NTNU
Faculty of Information Technology
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Department of Engineering
Cybernetics

# Integration of a machine vision plankton sensor in an unmanned surface vehicle for real-time autonomous ocean monitoring

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MASTER THESIS
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# Preface

This is a Master's thesis at the Department of Engineering Cybernetics of NTNU as part of the study program European Master in Embedded Computing Systems (EMECS). It was carried out during the spring semester of 2022. The idea of the project was brought up by biologists interested in studying algal blooms of the ocean plankton.

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Sergei Ovchinnikov

# Acknowledgment

I would like to thank the following persons for their help during this Master's thesis.

Glenn Angell – an engineer at the ITK Mechanical workshop – for the great help with design and implementation of the mechanical parts of the system.

Jo Arve Alfredsen – a professor at ITK, the main academic supervisor of the project – for numerous advice during the electronic design and on the components choice.

S.O.

# Executive Summary

The goal of this thesis project is to develop and implement an embedded subsystem for an autonomous surface vehicle (ASV). This system features a machine vision sensor (a microscope) for plankton research. During the carrying out of the project an open-source plankton microscope (so called "PlanktoScope") was adapted to be integrated into an ASV payload box. A prototype of this custom PlanktoScope was implemented and tested on a sea water sample. An additional subsystem for automatic onboard water sampling was designed and implemented. Software and communication protocols were developed for all the units.

# Contents

# Chapter 1

# Introduction

## 1.1 Background

As shown on Figure 1.1 aquatic biomass is dominated by tiny drifting plants and animals – phytoplankton and zooplankton – and bacteria. Plankton are vital components of aquatic systems:

> Plankton not only provide the food for higher trophic levels such as fish, seabirds, penguins, seals and sharks, but produce oxygen, cycle nutrients, process many of the pollutants that humans dispose of through our waterways, and help to remove carbon dioxide from our atmosphere.
>
> Suthers et al. (2019)

However, in the presence of surplus nutrients (particularly nitrogen and phosphorus), some phytoplankton may exponentially grow ('bloom') over and above what the ecosystem can assimilate. This leads to oxygen deprivation for other inhabitants. Therefore, it is extremely important to monitor phytoplankton dynamics for water quality management. One possible approach is to use a microscope on water samples to look for specific species and their density in dynamics to foresee possible HABs in certain areas.

Pollina et al. (2020) show how to build a modular, easily re-configurable imaging platform with a proclaimed resolution of 1.5 µm. The goal is to make an extremely affordable microscope that can be built and used by anyone all over the world to contribute to the study of plankton ecosystems. In de Vargas et al. (2020) it is described how using such a platform with a systematic approach and help of volunteer mariners it is possible to create a high quality dataset of plankton biodiversity. The microscope ("PlanktoScope", or previously "PlanktonScope") is a simple mobile platform that can be brought onboard and operated by any person without any special training. PlanktoScope ideas (see Chapter 3) are effectively used in this thesis to build own system.

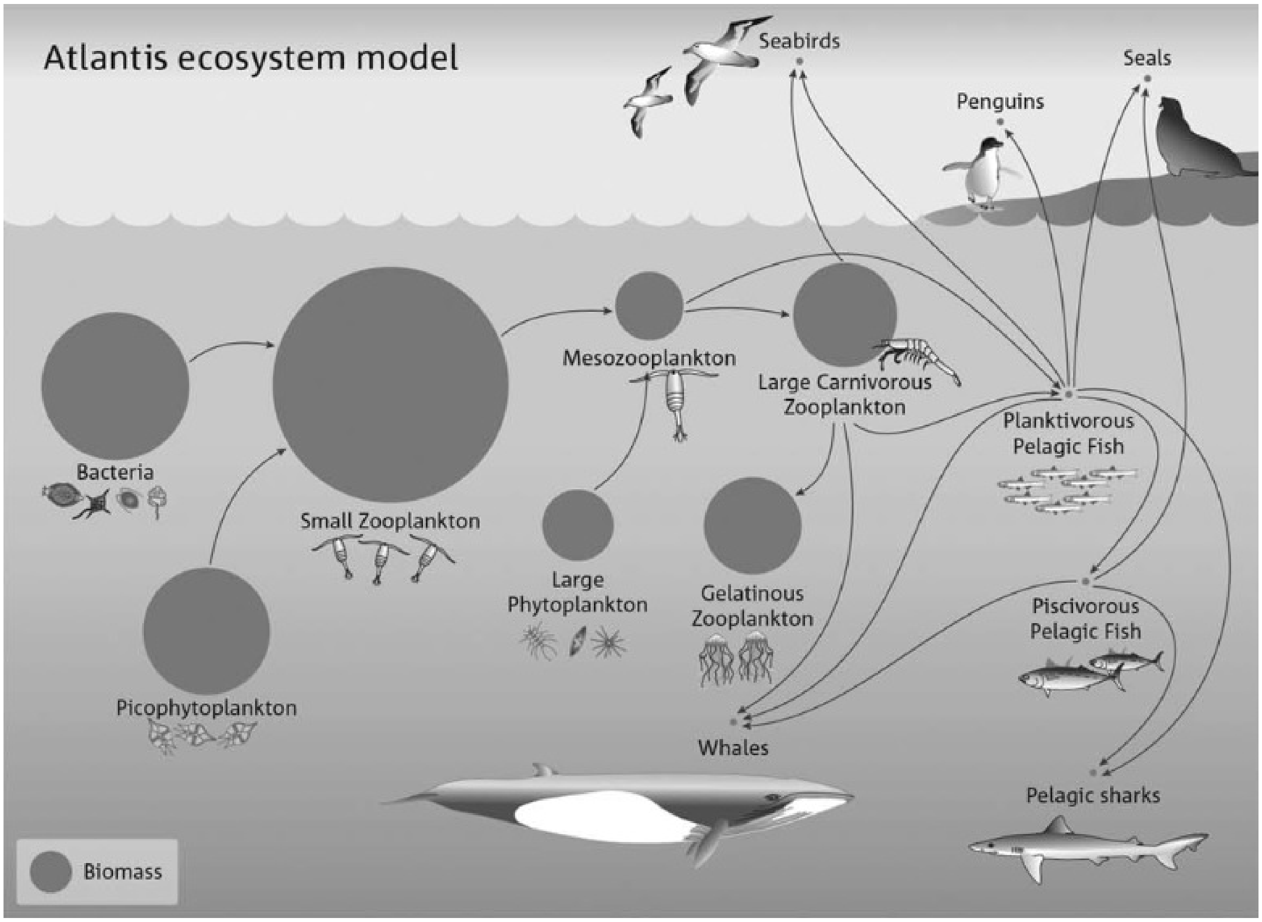


Figure 1.1: Diagram of a marine food web off south-east Australia, with the size of spheres proportional to the biomass of each group. Plankton dominate the biomass; the large species that we know well such as fish, whales, seabirds and penguins have a minuscule biomass in comparison. (Suthers et al., 2019, Chap. 1)

Bochdansky et al. (2013) present a more high-end solution using a digital inline holographic microscope. The system is able to take images at a depth of up to 6000 m making approximately 7 high-resolution images per second. However, the smallest size of a particle/a plankton species it can capture is 50 µm large limiting its usability for phytoplankton mostly ranging from 0.2 to 200 µm. The advantage of this system is that it operates fully autonomously without connection to external recording devices or power sources.

Zimmerman et al. (2020) make a lensless imaging system and focus on detection, tracking and classification of plankton in videos using machine learning with acceptable performance on an embedded computer (Raspberry Pi 3). This is exceptionally useful for an autonomous system as it would be able to filter the sampled data (plankton detected/not detected) and pre-annotate the pictures. That would allow to save energy on wireless communication, if majority of images do not contain any useful data, and would reduce scientists' workload when working with the received data.

A submersible microscope, which is able to detect plankton between ~10 μm to ~1 cm in size, is developed by Merz et al. (2021). Such a wide detection range is achieved by using two magnifications in the system (5x and 0.5x). The microscope delivers high-resolution, high-quality images. However, in order to operate fully autonomously on a mobile USV, it requires a dedicated immersing system not only to control the depth of a sample but simply to pull the microscope out of water (due to its significant sizes) to allow the USV to move without extra restrictions.

There are many options of plankton microscopes ranging in performance and complexity making it possible to find something for almost any application. PlanktoScope due to its exceptional affordability and simplicity, still good performance, was chosen as the base for this project. It is lightweight and small-sized which allows for its integrity into a USV (the Otter platform in our case – see Chapter 3) as an embedded subsystem. It lacks autonomy but due to its modular structure it is remediable.

## 1.2 Objectives

The main objectives of this Master's thesis are:

1. Short review of the biological role of marine phytoplankton, plankton dynamics, and HABs
2. Review of the PlanktoScope (the sensor) and the USV Otter platform
3. Technical design of the integrated system including solutions for:
    (a) Mechanical and electrical integration of the sensor in Otter payload compartment
    (b) Communication interface(s) between sensor and Otter control system
    (c) Real-time transmission of sensor images/samples to remote database
    (d) Control of water sample depth and size
    (e) Water sample flushing (to avoid cross-contamination of samples)
    (f) Interfacing and control of auxiliary sensors (CTD, oxygen, turbidity, fluorescence etc.)
    (g) Vehicle "sensor manoeuvre" DUNE task
4. Development and implementation of a "minimum viable solution" of the system and documentation its performance in lab tests and field trials. Extend the solution as time allows.
5. Discuss results and work out detailed documentation and project report

## 1.3 Approach

This project focuses mainly on the practical work. The whole design flow will be covered during the work starting from concepts development and abstract system diagrams all the way down to the actual implementation of a first prototype.

As the time allows, this prototype is to be tested in lab experiments and field work as well as upgraded.

## 1.4 Contributions

During the work on this project I have designed electronics and developed software for two functional units of the system as well as a communication protocol between them. I have tested one of them and got an image of the marine plankton from a water sample.

## 1.5 Limitations

The mechanical design of this project was limited by the abilities and availability of the ITK mechanical workshop. The design of electronics was limited to usage of ready solutions on the mass market that can be soldered or assembled with basic equipment.

## 1.6 Outline

- Chapter 2. Short review of the biological role of marine phytoplankton, plankton dynamics and HABs.
- Chapter 3. Overview of the hardware that was used, or based on which own hardware was developed.
- Chapter 4. Design and implementation of the units of the system.
- Chapter 5. Overview of results of the project.
- Chapter 6. Conclusions, discussion, and ideas for further work.
- Appendix A. Acronyms.
- Appendix B. Detailed electronic schemes of the developed units.
- Bibliography.

# Chapter 2

# Marine Phytoplankton Ecology

Phytoplankton are the autotrophic (self-feeding) components of the plankton community. They obtain energy through photosynthesis, as do trees and other plants on land. This means phytoplankton must have light from the sun, so they live in the well-lit surface layers (euphotic zone) of oceans and lakes. Phytoplankton can be also defined as follows:

> Phytoplankton (*phyto* = plant, *planktos* = made to wander) consist of microscopic algae, cyanobacteria (blue-green algae) and other protists that live suspended in the water. With tens of thousands of species identified in coastal and oceanic waters, microalgae are highly diverse, yet largely underexplored…
>
> Suthers et al. (2019, Chap. 6)

Phytoplankton form the basis of the marine foodweb, providing nutrition to higher trophic levels. Most phytoplankton are unicellular and range in size from 0.2 to 200 μm, with a few taxa attaining up to 2 mm in length. Pigments are chemical compounds contained in the chloroplasts of microalgae that assist in capturing solar energy for photosynthesis. In order to acquire more of the sun's energy, different phytoplankton produce several different kinds of pigments to absorb a broader range of wavelengths. As well as distinguishing between the major functional groups, pigments reflect evolutionary relationships between these groups and provide us with a method of measuring phytoplankton biomass and determining production rates (growth) of different phytoplankton communities.

Phytoplankton can rapidly reproduce in advantageous environmental conditions and blooms may take place. Blooms can vary in color and even be colorless. They may occur naturally or as a result of human activities. Not all the blooms are harmful, therefore, it is important to identify the species (often it is only one) making up the bloom and the conditions causing it. In addition, some water discolorations are not associated with phytoplankton at all.

Changes in the nutrient levels through run-off from land or upwelled bottom water layers can cause natural phytoplankton blooms as a harmless episodic response. Sometimes (usually because of human activities), excessive nutrients lead to excessive growth of phytoplankton, shading important plants, or depriving fish of oxygen leading to fish kills. This can affect human health, ecosystem function and fish resources. Besides that, other blooms may contain toxins that are transferred to higher trophic levels, including shellfish, fish, marine animals, birds and humans.

> Phytoplankton blooms that have the potential to cause harm are commonly referred to as **harmful algal blooms (HABs)**.
>
> Suthers et al. (2019, Chap. 3)

Consuming sea products affected by HABs can cause severe illnesses for humans, but it is difficult to predict them because toxic species are not always toxic depending on the situation. It is also expected that certain species may prove to be toxic in the future.

Preventing or reducing the discharge of excess nutrients into the coastal zone is the most effective means of minimizing HABs. Understanding the pathways of nutrient enrichment in each system is essential.

# Chapter 3

# Overview of Used Hardware

## 3.1 PlanktoScope

PlanktoScope (https://www.planktoscope.org) was chosen as the basis for the main unit, which this project is focusing on. PlanktoScope is a machine vision-based plankton sensor. It is an open-source microscope platform powered by a Raspberry Pi (https://www.raspberrypi.org).

As shown in Figure 3.1 Planktoscope consists of the following major parts:

- Raspberry Pi 4 Model B – computational unit responsible for controlling other parts.
- Stepper/DC motors driver – to control position of the Focus Stage and the pump.
- GPS unit – allows to add information on location into a taken sample.
- Pi Camera – a digital camera for taking pictures of the samples.
- Set of lenses – to amplify and focus an image into the camera sensor.
- Focus Stage with an Ibidi slide – movable component carrying a channel slide, which a sample is pumped into.
- LED – to light up the scene.
- Peristaltic pump – pumping samples through the slide channel.
- Two syringes – for sampling and disposal of used samples.

The Raspberry Pi running Linux uses existing open-source programs and python libraries such as Node-RED (https://nodered.org) for GUI and first layer of programming interface, MorphoCut (https://morphocut.readthedocs.io/en/stable/) for handling the image processing from the raw images to the online platform, and EcoTaxa (https://ecotaxa.obs-vlfr.fr/) for classification and annotation.

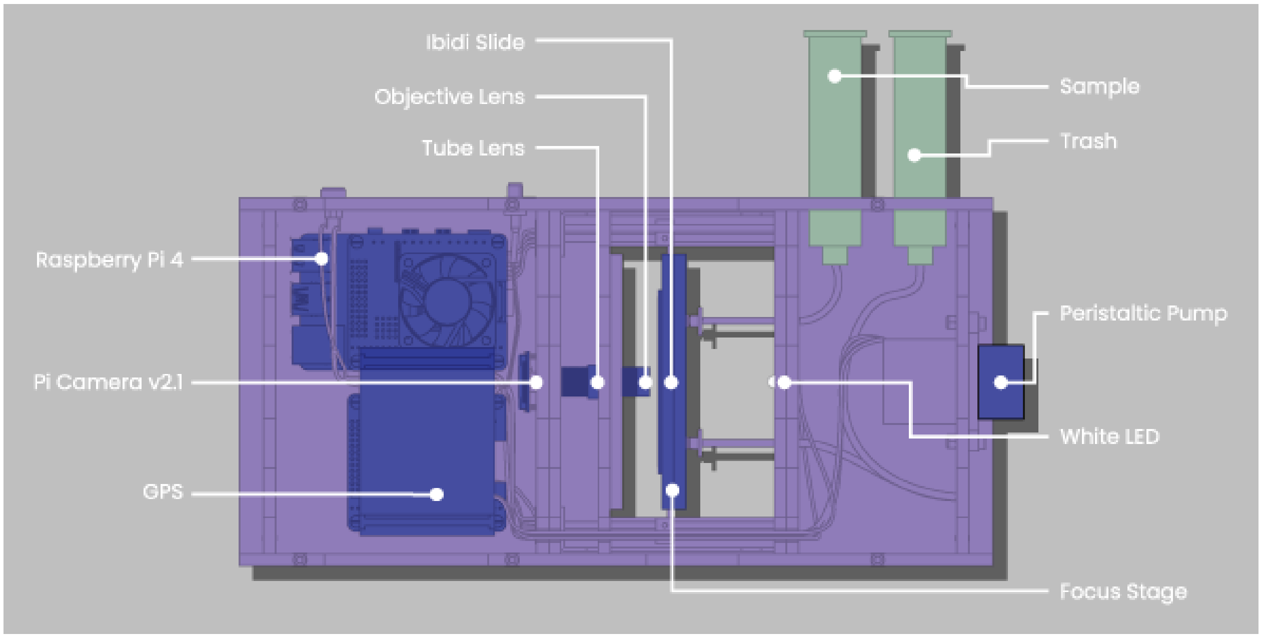


Figure 3.1: Planktoscope (`https://www.planktoscope.org/how-it-works`)

## 3.2 Otter USV

The NTNU Fish Otter (see Figure 3.2) is a small unmanned catamaran propelled by two electrical fixed thrusters. The vessel is based around the hull, thrusters and power-distribution from a Maritime Robotics Otter (`https://www.maritimerobotics.com/otter`), but with sensors and control systems designed at NTNU. This design is based on the LSTS toolchain (`https://lsts.fe.up.pt/about`), with DUNE (`https://lsts.fe.up.pt/toolchain/dune`) running onboard the vessel.

### 3.2.1 Control Box

The Control Box of the Otter USV is also based on a Raspberry Pi 4 with 4GB of RAM. Through its GPIO pins, it is connected to a Strato Pi CAN Board (`https://www.sferalabs.cc/product/strato-pi-can-board/`), which in addition to robust power supply provides several communication interfaces and an independent hardware watchdog. CAN network connects the Raspberry Pi to the Torqeedo Interface Board. Thus, it has access to both the power channel and the motor control. RS-485 interface of the board enables serial communication with a TBR-700-RT hydrophone (`https://www.thelmabiotel.com/receivers/tbr-700-rt/`).

LAN is based around a Teltonika RUT950 4G (LTE) router (`https://wiki.teltonika-networks.com/view/RUT950`). Wireless (airMAX®) communication is managed by a BulletAC-IP67 (`https://dl.ubnt.com/datasheets/bullet_ac/Bullet_AC_DS.pdf`) connected to the control box over PoE using a passive PoE injector inside the box. In addition, the box is connected to a Hemi-

Figure 3.2: NTNU Fish Otter (`https://otter.itk.ntnu.no/doku.php?id=start`)

sphere V104s GPS Compass (`https://www.hemispheregnss.com/wp-content/uploads/2019/06/hemispheregnss_v104s_userguide_875-0346-000_a3.pdf`) via a USB-RS232 converter.

Graphical overview of the featured hardware inside the control box is shown in Figure 3.3.

All of the hardware described above provides a set of convenient and flexible options for communication with the PlanktoScope unit.

### 3.2.2 Software Architecture

The software used to control the Otter is based on the LSTS Toolchain, which is a software toolchain meant for developing networked vehicle systems. It aims at creating a modular system for heterogeneous systems of vehicles to control them with much of the same software. The Otter is an autonomous surface vehicle (ASV), but it also supports autonomous underwater vehicles (AUV), unmanned aerial vehicles (UAV), remotely operated vehicles (ROV), and more. The three main components of the toolchain are Neptus, IMC and DUNE. Neptus is the operator's console, IMC is the communication protocol, and DUNE is the software controlling the vehicles.

The Control Box of the Otter USV uses a customized version of DUNE running on Raspberry Pi OS Lite (displayless version of Raspberry Pi OS – `https://www.raspberrypi.com/software/`) – see Figure 3.4. DUNE compiles as one executable file, but to actually use it, one has to make an `.ini` configuration file. This file says what tasks are to run and what parameters those tasks should use. The Otter is configured to run the tasks as shown in Figure 3.5.

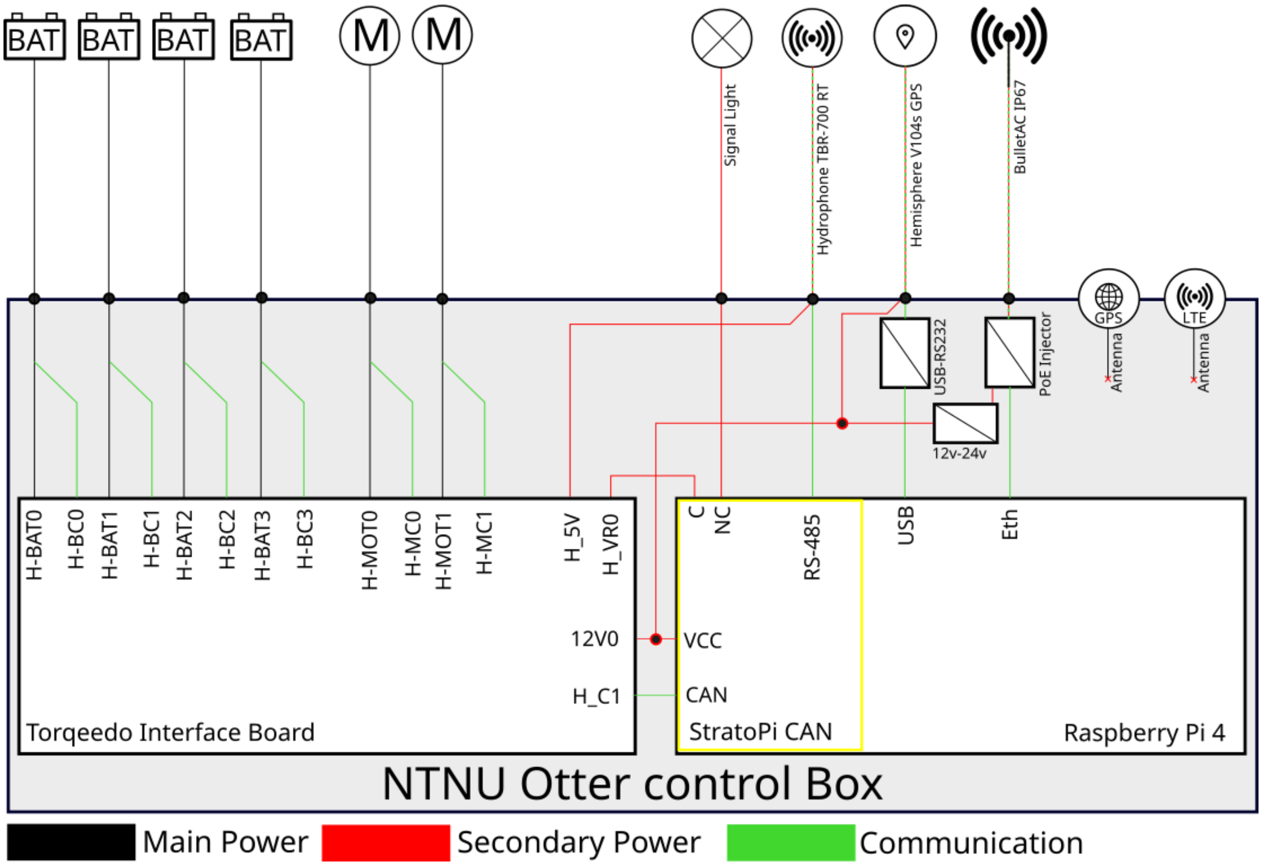


Figure 3.3: Overview of the Otter USV Control Box (`https://otter.itk.ntnu.no/doku.php?id=hw`)

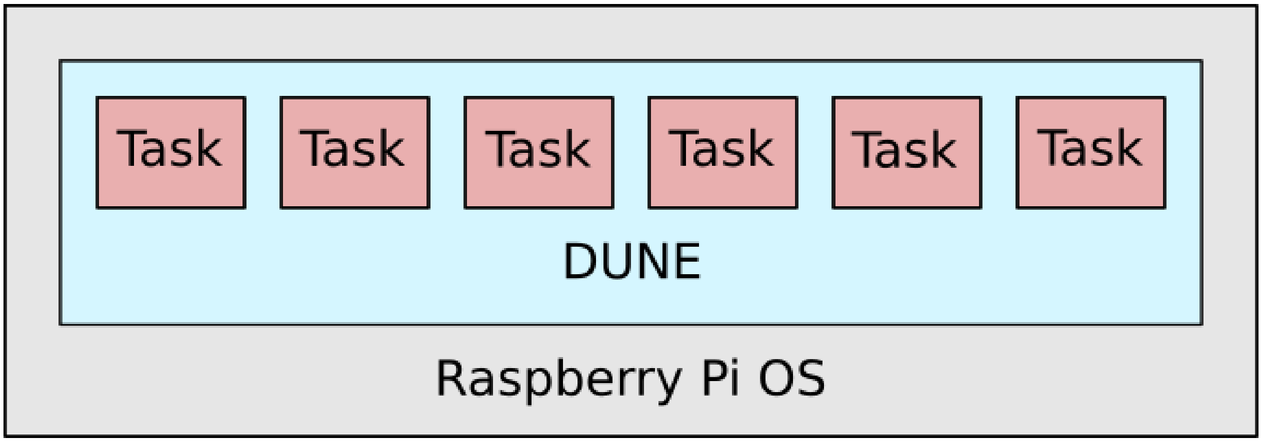


Figure 3.4: Otter USV SW Architecture (`https://otter.itk.ntnu.no/doku.php?id=sw`)

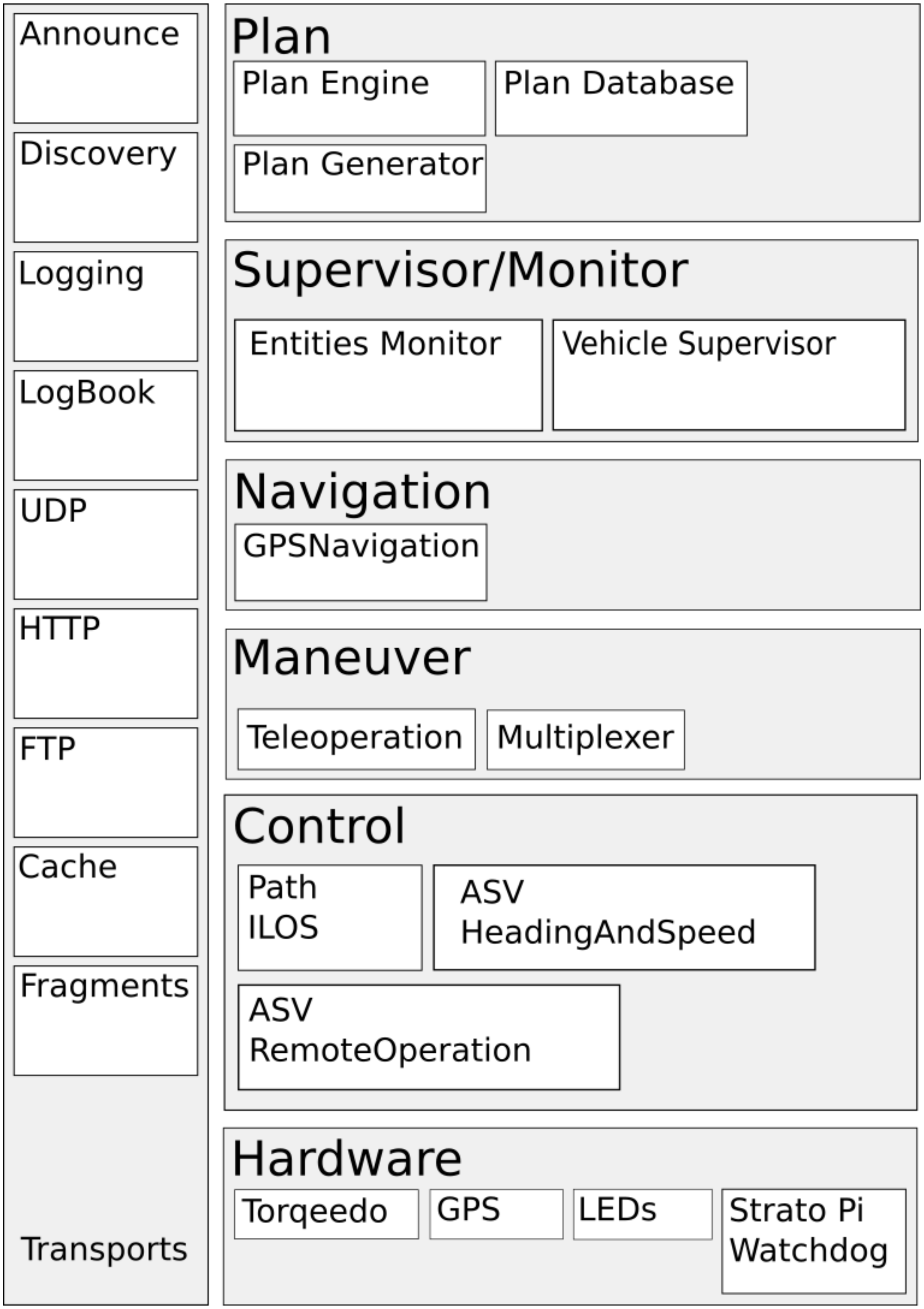


Figure 3.5: DUNE configuration for the Otter USV (https://otter.itk.ntnu.no/doku.php?id=dune_configuration)

# Chapter 4

# Design and Implementation

## 4.1 Mechanical Design

First step of the design process is to place all the components needed for PlanktoScope inside a payload box, which will be carried by the Otter USV along with the Control Box. The design should allow focusing the camera, i.e. changing the distance between the camera and the Ibidi µ-Slide surface. Also, it should minimize the probability of the electronic components to be exposed to the salty water being sampled, e.g. when pipes are damaged.

The original design of PlanktoScope is self-sufficient and does not require any further housing. However, since it is to be placed in the Otter payload box, it is reasonable to make it easier and more fitting to the box inner shape. In addition, it would be useful to decouple the fluidics from the electronics to make the design more reliable.

The mechanical design was performed by means of 3D-modelling of an assembly using cloud-based CAD software Fusion 360 (`https://www.autodesk.com/products/fusion-360`). Instead of moving the µ-Slide with attached to it pipes, which potentially brings a risk of spilling water in case the pipes get disconnected, it was decided to make the camera-lenses unit movable. Moreover, this system was separated from the two major electronic components (the Raspberry Pi and the motor driver) and placed on the bottom of the box. The electronics are to be placed on a plate above, which makes it more isolated. A first concept of the design is presented in Figure 4.1. A stepper motor, located at the bottom, through a lead screw precisely controls position of a platform holding the camera with lenses. This allows to adjust focus of PlanktoScope (to be able to scale images for different plankton sizes) without accessing it directly. In front of the camera is the Ibidi µ-Slide, behind which a white LED is placed to light up the scene of a photo. A detailed assembly model and the actual implementation were done by the ITK mechanical workshop.

Since the peristaltic pump filling the µ-Slide is dedicated to low-flow, low-power operation it is unable to pump water directly from the ocean. Because of that it was decided to bring

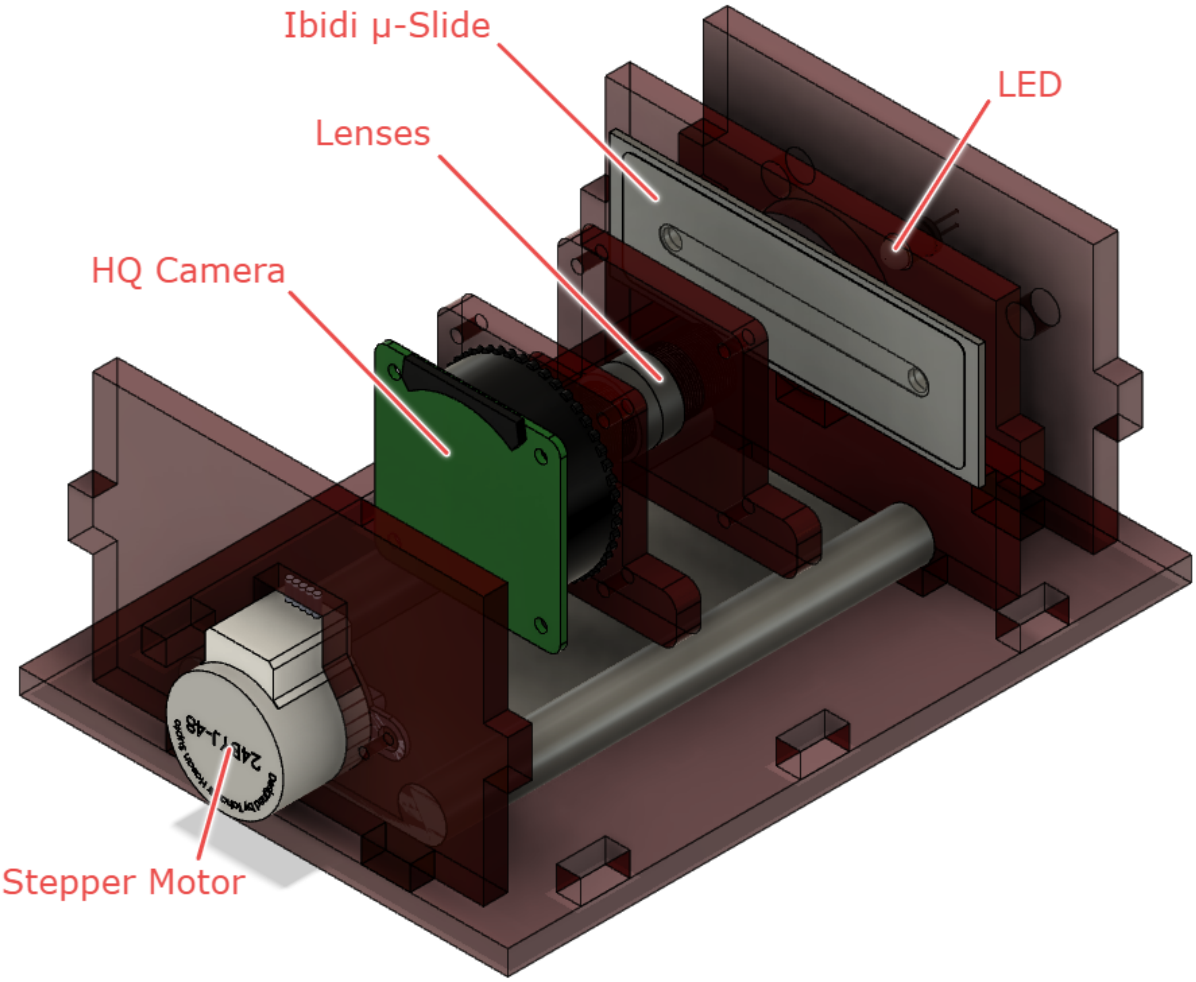


Figure 4.1: PlanktoScope: first concept model

another unit into the design featuring a stronger pump filling an external tank with the ocean water, which will be the source for the PlanktoScope peristaltic pump. This unit is to be placed outside of the PlanktoScope Box in a separate polycarbonate watertight box to protect the major electronic components from the high flow. In order to minimize the pump influence on the water samples it should be of certain types. In addition, its power source should conform with the voltage levels provided by the Torqeedo Interface Board (5V and 12V). A diaphragm 12V pump was chosen for that purpose. Along with the pump there is also a minimalistic control unit driven by an Arduino Nano Every (`https://store-usa.arduino.cc/products/arduino-nano-every`). A model of the control unit of the Pump Box is shown in Figure 4.2.

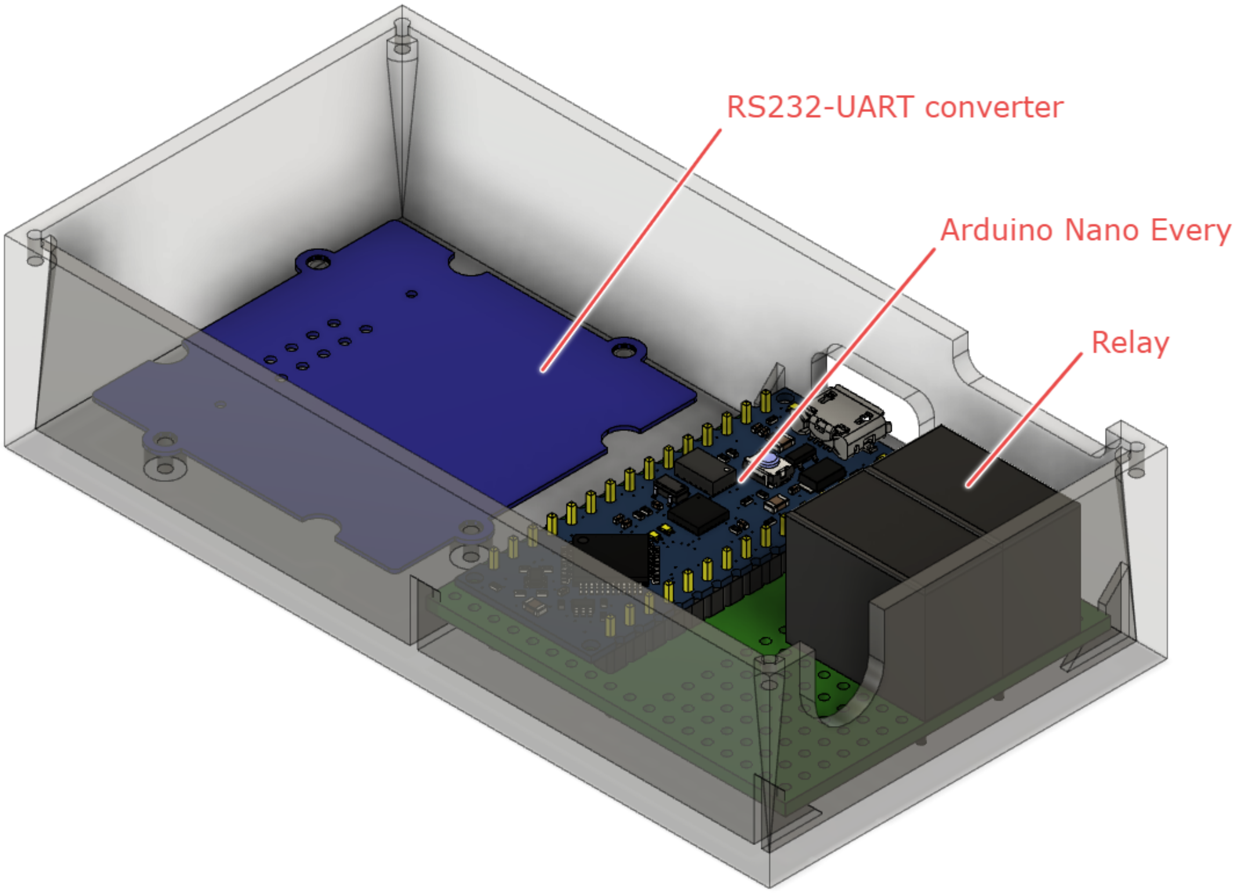


Figure 4.2: Pump Box

## 4.2 Electronic Design

The system under development is composed of two units: **PlanktoScope Box** and **Pump Box**. A basic system diagram is shown in Figure 4.3. More detailed electronic schemes of the functional units are presented in Appendix B.

One of the four Otter batteries is allocated for needs of the system. PlanktoScope Box features a Torqeedo Interface Board that translates the battery power into the voltage levels used by the system. A source of 5V power is used for needs of PlanktoScope and a 12V power is transferred to the Pump Box. The central component is the Raspberry Pi 4B controlling all other components and communicating with the Otter Control Box via WLAN. It also uses other communication interfaces to interact with internal (motor driver, HQ camera) and external (Arduino Nano from the Pump Box) components. An Adafruit Motor Bonnet (the motor driver) uses $I^2C$ for communication and controls the peristaltic pump and the focus stepper. The HQ camera uses a dedicated flexible cable to communicate with RPi. There is a USB-RS232 adapter to enable reliable serial communication between the units.

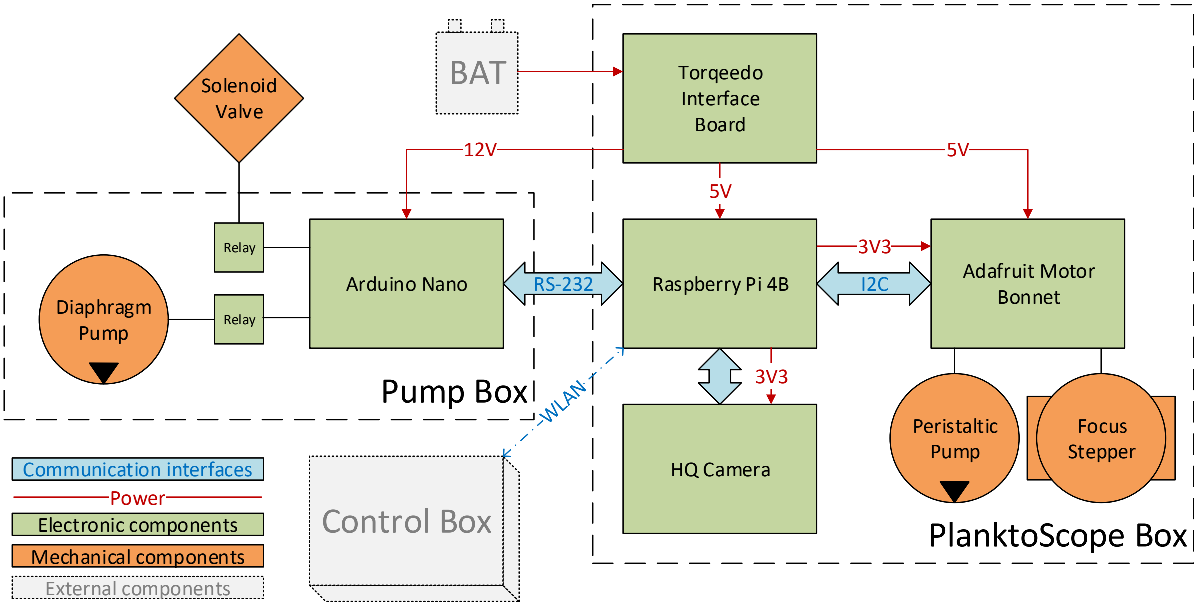


Figure 4.3: System diagram

The Pump Box, on the other side, features an RS232-UART converter and an Arduino Nano Every. Using its GPIO pins the Arduino board through amplifying transistors controls two relays. The relays connect a diaphragm pump and a solenoid valve to the source of 12V power controlling filling and emptying of a water tank respectively. Each relay has a flyback diode around its coil to protect the transistor from high current and to reduce the circuit noise when a relay closes. The tank also has a level switch to provide feedback about the water level inside it (full/empty). In addition, both boxes feature a trivial water detector to alert the users if a water leakage takes place.

Before assembling the electronics the concept of communication through RS232 and controlling the relay was checked on a simple breadboard prototype shown in Figure 4.4

## 4.3 Software Development

Originally PlanktoScope is supposed to be used by an operator and, therefore, has a dedicated GUI (see Figure 4.5) accessible via a web browser to make this process easier. All the adjustments and steps of the sampling process are invoked manually. This approach is obviously not suitable for an ASV where majority of the processes should be held automatically. Although, a minimal user interface should remain to enable, for example, optic configuration to visually evaluate camera focus, etc.

The main purpose of the system, and hence its software's priority, is taking pictures of plank-

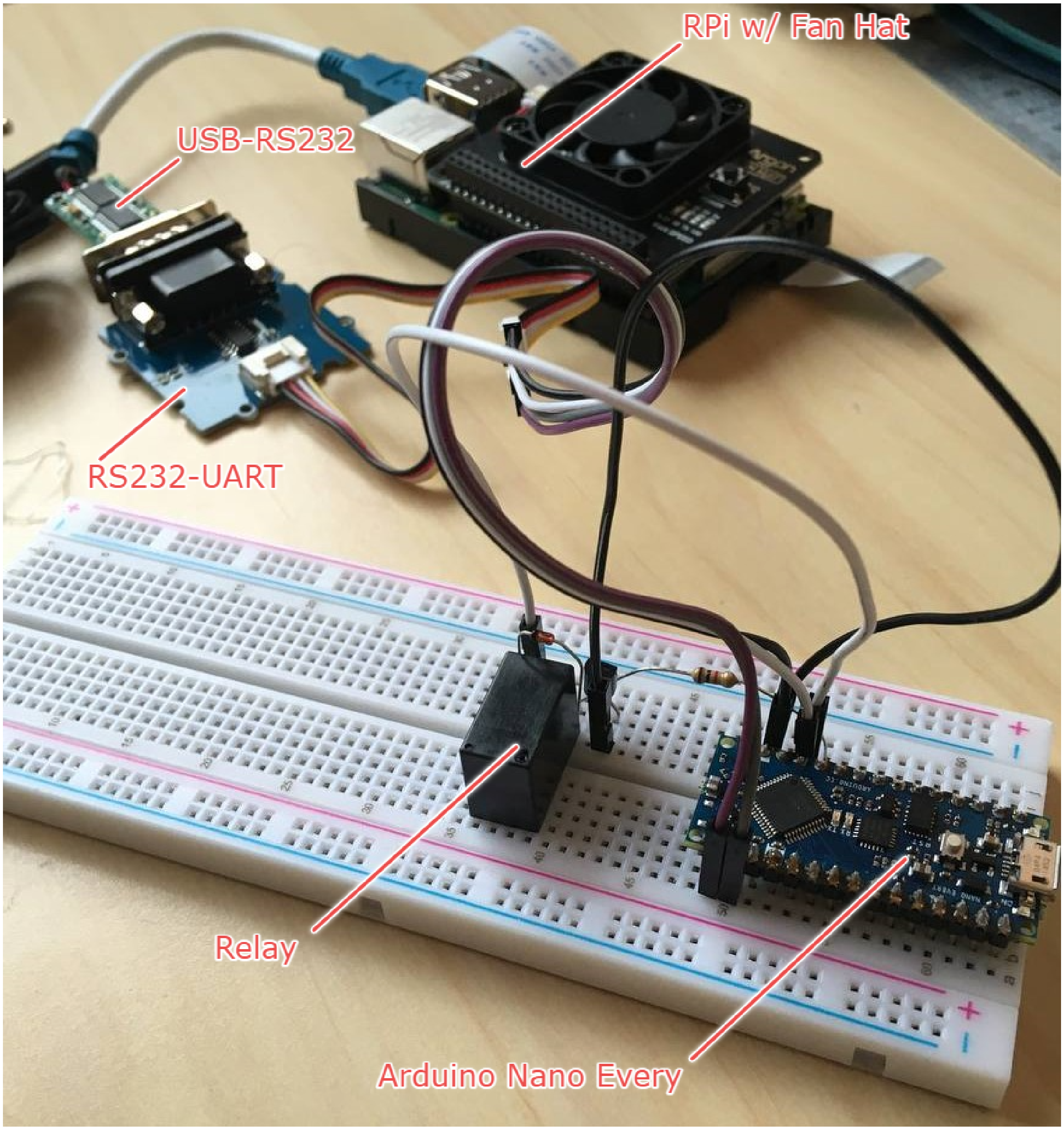
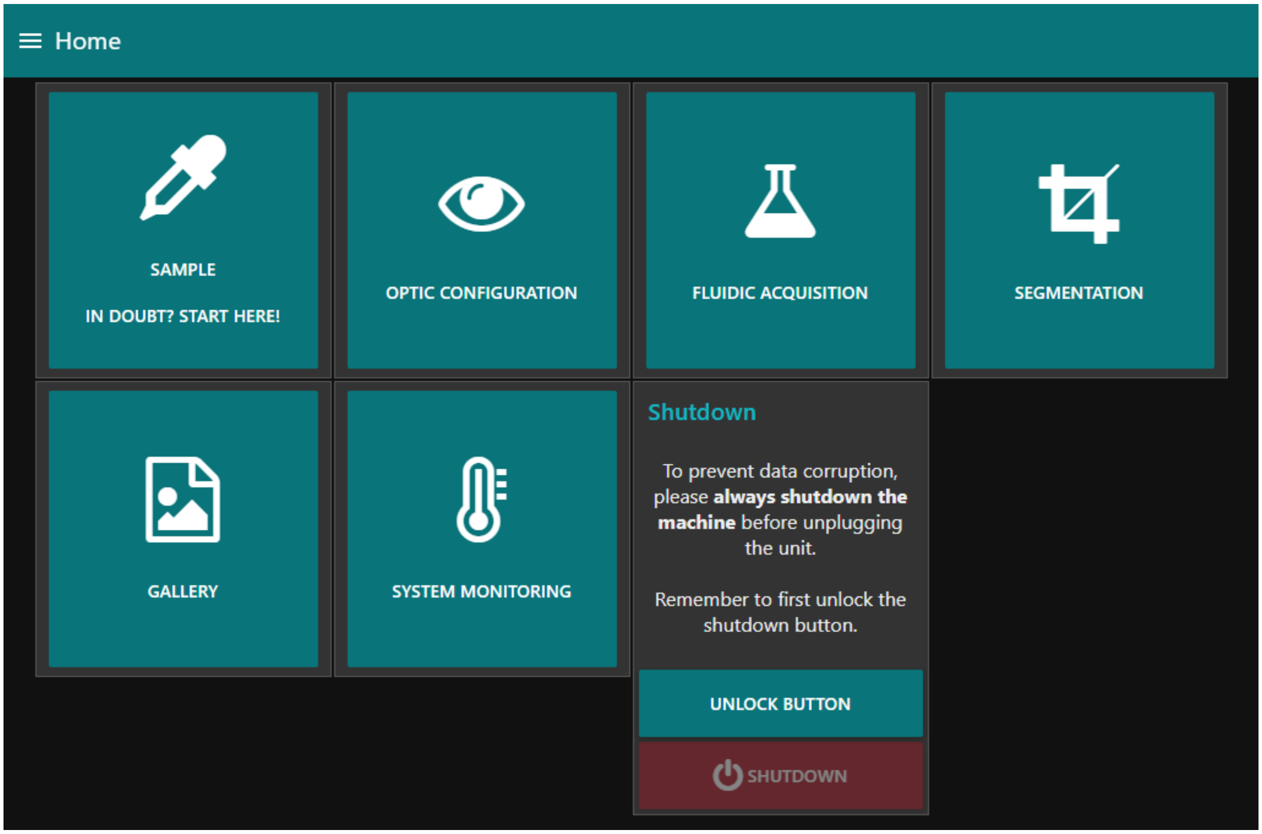


Figure 4.4: Concept check prototype



To prevent data corruption, please **always shutdown the machine** before unplugging the unit.

Remember to first unlock the shutdown button.

Figure 4.5: PlanktoScope Web GUI

ton. A flowchart of this process is depicted in Figure 4.6. Inter-unit communication is highlighted in blue and messages that are to form the communication protocols are written in quotes.

Communication between the Control Box of NTNU Otter and the PlanktoScope Box is done through WLAN. A good solution in this case would be **MTQQ** – a lightweight, publish-subscribe, machine to machine network protocol. It will enable simple communication between the existing nodes of the ASV as well as allow easy integration of more communicating units into the vehicle system. The MQTT protocol defines two types of network entities: a message broker and a number of clients. An MQTT broker is a server that receives all messages from the clients and then routes the messages to the appropriate destination clients (`https://developer.ibm.com/articles/iot-mqtt-why-good-for-iot/`). An MQTT client is any device that runs an MQTT library and connects to an MQTT broker over a network. In our case, the RPi of the Control Box will run an MQTT broker and other devices, including the PlanktoScope Box, will connect to it as clients over the network. In MQTT an application can use any data format for the payload, such as JSON, XML, encrypted binary, or Base64, as long as the destination clients can parse the payload (`https://developer.ibm.com/articles/iot-mqtt-why-good-for-iot/`). In the flowchart there are four messages exchanged over the WLAN, for which the payloads should be described:

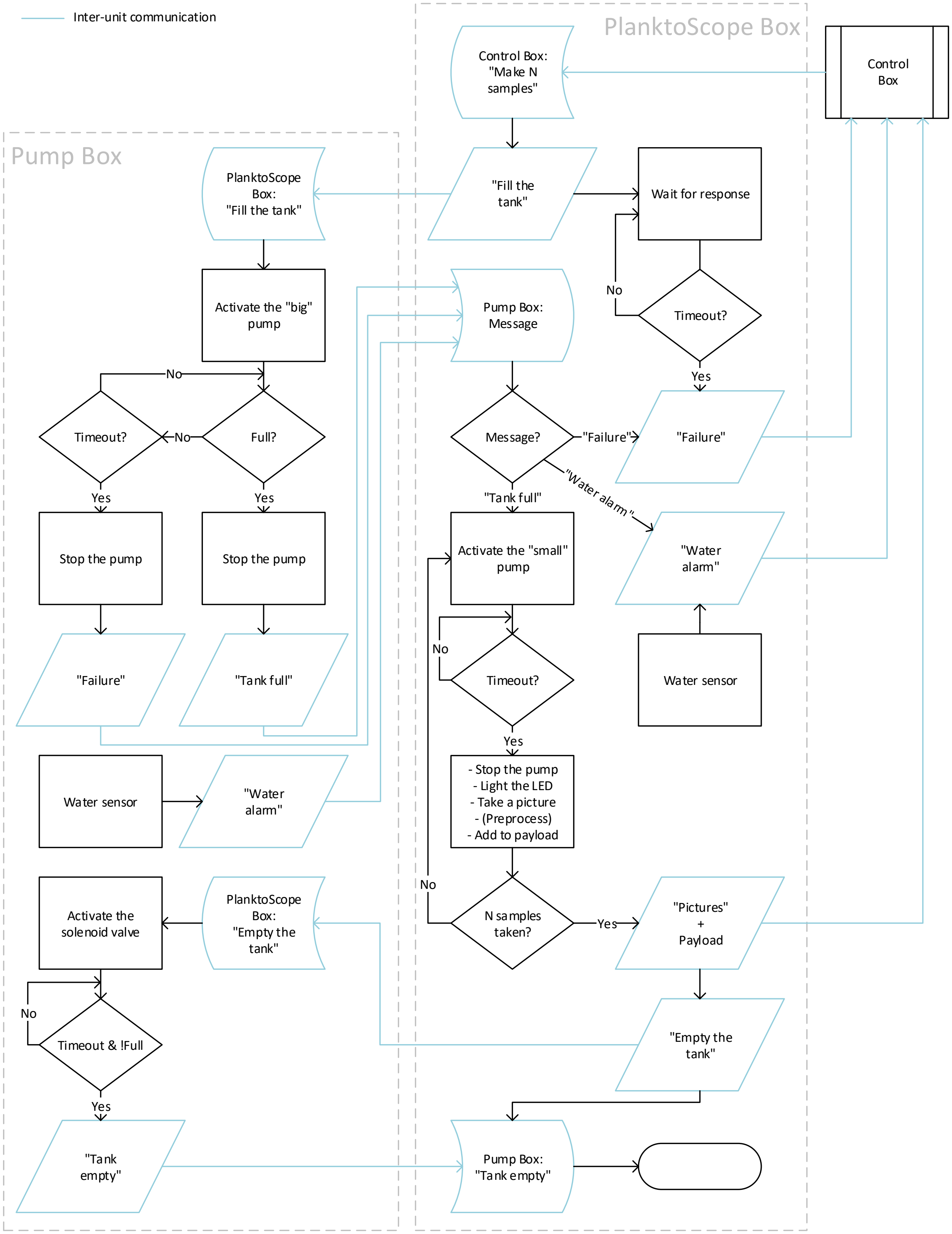


Figure 4.6: Flowchart

- "Make N samples": a simple JSON containing a number of samples to be taken

```
    {
        "action": "sample",
        "number": N
    }
```

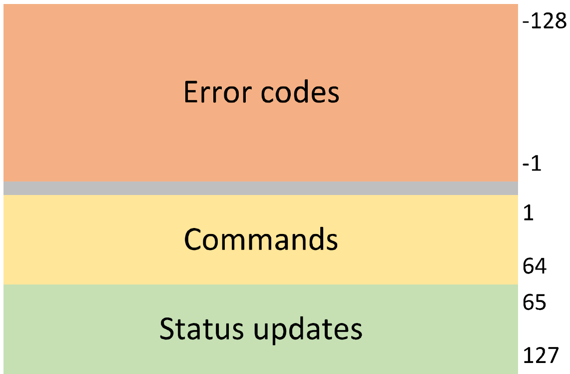
  where N is an integer.

- "Failure" and "Water alarm": can be instances of messages of a same type containing the type of a problem and additional information like what unit has experienced a water leakage or what kind of failure has occurred

```
    {
        "fault": "failure"/"water",
        "info": ‘a string describing additional info‘
    }
```

- "Pictures": MTQQ supports payloads in binary format, which can be used to transfer images.

Communication between the PlanktoScope and the Pump Boxes is carried through **RS232**, which is a standard for serial communication. Since all of these messages are just commands or status updates with no numeric data, they can be simply encoded with one byte signed integer (`int8_t` in C). I suggest the following allocation:



| | |
|---|---|
| **-2** | "Water alarm" |
| **-1** | "Failure" |
| **1** | "Fill the tank" |
| **2** | "Empty the tank" |
| **65** | "Tank full" |
| **66** | "Tank empty" |

The RPi controlling PlanktoScope runs Raspberry Pi OS. On startup a cron job (`https://pubs.opengroup.org/onlinepubs/9699919799/utilities/crontab.html`) starts a Python script with multiple threads ensuring the PlanktoScope functioning. Overall system software architecture is presented in Figure 4.7.

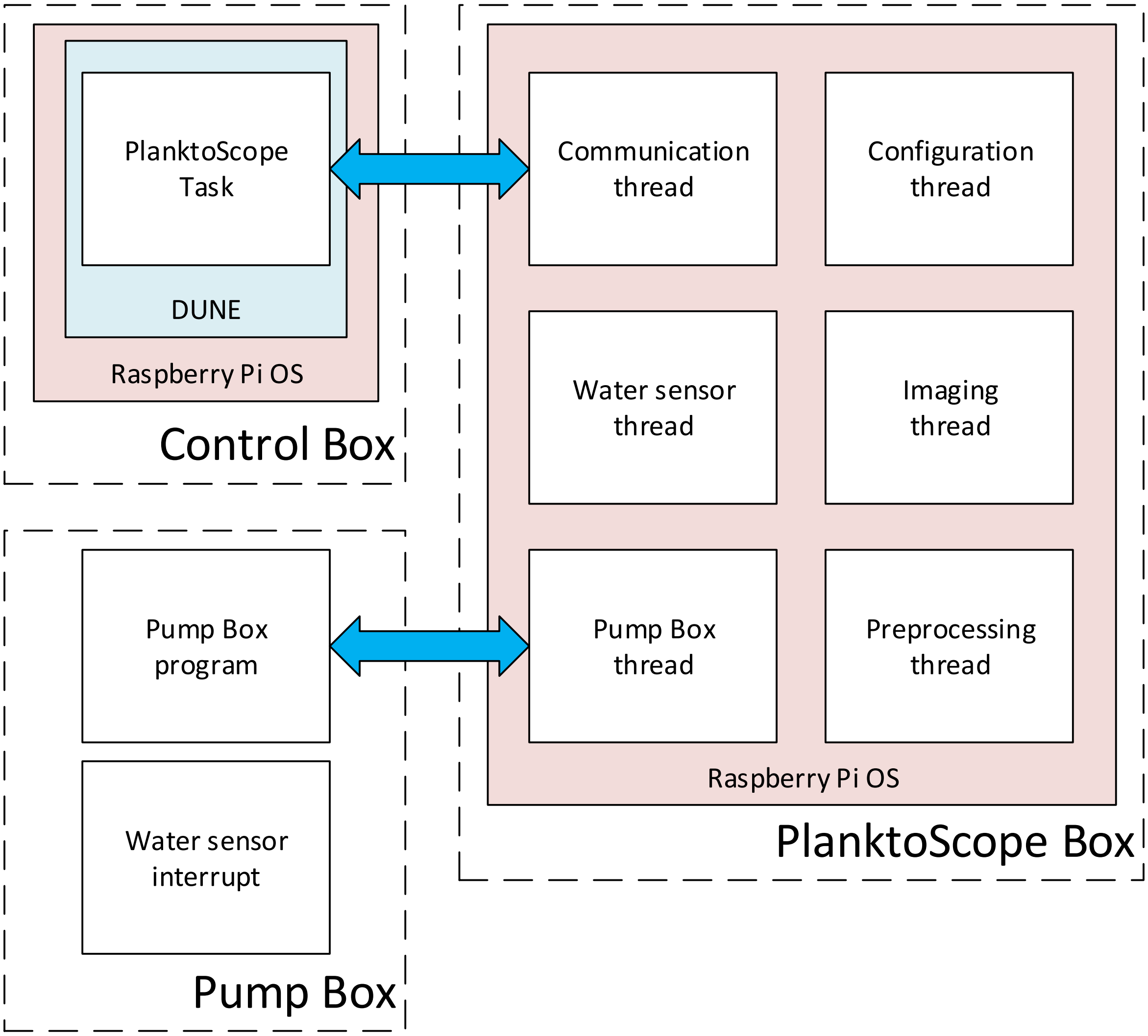


Figure 4.7: System software architecture

# Chapter 5

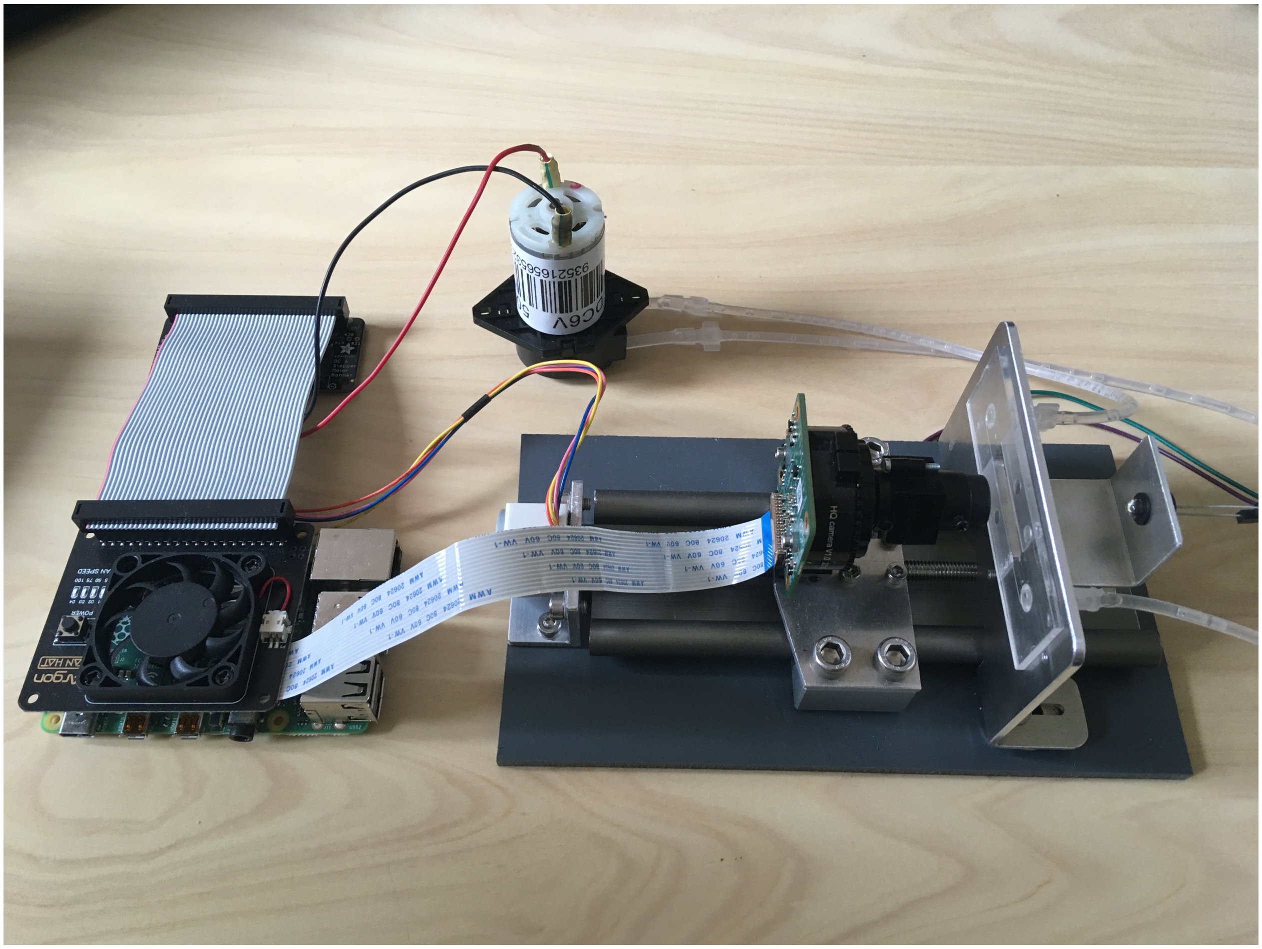
# Results

Carrying out this project has resulted in a developed and partly implemented embedded system consisting of two functional units. Technical documentation for the system has been worked out and presented throughout the report and in Appendix B.

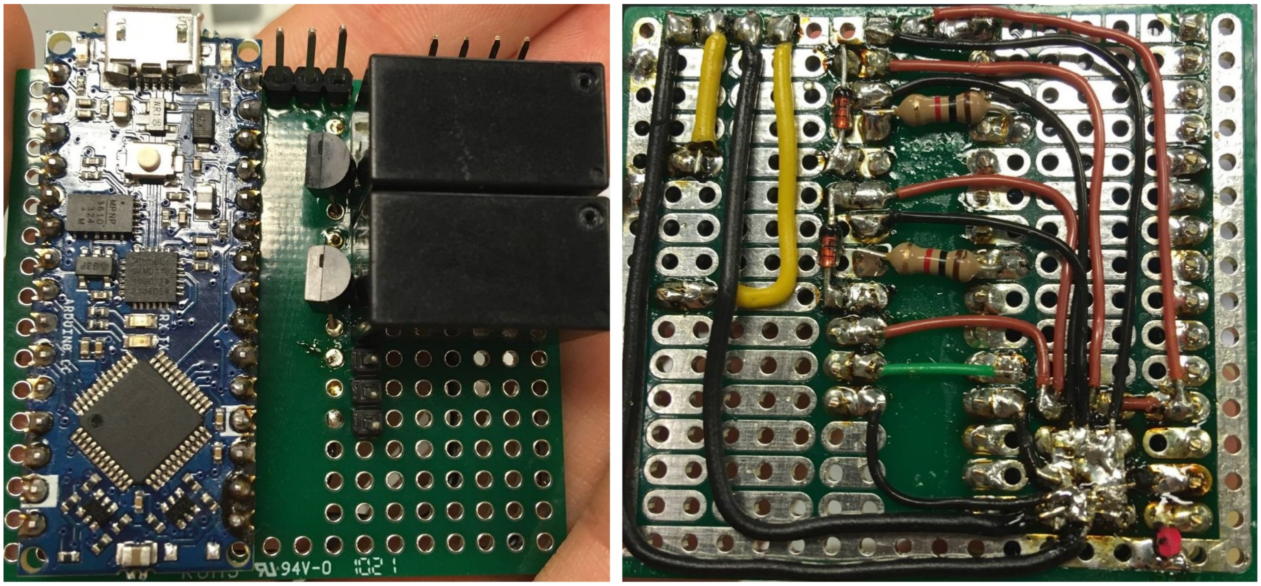
The implemented parts of the system are shown in Figure 5.1. The mechanical part of PlanktoScope has been implemented by the ITK mechanical workshop; I have assembled it and wired the electronics according to the earlier developed schematics. The control unit of the Pump Box has been soldered, and a cover box for it has been 3D printed.

Besides the hardware implementation PlanktoScope has been tested on a sample of sea water that was collected on the shore of the fjord. Examples of the captured plankton are shown in Figure 5.2.

During the experiments the peristaltic pump used in this setup appeared to be unsuitable. Featuring a DC motor it does not allow to control the flow rate precisely resulting in its "jumpy" behaviour. In addition, thin channel of the Ibidi slide is a great resistance to the flow and it got damaged by the pump running with full speed. A pump with a **stepper motor** would be a remediation to these issues.



(a) PlanktoScope



(b) Pump Box Control unit

Figure 5.1: Implemented parts of the system

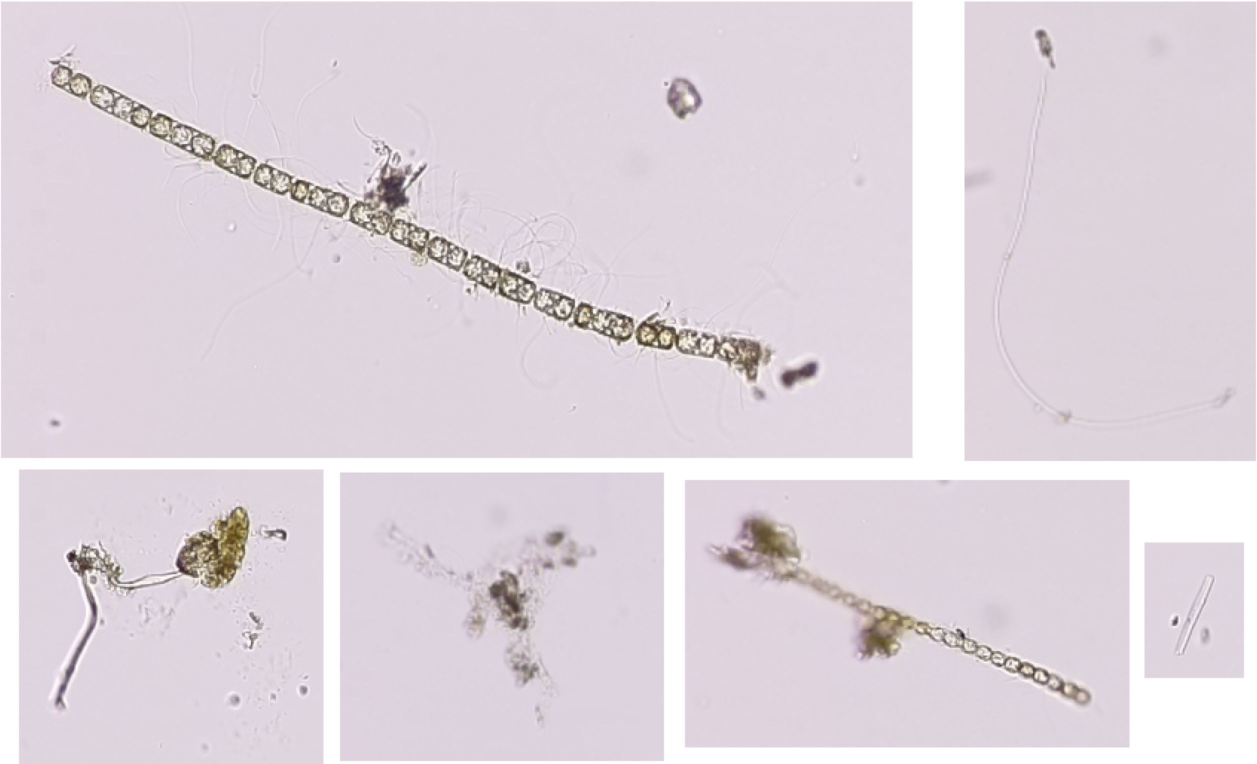


Figure 5.2: Examples of the images obtained with PlanktoScope

# Chapter 6

# Conclusions, Discussion, and Recommendations for Further Work

## 6.1 Summary and Conclusions

Carrying out this project the following results have been achieved:

1. Short review of the biological role of marine phytoplankton, plankton dynamics, and HABs has been done allowing to understand the importance of the system under development
2. Review of the PlanktoScope and the USV Otter platform has been done forming a base for the development of the own system
3. Technical design of the integrated system has been conducted in particular:
    - (a) Mechanical and electrical design of the sensor to be integrated into the Otter payload compartment
    - (b) Communication interface between the system units
    - (c) Real-time transmission of sensor images/samples to remote database
    - (d) (not stated as objective) An additional subsystem for automatic water sampling was developed
4. The sensor and the water sampling units have been implemented. A sample image has been taken using the sensor
5. Detailed documentation for the developed units has been worked out.

Unfortunately, not all the objectives have been met:

1. A "minimum viable solution" (i.e. integration of the developed units into the USV) has not been implemented due to unexpectedly long time the implementation process took. The ITK mechanical workshop was preoccupied with other tasks, leaving not enough time for this project.
2. Some of the technical design stages has not been done:
   (a) Proper water sample flushing would require a source of pure water (with no plankton in it) which is not possible on a USV. Instead, it was assumed that simply discarding a couple of samples after a used sample should reduce probability of cross-contamination to an acceptable level
   (b) Auxiliary sensors have not been added into the system due to their dependence on the implementation of the water sampling inlet
   (c) Vehicle “sensor manoeuvre” DUNE task has not been developed due to the lack of time and additional hardware to test it on in combination with the developed system

## 6.2 Discussion

Since plankton are the dominant part of any marine ecosystem, their state affects the whole system. Therefore, plankton studies are becoming more and more important as sea is a crucial source of sustainable food production. To aid these studies one needs off-shore technical solutions for monitoring the plankton dynamics.

Solutions like PlanktoScope, which was covered in this work, being simple allow fast deployment and ease of maintenance. Moreover, extreme affordability allows to have many of such systems largely expanding the range of studies.

This work has shown that PlanktoScope is easy to build and use and that it is suitable for visual research of plankton species. Utilizing the NTNU Otter capabilities for autonomous work and long-range wireless communication this system can work fully automatically and provide researchers with real-time data at low cost. Having a relatively powerful embedded computer (RPi 4B) onboard it can also serve as a first step filter and classifier of the obtained data.

## 6.3 Recommendations for Further Work

- Short-term. Since the objective of creating a minimum viable solution was not met, this should be the first priority to extend this work. Having a proper prototype will allow field trials that will show how suitable this solution is to the actual application.

- Medium-term. Having a prototype and first experiments' results it might be necessary to alter the solution by changing the developed or introducing new hardware and/or software. A good idea would also be to investigate the usage of machine learning for segmentation and classification of obtained data.
- Long-term. NTNU Fish Otter is an autonomous multi-agent system which can be used for the plankton dynamics research on a larger scale.

# Appendix A

# Acronyms

**HAB** Harmful Algal Bloom

**USV** Unmanned Surface Vehicle

**ASV** Autonomous Surface Vehicle

**GUI** Graphical User Interface

**PoE** Power over Ethernet

**RPi** Raspberry Pi

**GPIO** General Purpose Input/Output

**MQTT** MQ Telemetry Transport

# Appendix B

# Electronic schematics

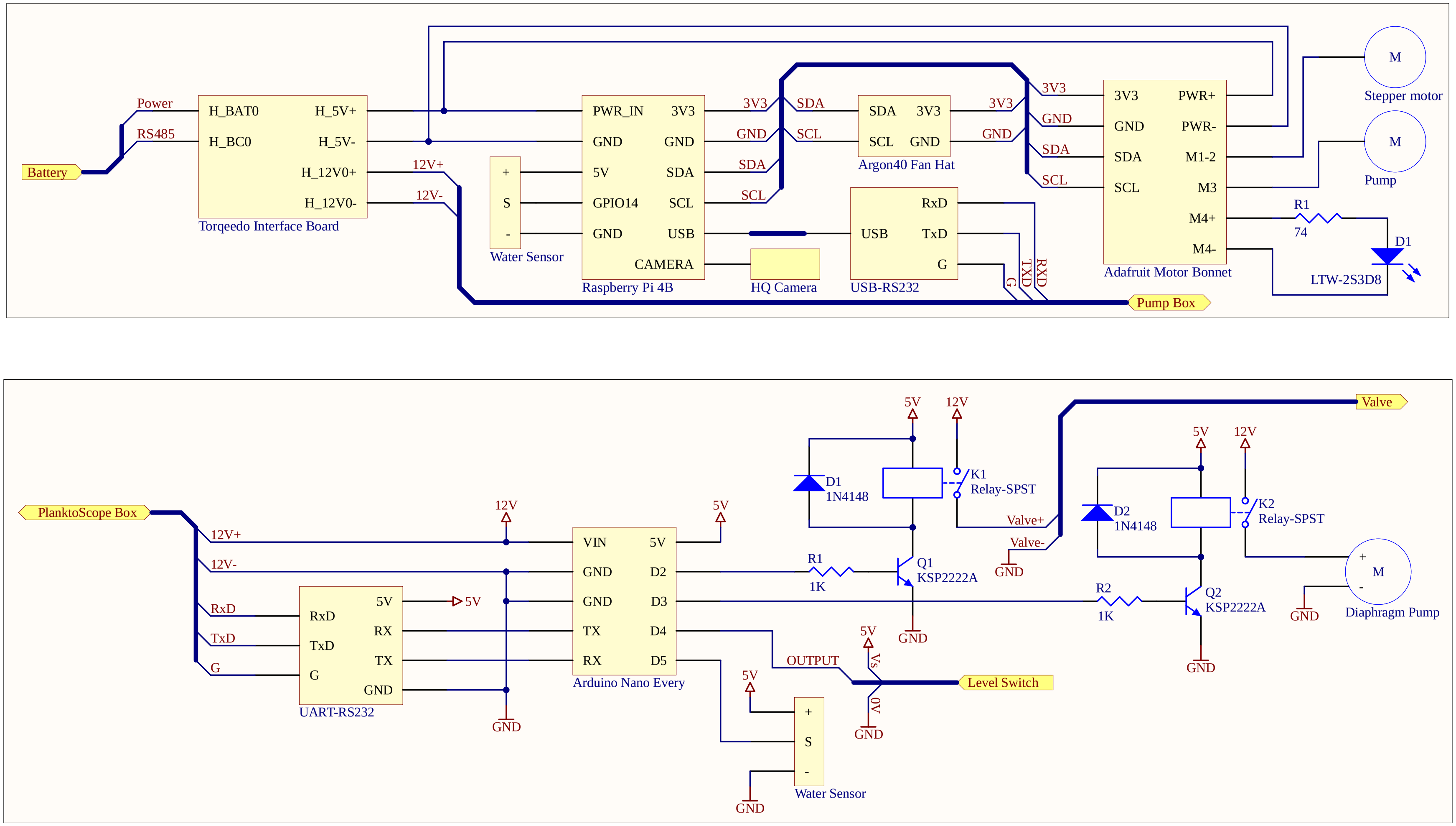


Figure B.1: PlanktoScope Box (top) and Pump Box (bottom) schematics

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