these results, dynamic tests were then carried out in order to validate the sensor's operation under movement.

However, once transferred to dynamic tests, the reliability of the measurements decreased significantly. When the sensor was correctly calibrated, the absence of an obstacle was correctly identified in most cases, with consistent feedback. On the other hand, the presence of an obstacle generated unstable behaviour: in some situations, the detected distance was accurate and true to reality, while in others, no detection was made despite the obvious presence of an obstacle in the measurement field.

In addition, a recurring phenomenon of phantom detection was observed after the obstacle was removed: the sensor sporadically returned erroneous measurements at fluctuating distances, often exceeding the actual detection range. This behaviour suggests residual instability in the system, possibly linked to persistent echoes, insufficient acoustic damping or parasitic effects induced by the configuration of the basin or the acoustic environment.

Overall, these observations highlight both the potential and the current limitations of the system. The static tests confirmed that the sonar can provide useful detection capability, but the dynamic conditions revealed instability and unreliability. A more extensive experimental campaign, based on a robust and systematic protocol, would be necessary to validate performance.

3.3.4 Limitations

The characterisation campaign of the ultrasonic sensor revealed several limitations that must be considered when evaluating its integration into an AUV.

- Short-range detection: The sensor was unable to detect obstacles closer than approximately 0.8–1 m. This blind zone significantly reduces the ability to identify nearby hazards, which is critical in confined environments.
- Long-range variability: At greater distances, the measurements exhibited strong variability, with fluctuations between successive readings that reduced the overall reliability of detection.
- Dependence on obstacle orientation: Reliable detection required the obstacle to be perpendicular to the acoustic beam. A slight angular deviation often resulted in missed detections, highlighting the sensitivity of the system to alignment and calibration.
- Phantom echoes: After the removal of an obstacle, sporadic erroneous detections at unrealistic distances were observed. These artefacts suggest residual echoes, insufficient acoustic damping or parasitic effects in the basin environment.
- Dynamic instability: While static tests showed promising results (≈80% successful detection with ±20 cm accuracy), performance decreased sharply in dynamic conditions. During movement, the sensor often failed to detect obstacles or produced inconsistent distance estimates.

3.3.5 Improvements

Several improvements can be suggested based on the experimental campaign.

First, it should be noted that the characterisation tests of the sonar were conducted in the large flume, whereas the dynamic tests had to be carried out in the small flume due to availability constraints. This difference in testing environments may have contributed to part of the observed inconsistencies, as the acoustic properties and parasitic reflections are not directly comparable between the two facilities. Repeating both static and dynamic tests under identical conditions would allow a more reliable comparison of performance.

In addition, further improvements could be considered:

- Repeatable evaluation: Designing a method to assess the sonar under controlled and repeatable conditions would make it possible to better quantify performance and compare results over time.
- On-board filtering: Implementing filtering of detections directly on the HermittCrab control board would help smooth out unstable measurements and reduce false detections.
- Acoustic environment: Additional damping or shielding may help minimise parasitic echoes caused by reflections in confined environments such as the flume.
- Wireless reprogramming: Adding a radio-frequency (RF) module to the sonar Arduino would allow the firmware to be updated between trials without disassembling the system. This would represent a considerable time gain and would make debugging and iteration more efficient.
- Alternative transducer: A fully waterproof 40 kHz transducer has been ordered and could be tested to investigate potential differences in performance compared to the current setup.

Overall, these improvements would strengthen the robustness of the sensor integration and provide more consistent results in both static and dynamic operating conditions.

4 Conclusion

This four-month internship within the SHIELD department at the University of Adelaide is part of the Harmonia project, dedicated to the design of experimental submarines for marine robotics research. The main objective of this mission was to evaluate the relevance of non-visual sensors, in particular ultrasonic sonar, for detecting submerged obstacles in a controlled experimental environment, the fluid vein. This project aimed to set up a complete chain, from sensor integration to results analysis, including the collection and processing of on-board data.

From a technical standpoint, the internship covered a wide range of engineering skills. The first step was to select a sensor compatible with the project's constraints. The choice fell on a module based on the JSN-SR04T sensor, drawing on the open-source resources of the OpenEcho repository. This sensor was integrated onto an Arduino Uno board and its shield. A custom 3D housing case was developed to interface with the other components of the system, as well as to control the power supply via a waterproof M12 connector.

Software development required mastering the OpenEcho code, implementing an efficient acquisition protocol, structuring data for storage on an SD card and enabling dynamic configuration of detection thresholds and blanking zones. All of these choices were made with the aim of creating an autonomous, resource-efficient, modular and reusable embedded system.

An experimental campaign was then conducted to characterise the sonar's behaviour. The focus was on two key parameters: the sensor supply voltage and the threshold factor `thr_factor`. Numerous logs were recorded under reproducible conditions and then processed using Python. The analysis highlighted an optimal operating range (12–15 V for voltage, 2.8–3.0 for threshold) and made it possible to evaluate the quality of the echoes, their consistency and the system's sensitivity to the presence of an obstacle. This analytical work represented an important step in validating the approach.

In a second phase, dynamic tests were conducted in a fluid flow, with controlled movement of the sonar module in front of fixed obstacles. Despite several repetitions, the results proved unstable: in some cases, the obstacle was detected correctly, but other tests showed a lack of detection or phantom echoes after the obstacle had disappeared. This behaviour indicates that the system is still sensitive to disturbances, probably related to the directivity of the sensor, the acoustic environment of the flume or the nature of the on-board processing. Although these tests did not fully validate the sensor's ability to be integrated into an autonomous control loop, they provide a valuable basis for future investigations.

On a personal and professional level, this internship was extremely formative. It allowed me to work independently in an international environment, in English, while participating in applied research. I developed practical skills in embedded electronics, data processing, robotic experimentation and technical documentation. I also learned how to structure a complete experimental approach and adapt to real material constraints. It was also an opportunity to implement a multi-domain integration approach, combining mechanics, electronics, embedded computing and post-analysis processing.

This internship confirmed my interest in the field of marine robotics. It reinforced my desire to continue in this direction, investing myself in projects where the challenges are technical, experimental and environmental. The low-cost, modular and flexible approach adopted here particularly appealed to me and I can easily see myself working on similar projects combining exploration, embedded engineering and innovation.

Finally, this work is fully in line with the Harmonia project. Although final integration into the Harmonia AUV was not part of the scope of this internship, the elements developed here (sensor, acquisition protocol, performance analysis) provide a reusable foundation for the future. The sensor is functional, mechanically integrated and the identified weaknesses (notably dynamic instability) are documented to guide the next phases. This contribution is therefore part of an iterative and progressive approach, in line with the logic of an applied research project.

In conclusion, this internship was an intense, enriching and formative experience, both technically and personally. It allowed me to contribute to a concrete project, develop my skills in embedded robotics and strengthen my position as an independent, rigorous and committed engineer.

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A Budget and resources required

Table 1: List of Components and Availability

Component	**Price (AUD)**	**Link**	**At the university**
Ultrasonic level sensor transducer	9.65	`https://de.aliexpress.com/item/1005006007865920.html`	Yes
Arduino Uno	52.29	`https://core-electronics.com.au/arduino-uno-r3.html`	Yes
Acrylic tube	47.75/m	`https://www.acrylicsonline.com.au/products/extruded-clear-acrylic-tube-100mm`	Yes
TUSS4470 shield	80.29	——	Yes
Wires	——	——	Yes
PLA	31,23/kg	`https://www.amazon.fr/gp/aw/d/B0BY25RJLH/?_encoding=UTF8&pd_rd_plhdr=t&aaxitk=c72071540eb96e087cdc2a2c3b29146a&hsa_cr_id=0&qid=1759138452&sr=1-1-e0fa1fdd-d857-4087-adda-5bd576b25987&ref_=sbx_be_s_sparkle_dlcd_asin_0_title&pd_rd_w=qlXt5&content-id=amzn1.sym.17d8b547-4978-434d-a051-2563e46b5baf%3Aamzn1.sym.17d8b547-4978-434d-a051-2563e46b5baf&pf_rd_p=17d8b547-4978-434d-a051-2563e46b5baf&pf_rd_r=9RVJCHF2B9K9X0ZH6VJX&pd_rd_wg=eFvX7&pd_rd_r=0894e3ef-1b4b-434d-95fb-63e708fe8dbc&th=1`	Yes
Total	189.98		

B Risk assessment

Risk/Event	**Type** (P/E/S/T/L/E)	**Likelihood** (H/M/L)	**Consequence** (H/M/L)	**Control measures**
A wiring or soldering error damaging a component during integration	T	M	M	Prototype on breadboard, verify pinouts and test incrementally
Damage to electronics due to leaks	T	M	M	Conduct housing pressure test before flume and integrate leak sensor
Flume unavailable during key experimental weeks	S	M	H	Reserve flume in advance

Table 2: Risk Assessment

Notes:

- **Risk/Event:** Identified potential risk
- **Type:** P – Political, E – Economic, S – Social, T – Technical, L – Legal, E – Environmental
- **Likelihood:** H – High, M – Medium, L – Low
- **Consequence:** H – High, M – Medium, L – Low