UNIVERSIDADE TÉCNICA DO ATLÂNTICO
INSTITUTO DE ENGENHARIA E CIÊNCIAS DO MAR

WEST AFRICAN SCIENCE SERVICE CENTRE ON CLIMATE CHANGE AND ADAPTED LAND USE

Master Thesis

DEVELOPMENT OF LOW-COST INSTRUMENTATION FOR ADVANCED UNDERWATER ECOLOGY OBSERVATIONS

ZINZINDOHOUE Coffi Gérard Franck

Master Research Program on Climate Change and Marine Sciences

São Vicente
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Master's thesis presented to obtain the master's degree in Climate Change and Marine Sciences by the Institute of Engineering and Marine Sciences, Atlantic Technical University in the framework of the West African Science Service Centre on Climate Change and Adapted Land Use

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Panel defense

President

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Examiner 1

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Examiner 2

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Dedication

I dedicate this work to my late parents. Today, you are no longer with me, but you constantly desire the best for me. So, wherever you are, I hope you are proud of the seed you planted.

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Resumo

A dinâmica do ecossistema marinho no contexto das alterações climáticas é uma preocupação científica, política e social crescente que requer uma monitorização regular através de tecnologias de observação e estudos apropriados. Assim, foi desenvolvida uma vasta gama de ferramentas com sensores químicos, biogeoquímicos, físicos, biológicos e outras plataformas (AUV, ROV, Sonar, etc...) para a monitorização marinha. Mas os seus elevados custos de aquisição e manutenção são frequentemente um obstáculo. Este estudo visa conceber um sistema sinóptico de baixo custo de observação avançada de ecossistemas marinhos a frequências temporais relativamente altas. O TDM PlasPi de baixo custo é uma versão melhorada do sistema de câmaras (câmaras marinhas PlasPI) desenvolvido pela Dr. Autun Purser do Alfred Wegener Institute (Helmholtz Center for Polar and Marine Research, Bremerhaven, Germany) em colaboração com outros investigadores em 2020. Incorpora vários desenvolvimentos inovadores tais como sensores multiespectrais, de temperatura e pressão. Inovador na medida em que pode registar o espectro de um objecto ao mesmo tempo que é fotografado e também alterações em vários parâmetros ambientais. O PlasPi TDM funciona a uma profundidade de 200 metros. As várias implementações de campo demonstram a capacidade operacional do PlasPi TDM para diferentes aplicações e ilustram o seu considerável apoio à vigilância marinha através de observações in-situ. Destinado a ser um projecto de fonte aberta, o desenvolvimento contínuo do PlasPi TDM é encorajado para um sistema de observação oceânica mais integrado, sustentável e de baixo custo.

Palavras-chave: Raspberry Pi, Observações marinhas, Oceanografia física, Imagem espectral, Instrumentos de baixo custo.

Abstract

The marine ecosystem dynamics in climate change is a growing scientific, political and social concern requiring regular monitoring through appropriate observation technologies and studies. Thus, a wide range of tools with chemical, biogeochemical, physical, biological sensors, and other platforms (AUV, ROV, Sonar, etc...) have been developed for marine monitoring. But their high acquisition and upkeep costs are often an obstacle. This study aims to design a low-cost synoptic marine ecosystem advanced observation system at relatively high temporal frequencies. The low-cost PlasPi TDM is an improved version of the camera system (PlasPI marine cameras) developed by Dr. Autun Purser from the Alfred Wegener Institute (Helmholtz Center for Polar and Marine Research, Bremerhaven, Germany) in collaboration with other researchers in 2020. The camera system developed in this thesis incorporates several innovative developments such as multispectral, temperature, and pressure sensors. Creative in that it can record the spectrum of an object and simultaneously take photographs and record the changes in various environmental parameters. The PlasPi TDM operates to a depth of 200 meters. The various field deployments demonstrate the operational capability of the PlasPi TDM for different applications and illustrate its considerable support to marine surveillance through in-situ observations. Intended to be an open-source project, the continued development of PlasPi TDM is encouraged for a more integrated, sustainable, and low-cost ocean observing system.

Keywords: Raspberry Pi, Marine observations, Physical oceanography, Spectral Imaging, Low-cost instrumentation.

Abbreviations and acronyms

ARM	Advanced RISC Machines
AUV	Autonomous Underwater Vehicle
BIIGLE	BioImage Indexing Graphical Labeling and Exploration
CRI	Color Rendering Index
CSI	Camera Serial Interface
CSV	Comma-Separated Values
CTD	Conductivity Temperature Depth
DC/DC	Direct Current/Direct Current
GND	Ground
GPIO	General Purpose Input/output
HTTP	Hypertext Transfer Protocol
LAN	Local Area Network
LED	Light Emitting Diodes
OEM	Original Equipment Manufacturing
PHP	Personal Home Page or Hypertext Preprocessor
POM	Polyoxymethylene
PuTTy	Popular SSH and Telnet Client
PWM	Pulse Width Modulation
RAM	Random Access Memory
SCL	Serial Clock
SDA	Serial Data
TD	Temperature/Depth
TDM	Temperature/Depth/Multispectral
USB	Universal Serial Bus
UVIR	Ultra-Violet Infrared
VIN	Input-Voltage
VIS	Visible Spectrum
VNC	Virtual Network Computing
Wi-Fi	Wireless Fidelity

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1. Introduction

1.1 Background and Context

At the core of Earth's Climate systems and the main reservoirs of biodiversity, the oceans are an essential component for life (source of food, energy, transport, etc.) and for understanding our planet through their function as regulators of the climate system. However, the ocean and, more specifically, the marine ecosystem is subject to many direct human pressures such as overexploitation, eutrophication, pollution, invasive species introduction (Halpern et *al.*, 2008; Hoegh-Guldberg & Bruno 2010; Burrows et *al.*, 2011; Danovaro et *al.*, 2016). Also, pressure from technological advances, population expansion, and global impacts such as climate change (Doney et al., 2012) lead to their change. Thus, understanding and accurately predicting ocean processes and their changes are essential for responsible and sustainable use of ocean resources (Lin & Yang, 2020). To achieve this, research uses different observation techniques. Traditionally, ocean observation consisted of collecting samples from ships and analysing them on board or in the laboratory. Still, nowadays, buoys or platforms relay information to land for analysis and dissemination (van den Burg et *al.*, 2021).

1.2 Problem Statement

In recent years, several explorations, observation, and oceanographic research projects have been carried out. The results of these research, observations, and exploration projects have in one way or another enabled us to recognize, understand and manage changes in marine biodiversity, resources, and habitats and to implement sound conservation and sustainable development strategies (Miloslavich et *al.*, 2019) such as the UN Sustainable Development Goal 14. Also, the challenges encountered during these explorations, observations, and research have resulted in significant advancement in the design and construction of observation tools or instruments. Technical, scientific, and human resources have been developed to deepen our knowledge of the marine ecosystem, its physical properties, and marine biodiversity as a channel to understand the fundamental mechanisms of their dynamics and their role in climate variability. However, the technological challenges of studying these environments, their limited accessibility, and extreme conditions make it difficult to understand these mechanisms.

Furthermore, there is the very high cost of underwater observation equipment, which many countries, particularly in Africa, with minimal resources, cannot afford today. The emergence in recent years of technologies that are three or more times cheaper than established technologies (Wang et al., 2019) may overcome this problem and represents one of the most innovative aspects of current oceanographic research (Marcelli et *al.*, 2014). Marine visual imagery has become an important assessment tool in the scientific, policy, and public understanding of our seas and oceans (Durden et *al.*, 2016).

1.3 Research Questions

A variety of underwater observation platforms, such as remotely operated vehicles, baited remote underwater video systems, autonomous underwater vehicles, seabed observation systems (Schoening et *al.*, 2016), have been developed to access those environments too distant for human exploration (Bellingham et *al.*, 2007; Picardi et *al.*, 2020). And also, to meet the challenges of monitoring changes in the marine environment (Bicknell et al., 2016). Amongst the multitude of platforms, underwater cameras are a widely used tool for making direct observations of the behaviour of organisms in their natural habitat, greatly complementing data obtained by other means (Bergshoeff et *al.*, 2017) and also providing highly reproducible sampling over extensive temporal (hours to years) and spatial (meters to kilometers) scales (Bicknell et *al.*, 2016). Despite their many advantages, some of these tools, shown positive results while others are limited in their observational task. Most of them do not allow data collection on water properties that could help to understand oceanic phenomena better. In addition, these imaging systems are often costly (Bicknell et *al.*, 2016), which limits their use in temporal, remote, or high-risk deployments such as in hydrothermal provinces or under the ice in polar regions (Purser et *al.*, 2020). However, what is the most effective strategies for improving these tools for advanced oceanographic observations in our ongoing quest to understand the ocean?

1.4 Relevance and Importance of the Research

The challenge of this study will be to design and build a more improved and advanced version of the PlasPi marine camera developed by Purser et *al.* (2020) to overcome some of these challenges mentioned above, such as cost and the addition of sensors for the measurement of physical properties of water. The project will be built around the Raspberry Pi microcontroller. This new device, the PlasPI TDM (Temperature-Depth-Multispectral), will also include a multispectral sensor, which, combined with the camera, will improve the identification of organisms or any marine object from their spectra for the study of marine life. It can also be used in underwater observation networks, which will allow continuous physical measurements of the marine environment and water column and seabed resources using wireless means. Many countries depend on the health of their coastal ecosystems to support their economies (tourism, fisheries, natural resources) and provide sustainable livelihoods for their people. Thus, this new open-source tool will help countries to better monitor their coastal ecosystems by providing data or information to guide their policies in the context of sustainable development and improved human-ocean interactions. Low-cost, PlasPi TDM can be made accessible to the local and scientific community for rapid assessment, monitoring, and conservation of the marine ecosystem.

1.5 Objectives of the work

The general objective of this study is to enhance the existing PlasPi camera by extending the payloads for advanced underwater ecological observations. Specifically, it involved:

- To extend loads of the PlasPi camera by adding pressure, temperature, and spectral sensors;
- To carry out performance tests of the newly designed device, and finally;
- To proceed to the analysis of the received data and demonstrate its potential.

1.6 Structure of the work

Therefore, this paper will describe all the stages of the development of this new device, from the different tests carried out to the results obtained. Thus, after the introduction, the literature review is presented, which is a section showing an overview of the most relevant work carried out by various researchers about the objective of this thesis. Then, in the next session, the difference between the initial PlasPi and what was designed is outlined. The materials and methods used for the design of the PlasPi TDM are described in the materials and methods section. After that, the results obtained from the different tests and their discussion will be developed. Finally, the conclusion and future recommendations for the improvement of this work will be presented.

2. Literature review

Recently, underwater videos have gained significant interest from marine ecologists for studying fish populations (Abdelouahid et *al.*, 2018). Imagery has become one of the most important and most used non-destructive tools by the scientific community and society to understand the marine ecosystem. However, the concept of the marine visual image is not a new idea. The first attempts to record ocean depths using the photographic camera date back to the 1850s by William Thompson, who used a camera mounted on a pole. In 1893, French biologist and diver Louis Boutan captured the first known diving photograph that earned him recognition as the world's first underwater photographer (Martinez, 2014). He also discovered the concept of using a flash to capture an underwater region where natural light cannot penetrate by using an alcohol lamp attached to a barrel and blowing magnesium over it to produce a strobe of light (Martinez, 2014; Elkays, 2019). However, in 1926, with the aid of magnesium to make a flash, botanist W.H. Longley and photographer Charles Martin took the first color photograph underwater, which marked the beginning of modern marine photography.

Underwater photography has evolved massively over the years. As early as 1972, Singleton and Cole developed an underwater camera system for deep-water underwater photography. The system consisted of a 35mm camera using standard torch batteries and operating to a depth of 4000 meters. In one descent, the device can capture 24 pictures (Singleton and Cole, 1972). Similarly, to quantify plankton in the golf stream, Otner et *al.* designed an in-situ silhouette camera system in 1981 that allowed plankton's vertical and horizontal distributions to be assessed at the meter scale while retaining taxonomic information (Otner et *al.*, 1981). The system consisted of a shutterless 35 mm film and an electronic flash with a xenon bulb (E.G. & G., Inc., FXI98). The film has a capacity of 800 to 1000 frames. Also, in the field of in-situ observation, as an improvement on the work of Otner et *al.*, (1981), Eisma et *al.*, (1990) developed an in-situ suspension camera, combined with an image analysis system to measure the size of in-situ suspended particles, which up to that time in-situ camera systems were not able to analyze particles smaller than 200 µm. The camera system consisted of an octagonal stainless-steel frame 180 cm high and 200 cm in diameter in which 3 cameras are mounted. Each camera was mounted in a stainless-steel tube with a lens protected behind an iconic 45 mm thick window. Also, for improved in-situ observations, Tiselius (1998) designed an in-situ video camera for plankton observation. A heavy aluminum structure supports the camera with a contrasting stroboscope that produces darkfield images of plankton larger than 0.3 mm.

However, image acquisition and analysis technology have evolved considerably with new cost-effective cameras, lighting systems, and analysis software (Durden et *al.*, 2016). These allow quantitative and qualitative data to be collected over relatively large areas cost-effectively for various applications (Sheehan et *al.*, 2010). Thus, several cost-effective camera design projects have been developed around microcomputer cards for more advanced observations. In 2014, Kresimir et *al.*, set a stereo underwater camera (TrigCam) that can trigger when animals are present in the camera's field of view. The most innovative aspect of the triggered camera system (TrigCam) is its triggering mechanism based on illumination from a far-red (660 nm) light-emitting diode (LED) array. The TrigCam consists of a camera housing two Canon Powershot 300 HS point and shoot cameras, a strobe box, a battery, and a single-board ARM system-on-chip computer, the Raspberry Pi. Mazzei et *al.*, (2015) have designed a low-cost autonomous device for underwater stereo imaging. The system is designed for deployment onboard autonomous, fixed, or towed platforms. It consists of two Raspberry Pi's, which are used to control the system. The two Raspberry Pi's are linked by an ethernet interface for communications and software synchronization in the image acquisition task. They were also used for image acquisition. The cameras are controlled via software running on an associated laptop.

Still, in 2015, Oleari et *al.* developed an underwater stereo vision system for 3D object detection. The system consisted of two AVT Mako G125c GigE industrial cameras with ethernet connection housed in two small black PVC cases with a stainless-steel back cover and transparent Plexiglas glass. Here, the Arduino MEGA 2560 microcontroller is responsible for triggering the camera. However, this year 2021, a new camera system was designed, a relatively low-cost (10-15 k€) with a High-resolution image done by Dominguez-Carrió et *al.*, (2021): the Azor Drift-Cam. It is a video system for the rapid assessment of deep benthic habitats. Operational to 1000m depth, with no need to be towed from a vessel nor propelled, the Azor Drift-Cam simply drifts with the supporting vessel taking advantage of water currents and surface winds. It consists of two action cameras, LED lights, external batteries, and a video converter/transmitter, as well as parallel lasers and a Temperature/Depth sensor.

Camera systems are now also being used to assess patterns of animal behaviour and fish abundance, as evidenced by the work of Bailey et *al.*, (2007), Fransworth et *al.*, (2007), and

Boldt et *al.*, (2017). They have used stereo cameras for their potential to increase fish biomass assessments in areas where trawl samples cannot be collected. Cameras are also an essential asset in the 3D reconstruction of the underwater environment from underwater images (Negahdaripour and Nadjidi, 2003; Andono et *al.*, 2012; Oleari et *al.*, 2014; Mazzei et *al.*, 2015). It is a technique for obtaining a three-dimensional representation of an object or scene from a set of images taken from different viewpoints of the object or scene. Cameras are also used in computer vision tasks, more precisely in automatic pattern recognition techniques based on Deep Learning (Sun et *al.*, 2016; Meng et *al.*, 2018; Abdelouahid et *al.*, 2018; Rathi et *al.*, 2018; Garcia et *al.*, 2019; Ahsan et *al.*, 2020).

As far as spectral imaging is concerned, however, it is much more widely used for biodiversity detection, monitoring, and assessment. These imaging systems are mainly carried on Unmanned Aerial Vehicles or are mounted on the outside of aircraft. For example, in 2006, Jusoff used airborne hyperspectral imaging to identify and map individual mangrove species in Port Klang and determine the wavelength regions that define the inherent spectral characteristics of mangrove species. A total of nine spectral separability groups of mangrove species from 19 selected mangroves were identified. In 2008, Schoonmaker et *al.*, developed an airborne spectral imaging system to detect, track and monitor marine mammal populations in St. Lawrence Seaway. The system consists of a low-cost ACT multispectral (MANTIS-3) system. It is a four-band multispectral imaging system using spectral bands suitable for marine imaging. Aerial imagery showed that white belugas were the most detectable.

Similarly, Lopez et *al.*, 2014, studied automated real-time detection of Great White Shark dummy targets using a multispectral imager. Targets to be detected were 2.5 x 1.2 m plywood shark cutouts submerged at 1 m, 2 m, and 3 m below the surface in the Pacific Ocean off the coast of San Diego. The detection system used the EYE-510 Multispectral Imager mounted on the left side of a single-engine fixed-wing Piper Saratoga (PA-32R) aircraft in a steel box behind the wing. Automatic detection was primarily limited by water turbidity in this test but other environmental conditions.

However, all of these camera systems only allow for taking images and recording the video when deployed. They do not accurately analyze the physical conditions of the environment in which they are deployed, which is also changing due to climate change. Although the new autonomous underwater vehicles and remotes are not only equipped with camera systems, some of them are also equipped with sensors providing characteristics of the environment in which they are deployed. But their use is limited to a small number of the public due to their relatively high cost. Thus, for this study, we decided to extend one of the most cost-effective cameras, the PlasPi developed by Purser et *al.*, (2020), by adding sensors measuring physical properties for advanced observations of Marine ecology.

3. Presentation of the different PlasPI marine camera version

3.1 First PlasPI marine camera version designed by Purser et *al.*, (2020)

The PlasPI (Plas = Plastic and Pi = Raspberry Pi) marine camera (Figure 1***Error! Reference source not found.***) is an open-source license imaging tool that is used in environmental, planetary, and agricultural sciences and was designed by Purser et *al.*, (2020). The system is built around a Raspberry Pi Zero W microcomputer board and runs open-source python 3.0 scripts to operate. The PlasPi is a shallow water (150 m depth rated) camera system with a plastic pressure housing (Purser et *al.*, 2020). To record image and video, the PlasPI Camera uses cheap, low-end Raspberry Pi camera module v2, a commonly used 3280 x 2464-pixel camera of moderate quality, 3 LEDs, two SAFT LSH 20 Lithium Battery 3.6 V Primary LSH20, and Wi-Fi (IEEE 802.11x) connectivity which minimizes pressure housing opening requirements.

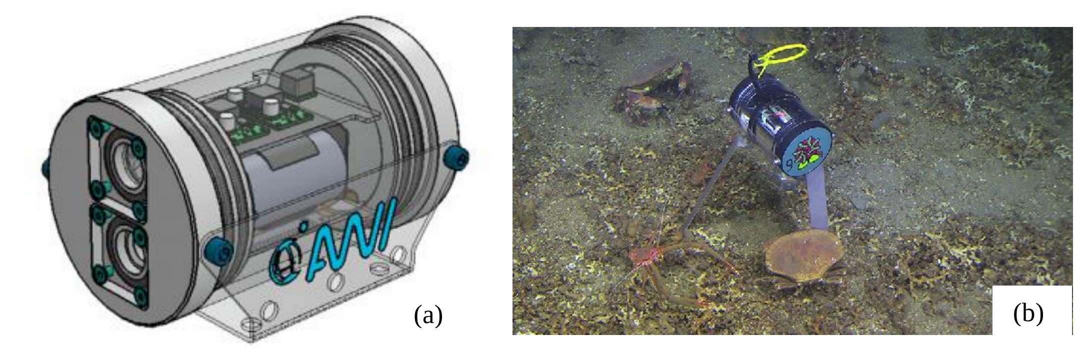


Figure 1: Photograph of the PlasPi (a); PlasPi camera, deployed at the Tisler cold-water coral reef, Norway. ~100 m depth (b); Source: From Purser et al., (2020).

PlasPi cameras were thoroughly tested during the RV POSEIDON research cruise POS526 to the Tisler Reef, a cold-water coral reef in the Norwegian Skagerrak, in the summer of 2018 (Figure 1). During this cruise, 20,000 images of the seafloor were taken in total by 10 PlasPi cameras deployed at depths of ~100–150 m. Cameras were placed on cabled oceanographic water sampling platforms and placed on the seafloor directly by a submarine to record the response of the seafloor community to tidal variation. Also, it has been tested on research cruises SO261, MSM77, PS109, PS117, PS118, and HK19 (Purser et *al.*, 2020).

3.2 The new PlasPI TDM

Unlike its predecessor, the new PlasPI TDM (Figure 2) will be designed to capture underwater images, measure temperature, pressure in the water column, and record the spectrum of marine objects or organisms. The structure of the new PlasPI will be much the same as that of the PlasPI camera, with the difference that the payloads will be extended by the addition of Temperature, Pressure, and Multispectral sensors. The architecture of this PlasPI will be based on a low-cost construction, a pressurized plastic housing, a robust neural network between the different sensors it will integrate, and a task-oriented intelligent control system.

Figure 2: PlasPi TDM

Therefore, the system will be a network of nodes linked by wireless channels, which will collect and send the information from the different sensors to a collection point, therefore, the base station. The base station will communicate with the sensors in the module through queries or commands via the Virtual Network Computing (VNC) platform and a webpage.

3.3 The use case for PlasPi TDM

The device has designed to operate in the open ocean and coastal areas. Transportable, easy to deploy, and integrate on any platform (ROV, AUV, Profiler, etc.). It has a 7 hours autonomy of use and can operate at a maximum depth of 200m. For this purpose, a set of usage conditions have been identified to illustrate the use of the device in a natural environment, among which we can mention:

- Assessment of marine pollution;
- Study of the spatial and temporal distribution of marine species;
- Survey of the characterization of the marine environment;
- Spectroscopic study;
- Mapping of the marine habitat;
- Ground Truth Survey.

4. Materials and Methods

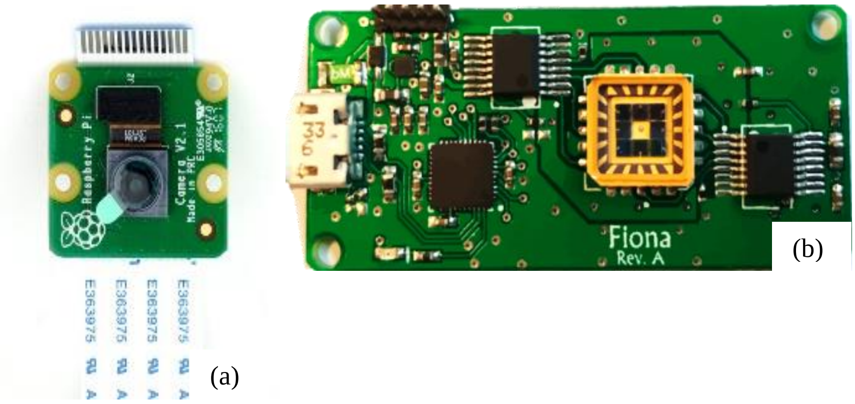
4.1 Materials of the PlasPi TDM

A PlasPi TDM is a fixed or mobile electronic observation system that records, processes, or saves images or videos of an object on a light-sensitive surface. When its invention or creation, the PlasPi was a low-cost, open-source licensed marine camera built around a microcomputer board that is the Raspberry Pi zero w (Purser et al., 2020). However, in the quest to improve our understanding of the marine ecosystem, the PlasPi TDM has been designed to make Eulerian, Lagrangian, and sustained physical and spectrum properties measurements in situ.

Compared to other platforms used in marine ecosystem monitoring and observation, such as CTDs, AUVs, or ROVs, the PlasPi TDM has not been deployed under the control of an active operator and does not require a lot of logistics. It has a low design cost, high data accuracy, does not depend on any support vessel to be deployed, and is easily integrated with other platforms. The PlasPi TDM is mainly composed of:

4.1.1 Imaging system

The imaging system of the PlasPi TDM consists of a Picamera V2 and a PixelSensor OEM (Original Equipment Manufacturing) VIS-8-UVIR (Visible Spectrum-8- Ultra-Violet Infrared). The Picamera V2 has a resolution of 3280x2464 and an image resolution of 8 Mega-pixels (Figure 3). It allows the recording of videos and images of objects. Designed by Ocean Optics company, the PixelSensor (Figure 3) is a small and compact spectrometer measuring 8 wavelengths in the visible spectrum. By measuring the reflectance of objects at different wavelengths of light, the PixelSensor OEM will identify the thing in the marine environment.



(a) (b)

Figure 3: Picamera V2 (a) and PixelSensor OEM VIS-8-UVIR (b).

4.1.2 Temperature/Depth (TD) sensor system

This system consists of a temperature and pressure/depth sensor (Figure 4). The temperature sensor is the BlueRobotics Celsius Fast-Response with an accuracy of ±0.1°C and communicates via I2C. The BlueRobotics Bar30 High-Resolution 300m Depth (Figure 4) was used for the pressure sensor. Having a resolution of 0.2 mbar and a depth measurement resolution of 2mm in the water column, it also communicates over I2C.

(a) (b)

Figure 4: Celsius Fast-Response, ±0.1°C Temperature Sensor (a) and Bar30 High-Resolution 300m Depth/Pressure Sensor (b). (Source: From BlueRobotics).

The TD system provides accurate depth, pressure, and temperature profiles, relevant data on changes in various physical properties of the marine environment.

4.1.3 Power supply system

Composed of two SAFT LSH20 lithium-ion batteries of 3.6V (Figure 5) each, the power supply system provides electrical energy to all the circuit components. It ensures the proper functioning of the PlasPi TDM.

Figure 5: Battery 3.6V D Lithium LI-SOCL2 (Source: from OSI Batteries).

4.1.4 Processing Unit

The processing unit of the device is the Raspberry Pi Zero W Development board (Figure 6). It is a single board ARM (Advanced RISC Machines) Nano-computer with 802.11n wireless LAN (Local Area Network), Bluetooth 4.0, 512 MB RAM (Random Access Memory), and contains a single 40-pin expansion connector that gives access to 28 GPIO (General Purpose Input/Output) pins. It can integrate multiple sensors and allows multi-tasking, inter-process communication, and executes the instructions of different computer programs by performing the basic arithmetic, logic control, and input/output operations specified by the instructions.

Figure 6: Raspberry Pi Zero W Development board (Source: From Amazon. in).

4.1.5 Lighting system

Given the environment in which it will operate, the LED (Light Emitting Diodes) is added to the device to illuminate the environment and provide a clear picture. The Triple Star Weiss CRI (Color Rendering Index) 90+ LED (Figure 7) has been used for this purpose.

Figure 7: Triple Star Weiss CRI 90+ LED (Source: from Google.com).

4.1.6 Storage system

It consists of a Samsung MicroSD memory card with a storage capacity of 32 GB. It is used to run the Raspberry Pi's operating system (Raspbian OS) and store photos, videos, environmental data taken, and the various server and python codes used to execute the commands of the different objects connected to it.

4.2 Methods

4.2.1 Hardware setup

The Hardware setup makes it possible to describe the connections and interactions between the different parts of the system in executing their functions (Figure 8 and Figure 9). In general, the processing unit is the system's core, and the different sensors are connected to it. The processing unit sends information or messages to the various sensors to execute tasks, receives a response in return, processes them, and stores them on the memory card. The camera module is connected to the CSI port of the Raspberry using a flat cable. Recall that the Raspberry Pi zero w includes a small form-factor CSI port that requires a camera adapter cable. The Raspberry sends instructions to the Picamera to take pictures and record videos, while the multispectral sensor is connected to the Raspberry via the USB Port. With its low power consumption, the LED light is the primary source of illumination for the system, allowing clear pictures to be taken in the dark marine environment. In the runtime control, it is the LED that controls the camera's shooting and video recording. The LED is connected to GPIO pin 13/Pin33 via a 4.7 k resistor and Ground GND/Pin39.

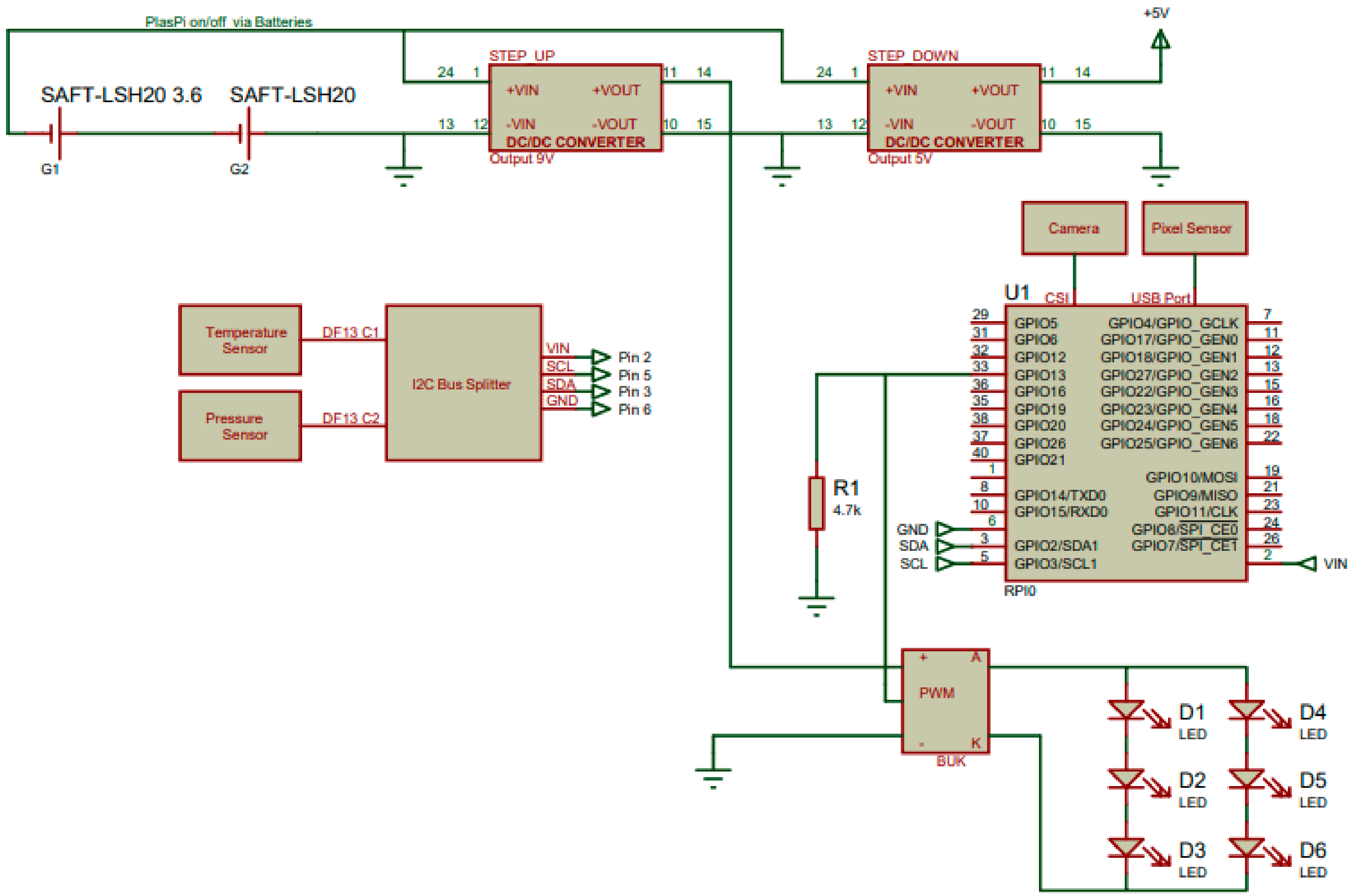


Figure 8: Wiring diagram of the PlasPi TDM

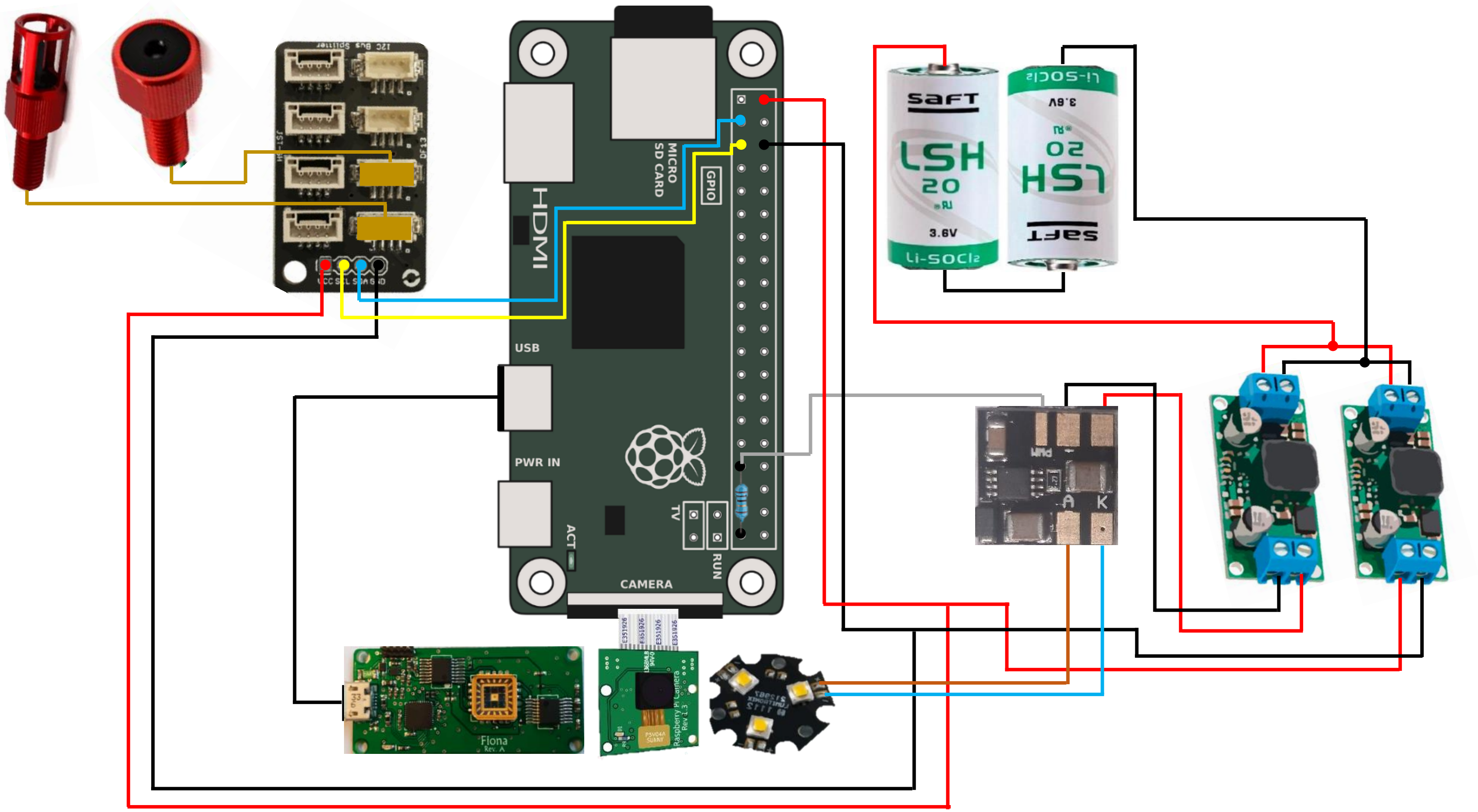
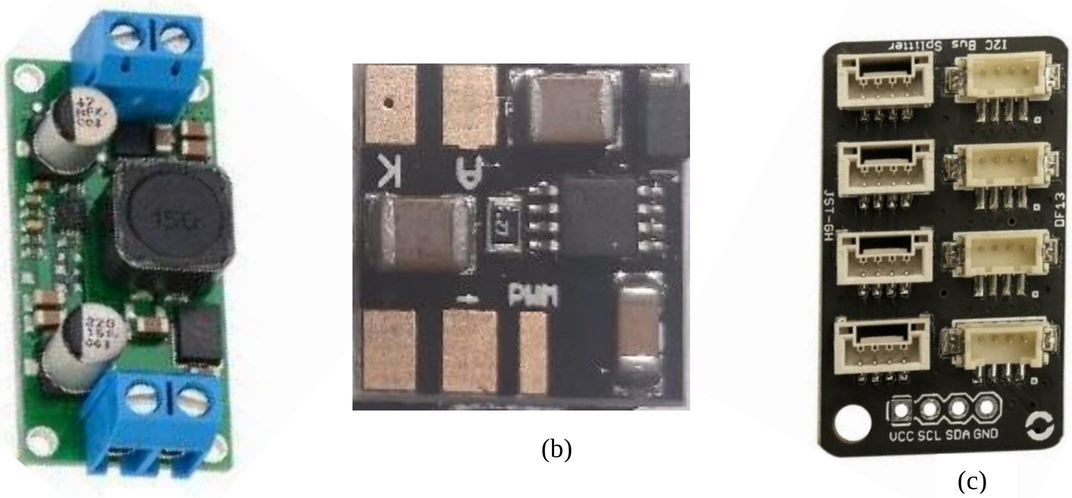


Figure 9: Wiring physical diagram of the PlasPi TDM

The more power a LED receives, the brighter it is, and the less energy it receives, the dimmer it becomes. So, to control the brightness of the LED, a PWM has been installed between the LED and the Raspberry Pi. The PWM (Figure 10 (b)) offers the ability to simulate different power levels by oscillating the output of the Raspberry Pi. The PWM is connected to GPIO 13/Pin33, GND to Pin6, and the Step-Up adjustable DC/DC converter.

The various sensors require specific voltage and current levels other than the raw power available for their operation and device. To achieve this, step-down and step-up converters (Figure 10 (a)) or transformers are used in the circuit to modify and control the flow of electrical energy.



(a) (b) (c)

Figure 10: Step-Up/Step-Down Voltage Adjustable (a); Pulse Width Modulation (b); I2C bus Splitter (c). Source: from Google.com.

Thus, a Step-Up Adjustable DC/DC converter is connected directly to the electrical system and has the role of detecting and increasing the voltage at the terminals of the load, which is the total of the battery voltage (7.2 V) to 9 V. Then, the second Step-Down Adjustable DC/DC Converter is connected to the first converter and essentially takes the 9 V input voltage and converts it to a lower output voltage of 5 V (Figure 11), which is needed to use the two 5 V pins of the Raspberry Pi to power the various externally connected sensors.

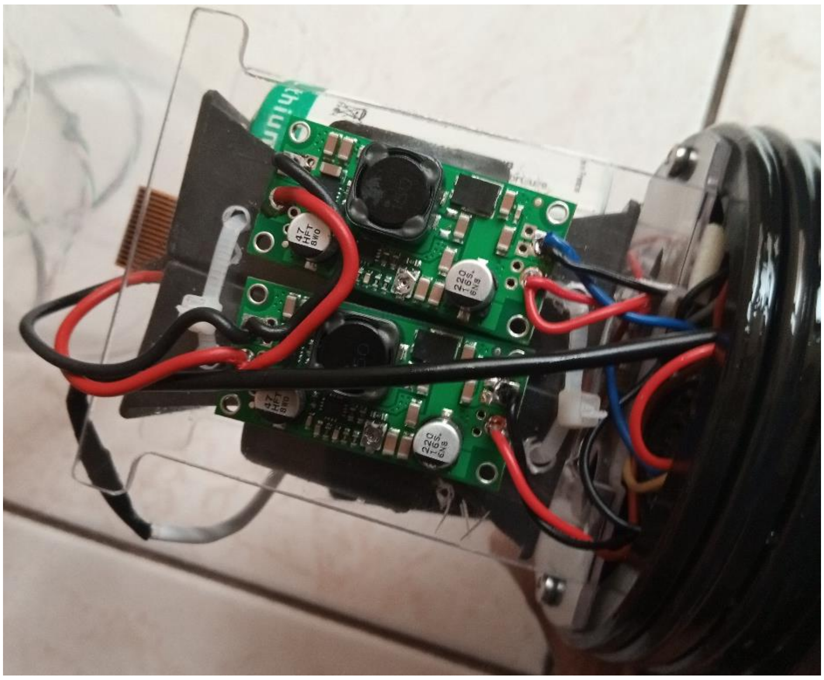


Figure 11: Step-Up adjustable DC/DC converters connected and mounted on the frame

The Temperature and Pressure sensors are connected to Raspberry's I2C bus, which also uses two pins (GPIO 2/Pin 3 and GPIO 3/Pin 5). The I2C is a bi-directional, synchronous serial communication interface (using a standard clock signal to synchronize data transfer between devices). Each sensor is connected via an address. The I2C has two lines or pins: the SCL_I2C, the clock line to synchronize the transmission, and SDA_I2C representing the data line through which data bits are sent or received. As I2C communication is very sensitive to the bus capacity, extending or using long wires increases the ability of the I2C bus and can cause messages to be shifted, resulting in communication problems. Instead of using an I2C converter for each sensor to interface with the Raspberry Pi, an I2C bus splitter (Figure 10 (c)) is used. The SCL, SDA, VIN, and GND pins of the I2C bus splitter are connected to the SCL (GPIO 3/Pin 5), SDA (GPIO 2/Pin 3), VIN (Pin 2), and GND (Pin 6) of the Raspberry Pi, respectively. The sensors are plugged directly into the I2C bus splitter via SCL, SDA, VIN, and GND (Figure 12).

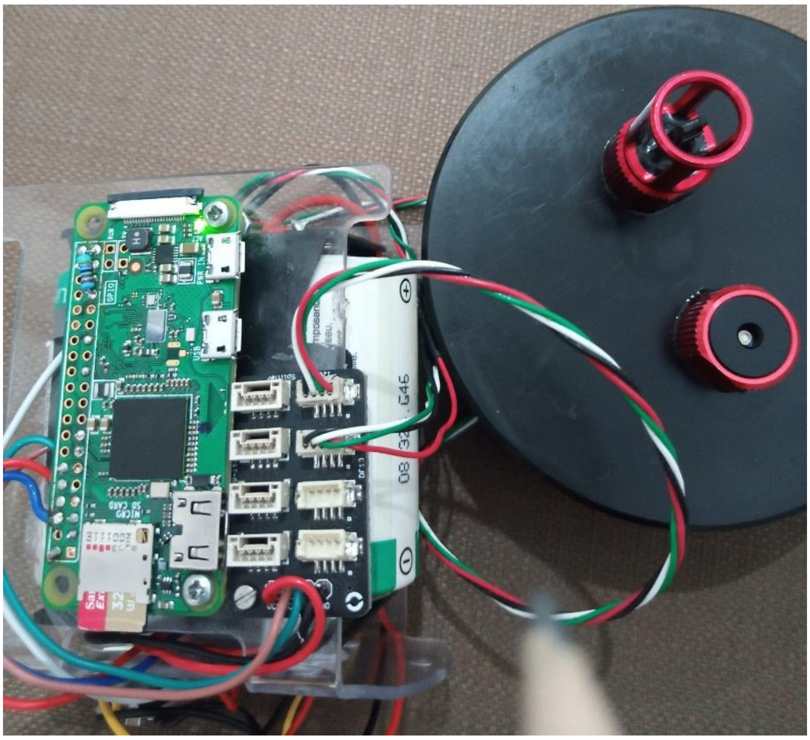


Figure 12: Temperature and pressure sensor connected to the I2C Splitter Bus

All electronics are mounted in the housing to avoid contact with water. Due to their role, only the temperature and pressure sensors are outside the housing and in touch with the water for data collection.

4.2.2 Construction of the waterproof enclosure

The watertight housing is an enclosure to protect the system's electronic components (not designed to be immersed) from submersion. It is strong enough to withstand crushing due to hydrostatic pressure. The same type of housing configuration as the first PlasPi version developed by Purser et al., (2020) was used. The housing comprises four (4) parts: the back-end cap, the cylinder housing, the front-end cap, and the mounting frame.

4.2.2.1 Back-End Cap

The back-end cap is a machined POM part, milled and turned to the dimensions shown in Figure 13. The rear end cap has been modified by creating two 10.2mm diameter holes in the middle of the end cap for the Temperature and Pressure sensors. Two holes are also drilled on the sides of the end cap to allow later connection to the mounting frame (Purser et al., 2020). Two O-ring rubbers and silicone grease provide sealing, and then placed in the two grooves inside the end cap are set in a piston-type mounting.

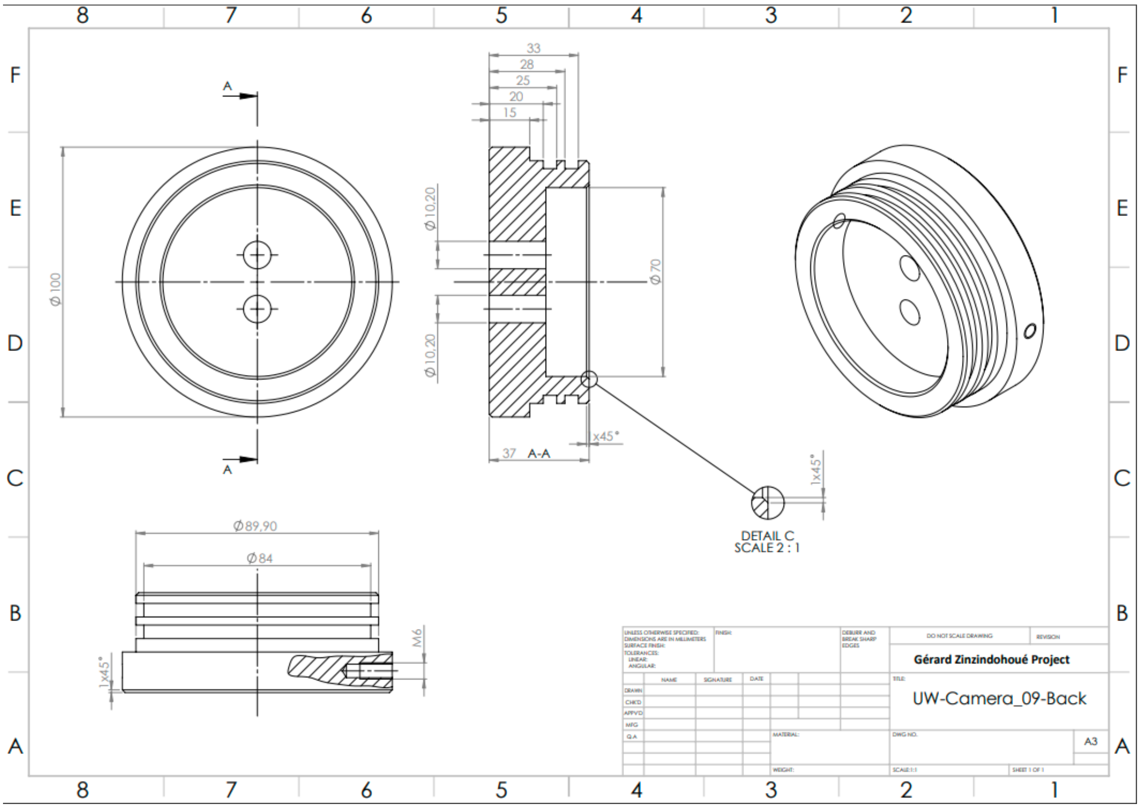


Figure 13: Schematic of the Back-End Cap.

4.2.2.2 Cylinder case

The cylinder housing is made of polycarbonate with a diameter of 90cm, a length of 130cm, and a width of 100cm (Figure 14**Error! Reference source not found.**). The inner edges of each tube end are slightly filed to allow easier access to the back and front end (Purser et al., 2020).

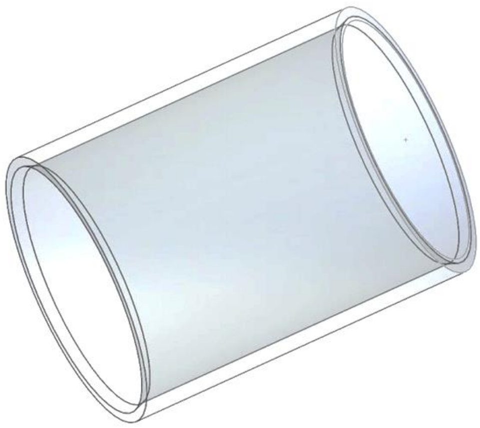


Figure 14: Schematic of the Cylinder case.

4.2.2.3 Front-End Cap

The front-end cap is similar to the rear-end cap, milled and built to the dimensions shown in Figure 15. Two holes are also drilled on the sides of the end cap for later connection to the mounting frame (Purser et al., 2020). It has also been modified by creating three holes in the POM to accommodate the camera, the LED, and the multispectral sensor to image, illuminate and record the spectrum of the objects in the water column.

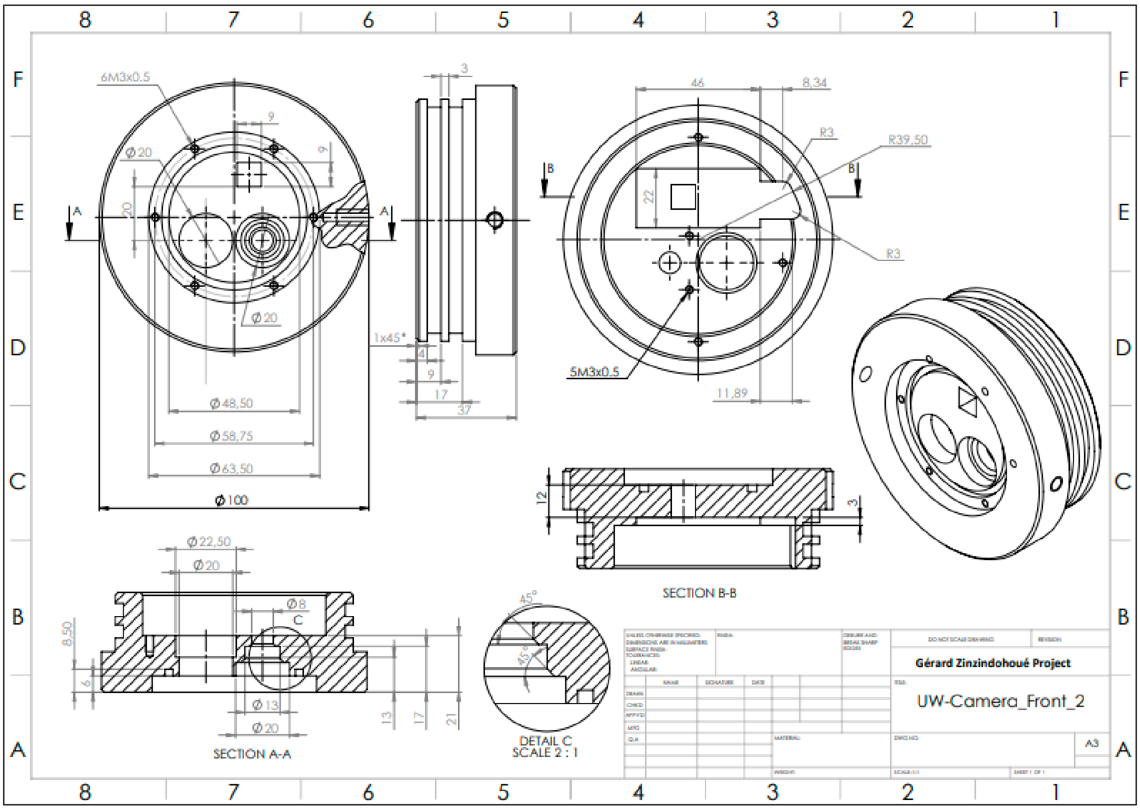


Figure 15: Schematic of the Front-End Cap.

A circular acrylic plastic covers the entrance (Figure 16). Sealing is also ensured by two silicone greased O-ring type rubber seals placed in the two grooves inside the end cap. Similarly, a rubber seal and silicone grease are also placed on the front of the front-end cap. All seals are placed in a piston-type assembly.

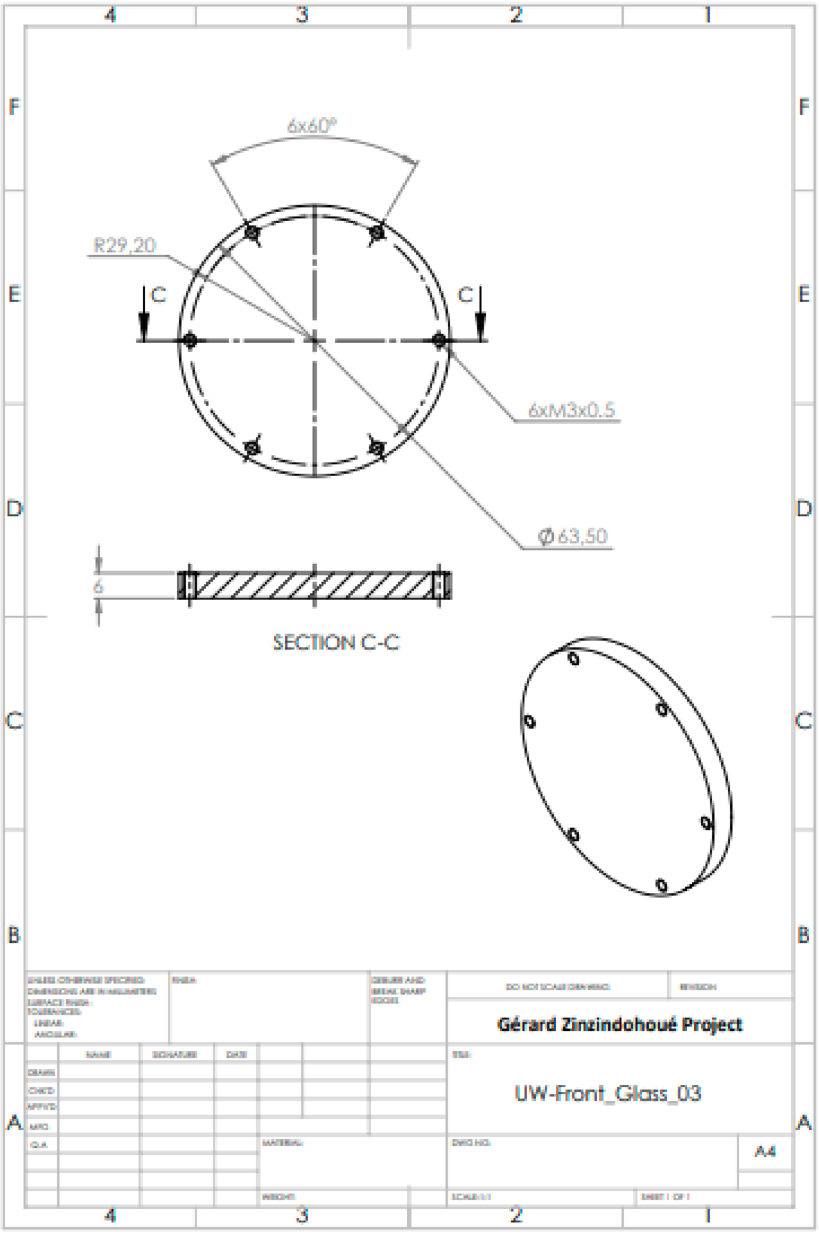


Figure 16: Front Glass

4.2.2.4 Mounting frame

It is constructed from polycarbonate to the dimensions shown in the figure (Purser et *al.*, 2020). Also, a small additional piece of polycarbonate is cut to hold all the electronic components inside the box (Figure 17).

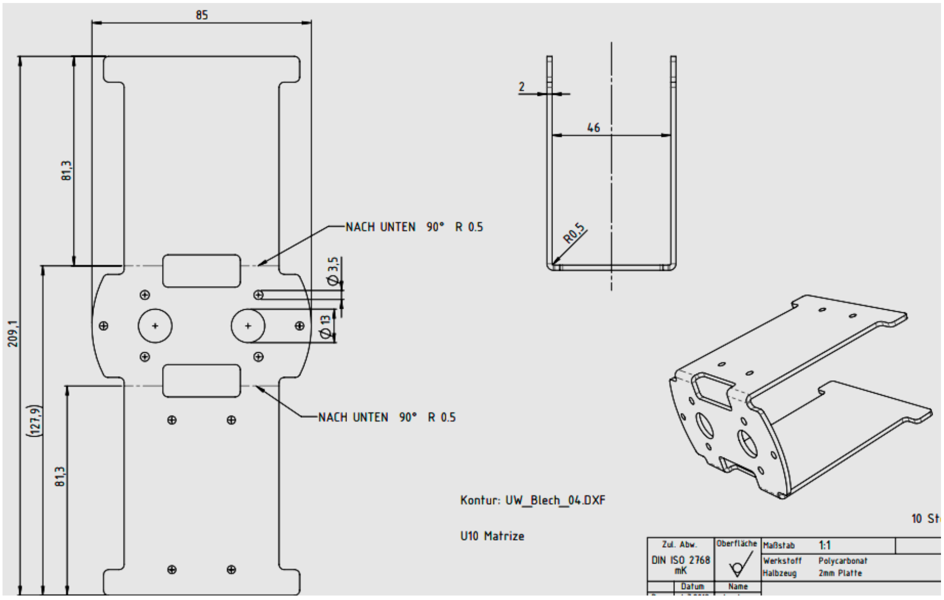


Figure 17: Schematic Mounting Frame (Source: From Purser et al., (2020)).

To achieve the next step, the hydrostatic pressure test, the different parts of the waterproof enclosure system (Figure 18) were assembled.

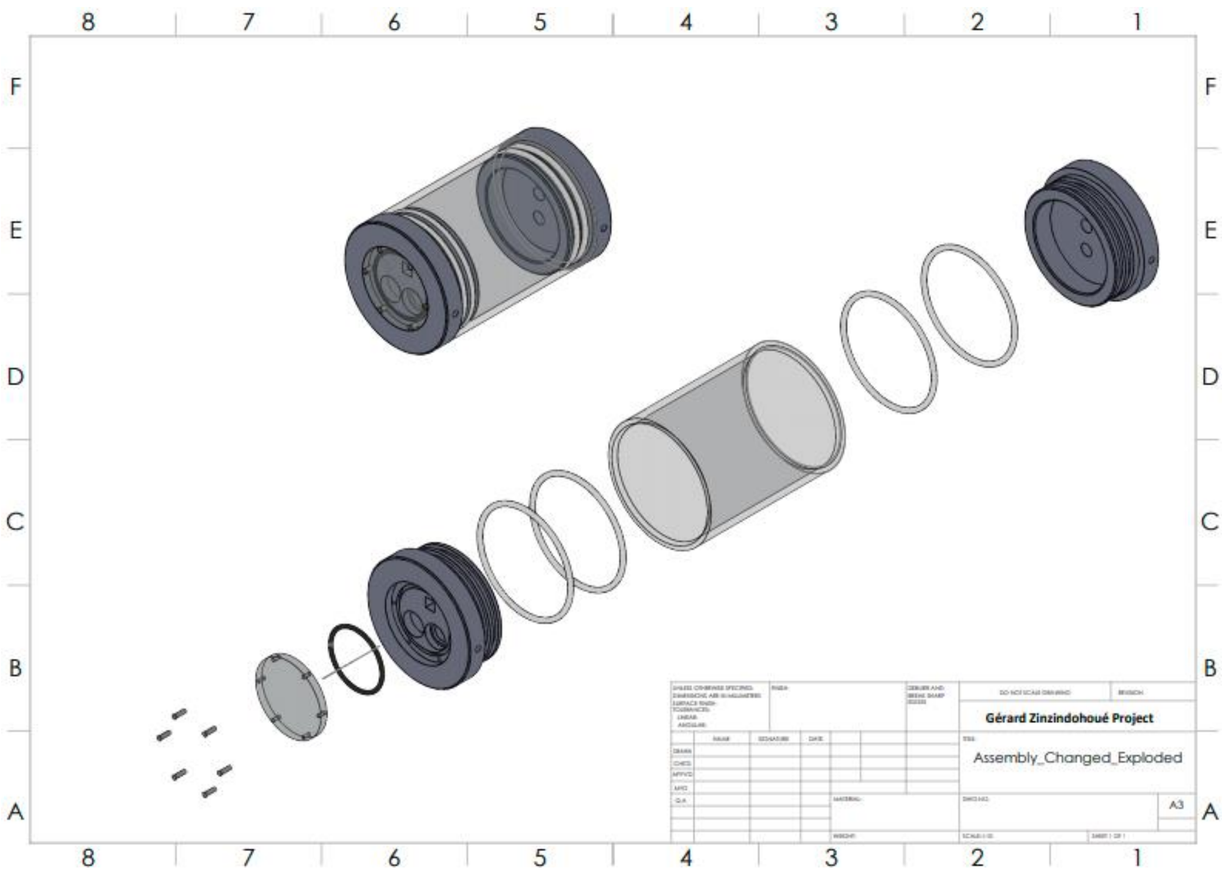


Figure 18: Exploded view of the various assembled parts.

4.2.3 Hydrostatic pressure evaluation

In the marine environment, the maximum safe operating depth of the housing depends on the construction material and its assembly. Therefore, before mounting the electronics in the housing, the hydrostatic test was made. The hydrostatic test consisted of holding the housing at different pressure levels to ensure that it functioned correctly and would not fail. The housing was first tested in a 4200L tank to ensure that there were no leaks or bubbles. Then it was tested at sea for hydrostatic pressure by steadily increasing the pressure to a maximum depth of 200m, exceeding the 150m depth design for the study. Each test was carried out for 45 minutes.

4.2.4 Program design concepts for data collection

In the program architecture (Figure 19), only the processing unit executes all tasks. The execution of the commands between the different system elements works using a programming approach based on open-source Python scripts. The program's role is to set various parameters for shooting, video, and collecting physical and spectrum data from the multiple sensors. It allows direct communication via Wi-Fi between the device and the user. It consists of a web page (Figure 20) using the IP address of the Raspberry Pi as HTTP for data transmission over the computer network. To enable the Raspberry Pi to serve the web page, an Apache webserver has been installed. The fundamental purpose of the webserver is to gather data from a server to provide the contents of the server file system to a client request. The client is the web browser, and the file system is where the website's content is stored, the Raspberry Pi.

The construction of the program is done in two parts: the server code and the Raspberry code. The code server allows the different settings of the system camera-multispectral and the TD sensor. It visualizes the data coming from the latter in a table on the web page. The code server consists of the creation of three main .php script files. A database in CSV format was also created to store all the data from the TD and the Multispectral.

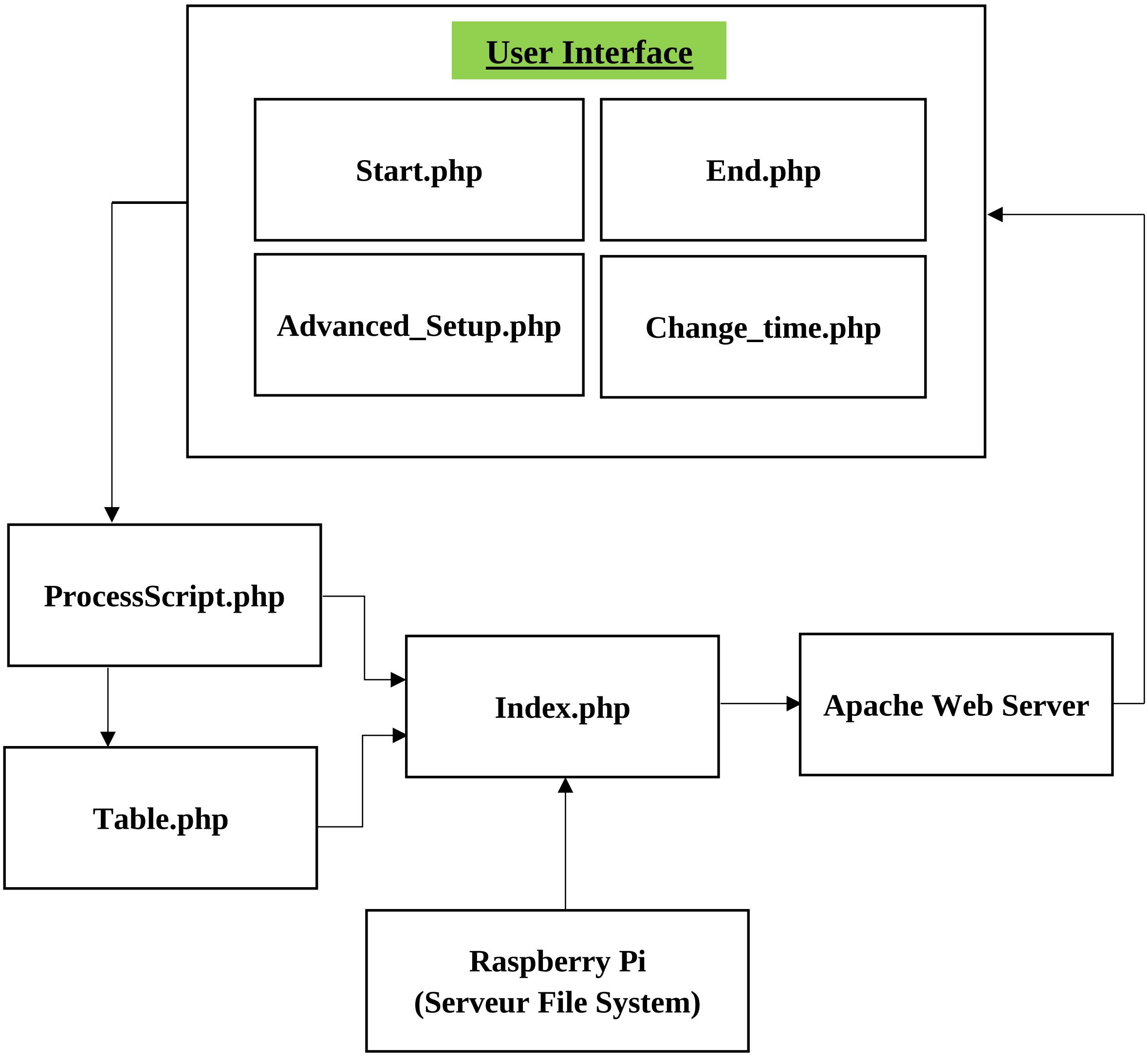


Figure 19: Program Architecture.

The first file, processScript.php, contains the data from the camera and sensors sent by Raspberry. The processScript.php on the server extracts the data and saves it in each folder or database assigned for this purpose. The second PHP file is the table.php. It allows the display of the TD sensor data and the spectrum data on the web page. This file is connected to the CSV database created by the data collection program on Raspberry and stores the data in the database. The last file, index.php, allows the visualization of the different configuration parameters of the various objects (Camera, PixelSensor, and TD sensors), a view of the camera, and the database on the web page.

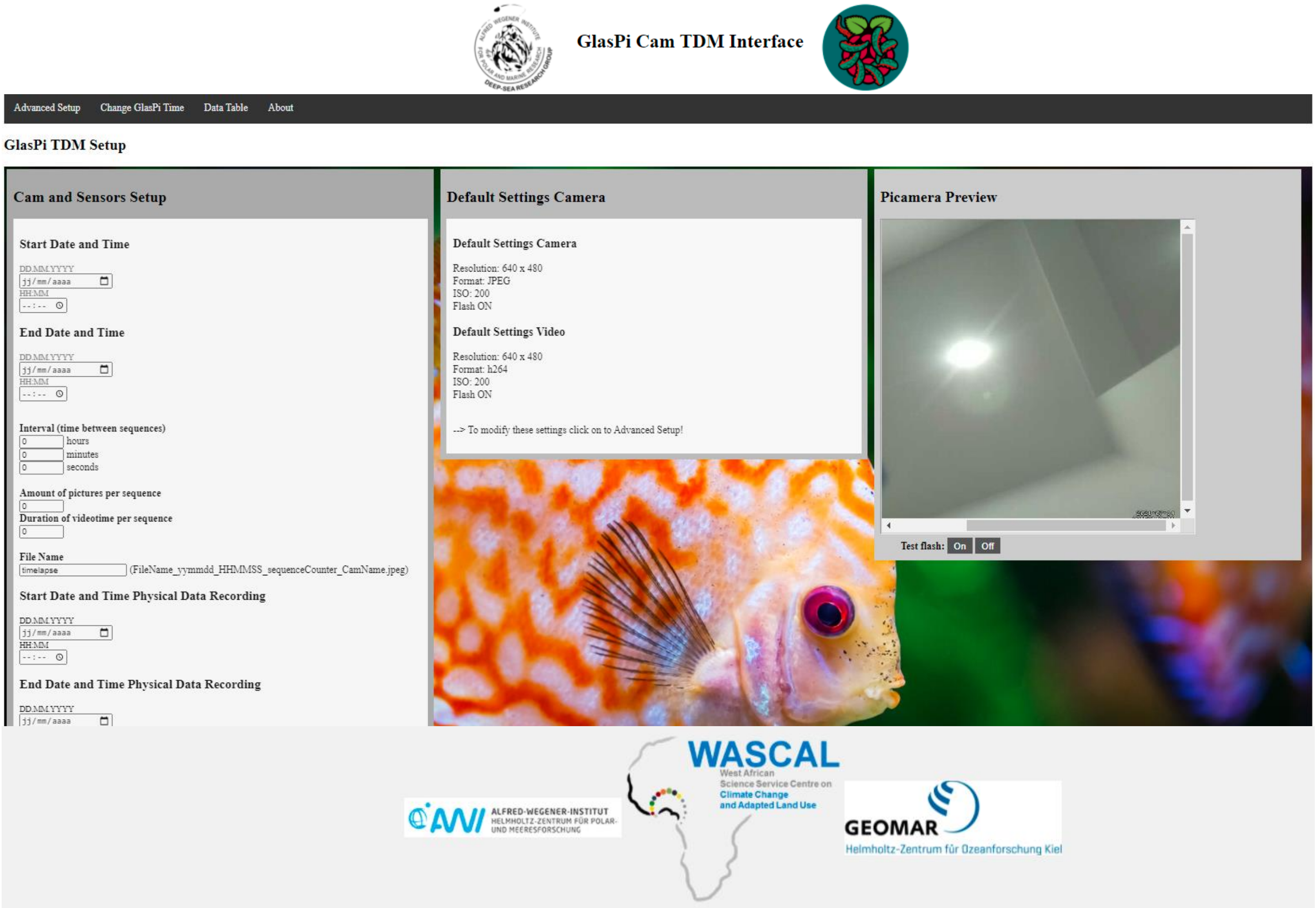


Figure 20: Webpage of PlasPi TDM to configure the system before deployment.

The index.php script connects to other PHP files such as the processScript.php, PHP sub-files containing the configuration parameters of the camera and the TD sensor, the table.php to return the data stored on the latter on the web page in an HTML table. The raspberry code consists of codes that allow photos and videos to capture and collect temperature, pressure, depth, and multispectral data. A synchronization module was also developed so that all images are time-stamped using the Raspberry Operating System timer. In the configuration of the program, obtaining photos, videos, and physical data from the camera and the TD sensor respectively can depend on each other or not depending on the settings made by the user. However, the collection of multispectral data is dependent on the shooting of the images. This will allow thorough discrimination of the objects taken in the photos by using their spectral measurements. Thus, the Multispectral sensor or PixelSensor executes the same camera setting command made by the user through the web page.

4.2.5 Communication

Communication to operate the device is done via Wi-Fi, using remote access software such as PuTTy or Real VNC application once the box is sealed. The software consists of a server (Raspberry Pi) and client (User) application for VNC (Virtual Network Computing) protocol to control the device remotely. The system's internal clock must be set before deployment.

4.2.6 Bench test and Field test

Before deployment in a natural environment, a bench test was carried out. The bench test is a functional test in which the device is physically tested. This allows us to recreate the scenarios in which the device will be used. This is to analyze its behaviour, improve the camera parameters about shooting and video recording, and check that all the data (temperature, pressure, spectral) are recorded as desired. A $1m^3$ tank filled with seawater was used for the test. Field tests were done in Mindelo Bay (São Vicente, Cabo-Verde). Profiling tests up to 150 m were carried out at several locations.

4.2.7 Processing of the recorded video/image data

Once the images and videos data have been acquired, the contents of the photos and videos need to be extracted and integrated with other data to be considered in scientific analysis or integrated into decision-making processes (Schoening et *al.*, 2016). Thus, annotation of images and videos was carried out. Image annotation is an analysis process that allows the content of an image or video to be labelled for object recognition and detection. For this purpose, the web-based marine image annotation tool BIIGLE (BioImage Indexing Graphical Labeling and Exploration) (Ontrup et *al.*, 2009; Schoening et *al.*, 2009). A cloud drive was created to upload the images and make them available online.

4.2.8 Spectrum data analysis

Objects that receive light absorb some part and reflect the remaining as electromagnetic radiation, which the PixelSensor measures. Also, the absorbance of an object is a function of its composition and physical state. For example, as the temperature of the object increases, more radiation is absorbed, and absorbance increases. Also, the longer the distance between the radiation beam and the object, the higher the absorbance. As the shutter time of a single capture was set to 0.1 seconds, each spectral measurement was taken at half the time of a single capture, i.e., 0.05 seconds. This allowed us to make the spectral measurement of each image. Normalization of the recorded spectral values was performed by calculating the noise at each wavelength of the visible spectrum for the 10 sample images (containing no objects) taken in surface and deep water. The normalization process consisted of calculating the average value of the radiance and then the standard deviation for each wavelength of the set of photos taken in shallow and deep water using the following formulae:

$$\boldsymbol{Average\ (\bar{x})\ = (\sum_{i=1}^{n} X_{radi/\lambda})\ /\ \mathbf{n}}$$

With $\mathbf{X_{radi/\lambda}}$ the observed radiance values for each wavelength are considered for all 10 images (of shallow or deep water) and **n** the number of observations for the wavelength considered.

$$\boldsymbol{Standard\ Deviation\ (s)\ = \sqrt{\frac{\sum_{i=1}^{n}(X_{radi/\lambda} - \bar{x})^2}{n-1}}}$$

With $\mathbf{X_{radi/\lambda}}$ the observed radiance values for each wavelength considered for all 10 images (of shallow or deep water), $\boldsymbol{\bar{x}}$ the average calculated for the wavelength considered and **n** the number of observations for the wavelength considered.

The spectral values of each image were determined by applying the background correction to enhance the visibility and differentiate species from the background scene. It is done by making the difference between the different radiance values measured in each length and the average radiance values calculated for each wavelength of the set of photos taken in surface water (if the image comes from a surface water) or deep water (if the picture considered is taken in deep water) as shown in the formulas below:

$$SpV_{obj} = Average - \ Initial\ SpV_{obj}$$

SpV_{obj} is the spectrum values of the object or target, and ***Initial SpV_{obj}*** is the initial spectrum values of the thing measured by the PixelSensor.

Finally, the spectral profile plots of the images as a function of the different wavelengths are generated. For species identification, each species has its unique pattern of spectral values. And the ability of a species to reflect or absorb light depends on its physical, chemical, and physiological composition. And since the reflectance of an object is the ability of that object to reflect energy incident on its surface, these values are used to describe the nature of an object. Therefore, species identification is made by the wavelength with the highest reflectance in the visible spectrum, allowing for the lowest detection limits.

4.2.9 Physical data analysis

The collection of physical data (Temperature/Depth) was done in profiling mode. The water temperature as a function of depth was measured from top to bottom in most water columns at the different stations created for this purpose. The temperature/depth curve was plotted to observe the variation of these properties as a function of time and location to better characterise the habitat or marine environment.

5. Results

5.1 Hardware hydrostatic pressure test

The results of the performance evaluation of the housing are satisfactory. After removing the housing from the tank (Figure 21) and checking the housing, there was no water inside and no leakage.

Figure 21: Tank (a); Housing carried out of the Tank after the test (b).

The hydrostatic pressure test carried out at sea (Figure 22) between the island of Sao-Vicente, and Santo Antao (Cabo-Verde) was also very successful. The pressure of 21 bars (at a depth of 200 m) was withstood by the box during the 45 minutes. There was no implosion or leakage.

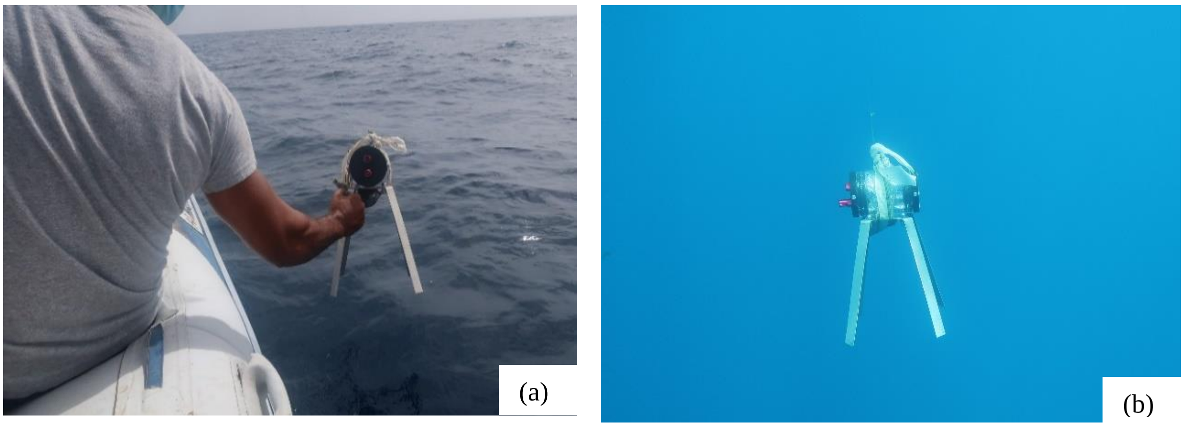


Figure 22: Dropping down the housing (a); Housing in the water column (b).

5.2 Bench test

The results of the bench test were satisfactory. The waterproofness of the device was once again tested, but this time with the whole electronic part (Figure 23). No water ingress was observed. During this test, several data acquisition modes were used: Photo and physical data collection mode, photo + video + physical data collection mode, and video + physical data collection mode. Each mode was tested for 45 minutes. The various data obtained from this test are in line with those expected. But very soon, it was found that the memory storage was insufficient. Therefore, a resolution of 640x480 was defined as the most appropriate.

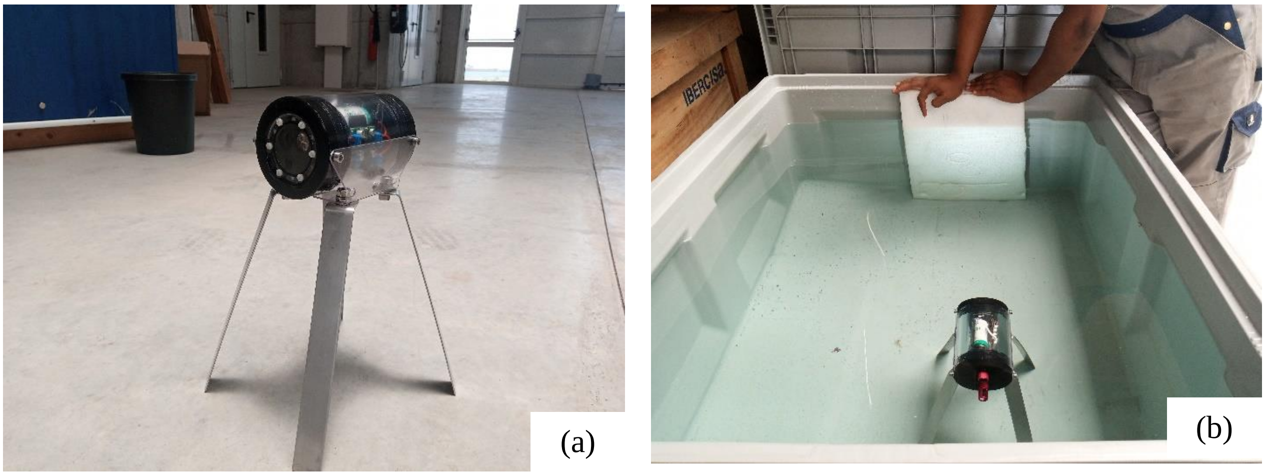


Figure 23: Bench test: (a) PlasPi TDM assemblage; (b) Calibration Of the brightness and the resolution.

The bench test also allowed us to modify the device about the total weight of the device. The standing frame used to support the device did not let the device be heavy enough to be easily deployed to the desired depths. Thus, at the base of the standing frame, square support was designed so that weights (Figure 24) could be fixed and allow the device to be heavy enough not to drift with the sea current.

Figure 24: Standing frame modified: (a) Square heavy metal; (b) Square heavy metal fix at the bottom of the standing frame; (c) Weights attached to the support square heavy metal on the standing frame.

5.3 Underwater dataset acquisition

The acquisition of underwater data was made by deploying the device at four different locations on the island of São-Vicente (Cabo-Verde), namely São Macario (an 80 meters long shipwreck located in the bay of Mindelo and at a maximum depth of 15 meters), São Pedro, precisely at the site of the marine turtles, Cubos, a scuba-diving hotspot and Praia Grande (Figure 25).

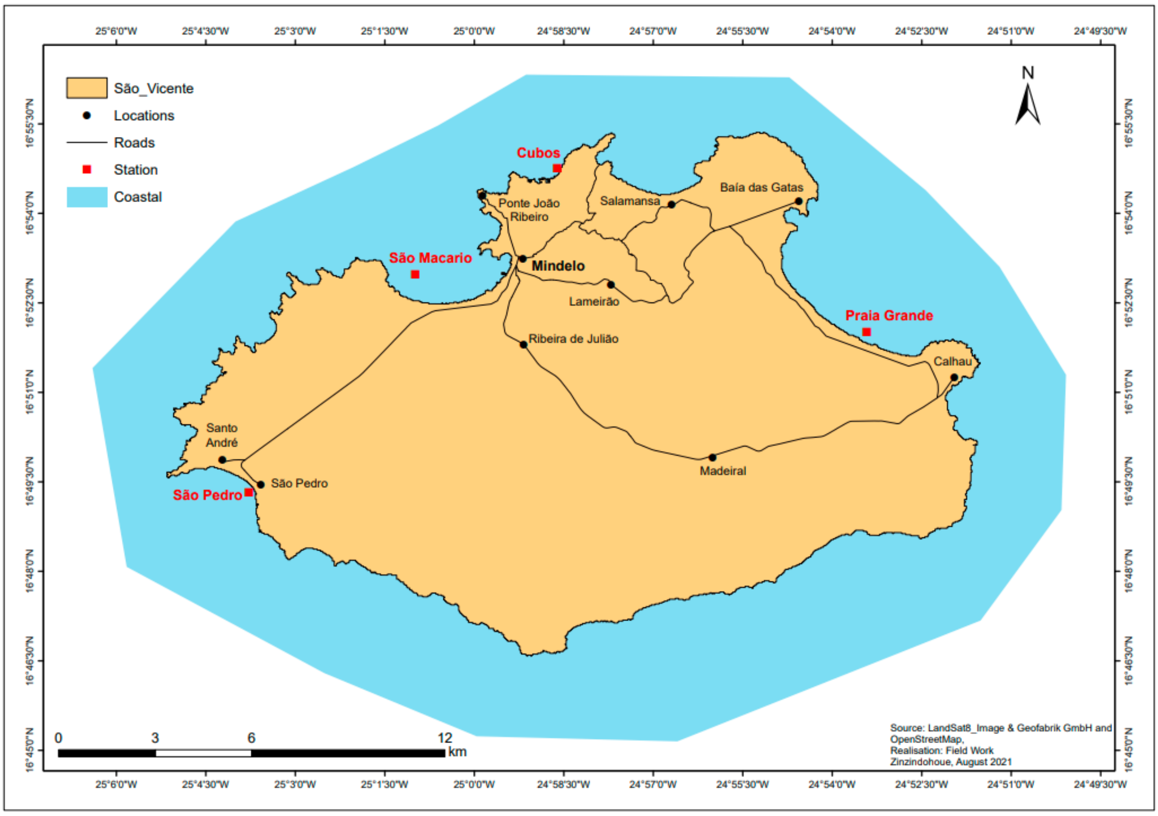


Figure 25: Location of the field test areas.

The maximum depth reached during all deployment tests was 20 meters. The deployment of the device was done in most cases by diving, as shown in Figure 26. The data set was acquired with one image every 5 seconds, while temperature and pressure data were recorded every 10 seconds.

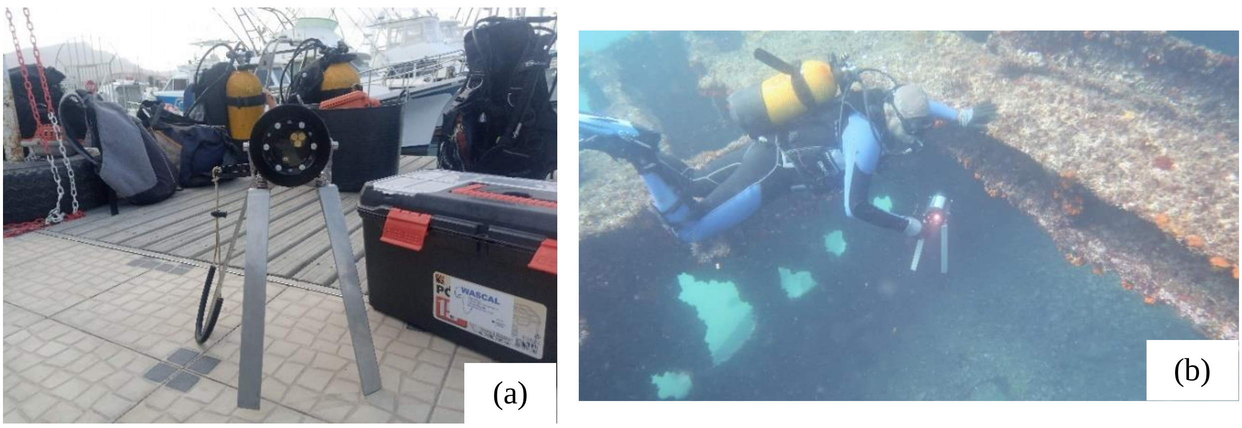


Figure 26: Deployment of the PlasPi TDM deployed on the São Macario shipwreck: (a) PlasPi TDM assemblage; (b) PlasPi TDM submerged by the diver.

During the data acquisition tests, two types of deployment were made: Profiling and Benthic observation.

5.3.1 Profiling Deployment

The profile deployment consisted of lowering the device into the water column. For this deployment mode, the data collection is done during the descent of the device (Figure 27).

Figure 27: PlasPi TDM on the São Macario Shipwreck in the water column.

5.3.2 Benthic Observation Deployment

The deployment for benthic observation consisted of placing the device on the seafloor (Figure 28). For this purpose, additional weights were added to the device to be firmly fixed in the sediment.

Figure 28: PlasPi TDM posed on the seafloor by a diver.

5.4 Characterization of the marine environment

The characterization of the marine environment was illustrated by analyzing the temperature and pressure data measured by the different sensors at Cubos. The curve shows the temperature decreases with the increase of the pressure (Figure 29). The average value observed for the temperature is 21.97 °C with a standard deviation of 1.02 °C.

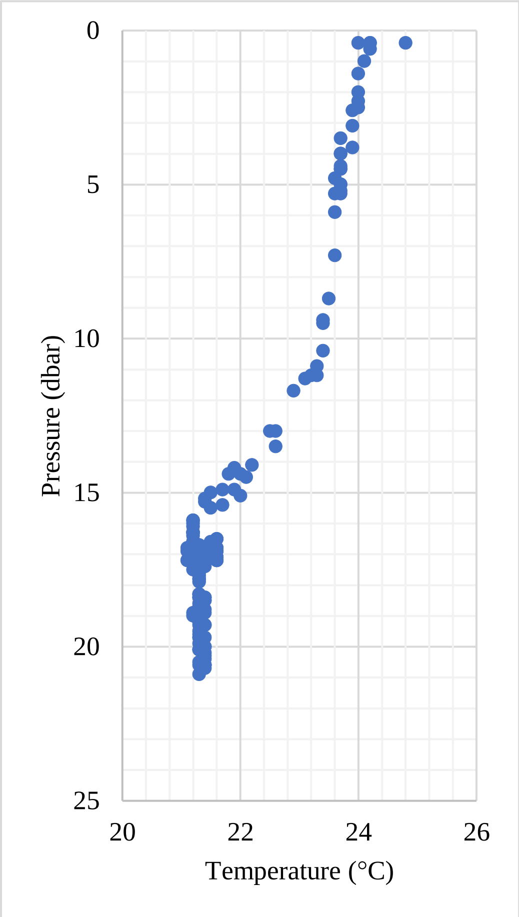


Figure 29: Temperature variation as a function of pressure (descend) during a field test at Cubos. At each measurement point, pictures, as well as multispectral data, were recorded.

5.5 Image Annotation

The images from the test deployments were then made available in the BIIGLE online platform for browsing and annotation. Only the pictures from São Pedro and Praia Grande were annotated with information and metadata attributes (Figure 30). For these two locations, 197 images were annotated. Seventeen (17) different species, including 02 species endemic to Cabo Verde and grouped in 12 families, have been identified (Table 1). The image annotation abundance report (Figure 31 and Figure 32) lists the abundance of annotation tags for each image as exported the identified species.

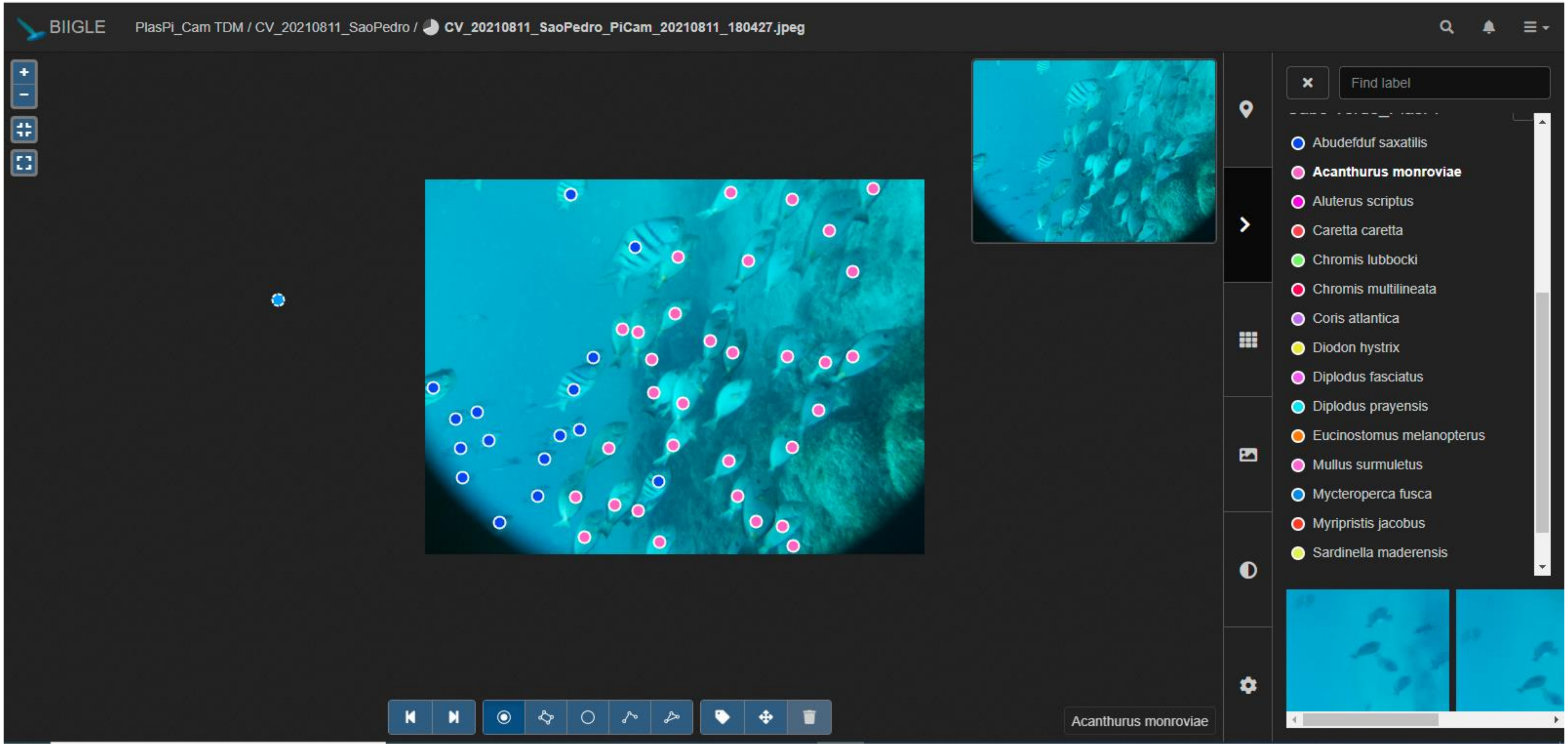


Figure 30: Image Annotation using BIIGLE: identification of the species *Abudefduf saxatilis* (blue point) and *Acanthurus monroviae* (pink fact).

Thus, the most abundant species annotated for both locations were observed in Sao Pedro (Figure 31). These were *Abudefduf saxatilis* (548 individuals), *Acanthurus monroviae* (174 individuals), *Caretta caretta* (139 individuals), and *Eucinostomus melanopterus* (132 individuals). In terms of diversity, for both locations, Praia Grande has a very high diversity with 14 different species, few in terms of abundance (Figure 32) against 7 species for Sao Pedro.

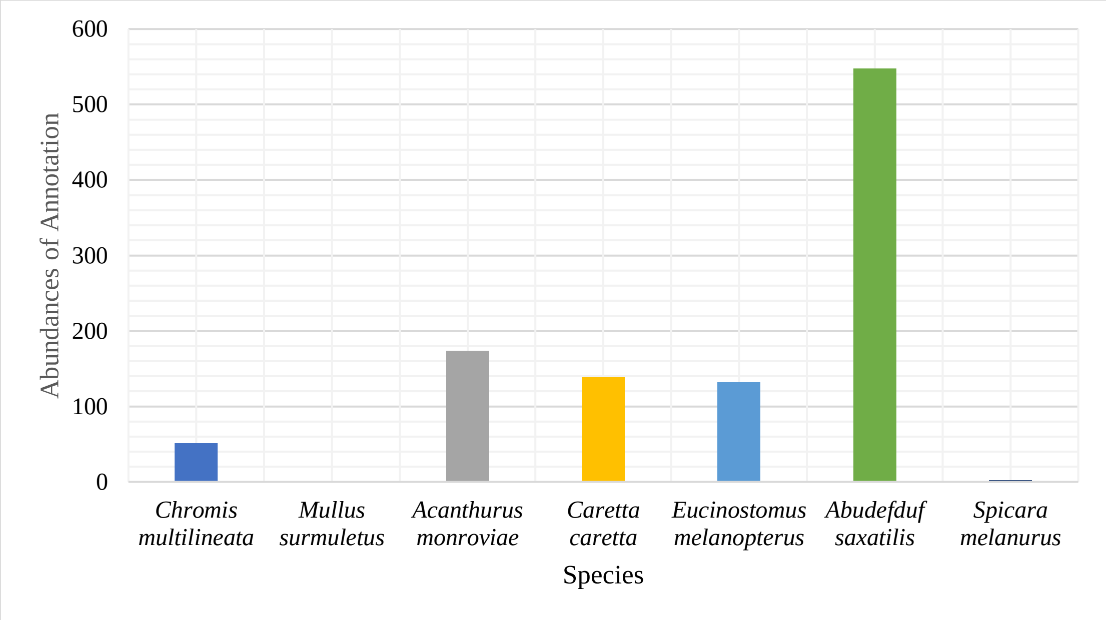


Figure 31: Image annotation abundance of species of São Pedro.

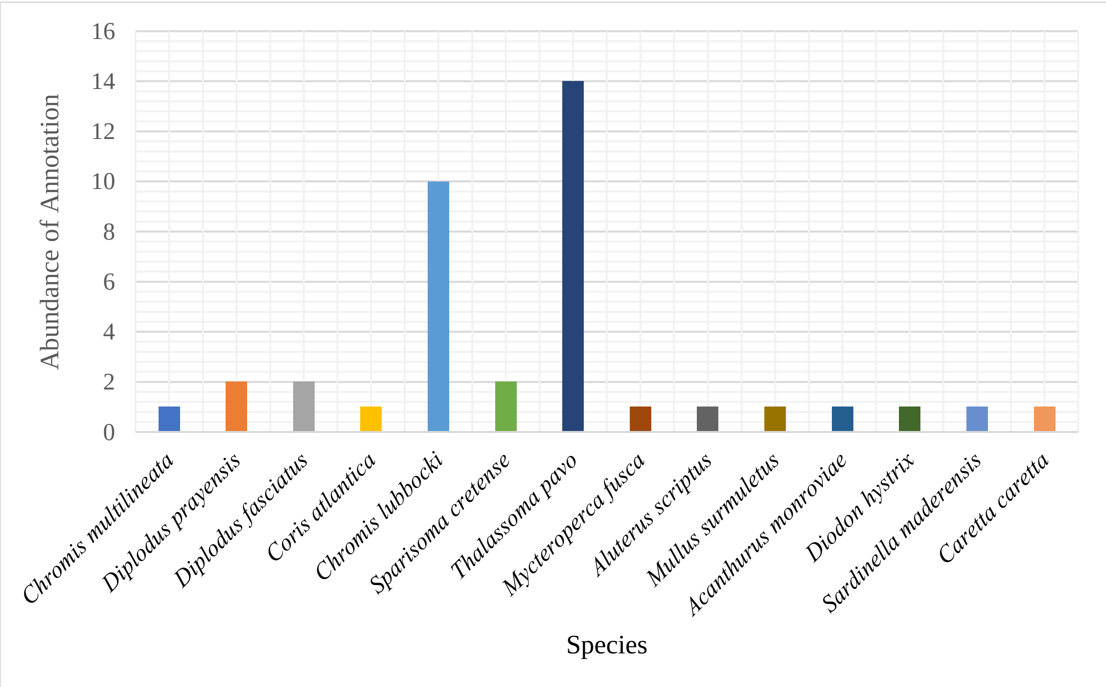


Figure 32: Image annotation abundance of species of Praia Grande.

The Pomacentridae, Acanthuridae, Cheloniidae, and Gerreidae families are the most represented in both locations (Figure 33). The Serranidae, Monacanthidae, Diodontidae, and Clupeidae are very poorly represented.

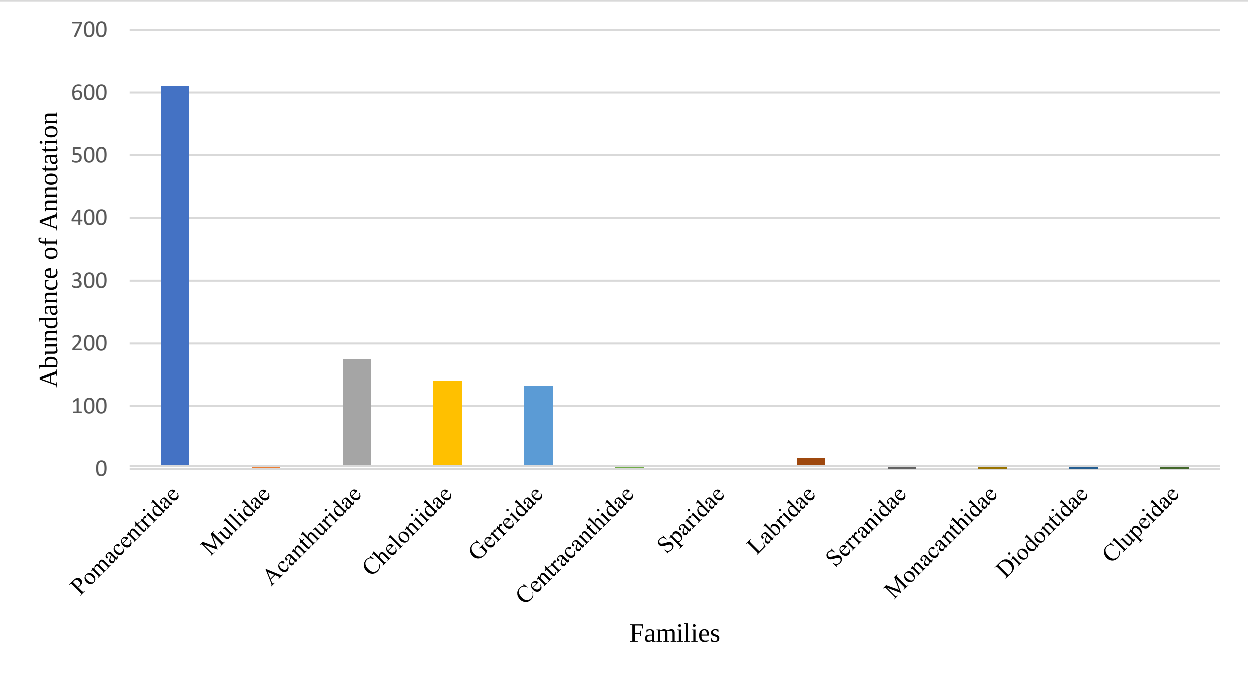


Figure 33: Image annotation abundance of species' family of São Pedro and Praia Grande.

Table 1: Species identified from images.

Species	Family	Trophic	Type
Abudefduf saxatilis	Pomacentridae	Omnivore	Fish
Chromis multilineata	Pomacentridae	Planktivore	Fish
Chromis lubbocki	Pomacentridae	Planktivore	Fish
Mullus surmuletus	Mullidae	Mobile Invertivore	Fish
Acanthurus monroviae	Acanthuridae	Rov. Herbivore	Fish
Caretta caretta	Cheloniidae	Carnivore	Turtle
Eucinostomus melanopterus	Gerreidae	Carnivore	Fish
Spicara melanurus	Centracanthidae	Mobile Invertivore	Fish
*Diplodus fasciatus**	Sparidae	Omnivore	Fish
*Diplodus prayensis**	Sparidae	Omnivore	Fish
Coris atlantica	Labridae	Mobile Invertivore	Fish
Sparisoma cretense	Labridae	Roving Herbivore	Fish
Thalassoma pavo	Labridae	Mobile Invertivore	Fish
Mycteroperca fusca	Serranidae	Piscivore	Fish
Aluterus scriptus	Monacanthidae	Omnivore	Fish
Diodon hystrix	Diodontidae	Sand Invertivore	Fish
Sardinella maderensis	Clupeidae	Planktivore	Fish

* Endemic species of Cabo Verde

5.6 Spectral Study

The average and standard deviation plots of the values of all images taken in shallow and deep water without any target are shown in Figure 34 and Figure 35. When considering all wavelengths, the average absolute reflectance or radiance values are higher in shallow water than deep water. This is due to the impact of solar radiation, which brings much more luminosity in the shallow water. Also, whether in shallow or deep water, the highest average radiance values are observed in the 575.5 nm wavelength and are 9152.1 w/m^{2}sr nm (watt per square meter per steradian per nanometer) and 1281.6 w/m^{2}sr nm for shallow and deep-water images, respectively. The standard deviation values, which measure the data's dispersion relative to its mean, for the shallow and deep-water cases are low and below the mean. This means that the radiances measured at the same wavelength for each shallow and deep-water image are clustered around the average of the radiances measured at different wavelengths for each image. As a result, the images have a low noise level. The standard error bar indicates the reliability of the average of the spectrum values in shallow and deep-water are short, which means that the sample average is a more accurate reflection of the actual data average.

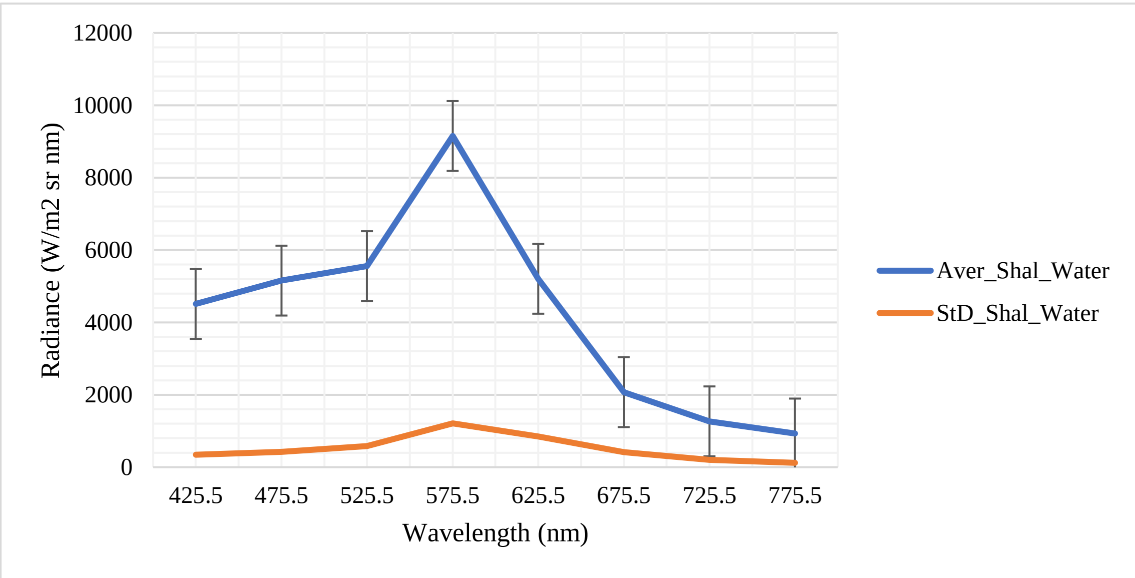


Figure 34: Average value and standard deviation of the radiance for each wavelength of all images taken in shallow water. Colour blue: Average shallow water. Colour red: Standard deviation shallow water.

Unlike the PlasPI marine camera, which only takes pictures of species and makes a visual identification, the PlasPi TDM combines photography and spectral data for a more in-depth identification of species. A case study of the use of spectral signatures of different species for identification has been done by applying the background spectra correction mentioned early.

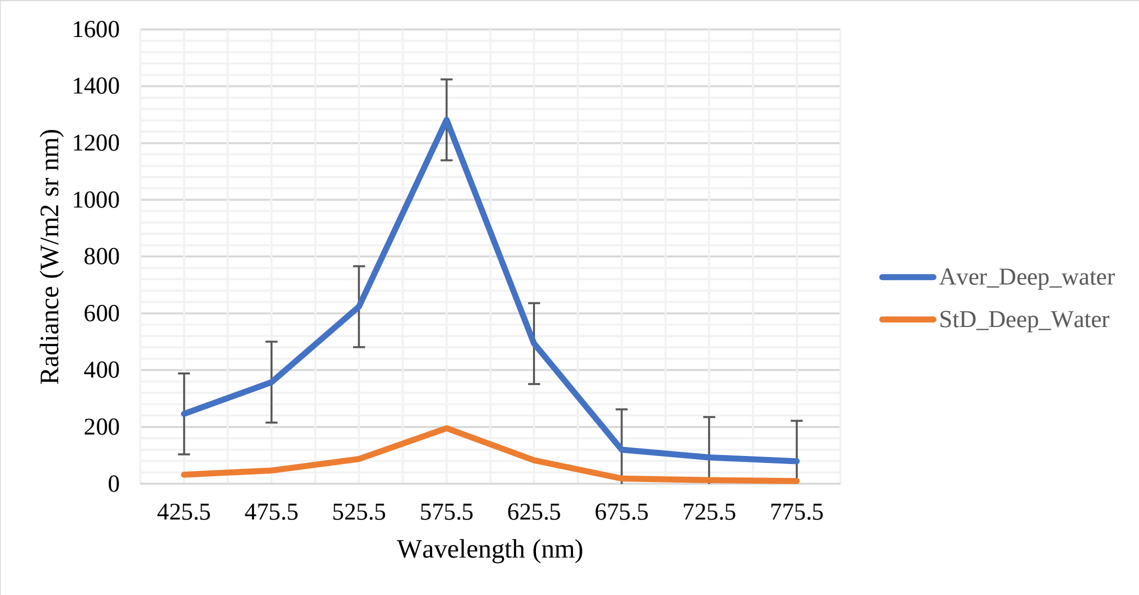


Figure 35: Average value and standard deviation of the radiance for each wavelength of all images taken in deep water. Colour blue: Average deep-water. Colour red: Standard deviation deep-water.

As an example, six (6) spectral profiles in shallow water (Figure 36 and Figure 37) and deep-water (Figure 38) from 6 different species were plotted. *Abudefduf saxatilis*, *Acanthurus monroviae*, *Eucinostomus melanopterus*, *Caretta caretta*, *Priacanthus arenatus*, and *Chromis multilineata*. Thus, we find that all species Abudefduf saxatilis, Acanthurus monroviae, Eucinostomus melanopterus, and Caretta caretta have in shallow water a high reflectance in the wavelength 625.5 nm (Figure 36 and Figure 37). But to discriminate between species, they use the wavelength to register a second and third high reflectance. Thus, *Abudefduf saxatilis* records its second reflectance at 575.5 and 475.5 nm (Figure 36 (a)) while *Acanthurus monroviae* (Figure 36 (b)) records it at 575.5 nm. For *Eucinostomus melanopterus* (Figure 37 (a)), this second high reflectance value is found at 475.5 nm. In contrast, *Caretta caretta* (Figure 37 (b)) has two different reflectance peaks at wavelengths 475.5 and 575.5 nm in addition to 625.5 nm. For the species *Priacanthus arenatus* (Figure 38 (a)) and *Chromis multilineata* (Figure 38 (b)), whose photographs were taken in deep-water, the highest reflectance or radiance values were recorded in the wavelengths 575.5 nm. The discriminating wavelengths for these species are 475.5 and 625.5 nm for the *Priacanthus arenatus* school, and the wavelength for the *Chromis multilineata* species is only 625.5 nm.

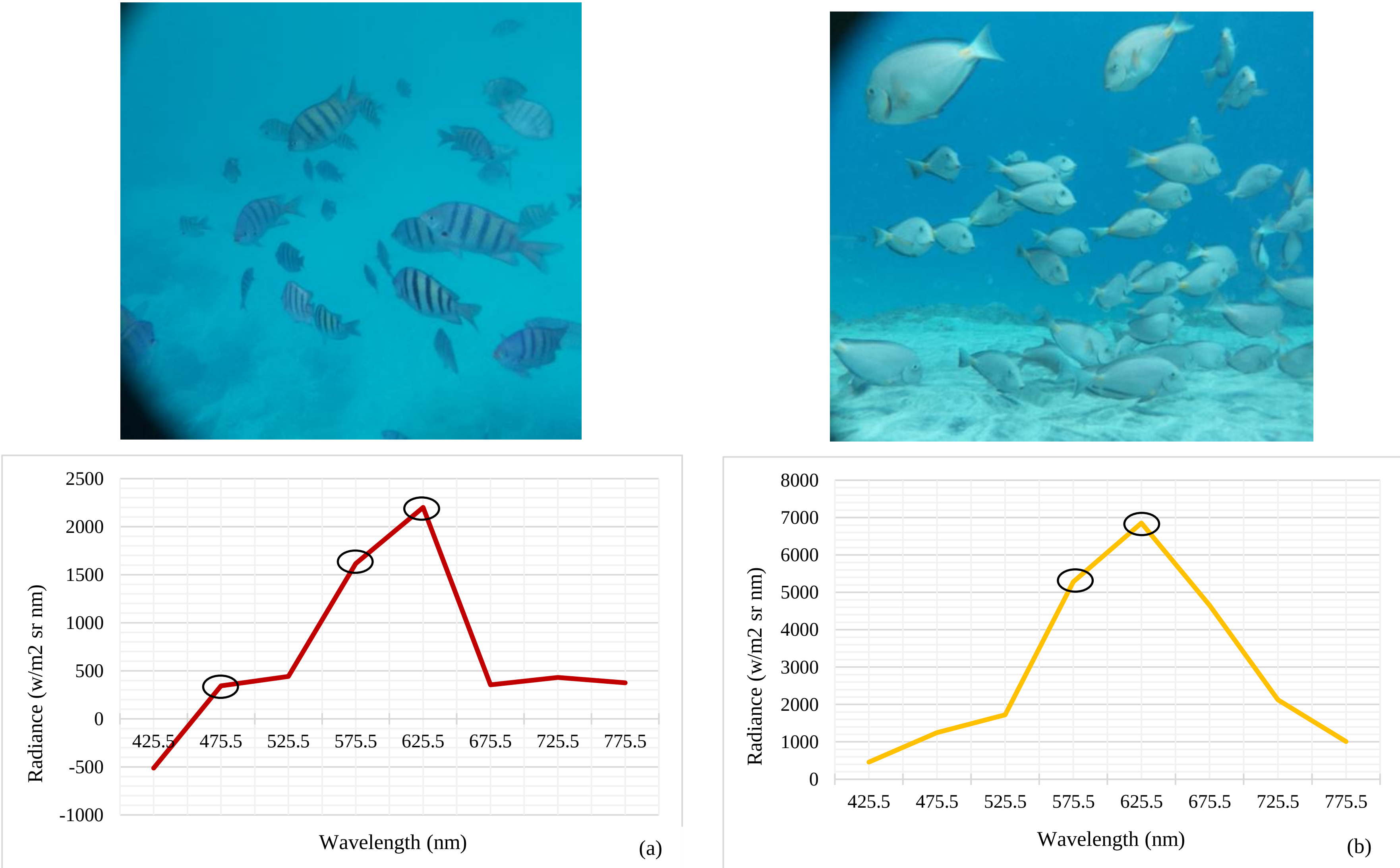


Figure 36: Different spectral profiles of species in shallow water: (a) *Abudefduf saxatilis*; (b) *Acanthurus monroviae*. The circles show the peaks of wavelengths used for identification.

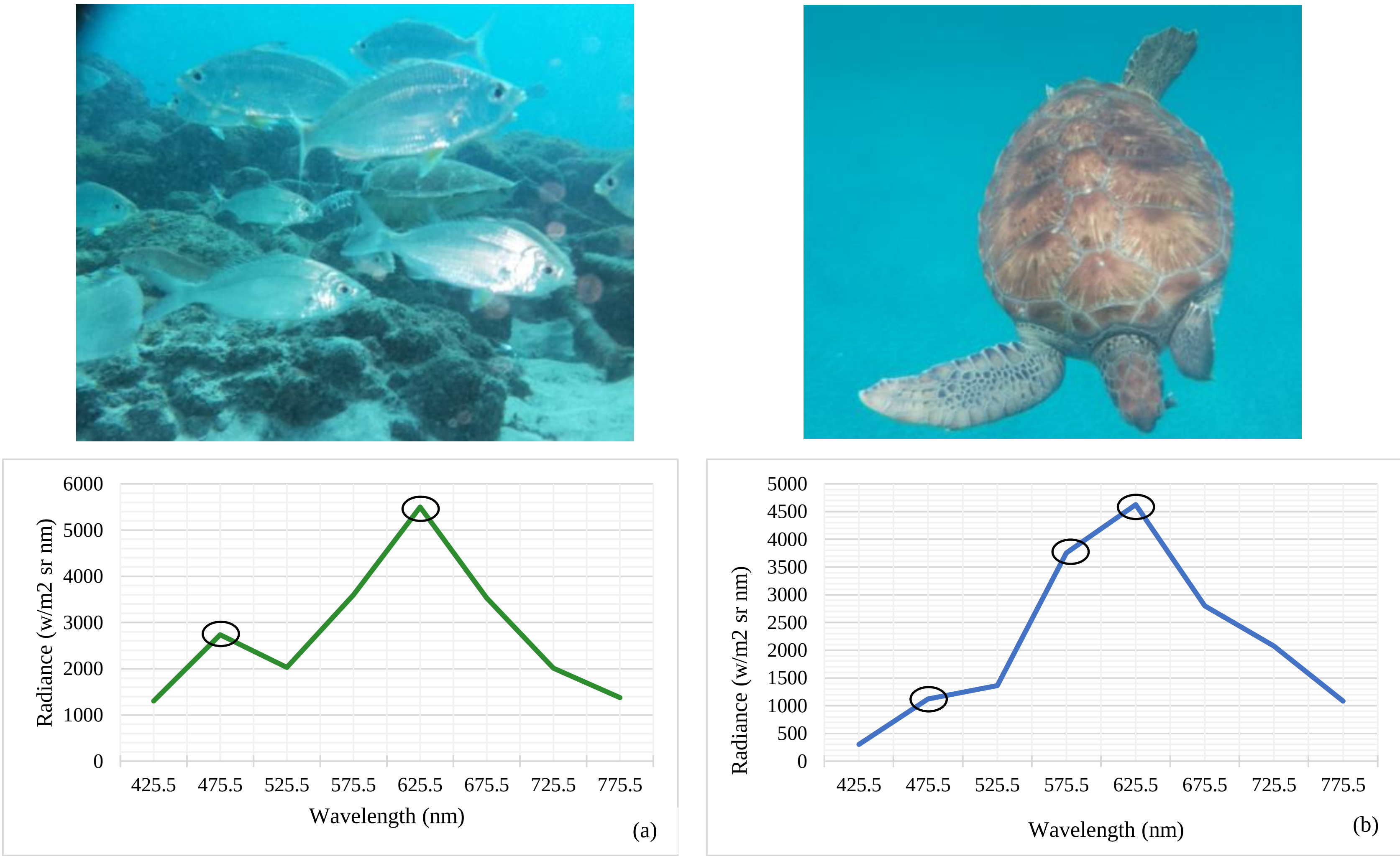


Figure 37: Different spectral profiles of species in shallow water: (a) *Eucinostomus melanopterus*; (b) *Caretta caretta*. The circles show the peaks of wavelengths used for identification.

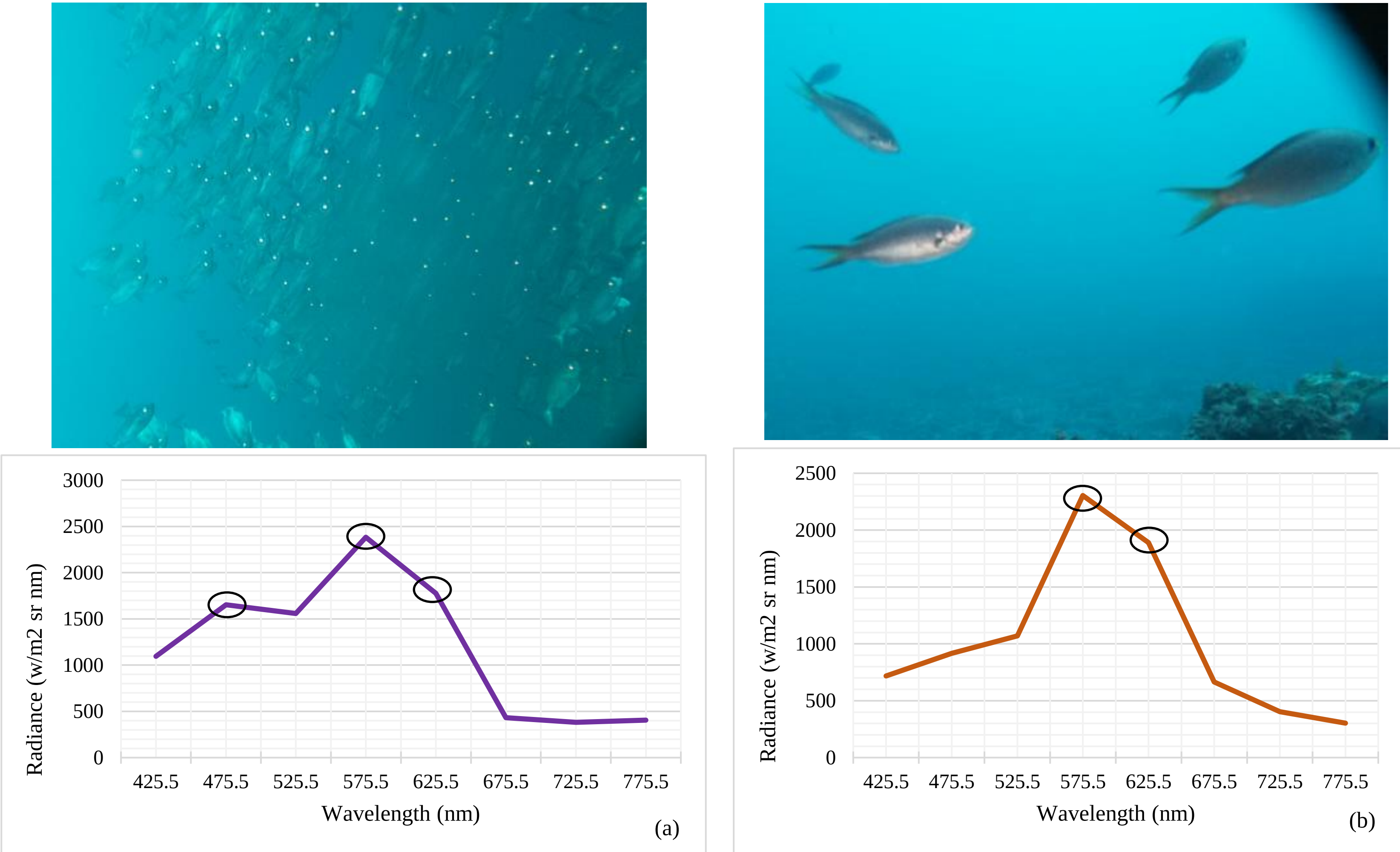


Figure 38: Different spectral profiles of species in deep-water: (a) *Priacanthus arenatus*; (b) *Chromis multilineata*. The circles show the peaks of wavelengths used for identification.

6. Discussion

During the test deployments, the PlasPi TDM performed well, allowing the acquisition of new types of data to study the marine environment. Compared to other underwater observation development projects such as the Azor drifting camera (Dominguez-Carrió et *al.*, 2021) and the TrigCam (Kresimir et *al.*, 2015), and other low-cost camera systems on the market, the PlasPi TDM has enabled visual and spectral identification of different species. Spectral signature identification, known to have been used in aerospace technologies and terrestrial applications (Gomez Richard, 2002; Paz-Kagan et *al.*, 2015; Gomez & Lagacherie, 2016; Wheeler et *al.*, 2017; Chengxing et *al.*, 2017), is now used with the PlasPi TDM for the first time in observational oceanography, to our knowledge. Thus, as the results show, the wavelengths allow identification and let us know the part of the water column in which the image was taken. This is because the wavelength where the peaks were reached in shallow water is longer (625.5 nm), which means that it has a shorter frequency and lower energy than deep water (575.5 nm), where the frequency and energy are higher. The differences in reflectance spectra observed at the species level are due to their unique optical properties, which function as their physical, biological, and chemical characteristics. Also, differences in the amount of energy absorbed and anatomical and morphological differences of species that enhance light scattering at different wavelengths allowing differentiation between taxa (Ustin & Jacquemoud, 2020), could also account for this observed difference.

The image annotation shows how images taken by the PlasPi TDM can be used in ecology and biology. Indeed, image annotation allows a complete interpretation of the different contents of an image collection. Image annotation in BIIGLE is based on a machine-learning algorithm. This consists of a general object detection system that acquires knowledge of the structural features of objects of interest (in this case, different species) and non-interesting patterns from a set of image patches showing representative examples of all species (Schoening et *al.*, 2012). The method uses the Support Vectors Machines (SVM) machine learning algorithm. The abundance of species results from the annotation offers ecologists and biologists the advantage of assessing fish stocks well without effort. Indeed, from the species annotation, the biomass of a stock can be estimated if the average weight of the sample is known (Costa et *al.*, 2006; Li et *al.*, 2019). This saves time and productivity, unlike traditional methods that rely mainly on manual sampling, which is usually invasive, time-consuming, and laborious (Daoliang et *al.*, 2019). The PlasPi TDM is a good tool for coastal ecosystem observation if applied systematically during concerted (and regular) surveys. The integration of photographic and spectral data will allow the creation of a catalogue to identify underwater species.

The temperature and pressure data were recorded to demonstrate the use of this device in the characterization of the marine environment. It proves its ability to monitor the changes in marine ecosystems, which were a limitation due to the high cost of instruments, thus demonstrating one of its applications in physical oceanography.

The tests also revealed that PlasPi TDM is very useful for marine ecology and biology, and physical oceanography in different aspects (Figure 39). The use of PlasPi TDM in marine ecology and biology not only allows the observation of the marine habitat but also provides a considerable amount of data that can be extracted from the recorded images and videos such as species, fish size, position, orientation, etc.., helping researchers to address a variety of questions and hypotheses. In addition, it can provide information on the physiology and behaviour of animals, even in high pressure and low light environments (up to 200 m deep).

Table 2: Cost of the PlasPi TDM Material

Items	Amount	Cost per unit	Total cost
Housing	1	€ 100.00	€ 100.00
Raspberry Pi zero w	1	€ 20.90	€ 20.90
Picamera V2	1	€ 23.32	€ 23.32
BAR30-SENSOR-R1-RP	1	€ 80.09	€ 80.09
CELSIUS-SENSOR-R1-RP	1	€ 67.35	€ 67.35
Osram Oslon SSL 120 Triple Star Weiss CRI90+	1	€ 10.00	€ 10.00
Step-Up/Step-Down Voltage Adjustable	2	€ 15.00	€ 30.00
I2C bus Splitter	1	€ 15.59	€ 15.59
LEDIL Satu Triple Star Linse 30o	1	€ 4.00	€ 4.00
SAFT LSH 20 Lithium Battery 3.6 V Primary LSH2	2	€ 25.00	€ 50.00
PixelSensor OEM VIS-8-UVIR	1	€ 800.00	€ 800.00
Samsung MicroSDHC 32 GB PRO Plus UHS	1	€ 10.00	€ 10.00
Total			€ 1,211.25

The low-cost (Table 2) device, with all its technology, is comparable to other low-coast camera systems on the market (Azor drifting camera, ROV, AUV, etc.). The system is flexible and easy to reconfigure, and anyone can use it without the help of highly trained technicians, which reduces the costs of deep-water exploration. In addition, it is quick to assemble, easily transportable, and replacement of any of the components in the event of a problem is straightforward. As for the user interface or settings, it is effortless to use. Due to its minimal physical size, the PlasPi CT has little impact on modifying animal behaviour by its presence. This has been proven by viewing images and videos in which the species did not move away from the device, nor did they show fearful behaviour. In addition, thanks to its time-lapse system, the PlasPi TDM can take images and record videos at brief time intervals with good resolution and store them efficiently as long as there is sufficient storage space.

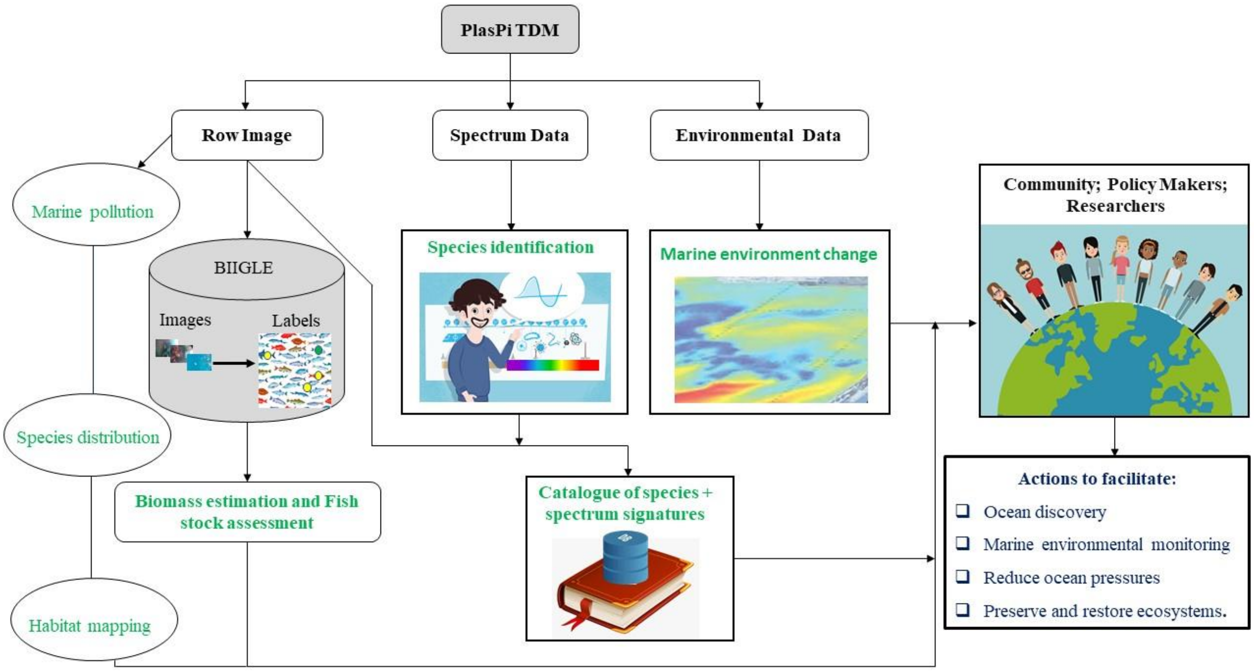


Figure 39: Conceptual framework of the PlasPi TDM.

7. Conclusions and Future direction

7.1 Conclusions

This study presents a new low-cost, automatically operating research tool for continuous advanced short and long-term underwater ecological observations. With its onboard camera, spectral, temperature, and pressure sensors, the PlasPi TDM provides access to marine environments inaccessible to humans. It also offers new data perspectives to understand better the marine habitat and biodiversity and how it is affected by human activities. Thus, it allows an accurate assessment of the health of marine ecosystems by providing information on biotic (species diversity and behaviour) and abiotic (temperature and pressure) components. The possibility to be embedded on several other platforms such as CTDs, AUVs, profilers, to name a few, makes PlasPi TDM a suitable device for advanced underwater observations.

7.2 Future directions

Despite the many application advantages of the PlasPi TDM, we still have no intention of developing the perfect product. There are still several avenues to improve this observation system to enable it to reach its full potential. As for the technological aspect, one of the relatively simple improvements to be made is to equip it with a switch that will allow the circuit inside the waterproof housing to be switched on and off without opening it. This will allow the system to be quickly rebooted for future data collection settings. Another direction we should explore is improving the lighting system. The light intensity of the LED at great depths does not allow good illumination of objects in the distance. This would later affect the image quality. In addition to all these improvements, the camera's resolution could be improved by opting for a 4k resolution camera. As for the watertight enclosure, for future improvement, it would be good to increase the diameter or dimensions of the front cap and, therefore, of all the parts forming the waterproof enclosure. This will allow the different components of the front cap, mainly the camera, to be well fixed inside to avoid distortions on the images. We can also equip the PlasPi TDM with a GPS receiver to know the precise location of the objects taken in pictures. All these future directions will lead to an improved underwater camera. As to the scientific perspective, the PlasPi TDM will be used as a systematic observation tool. This will help describe and explain the phenomena that occur in the marine environment for a better understanding. In addition, the data collected will all be stored to establish a database or catalog with a complete description of the species, their spectral signatures, and the description of their habitat. Finally, elaborate field trials near the coast will be integrated into regular coastal monitoring efforts to document changes in biodiversity.

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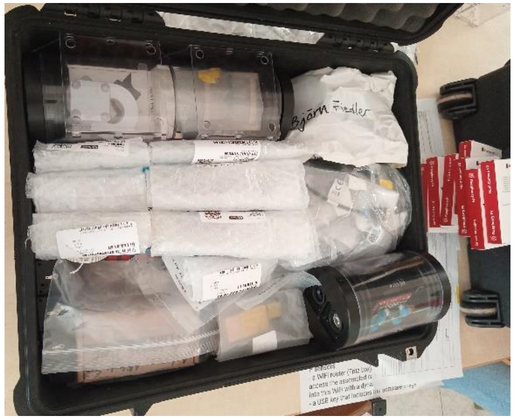
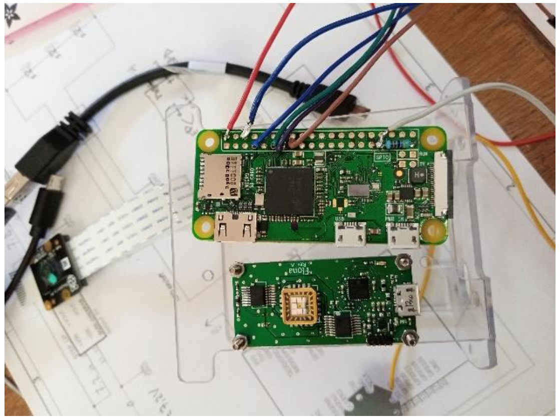
Appendices

<u>Appendix 1:</u> Some pictures of the PlasPi TDM assemblage.



Materials and tools for assemblage

Soldering of the I2C bus splitter



Electric wire soldered to the Raspberry Pi and next to the PixelSensor

Plugging of the Temperature sensor to the I2C bus splitter

Setting up the supply system

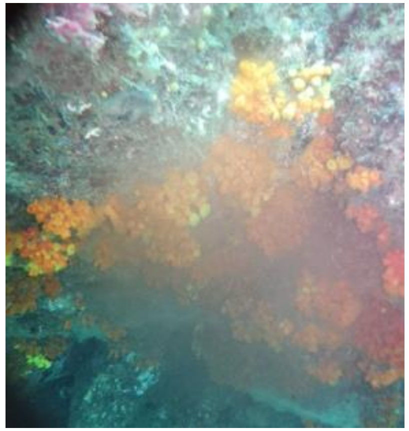
PlasPi TDM assembled

<u>Appendix 2:</u> Some images of species taken by the PlasPi TDM during the test deployment.

Myripristis jacobus

Diplodus prayensis

Muraena melanotis



Atlantia caboverdiana

Diodon hystrix

Diplodus fasciatus

Taeniura grabata