DESIGN OF A COMPACT UNDERWATER IMAGING AND GEOLOCALIZATION PLATFORM WITH EDGE COMPUTING CAPABILITY

By

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Abstract

With its endless dark blue tone, the underwater world is filled with color, life, and beauty. It has many scientific imaging research opportunities. However, during the development of an underwater geolocation instrument based on polarization imaging sensors, we noticed that the underwater devices are all designed for cinematography applications. They are bulky and complicated, and they cannot satisfy the ever-changing scientific research needs. In this thesis, we report on the design of a compact, expandable underwater edge computing platform based on the Nvidia Jetson devices. This platform is capable of recording and processing more than 4 hours of footage underwater. With its modular design, the platform can support image sensors up to 70 mm/2.75" diagonal and virtually any lens. This platform opens up possibilities for researchers to perform underwater data collections, real-time machine learning inferences, and marine biology studies.

Subject Keywords: polarization; imaging; underwater navigation; edge computing

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Contents

1. Introduction

Nowadays, we all have smartphones. The embedded global positioning system (GPS) reception inside our smartphones has significantly simplified our lives by providing accurate geolocalization information to us. However, when we are underwater, the GPS cannot provide reliable service due to the high reflectivity of the water-air boundary and the high electromagnetic losses underwater [1].

Nevertheless, geolocation is critical for many underwater activities, for example submarines. Modern submarines are equipped with multiple geolocalization and navigation instruments, and two commonly used systems are active sound navigation ranging (SONAR) and inertial navigation system (INS). However, each system has its limitations and drawbacks. Active SONAR will require detailed hydrographic data; hence it can only be used in the charted area and often is further limited to friendly waters as it can be detected and tracked by an enemy [2]. INS is a system that calculates the location base on a known initial state and integration of movements. However, INS usually suffers from unbounded errors due to sensor noise and drift, causing geolocalization errors over time [3]. Hence, INS requires frequent calibration by GPS or other accurate geolocalization systems [4].

Humans developed SONAR technology by learning how bats navigate with their echolocation capability [5]. Similarly bioinspired, we have turned our focus to the mantis shrimp, a crustacean that is known for its unique vision system that is capable of sensing the polarization of light [6]. Studies have shown that many marine animals, including mantis shrimp, are using polarization vision for communication, prey detection, and potentially for navigation [7].

In previous works, researchers were able to develop a polarization imaging sensor and integrate it into a camera. Then they modified an underwater cinematography system to perform underwater geolocalization tasks based on celestial polarized light. Using this system, they proved the feasibility of using polarization for underwater geolocalization and navigation and achieved an average of 61 km of accuracy [8, 9].

Machine learning has benefited many industries in recent years. It is also considered to be a feasible method for further improving the accuracy of polarization-based underwater geolocalization. However, such a method will require a large amount of real-world data to help the algorithm to "learn" the features presented in celestial polarization images. The current underwater data collection device was not designed for research, and it poses many challenges and dangers for mass data collection.

This thesis reports on the design of a compact, modular, and expandable underwater research platform that can suit data collection and research needs. Chapter 2 analyzes the issues with several current underwater data collection devices and proposes the design goals for the new platform. Chapter 3 and 4 discusses the mechanical and electrical design of the new platform in detail. Finally, chapter 5 explains the current progress and future work of this project.

2. Motivations

2.1. Overview of Previous Devices

Powell [9] describes the first-generation underwater geolocalization system. The system was modified base on a Light and Motion Bluefin VX2000 underwater housing that was designed for camcorders. An Aquatica 4-inch underwater glass dome port was attached to the housing to ensure high-quality images. A custom CCD camera was used to sense the polarization information, and a PNI TCM-MB electronic compass module was used to record the device's gesture and heading. An ADL Single-Board Computer (SBC) with 2nd generation Intel Core-i7 processor was used for system control and data logging. This computer provided enough computation power to record the uncompressed image data to a solid-state drive at around 20 MB/s while streaming a real-time preview to the underwater monitor. This device could accommodate a large Canon zoom lens and an 81.4 Wh battery pack, allowing the device to operate for around 2 hours.

Later this device was upgraded by the author and his colleague to accommodate a newer imaging subsystem. The new imaging subsystem utilizes a FLIR BFS-U3-51S5P-C machine vision camera. This camera contains a Sony IMX250-MZR 5.0 MP polarized monochrome sensor. A Fujinon FE185C057HA-1 185° field-of-view fish-eye lens was used to collect the celestial image. The new imaging subsystem will now produce around 150 MB/s of uncompressed image data. To address this higher throughput, the author upgraded the processing unit to an ADL120S SBC with a 6th generation Intel Core-i7 processor. The final device measures about 40 cm long, 25 cm wide, and 30 cm tall. The underwater housing and underwater monitor assembly weigh around 15 kg. When traveling, the complete device and accessories were put into a heavy-duty case, causing the final weight to approach 30 kg.

Samuel Powell later joined a research lab at the University of Queensland, where he and colleagues developed a new underwater device reported in 2019 [10]. This device was built within a Nikon DSLR underwater housing with a 6-inch dome port. They utilized an Nvidia Jetson TX1 System-on-Module (SoM) to perform the data collection and data processing tasks underwater. Three Sony IMX219 image sensors and 190° field-of-view fish-eye lenses were used to create overlapping panoramic images underwater. They were able to achieve a 4 hour operation time with this device.

All three of these devices were built to accommodate underwater cinematography housings. These housings are built around a specific commercial camera or camcorder; hence they are very bulky, and it is hard, if not impossible, to modify these housings to fit research needs.

2.2. Goals for New Platform

In order to collect more underwater celestial polarization images and prepare for the upcoming machine learning tasks, a new underwater research platform was proposed by the author.

The new platform needs to be compact. As the buoyant force is proportional to the volume of the platform, having a compact platform also means a lightweight platform. During several previous data collection trips, the complete device weighed around 30 kg, making traveling with the device costly and difficult.

The new platform also needs to sustain water pressure. The goal is to design a platform that can sustain up to 50 meters of water pressure. Previous research has shown that polarization information can be observed as deep as 200 meters [11]. However, due to the author's scuba diving license restriction, he can only reach as deep as 40 meters.

Furthermore, the new platform needs to suit the imaging and geolocalization needs. The imaging subsystem needs to be able to accommodate a wide variety of imagers and cameras. The optical center of the sensor should be precisely aligned to the exterior glass dome port. The gesture, location, and time data will be necessary for machine learning tasks. The system should include an integrated inertial measurement unit (IMU) to measure the gesture and the heading of the platform. It should also integrate the GPS receiver to provide accurate time and ground truth geolocation to the processing subsystem.

As a scientific research platform, the new device should be modular and upgradable. When we make new discoveries, we may change our device to add more sensors and record a wider variety of data. The old devices were unable to fulfill our ever-changing research needs, and that is one primary motivation for us to design this new platform from scratch.

The new platform also needs to have a powerful processing unit. It needs to be able to perform high-throughput data recording, processing, and streaming. In the long run, it also needs to perform real-time inference of the machine learning model to demonstrate the geolocalization capability underwater.

3. Mechanical Design

In order to fulfill all the requirements posed in the previous chapter, the author first started with the mechanical design of the new underwater research platform. This chapter introduces the design by providing an overview of the platform, and then explains multiple factors considered during the design process.

3.1. Overview

As shown in Figure 1, the final design can be divided into three compartments: the cover, the main housing, and the lens compartment.

During the underwater data collection process, we need to adjust the exposure of the imager and the heading of the device. Having an underwater monitor is crucial for performing this task. However, in previous generations of the underwater geolocalization devices, we were unable to integrate monitor into the device due to the construction of both the underwater housing and the off-the-shelf monitor. Having an external underwater monitor forces us to carry an extra 5 to 10 kg of weight, and the dangling monitor cable poses hazards during the underwater data collection process. In this new platform design, the author decided to integrate a monitor into the housing. The author chooses a WF50DTYA3MNN0 5-inch Mobile Industry Processor Interface (MIPI) DSI LCD panel with 1280 by 720 pixels resolution. This screen has the same size and resolution as the one used in the previous generations. The screen has high enough resolutions to ensure that divers can observe the video stream and system status underwater, while its small size can ensure the overall compactness of the new platform. In order to view the screen, the cover compartment has a 6 mm thick transparent acrylic viewing window that can sustain high water pressure while providing a wide viewing angle

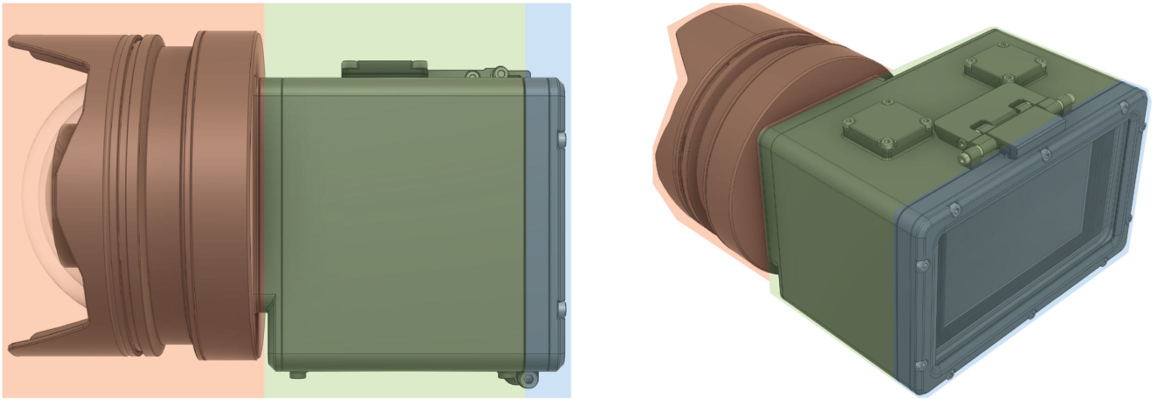


Figure 1. Overview of mechanical design. Image on the left shows the left side view of the device. Image on the right shows the corner view of the device. Red section represents the lens compartment; Green section represents the main housing; Blue section represents the cover.

underwater. The cover compartment also hosts a u-blox CAM-M8Q GNSS module that can provide consumer-grade GPS, Galileo, GLONASS, and BeiDou signal reception when the diver above water.

The main housing hosts the image sensor, processing subsystem, and power subsystem. Compare with the old design, the new design highly utilizes all the internal spaces while ensuring users can upgrade and expand the system based on their research needs in the future. The main housing connects to the cover via a custom-designed hinge on the bottom of the system, and users can easily open the cover to swap batteries and storage medias via a lever on the top of the device, as shown in Figure 2. The internal design is further explained in the following sections.

In previous devices, the lens of the imaging subsystem is enclosed inside the main housing. Such design causes a lot of unused spaces around the lens. In this new design, the author designs a modular external dome port adapter interface to ensure the expandability of the imaging subsystem. Users can use off-the-shelf extension rings to create a small compartment that dedicates to the lens. Such a design can save the fabrication cost by using more off-the-shelf parts and reducing the size of the main housing. The imaging subsystem design is further explained in section 3.3.3.

3.2. Water Tightness

For an underwater research platform, its water tightness is crucial for its normal operations. As shown in Figure 3, the new design utilizes 12 O-rings across the system to ensure the water-tightness of the device. The author first designs the O-ring groove base on the design guidelines [12], then the author determines inner and outer diameters based on the contour of the groove.

The design guideline encourages using O-rings with larger cross-section areas. The author uses -2xx O-rings wherever possible in the design. When a large cross-section O-ring is not applicable due to other limitations, the author uses small double O-rings to ensure the design can sustain at least 50-meter of water pressure.

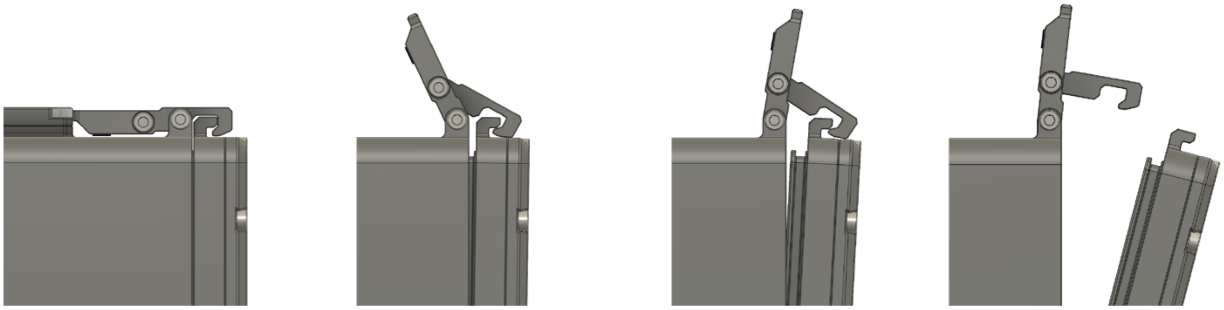


Figure 2. Latching mechanism on the top of the housing. Pictures from left to right demonstrate the opening process.

The durometer, or the "toughness," of the O-ring will also impact the water-tightness of the system. The author uses hard O-rings with 70A durometer wherever possible in the design, with the exception of using soft 50A durometer O-rings between the cover and the main housing. The soft O-rings ensure the user can easily open and close the cover.

Different O-ring materials can sustain different chemicals, but luckily a wide variety of materials can sustain the corrosion of salt water. The author picks the nitrile Buna-N O-rings due to their high availability and low cost.

The saltwater will corrode not only the O-rings but also the housing itself. 6061 aluminum is commonly used to construct underwater equipment due to its corrosion-resistant characteristics. All the structural components in the design are machined from 6061 aluminum. Machined parts will then go through the bead-blast process to remove tool marks and improve surface roughness. Then the parts will go through Type-III anodization process, creating a hard abrasion resistant coating on the aluminum surface to ensure the long-term durability of the system.

In order to ensure the housing can sustain 50-meter of water pressure, the author ensures that the minimum thickness around the housing is at least 5 mm. This value is referenced from multiple underwater camera and monitor housings, and it is a conservative value due to the author's lack of access to the finite element analysis (FEA) tools.

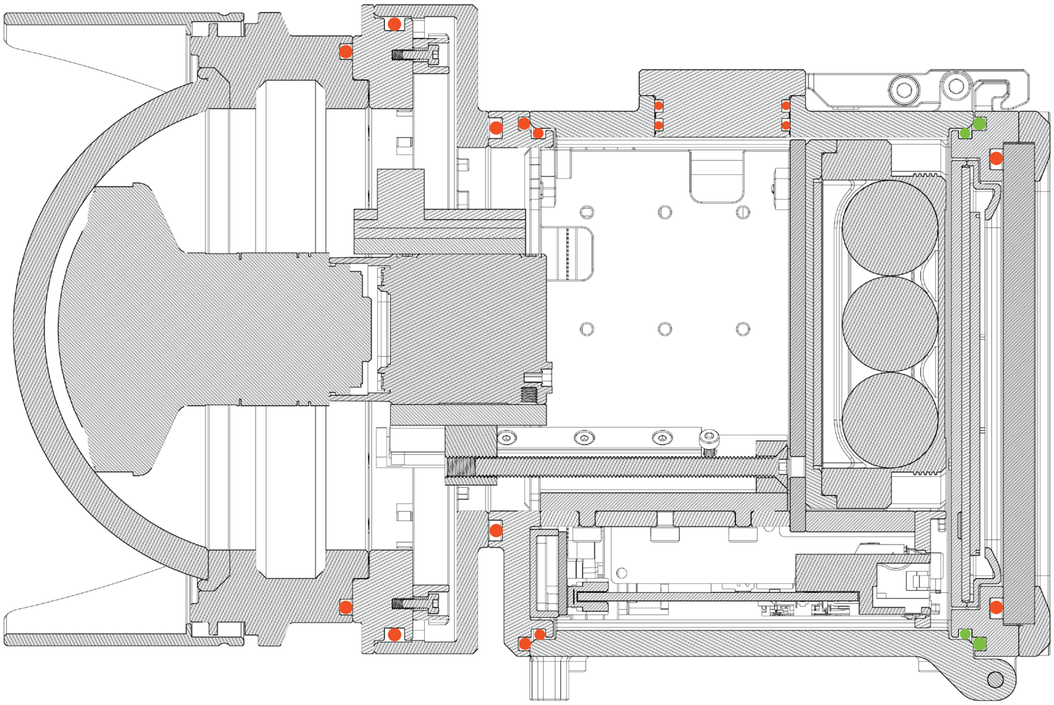


Figure 3. O-rings around the housing. Hard Shore 70A O-rings are shown in red. Soft Shore 50A O-rings are shown in green.

Most underwater housings use a circular or oval shape to maximize their pressure-resistance. However, the author notices that such shapes will pose challenges to the internal component organization and decides to use a rectangular shaped design. The author adds multiple support structures inside the housing to improve its rigidity, as shown in Figure 4.

3.3. Internal Arrangement

3.3.1. Power Subsystem

The internal space of the main housing can be further divided into four sections, as shown in Figure 5. The power subsystem, as shown in red, consists of two battery packs and a printed circuit board (PCB) that regulates the power conversion and distribution for the system. Inside each battery pack, there are three 18650 industrial standard lithium-ion rechargeable batteries and another PCB that monitors the battery status. We commonly refer to the PCB inside the battery pack as the "Battery Board" and refer the power regulation PCB inside the housing as the "Power Board."

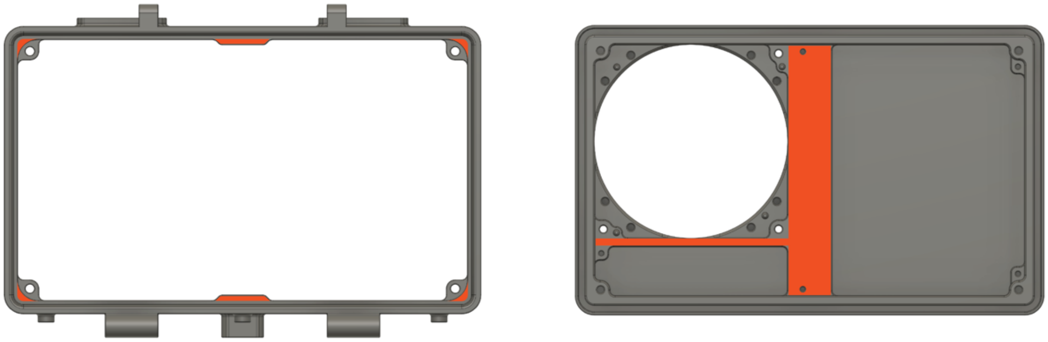


Figure 4. Main housing exterior shell viewing from back side. The red sections are designed to improve the overall rigidity of the device.

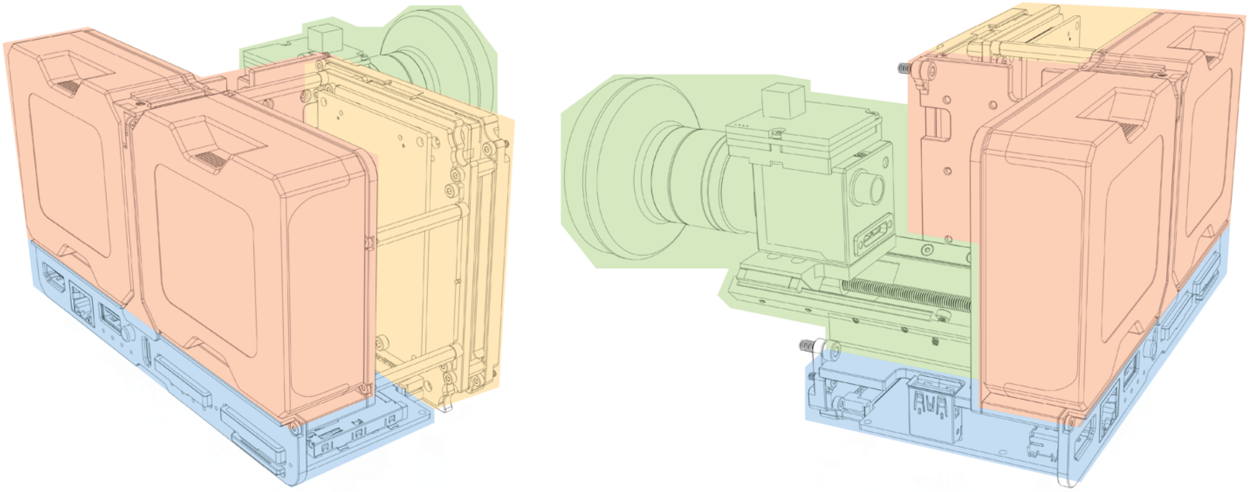


Figure 5. Internal arrangement inside main housing. Left and right picture shows the system from two perspectis. Red section represents the power subsystem; yellow section represents the processing subsystem; green section represents the imaging subsystem; blue section represents the user interface.

Battery packs are magnetically attached to the system so that users can quickly change batteries. Dual-battery design allows users to swap batteries without interrupting the system's operation. Three 18650 batteries are spark-wielded to a nickel strip, and a conductive wire is soldered between the Battery Board and the nickel stip.

The Battery Board and the Power Board are connected with a Samtec SIR1-10-S-S spring-loaded power connector. This connector is soldered onto the Power Board, and there are ten corresponding contact pads on the Battery Board to ensure proper connection.

Battery packs are designed to be the only plastic component inside the underwater housing, as a metal battery enclosure can pose hazards to users. Battery pack enclosure needs to be able to sustain high impact force given the possibility of accidental dropping; hence battery packs are designed to be 3D-printed with Accura Xtreme White 200 SLA resin. Such resin has a low water absorption rate, is corrosion resistant to saltwater, and is more rigid compare with other 3D-printing materials [13].

3.3.2. Processing Subsystem

The processing subsystem shown in yellow in Figure 5 is the brain of the new research platform. Since this platform will be used to perform real-time inference of the machine learning model, the author decides to use Nvidia Jetson System-on-Modules (SoMs) as the processing unit. Jetson SoMs are widely used in industrial applications as an edge computing device. These modules can not only perform traditional data recording and processing tasks but also provide machine learning acceleration through Nvidia's powerful general-purpose Graphics Processing Units (GPU). A detailed comparison between Nvidia Jetson SoMs and the old Intel CPUs can be found in Appendix A.

In this design, the processing subsystem section can accommodate three out of four currently available Jetson SoMs. Jetson Nano is the entry-level SoM that has the least processing power, and it is ideal for simple data collection tasks. Jetson TX2 is one of the most widely used SoMs in the industry. It provides moderate processing power and real-time inference capability. Jetson Xavier NX is the latest and most powerful SoM that can fit inside this new research platform. It includes Nvidia's unique Tensor Cores and NVDLA deep learning accelerator.

The Jetson SoMs is connected to a custom-designed PCB that we call the "Carrier Board." Jetson Nano and Jetson Xavier NX share the same footprint and pinout; hence they can share a same Carrier Board design. Jetson TX2 uses a unique 400-pin connector, which requires a different Carrier Board design. However, all of these three Jetson Modules can fit into the same position, share similar thermal solutions, and provide similar connectivity.

In order to protect the Carrier Board from bending and twisting during the assembly and maintenance processes, the author designs a custom aluminum frame that attaches to the Carrier Board. This metal frame significantly increases the rigidity of the Carrier Board and protects it from accidental damage.

The lifecycle of Jetson SoMs will also impact the lifecycle of our new platform. According to Nvidia's website, both Jetson Nano and Jetson TX2 will be available to purchase until 2025, while Jetson Xavier NX will remain available until 2026 [14].

3.3.3. Imaging Subsystem

The imaging subsystem is shown in green in Figure 5. When our system captures images underwater, the light must first go through a waterproof dome port or flat port, then go through a lens, and finally hit our image sensor. This section will introduce the design considerations and possible configurations of these three components in the imaging subsystem.

Underwater Ports

When the light first enters the underwater system, it will first go through an underwater port. Underwater ports are usually made with acrylic or glass front pieces. For general underwater photography, acrylic front pieces are more widely used as they are cheaper and more lightweight. However, for our underwater polarization imaging, acrylic ports will create polarization effects when they are under high pressure [9]. Hence, such research platforms can only use high-quality BK-7 optical glass with anti-reflection coating in our system.

However, these stringent requirements also mean that it is hard to custom order such glass pieces and integrate into our system. Luckily there are quite a few manufactures produce underwater ports with these glasses, and designers only need to follow their mechanical specification to mount their ports onto our research platform. One of the most widely used underwater port standards is the Nauticam port system. They define four different port diameters: N85, N100, N120, and N200. The letter "N" stands for Nauticam and the number specifies the diameter in millimeters at the port bayonet.

In the current design, the system utilizes the N120 ports. A dome port is attached to the main housing with a custom-designed port adapter. By changing the port adapter, the system can accommodate different port standards. To ensure the precise optical center alignment, the author designs four alignment pins on the port adapter and four alignment holes on the front plate of the main housing. During the fabrication, technicians are told to ensure a snug fit between the port adapter and the front plate.

Lenses

There are many lens choices on the market, and they come with different sizes, bayonets, and optical characteristics. It is hard to design an enclosure that can fit all lenses. However, as the new design utilizes the Nauticam port system, the research platform will be able to physically accommodate any lens supported by Nauticam.

When a bare sensor directly mounts to the underwater housing front plate, a custom-designed lens bayonet can be mounted to the port adapter to ensure the precise optical center alignment and accurate focal distance. The lens can then be mounted to the lens bayonet to ensure ideal optical performance. Currently, the author was able to successfully implement the Canon EF mount, C and CS mount, and PL mount lens bayonet adapter.

When a complete camera module is mounted inside the main housing, users can simply purchase a lens bayonet converter to properly mount the lens.

Imagers

When an imaging device is designed from scratch, the image sensor and its carrier PCB can be directly mounted to the front plate of the main housing. The front plate will be able to fit an image sensor with up to 70 mm diagonal size. Similar to the port adapter design, several precision alignment pins were reserved to ensure the optimal optical center alignment.

When an off-the-shelf camera module is desired, users can mount the module to a custom-designed slider, as shown in Figure 6. The slider sits on top of a "V" shaped base to ensure precise alignment, and the slider position can be easily adjusted with a long adjustment screw. Two linear ball bearing

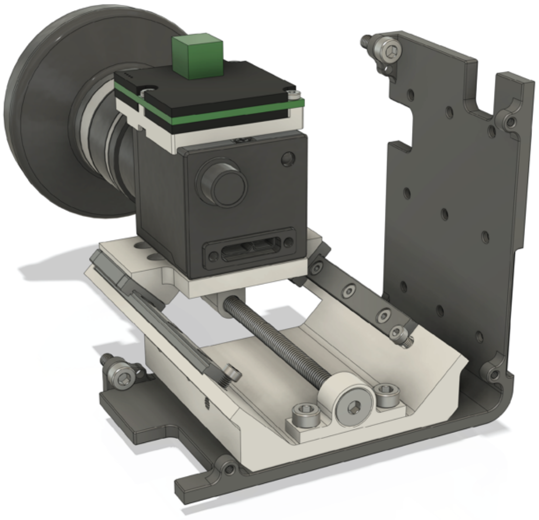


Figure 6. Imaging subsystem assembly. A FLIR BlackFly S Machine Vison Camera and Fujinon FE185C057HA-1 is shown. The camera is attached to a slider system whose position can be adjusted with the long grey screw at the back.

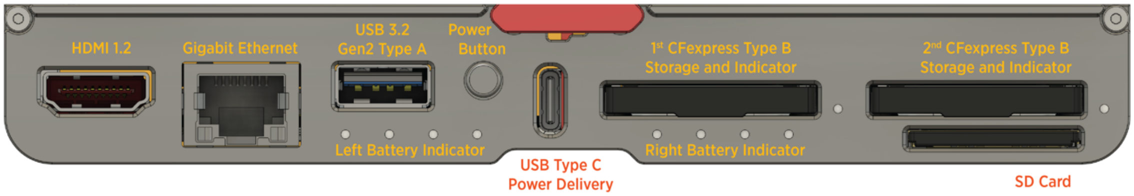


Figure 7. User interface inside the main housing. The name of each IO is labeled on the picture.

assemblies on the base can ensure the smooth operation of the slider. The base is then attached to an "L" shaped bracket, and the bracket is attached to the front plate. Again, multiple alignment holes and alignment pins were designed between these parts to ensure the optical center of the camera is precisely aligned to the external dome port.

3.3.4. User Interface

The user-accessible inputs/outputs (IO) are shown in blue in Figure 5. A detailed user-accessible IOs diagram is shown in Figure 7. Since this underwater imaging platform is designed for research purpose, users may frequently modify and debug the software on this platform. To facilitate development needs, the author includes multiple commonly used IOs. Users can access these IOs when the cover is opened. These debug IOs includes a high-definition multimedia interface (HDMI) 1.2 connector, an RJ45 connector that supports IEEE 802.3ab 1000Base-T Gigabit Ethernet standard, and a universal serial bus (USB) 3.2 Gen1 Type-A connector. The HDMI connector allows users to connect the system to an external monitor for easy debug access. The ethernet connector allows users to connect Jetson module to a local area network for debugging or connect to the internet for system and software updates. The USB connector allows users to plug keyboard and mouse to the system.

In addition to the debug access, user IOs also include a push-button for system power on, and a USB Type C Power Delivery connector for up to 100-watt fast charging for the battery. Two groups of light-emitting diodes (LED) are also available to indicate battery status.

In the old underwater system, data were stored in a non-removable M.2 solid-state drive, posing a significant challenge when users want to transfer data on the boat. In this new design, the author adopts the new Compact Flash Association CFexpress 2.0 Type B removable storage standard. This new standard utilizes Non-Volatile Memory Express (NVMe) specification as the data transmission protocol, allow users to write to CFexpress removable cards at up to 2 GB per second speed [15]. Currently, this storage solution will allow users to have a maximum of 2 TB of storage space inside the new system, but the CFexpress card manufactures may produce higher capacity variants in the future. In addition to the CFexpress card, users can also use a Secure Digital Card (SD Card) to store

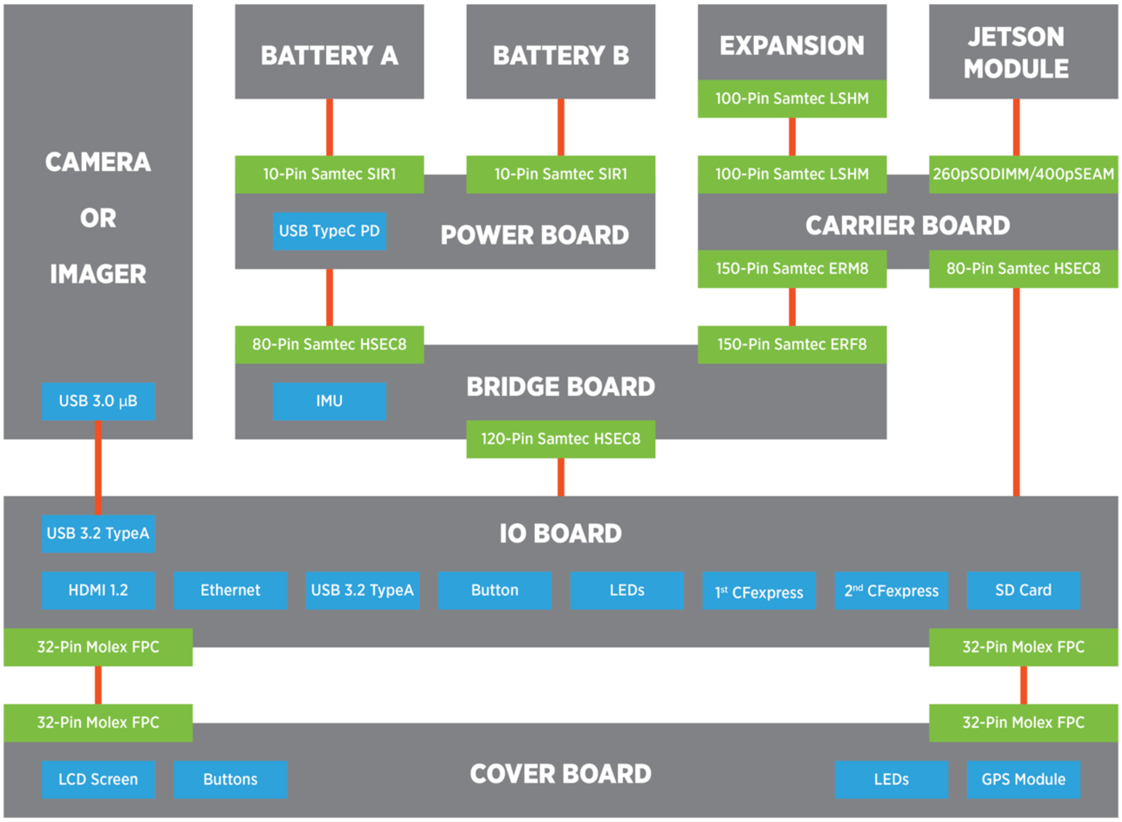


Figure 8. Overall system architecture. Green blocks represent internal connectors; blue blocks represent external connectivity; red line represent connection; grey blocks represent module or printed circuit board.

the system and software configuration files. This feature allows users to quickly swap between multiple software versions or configurations when they are out in the field.

All of the connectors and sockets mentioned above are soldered to the "IO Board." This design gives users the flexibility of migrating to other emerging specifications or changing to a different IO combination in the future.

3.3.5. Interconnect

As shown in Figure 8, subsystems mentioned above are connected by a “Bridge Board”. The Carrier Board is connected to this Bridge Board with a Samtec ERx8 rugged high-speed connector. The IO Board connects to the Bridge Board and the Carrier Board via a pair of Samtec HSEC8 rugged edge card connector. The Power Board connects to the Bridge Board via another HSEC8 connector.

The imaging subsystem can connect to the IO Board via an internal USB 3.2 Gen1 Type-A connector, or it can connect to the MIPI-CSI2 compatible connector on the Carrier Board via a custom-made flexible cable. In addition, an inertial measurement unit (IMU) is mounted inside the imaging subsystem section and is connected to the Bridge Board with a flexible cable.

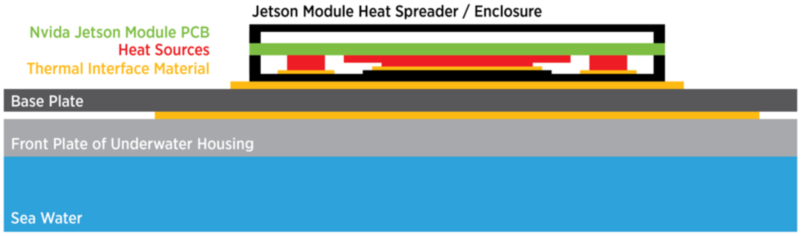


Figure 9. Jetson module thermal stack up inside the system. All yellow blocks represent thermal interface materials.

3.4. Thermal Design

Electronics need to be kept in an acceptable temperature range to ensure their optimal operation. In the new underwater research platform, four main components will generate a significant amount of heat.

The first component is Jetson Module. In the new design, the author strictly follows the Jetson Device Thermal Design Guideline published by Nvidia, and efficiently dump the heat into the outermost housing. The housing can then be cooled by seawater. A detailed thermal stack up is shown in Figure 9.

CFexpress Cards, power regulators on the Power Board, and imager or camera module inside the imaging subsystem will also create a significant amount of heat. Each of these components is attached to a metal plate and the heat will be conducted to the exterior and the heat will be dumped into the seawater.

3.5. Expansion and Upgrade

3.5.1. External Expansions

This new underwater research platform is designed with future expansion and upgrade in mind. At the bottom side of the main underwater housing, five external mounting points allow users to design custom bottom plates to fit different needs.

The weight of the system may change after future modifications. Hence, additional weight can be attached to the custom bottom plate to ensure the system remain negatively buoyant. One or two handles can also be attached to a custom bottom plate to ensure easy device handling during the data collection process underwater. During most of our data collection trips so far, the device will be attached to a tripod underwater. A quick-release bottom plate can also be attached to a custom designed bottom plate to help divers expedite the device setup process underwater.

This mounting option also enables the possibility of attaching the new system to a remotely operated underwater vehicle (ROV) to explore and record data in dangerous areas.

3.5.2. Underwater Connections

Although the new system has an embedded monitor and other external connections are unlikely under current research requirements, the author still reserved two 26 mm diameter external connection ports.

These two ports are large enough to fit a Nauticam Underwater HDMI or Serial Digital Interface (SDI) connector, allow users to have an additional monitor underwater or transmit the video to a boat. These two ports can also accommodate underwater ethernet, power, and coaxial cables designed by SubConn [16]. A further discussion of potential use cases is covered in section 4.2.

Users can also design expansion modules that directly attach to these two ports. An expansion module with button inputs, water depth sensor, and water temperature sensor is proposed and will be implemented by the author.

3.5.3. Internal Upgrades

It is also possible to upgrade the internal components of the system. In the current design, the power subsystem, the processing subsystem, and the user interface module are all attached to a base plate. This base plate is attached to the front plate of the main housing via only five mounting screws. Hence, it would be straightforward to upgrade and reuse the housing to fulfill other research needs by redesign the base plate.

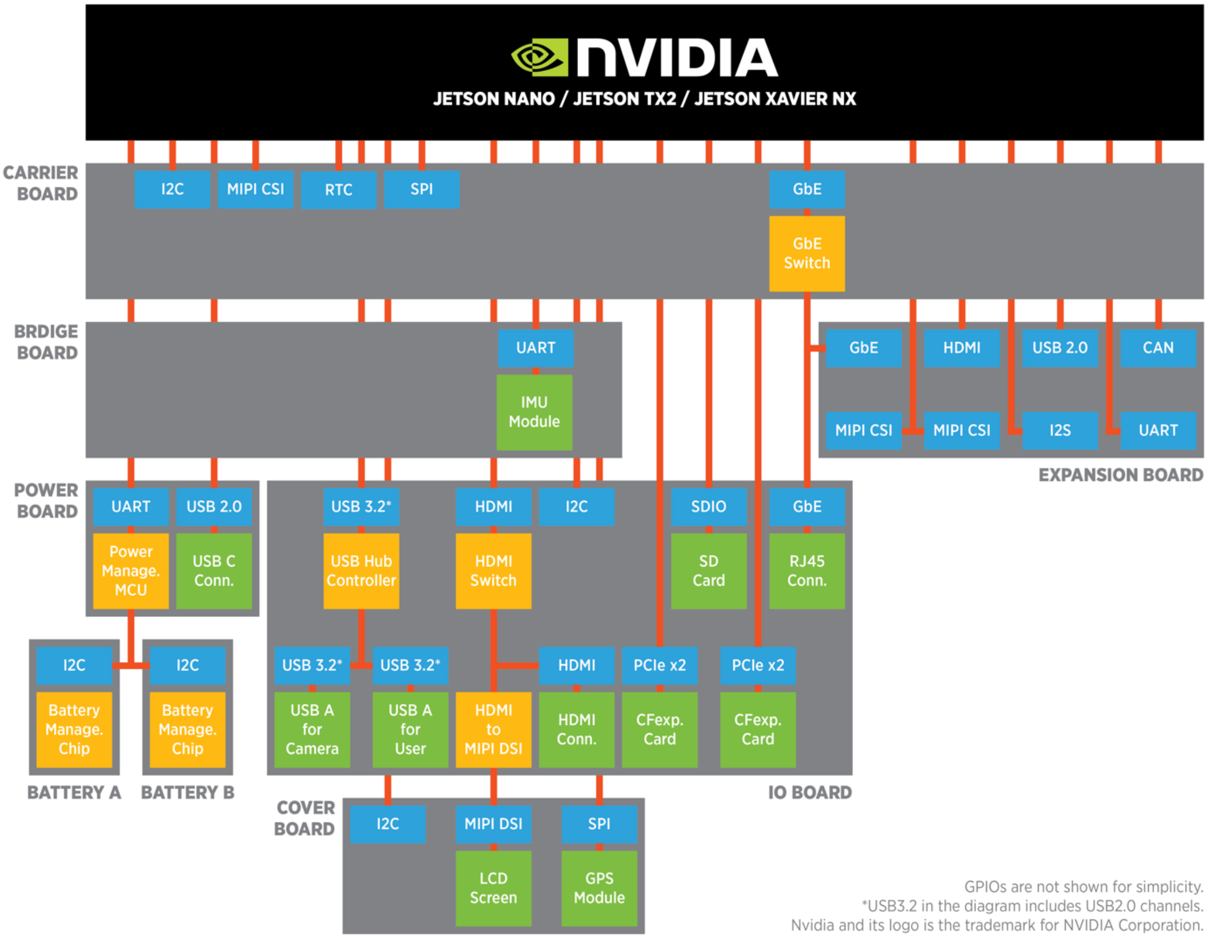
4. Electrical Design

After finalizing the mechanical design, the author breaks out the signals coming from Nvidia Jetson Module and assigns all the signals to different printed circuit boards (PCB). Section 4.1 provides an overview of the electrical design. Section 4.2 covers several examples of possible future use cases.

4.1. Overview

As mentioned in previous sections, the new underwater research platform consists of seven different PCBs. Such a modular design allows users to modify one or more PCBs to suit their needs without redesign the whole system.

Figure 10 shows some common interfaces Jetson modules provide. Jetson TX2 will provide many additional interfaces due to its dense 400-pin connector. Jetson Nano and Jetson Xavier NX will be limited to the interfaces shown in the figure [17].



GPIOs are not shown for simplicity.
*USB3.2 in the diagram includes USB2.0 channels.
Nvidia and its logo is the trademark for NVIDIA Corporation.

Figure 10. Jetson interfaces and corresponding endpoints in our design. Grey boxes represent printed circuit boards; green boxes represent connection endpoints; yellow boxes represent active components; blue boxes represent different signals from Jetson; red lines demonstrate the signal path.

Jetson Modules directly attache to the Carrier Board, making the Carrier Board the most complex PCB in the system. Jetson Modules only provide one Gigabit Ethernet (GbE) interface, but the new design requires one GbE reserved on the Expansion Board while having another GbE connector available for debugging and software update access. The new design utilizes a GbE switch to split the interface into two to fulfill system needs. In addition, a MIPI CSI-2 x4 interface is reserved on the Carrier Board, allow users to use the MIPI interface camera inside the system. An Inter Integrated Circuit (I2C) interface and a Serial Peripheral Interface (SPI) is also reserved on the Carrier Board for potential upgrade. A Real-Time Clock (RTC) module is placed on the carrier board to provide the Jetson Module accurate time when the system is not powered up.

Most of signals from Jetson Module are passed to the Bridge Board, IO Board, and Expansion Board. There are two possible routes for signals to travel from the Carrier Board to the IO Board. The first set of signals goes directly from the Carrier Board to the IO Board. This set of signals include four Peripheral Component Interconnect Express (PCIe) channels for CFexpress storage cards and a GbE for user access. These signals are high speed differential signals and usually have a higher signal integrity requirement. Directly route these signals from the Carrier Board to the IO Board can ensure higher signal quality. The second set of signals goes from the Carrier Board to the IO Board via the Bridge Board. This set of signals include a few low speed signals like SPI and I2C, and a few low-priority high speed signals like HDMI and USB. This design is due to the limited space inside the housing, and the Carrier Board to the IO Board interface has a limited pin-count on the edge connector. Having a second signal path is not ideal but is the only solution for the new system.

The Power Board is attached to the Bridge Board in the system. As the Bridge Board is connected to both the Carrier Board and the IO Board, power from the battery can be easily divided. The Power Board features a microcontroller unit (MCU) that can talk with Jetson Module via Universal Asynchronous Receiver-Transmitter (UART) interface. The MCU on the Power Board act as a power management unit that switches the power source between battery A, battery B, and external power. It can also wake up and shut down Jetson Module when necessary. The Power Board also features a USB Type C Power Delivery capable connector. This user-accessible interface provides up to 100 W of power, allow users to charge two batteries when the system is running.

The Battery Board is inside all battery packs. There is an IC on the Battery Board that controls the charging and discharging process of the battery. This chip will also monitor the battery health status, the battery temperature, and the battery use cycles. It will alert the power management MCU and Jetson Module when the battery abnormally occurs. This design guarantees the battery safety and can prevent most, if not all, battery-related safety hazard in the system.

The Cover Board mainly serves the MIPI DSI screen and the GPS module. The MIPI screen can help users understand the system operating status when user is underwater, and the GPS module can provide accurate time and location when user is above water. However, Jetson Xavier NX module does not provide a MIPI DSI signal, hence the system needs to convert HDMI signal to MIPI signal. As users will not use the embedded display when the HDMI is accessible, a HDMI switch is placed on the IO Board. Jetson Module can switch between two possible HDMI downstream port by toggling a General-Purpose Input Output (GPIO) pin. One of the downstream HDMI port connects to HDMI connector, allow users to connect the system to an external monitor for debug access. The other downstream HDMI port connects to a HDMI to MIPI DSI converter. Converted signal then goes to the embedded screen.

Lastly, the Expansion Board features a lot of reserved interfaces. Next section introduces a few possible use cases involve the Expansion Board.

4.2. Expansion Use Cases

4.2.1. Camera and Imager Configuration

Figure 11 shows two possible imaging configurations in the system. When a camera module is desired, the reserved USB Type-A connector inside the imaging subsystem compartment can be used to connect the camera. When a bare imager is desired, users can create a three-board stack to handle the data transmission. An imager board can be mounted to the front plate of the underwater housing, as described in section 3.3.3. Then a Field Programmable Gate Array (FPGA) board can be attached to the Imager Board. FPGA can be used to perform imager readout sequence, image processing, and MIPI transmission. Then the MIPI signal can be transmitted to the Carrier Board via the Transmitter Board. This design allows us to reuse the FPGA Board and Imager Board in other configuration or application, such as the underwater panoramic application mentioned in section 4.2.5. The Transmitter Board and the Carrier Board can be connected with a I-PEX micro coaxial cable [18]. Such cables are flexible and are designed for differential signals, provides users reliable MIPI signal transmission.

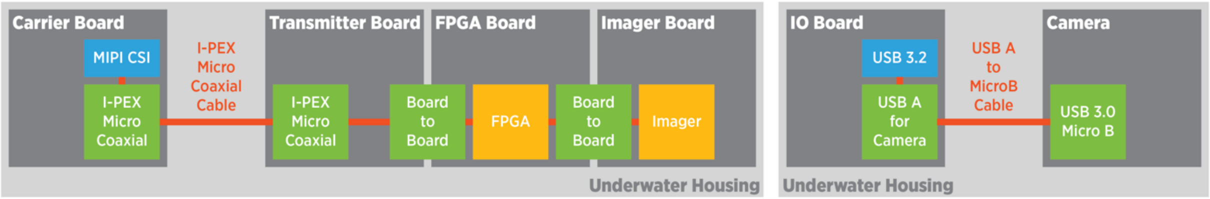


Figure 11. Possible camera and imager configurations in the system. Figure on the left shows a configuration for imaging sensors; right figure shows a configuration for camera.

4.2.2. External Module

Figure 12 shows a possible external module use case. As the underwater housing does not integrate any button input, users may have difficulty adjust settings underwater. This module attaches to one of the two underwater expansion ports on the main housing. The external expansion module contains an MCU that can control the buttons, LEDs, and sensors on the external module. The external module can connect to the Expansion Board and talk with Jetson Module through UART. However, as the external module has buttons, it has a higher possibility of water leaking. In case of leaking, epoxy-filled connection can prevent any damage to the main housing.

4.2.3. External Monitor

Although the embedded 5-inch monitor is sufficient for most use cases, there might be scenarios that a second external underwater monitor is required. Figure 13 shows two possible external monitor configurations. The figure on the top shows a configuration for HDMI monitors. Nauticam has an underwater HDMI connector that utilize the Micro HDMI connector. As the Expansion Board has a reserved HDMI interface, the Nauticam adapter can be directly connected to the Expansion Board. The other end of the Nauticam cable goes into the underwater monitor housing and can be directly plugged into the monitor. The figure on the bottom shows a configuration for SDI monitors. HDMI signal can converts to SDI signal with a small Lattice FPGA. As the SDI utilize a coaxial cable to

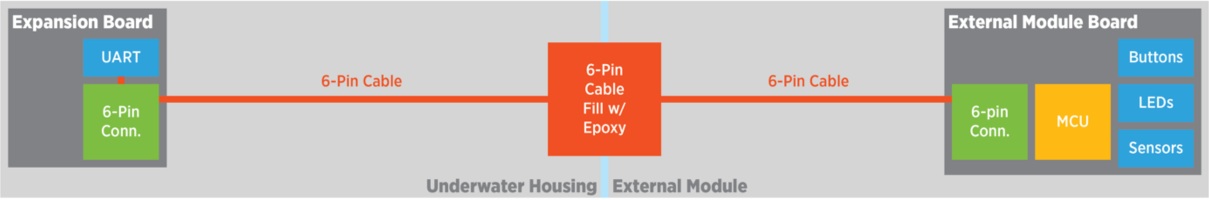


Figure 12. Example external module configuration.

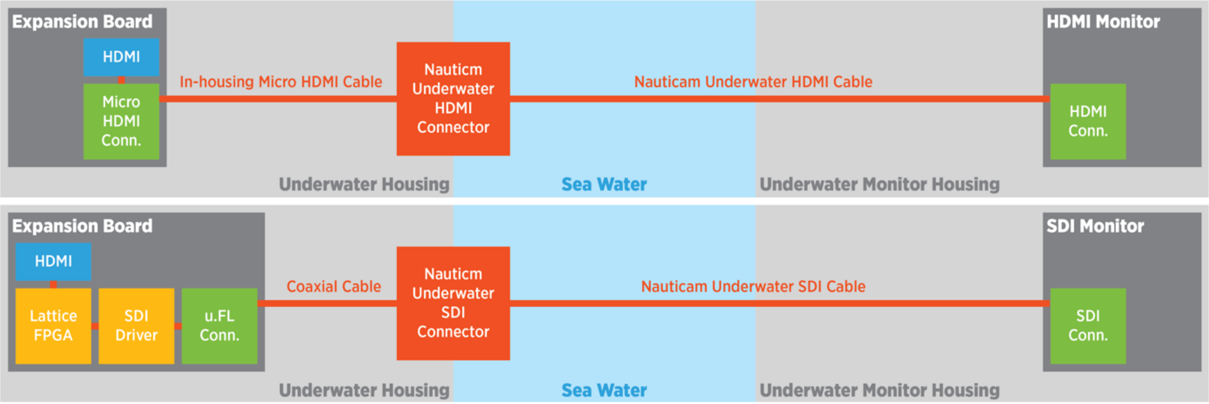


Figure 13. Two possible external monitor configurations. Figure on the top shows a possible connection with HDMI monitors. Figure on the bottom shows a possible connection with SDI monitors.

transmit the data, an additional driver circuitry is required. The SDI signal can then go through the Nauticam SDI connector, and feed into the SDI monitor.

4.2.4. Continuous Recording

Currently the new system is capable of performing continuous recording for around four hours. However, users may need to record the polarization images continuously for days or weeks in the future. It is impossible to design a battery pack that last several days or fit a disk that can store hundreds of terabytes of data inside the housing. The new design needs to be able to continuously transmit data to a PC above water while providing power to the system from the ground station. Qualcomm QCA7500 is a chipset that can perform Power Line Communication (PLC) [19]. It allows us to achieve a 1000Mbps data transmission while providing power for the system through a neutrally buoyant power cable. The PC attached to the ground station will be able to see Jetson Module inside the underwater system as a normal ethernet device, and Jetson Module can transmit data to the PC as if they are in a local area network.

As shown in Figure 14, one of the two batteries inside the underwater system can be replaced with the PLC module. This modified battery will keep the original contact pads so that it can provide power to the system without modifying the power path. The ethernet signal can be connected to the reserved Gigabit Ethernet interface on the Expansion Board via a Flat Printed Circuit (FPC) cable.

4.2.5. Underwater Panoramic

As mentioned in section 2.2, researchers are exploring the possibility of using multiple polarization cameras to create a panoramic polarization image underwater. However, having three imaging device fit in one housing will not only affect the image quality but also pose risks to the whole system due to the additional complexity. In the new system design, it is possible to use the current housing

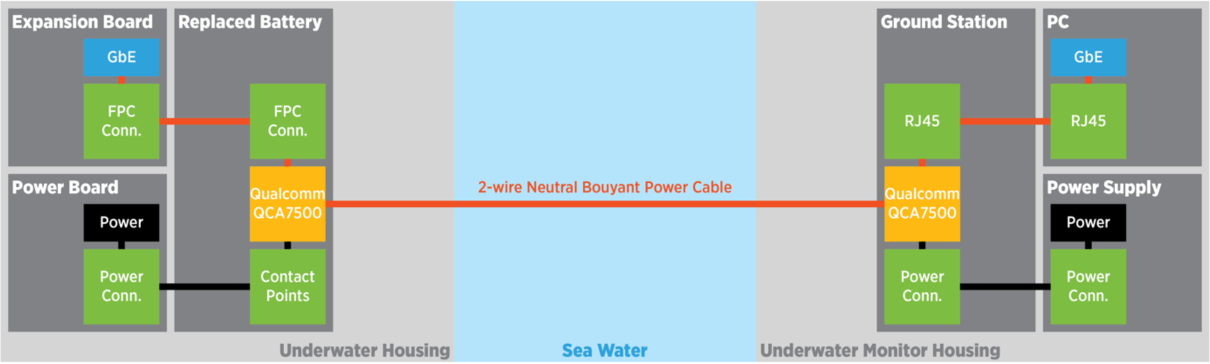


Figure 14. An example diagram of using Power Line Communication to enable long-term continuous recording. The black boxes and traces represent the power path.

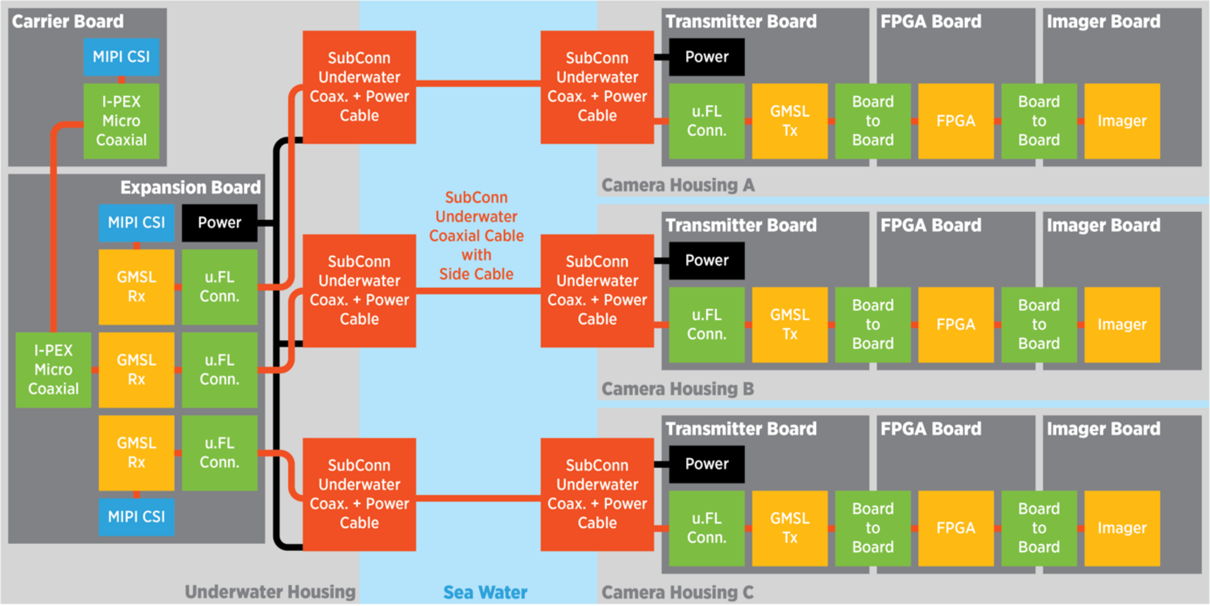


Figure 15. An example diagram of connecting three external camera modules to perform underwater panoramic imaging.

as a data recording and processing center underwater and connect to three or more external cameras to perform panoramic recording.

Figure 15 shows a possible expansion of the system that allows researchers to connect three external camera modules to record underwater panoramic images.

On the left side of the diagram, inside the main housing, Jetson Modules can record three video streams via the MIPI interface. However, each MIPI interface has at least a 16-pin differential signal connection, making connecting the MIPI signals to the outside of the main housing impractical. Gigabit Multimedia Serial Link (GMSL) is designed to solve this issue [20]. GMSL was initially designed to be used in automobiles, and a single cable solution will make the automobile assembly process a lot easier. MIPI signals can be converted to a GMSL signal via a GMSL serializer, and a GMSL signal can be deserialized to MIPI signals as well. The GMSL signal can be transmitted via a coaxial cable. SubConn offers an underwater Coaxial Cable with Side Contacts, which can allow us to receive GMSL signal from the external cameras while providing power to them [16].

Inside the external camera housing is a three-board stack. The Imager Board and FPGA board is already introduced in section 4.2.1 and is reused here. The Transmitter Board receives the power from the main housing while converting MIPI signals to the GMSL signal. This design allows us to reuse most of the imaging system design and minimize the extra engineering cost.

When the GMSL signal arrives in the main housing, the Expansion Board can deserialize the GMSL signal to MIPI signals. However, as shown earlier in Figure 10, the Expansion Board only has two

MIPI interface, while the Carrier Board has an additional one. This configuration was intended to benefit users when only one MIPI interface is required, as they do not need to design a new Expansion Board to fulfill their need. When three MIPI interfaces on the Expansion Board are desired, the user can use a small I-PEX jumper cable to connect the Carrier Board MIPI interface to the Expansion Board.

5. Conclusion and Future Work

The author successfully designed a compact, waterproof, and high-performance underwater research platform that is capable of performing underwater geolocalization tasks. The design has been prototyped with 3D printed technology and proved the water-tightness of the system. The design is user friendly and easy to operate and has much potential for future upgrades. The final design weighs only 3 kg and measures only 105 by 105 by 170 mm for the main underwater housing.

The author worked with his colleague and finalized the power subsystem design and tested its functionality. The power subsystem can charge and discharge the battery pack, and the power management MCU can control the power subsystem to switch between multiple power sources. The power subsystem can accept up to 100 W of power from the USB Type C Power Delivery port.

However, this is an ambitious project with many skills and efforts involved. There are many ongoing works to improve the design further. The author is currently working on a prototype of the external modules that can take button input underwater. The author is also evaluating the design for compatibility with various imaging systems. Also, the author is looking to further optimize the mechanical design with finite element analysis tools.

The author is also working closely with his colleagues to implement, prototype, and test the electrical design. Firmware and software on the Power Management MCU and the Jetson Module are also under development, and the author is performing various tests and benchmarks on the system.

References

[1] A. I. Al-Shamma'a, A. Shaw and S. Saman, "Propagation of electromagnetic waves at MHz frequencies through seawater," in *IEEE Transactions on Antennas and Propagation*, vol. 52, no. 11, pp. 2843-2849, Nov. 2004.

[2] L. Whitcomb, D. Yoerger and H. Singh, "Advances in Doppler-based navigation of underwater robotic vehicles," in *Proceedings 1999 IEEE International Conference on Robotics and Automation (Cat. No.99CH36288C)*, vol.1, pp. 399-406, 1999.

[3] D. Goshen-Meskin and I. Y. Bar-Itzhack, "Unified approach to inertial navigation system error modeling," in *Journal of Guidance, Control, and Dynamics*, vol. 15, no. 3, pp. 648653, 1992.

[4] L. Paull, S. Saeedi, M. Seto, and H. Li, "AUV Navigation and Localization: A Review," in *IEEE Journal of Oceanic Engineering*, vol. 39, no. 1, pp. 131-149, 2014.

[5] Kuc, Roman. "Echolocation with Bat Buzz Emissions: Model and Biomimetic Sonar for Elevation Estimation," In *Journal of the Acoustical Society of America*, vol. 131, no. 1, p. 561, Jan. 2012.

[6] H. H. Thoen, M. J. How, T.-H. Chiou, and J. Marshall, "A Different Form of Color Vision in Mantis Shrimp," in *Science*, vol. 343, no. 6169, pp. 411–413, 2014.

[7] D. C. Parkyn, J. D. Austin, and C. W. Hawryshyn, "Acquisition of polarized-light orientation in salmonids under laboratory conditions," in *Animal Behaviour*, vol. 65, no. 5, pp. 893–904, 2003.

[8] S. B. Powell, R. Garnett, J. Marshall, C. Rizk, and V. Gruev, "Bioinspired polarization vision enables underwater geolocalization," in *Science Advances*, vol. 4, no. 4, 2018.

[9] S. B. Powell, "Underwater Celestial Navigation Using the Polarization of Light Fields," in *Engineering and Applied Science Theses & Dissertations*, no. 245, 2017.

[10] Marshall, Justin. "Bio-inspired GPS-free Navigation Using Mantis Shrimp (Stomatopod) Vision," in *Defense Technical Information Center*, 2019.

[11] T. H. Waterman, "Polarization of scattered sunlight in deep water," in *Deep Sea Research*, vol. 3, pp. 426-434, 1955.

[12] O-Ring Design and Technical Quick Reference Information, webpage, accessed April 2020. Available at: https://www.marcorubber.com/o-ring-design-technical-index.htm

[13] Materials Selection Guide for Stereolithography, datasheet, 3D Systems, Inc., 2020. Available at:

https://www.3dsystems.com/sites/default/files/2019-12/3d-systems-sla-material-selection-guide-usen-2019-11-07-web.pdf

[14] Jetson Product Lifecycle, webpage, accessed April 2020. Available at: https://developer.nvidia.com/embedded/community/lifecycle

[15] The CompactFlash Association Announces CFexpress 2.0 Specification, press release, CompactFlash Association, 2019. Available at: https://cofa.memberclicks.net/assets/docs/cfapress/cfexpress_2_0_press_release_20190228.pdf

[16] SubConn Underwater Connectors, webpage, accessed April 2020. Available at: https://www.macartney.com/what-we-offer/systems-and-products/connectors/subconn/

[17] Hardware For Every Situation – Nvidia Jetson Modules, webpage, accessed April 2020. Available at: https://developer.nvidia.com/embedded/develop/hardware

[18] I-PEX Micro Coaxial Cable Product Page, webpage, accessed April 2020. Available at: https://www.i-pex.com/products#micro-coax-discrete-wire

[19] QCA7500 - Gigabit-Class Speeds Everywhere, product brief, Qualcomm Atheros, Inc., 2020. Available at: https://www.codico.com/fxdata/codico/prod/media/Datenblaetter/AKT/QCA7500%20Product%20Brief.pdf

[20] Gigabit Multimedia Serial Link (GMSL) SerDes ICs, webpage, accessed April 2020. Available at: https://www.maximintegrated.com/en/products/interface/high-speed-signaling/gmsl-serdes.html

Appendix A. Processing System Comparisons

Table 1. Comparison between Nvidia Jetson Nano, Jetson TX2, Jetson Xavier NX, and Intel Core i7 6700TE.

	NVIDIA JETSON NANO	NVIDIA JETSON TX2	NVIDIA JETSON XAVIER NX	INTEL CORE I7 6700TE
CPU	Quad-Core ARM A57	Dual-Core NVIDIA Denver and Quad-Core ARM A57	6-core NVIDIA Carmel 64-bit CPU	i7-6700TE @ 2.4GHz ~60% of i7-6700K
GPU	128-core NVIDIA Maxwell	256-core NVIDIA Pascal	384-core NVIDIA Volta with 48 Tensor Cores	Intel HD Graphics 530
ACCELERATOR	-	-	2x NVDLA Engine 7-Way VLIW Vision Processor	-
MEMORY	4GB LPDDR4	8GB LPDDR4	8GB LPDDR4x	64GB DDR4
PERFORMANCE (TFLOPS, FL16)	0.472	1.33	1.69	0.265[1]
POWER (W)	10	15	15	35
DIMENSION (MM)	69.6x45	87x50	69.6x45	120x120[2]

[1] Approximated base on 6700TE and 6700K performance matrix.
[2] Minimum system size.