Mizzou Student Underwater Robotics Foundation
Robosub 2022 Technical Design Report

Colm Barry
University of Missouri
Columbia, MO, USA
crbtvc@umsystem.edu

Matthew Cira
University of Missouri
Columbia, MO, USA
mjcvyd@umsystem.edu

Nathan Crum
University of Missouri
Columbia, MO, USA
nac4dc@umsystem.edu

Mason Fleck
University of Missouri
Columbia, MO, USA
mrfcgr@umsystem.edu

Maria Lusardi
University of Missouri
Columbia, MO, USA
mclntg@umsystem.edu

Amelia Truong
University of Missouri
Columbia, MO, USA
ajt9zn@mst.edu

***Abstract* - Coming into the 2022 competition, Mizzou SURF decided it would be best to improve upon the 2021 submarine. Mechanical team designed and tested custom parts to make the sub smaller and lighter. Electrical team innovated new circuitry to fit within the cylindrical bay of the sub and worked to add hydrophones to aid in pose estimation. Software team used OpenCV's line and corner detection algorithms to locate task objects and built a foundation of software knowledge with ROS, Gazebo Simulation, and OpenCV. Altogether, the individual teams worked alongside each other to achieve navigation based tasks (passing through the gate, visual tracking of markers on the pool floor, and touching buoys) to create a foundation for future competitions.**

I. COMPETITION STRATEGY

A. *Introduction*

For this competition we have opted to focus our efforts on navigation based tasks, specifically passing through the gate and, if time allows, visual tracking of the markers on the floor of the pool and touching the buoys. Upon being placed in the water, the sub will first submerge and pivot around its vertical axis until the cameras detect the gate. Once the gate has been located, the sub's position and orientation relative to the gate will be determined and it will head that direction. As the sub approaches the gate, it will search for the bootlegger image and opt for that side of the gate. The sub will complete a full rotation in both the pitch and yaw axis to obtain the 8x point multiplier. Upon passing the gate it will activate its next task, locating the path markers on the floor below. It will map this as a line in space and follow that line forward until the cameras can detect the third task, the tommy gun image on the buoy. Using the same methods as finding the gate, the sub will calculate its position relative to the buoy and head towards it. This will be the end of the competition based tasks, but for pre-qualification after touching the buoy, the sub will go back to rotating around its vertical axis to locate the path once again. It will head the opposite direction down the path until it locates the gate and then return through it.

While this is unlikely to earn many points, it will mark a significant achievement for the team. SURF's previous, and first, model of submarine ("Subby") could not adequately demonstrate autonomy. In particular, our goals as a team are to improve vastly on mechanical design by downsizing the sub, build a solid software foundation by utilizing tools such as ROS, Gazebo, and OpenCV, and integrate hydrophone sensors to improve pose estimation and prepare for future competition tasks requiring pingers.

B. *Mechanical Strategy*

Our submarine was designed to be small and tightly packed with a low center of gravity to allow easy maneuverability and implementation of the navigation systems. (Fig. 1) The legs and other custom parts were designed with hydrodynamics in mind to reduce resistance when traveling in water. All water-tight components were sealed in acrylic cylinders to allow relatively even and stable pressure distribution and tight seals to prevent water leakage. Since our submarine was designed with eight thrusters, it is overconstrained in the six-degree of freedom operation space, guaranteeing that both position and attitude constraints can be met simultaneously.

C. *Software Strategy*

To locate key objects for tasks, OpenCV's line and corner detection algorithms are used. Then, by comparing the size of each member to the known size of the object, the object's approximate position and orientation relative to the submarine can be determined. From there, a path planning algorithm can chart where to go. When passing through the gate the path planning algorithm calculates a trajectory obeying the constraints that the trajectory must end at just beyond the center of the gate and that the submarine trajectory must be perpendicular to the gate at the gate interface. When following the path, the algorithm should not attempt to move toward the marker but rather move in a defined 'forward' direction following on the line the path indicates. A bottom facing camera assists with this, ensuring the sub's movement does not take the path line out of view. Similar constraints as for the gate can be used for the buoys.

A common challenge for SURF has been a shortage of people to work on software. Because of this, the team has limited working hours to achieve tasks needed for the competition. This season it was decided to focus on laying a strong foundation for the software team, despite the limits this would impose on the number of tasks that the sub could achieve. In particular, the focus is working with tools such as ROS, Gazebo Simulation, and OpenCV. By achieving the simpler tasks with these tools we are building up a bank of expertise our software team can draw upon to achieve much more complicated tasks in future competitions. Additionally, a goal is to establish solid procedures of simulation-first testing which will make crafting future design improvements much faster.

D. *Electrical Strategy*

Three hydrophones will be used to aid in pose estimation. The time difference between when the sound wave hits each hydrophone can be used to calculate bearing angles of two hydrophones in relation to the third hydrophone. Then these two angles can be used to compute the overall angle in 3D space. It is similar to finding the intersection of three spheres. Two points can be found from the intersection of three spheres, one in front of the sub and one behind the sub. The point behind the sub can be ignored since it is assumed sound is mostly blocked from that direction.

The time difference between when the sound wave hits each hydrophone is computed using a cross correlation between the reference hydrophone and the two others [1]. This is a computationally intensive process since cross correlation involves a convolution operation in the time domain, but it can be significantly sped up by transforming the audio data into frequency domain, doing a multiplication operation, and then transforming the data back into time domain [2].

II. DESIGN CREATIVITY

A. *Introduction*

Rather than a complete redesign, SURF opted to improve the internal part design of our virtual 2021 robosub submission, and optimize external parts to be lightweight to fit within the design constraints of additive manufacturing technology. In this year's design, our team decided to use a strategy of continuous improvement on the mechanical components of the sub using 3d printing technology. This strategy allowed us to rapidly prototype parts designed ourselves, make comments and adjustments to the part file as needed, and quickly manufacture an adjusted part without the need to purchase parts with long lead times through 3rd party vendors. Architecturally, the modeled parts were constrained to relatively uniform single pieces without hangovers in order to manufacture a structurally sound part with accurate tolerances.

B. *Propulsion Systems*

The propulsion system is a vectored ROV with four vertical thrusters and four horizontal thrusters. (Fig. 2) This configuration provides the submarine with the power needed to move quickly from task to task, the precision to perform the tasks, and is easily integrated into ROS. Motors were mounted in this configuration on the main plate and then extended the mounts for the corner rotors to allow Jelly to sit comfortably on any surface.

C. *Electronics Bay*

The electronics bay of Jelly was designed to ensure simple access. It has a cylindrical top with 6 double-threaded bolts and allows access to all of the electronics without disconnecting any wiring. An improvement from the 2021 sub was the inclusion of a tri-layered mounting bay to attach all of our electronics onto (Fig. 3). These pieces are easily removable and highly modifiable as they are 3d printed, and allow for easy replacement of any electronic components on the sub (Fig. 4). These include the ESC's for the thrusters, IMU, and power relay on the bottom level attached which attaches to bus bars that lead to the middle and top layers of the platform. The middle layer contains a camera for navigational purposes and hydrophone drivers.

The top layer contains the sub kill switch, the Nvidia Jetson processor, and a few other circuit boards necessary for operation. All signal cables are routed through the center of the platforms allowing for easy access and attachment to the rest of the sub systems.

D. *Battery*

In order to keep a stable and low center of mass, the battery is mounted in its own acrylic tube below the electronics bay. The close proximity to the electronics bay allowed us to easily route power to all of the essential electronic components of our sub. Due to the weight of the lithion battery, it has a great effect on the center of mass of the system. This inspired the decision to mount the battery below the electronics bay to bring the center of mass down to the level of the thrusters. Within the acrylic tube is also a downward facing camera to allow tracking of lines along the bottom of the pool.

E. *ROS Software Structure*

ROS is utilized for code structure and pre-built libraries, giving access to many high-level software features that would otherwise be difficult to implement. Figure 5 shown below illustrates the planned software structure, with each block representing either a physical sensor or a node of code. Nodes are connected by topics, which stipulate what kinds of information are passed between them [3]. Overall this allows for an asynchronous structure, critical for ensuring submarine systems do not fail should issues arise [3].

The structure is initiated with the blue sensor boxes, which input data into the submarine's Jetson Xavier. The green boxes take data from the sensors and publish pertinent data onto ROS topics. The "Camera" node is unique in that it not only reads raw camera data, but uses this data to calculate relative positions to notable objects. The pink "current state estimator" block combines sensor data to estimate the orientation and pose of the vehicle. The "main" node in yellow monitors the vehicle's progress through each task and determines which task should be accomplished at any given time, controlling the "desired state selector." The six nodes representing the states all perform path planning calculations for their individual tasks. This includes both task goals for this competition as well as task goals for future competitions. The task nodes feed desired positions as a function of time into the controller node, which commands the submarine to the desired positions and attitude, translating the required torques and forces into motor settings. Finally, the red "motor commander" node communicates with the PWM motor driver to give final motor commands.

III. EXPERIMENTAL RESULTS

A. *Software testing*

Our testbench includes test motors in the same configuration as the sub itself, which allows us to experiment and test nodes related to motor control before the electronics of the sub are fully implemented. Nodes for sending PWM outputs to the motors have been validated, as well as nodes for reading sensor inputs.

Modeling the submarine via Gazebo is still in process, but through this method of testing many of the foundational algorithms for path planning and pose estimation can be verified before the submarine enters the water. Additionally, it will help in training the image recognition model. Instead of taking pictures in a real environment to train in, pictures can be taken in a simulated competition environment. This will save much time needing to test in pool facilities, which we have limited access to.

B. *Electrical Testing*

The hydrophone driver circuit, analog filters, and ADC have been tested and confirmed working. A custom PCB designed by our electrical team has been manufactured and is working as expected (Fig. 6). The hydrophone DSP software for determining a bearing angle has been tested for two hydrophones both in MATLAB simulations and in the water. Results simulated in MATLAB are as expected, and the in-water tests were promising. The environment for the in-water tests was a small tank with hard walls, and consequently, there were a lot of reflections off of the walls that occasionally produced inaccurate results. This problem should go away in the competition and test pools.

C. *Mechanical Testing*

After manufacture, all parts are immediately tested for tolerancing and meshing with the existing parts. If parts do not fit, they are tweaked until they do. Using 3D prints greatly sped up this process. For waterproof testing, all electronics were removed and replaced with coffee filters to ensure all of the seals were tight. Once this is ensured, electronics will be added back to test the required buoyancy. From there, motor movement will be tested, first using remote control of the sub. This also provided the opportunity to test both the physical and remote kill switches. After these tests, autonomous tests for each task will gradually be implemented.

ACKNOWLEDGEMENTS

Mizzou SURF would first like to thank our sponsors and contributors: Mizzou College of Engineering, SolidWorks, MathWorks, NASA, Blue Robotics, and Nvidia for providing us with the money and materials to create our sub. We are very grateful for our faculty advisor Kristofferson Culmer for his guidance and advice. We also want to give a big thank you to the RoboSUB organizers, judges, and the entire rest of their team for creating and running this amazing competition.

REFERENCES

[1] Wikipedia. (20 April 2022). *Cross-correlation* [Online]. Available: https://en.wikipedia.org/wiki/Cross-correlation Birmingham: Packt Publishing Ltd, 2020

[2] Wikipedia. (14 May 2022). *Convolution* [Online]. Available: https://en.wikipedia.org/wiki/Convolution

[3] B.R. Japón, *Hands-On ROS for Robotics Programming: Program highly autonomous and AI-capable mobile robots powered by ROS.*

APPENDIX A: COMPONENT SPECIFICATIONS

Component	Vendor	Model/Type	Specs	Custom / Purchased	Cost	Year of Purchase
Buoyancy Control	N/A	N/A	Using 4x of the thrusters. See Thrusters section below	N/A	N/A	N/A
Frame	Custom	Custom	Custom	Custom	No Data	2019
Waterproof Housing	Blue Robotics	Watertight Enclosure	11.75x4” Acrylic Tube	Purchased	$158	2019
Waterproof Connectors	No Data	No Data	No Data	Purchased	No Data	2019
Thrusters	Blue Robotics	T200	(8x) High performance thrusters	Purchased	$1,200	2019
Motor Control	Skystars	BLHeli_32	(2x) 4 channel ESC with current and voltage sense	Purchased	$80	2021
High Level Control	Adafruit	PCA9685	16 channel PWM driver that is configured via I2C	Purchased	$15	2021
Actuators	N/A	N/A	Thrusters are in fixed positions	N/A	N/A	N/A
Propellers	N/A	N/A	Using stock propellers on the thrusters. See Thrusters section	N/A	N/A	N/A
Battery	Turnigy	High Capacity LiPo Pack	20,000mAh 4S 12C	Purchased	No data	2018
Converter	DROK	DC 5-40V to 1.2-36V Power Supply	100W Adjustable Buck	Purchased	$20	2019
Regulator	N/A	N/A	Using voltage sense on the ESCs for battery monitoring and the Converter has 12V regulation	N/A	N/A	N/A
CPU	Nvidia	Jetson Xavier NX	Jetson Xavier NX Modules in a Seeed Studio A203 v2 Carrier board with 512GB NVMe SSD	Purchased	$860	2022
Internal Comm Network	N/A	I2C, USB	I2C for internal communication between Jetson and the IMU and depth sensors. USB	N/A	N/A	N/A

			communication between the Jetson and the cameras and hydrophones circuit			
External Comm Interface	N/A	Ethernet	A waterproof ethernet connector is used to attach to jelly and ssh into the Jetson	N/A	N/A	N/A
Compass	N/A	N/A	See IMU	N/A	N/A	N/A
Inertial Measurement Unit (IMU)	Adafruit	BNO055	accelerometer, magnetometer, and gyroscope	Purchased	$35	2020
Doppler Velocity Log (DVL)	N/A	N/A	See IMU	N/A	N/A	N/A
Manipulator	N/A	N/A	Custom, 3D printed grabber mechanism	Custom	N/A	2021
Algorithms	N/A	N/A	Custom navigation, localization, and autonomy algorithms	Custom	N/A	2021
Vision	Logitech	C270	(2x) 720p, 30fps	Purchased	$50	2018
Acoustics	Aquarian Audio and Scientific	H1C	(3x) hydrophones and custom driver/filter/ADC circuitry	Custom	$500	2018/2022
Localization and Mapping	N/A	N/A	Custom algorithm	Custom	N/A	N/A
Autonomy	N/A	N/A	Custom algorithm	Custom	N/A	N/A
Open-Source Software	Multiple	Multiple	OpenCV, many of the low-level drivers for the sensors and controller boards	Custom	N/A	2020
Inter-Vehicle Communication	N/A	N/A	We only have one submarine	N/A	N/A	N/A
Programming Languages	N/A	N/A	Python, C/C++, Matlab	N/A	Free/Sponsored	2018

APPENDIX B: FIGURES

Fig. 1: Jelly

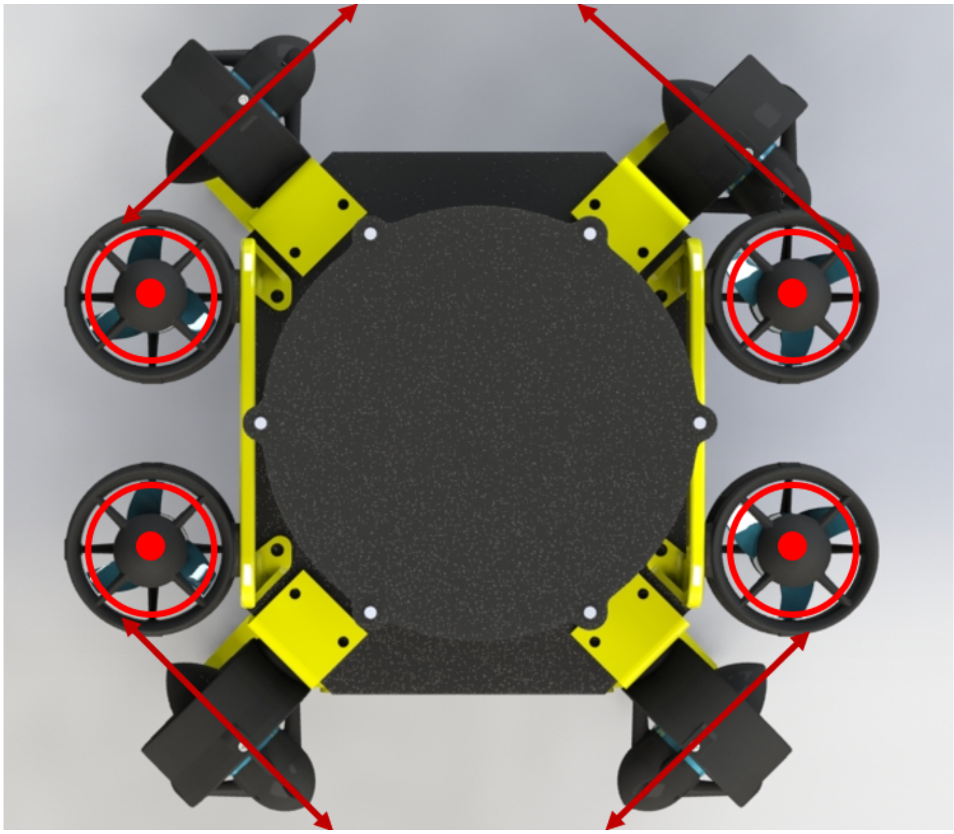

Fig. 2: Propulsion system design

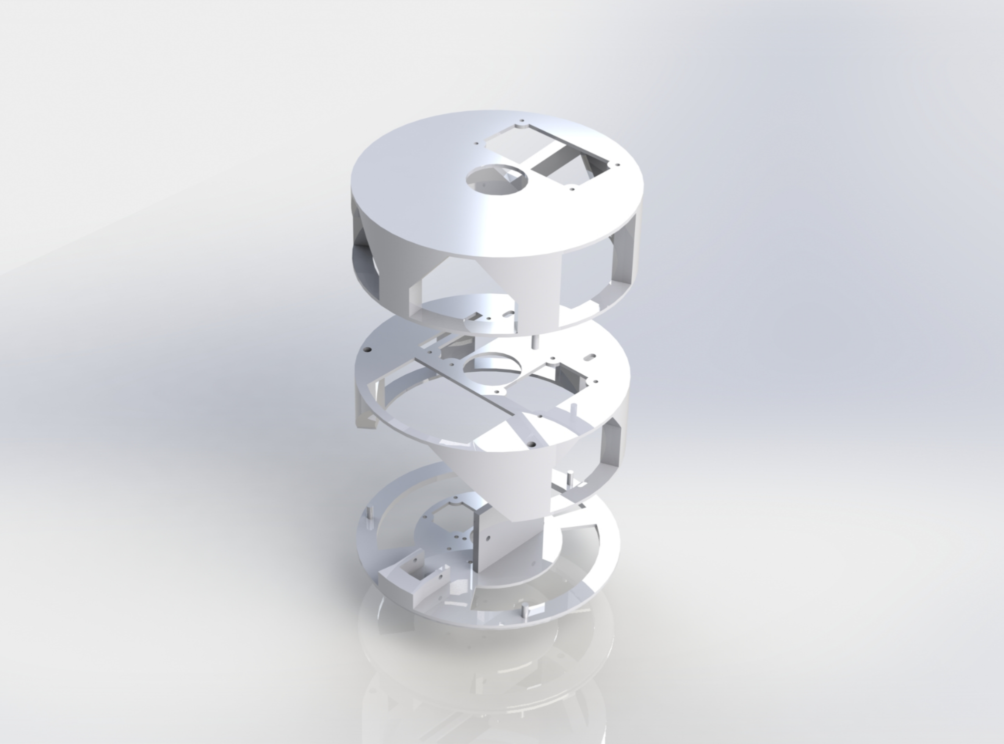

Fig. 3: Electronics Bay Model

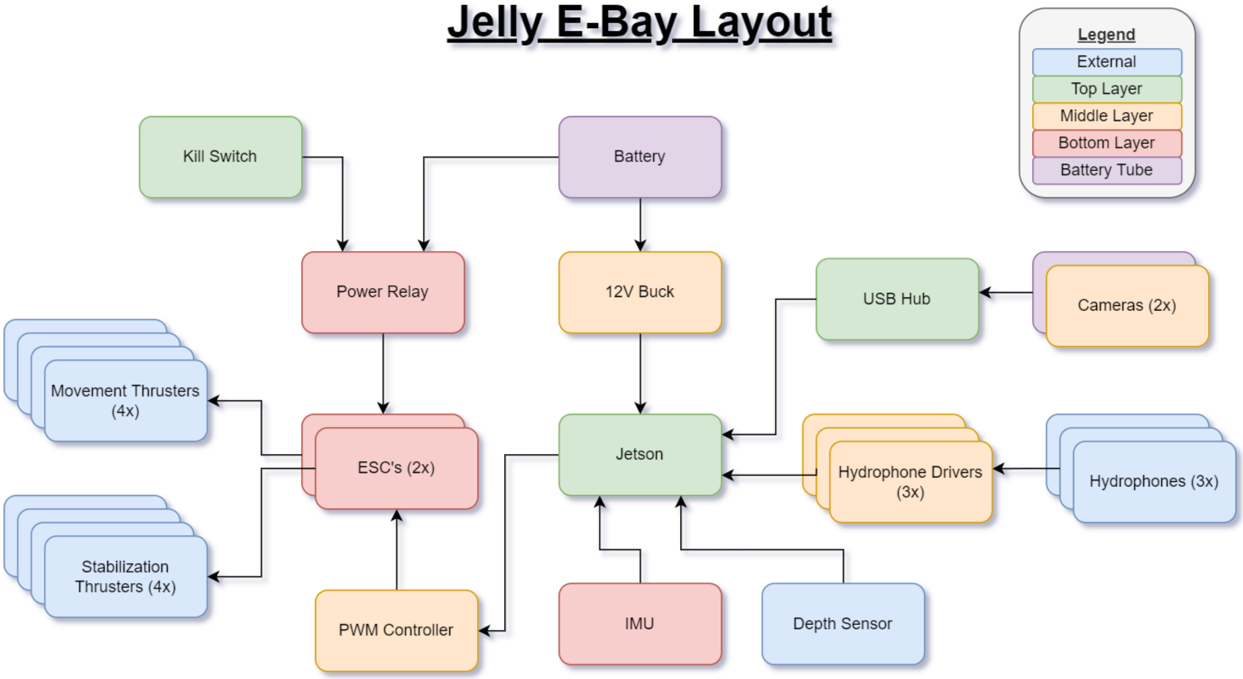

Fig. 4: Electronics Bay Modules Schematic

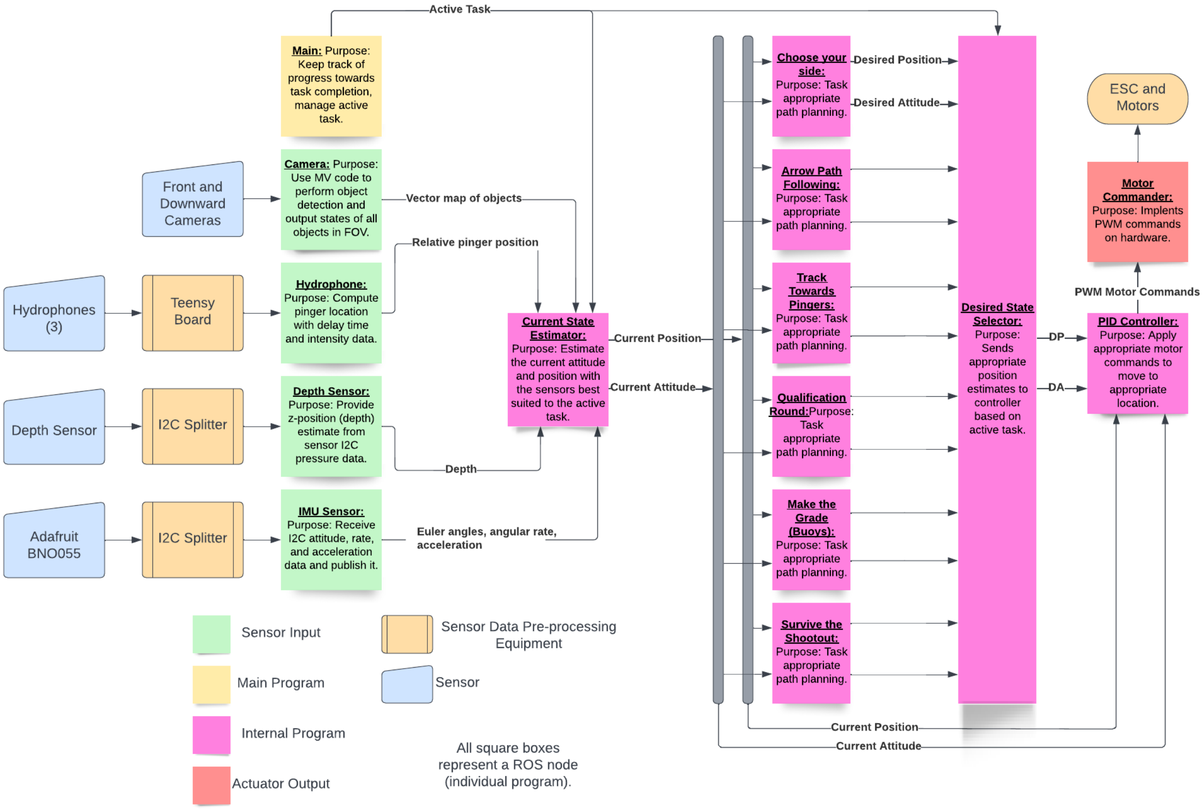

Fig. 5: System engineering design of submarine operation

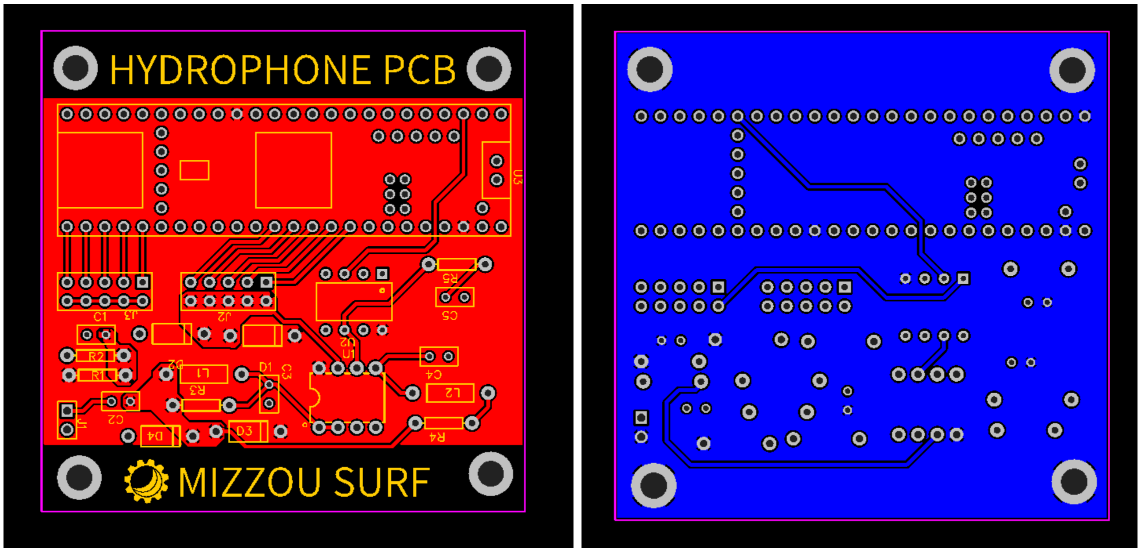

Fig. 6: Hydrophone PCB