2022~2024

DESIGN REPORT

NATIONAL CHENG KUNG UNIVERSITY

討海人_Human-Powered Submarine Team

Contents

List of figures

List of tables

Introduction

✧ About NCKU HPS TEAM

The NCKU Human-Powered Submarine Team was initiated by students from the Department of Systems and Naval Mechatronic Engineering at National Cheng Kung University (NCKU). The team was established in 2020. The primary focus of our team lies in "academic" research, studying submarine design, power performance, and maneuverability. The project enhances the combination of theory and practice, promotes the sustainable development of underwater vehicles, and cultivates students' abilities in independent learning and innovation. The team also establishes a database for human-powered submarines, laying the groundwork for designing even better-performing submarines in the future. In addition to training students from the Department of Systems and Naval Mechatronic Engineering, the human-powered submarine project also offers opportunities for students from other departments at NCKU to showcase their talents, such as those from the Mechanical Engineering, Hydraulic & Ocean Engineering, Electrical Engineering, and Accountancy, among others.

Due to the fact that the NCKU Human-Powered Submarine Team was established less than four years ago, much of the data collection still relies on our own exploration, which has also fostered the resilience of team members in facing new pressures. Located in the southern part of Taiwan, a hub for Taiwan's shipbuilding industry. Therefore, the team has gained access to many submarine technologies due to its geographical proximity. Additionally, southern part of Taiwan's subtropical climate provides the team with many dive sites for underwater training.

The composition of team has three main characteristics: an equal gender ratio of 1:1, comprised of students from four different departments, and includes students from freshman to senior year, with the gender ratio in the engineering group also being 1:1.

✧ Team Organization

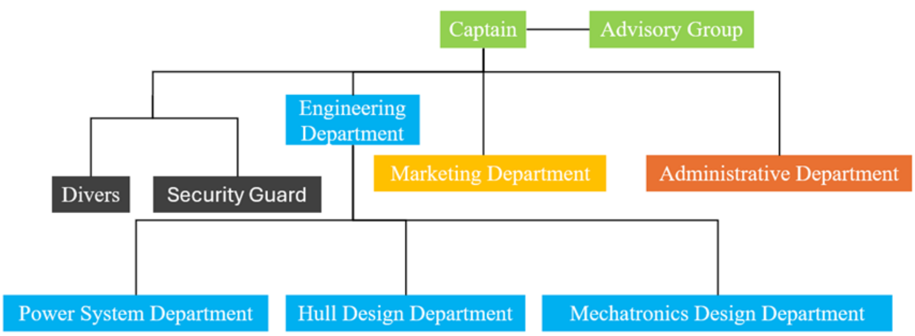

Figure 1 **Team organizational chart**

The team captain is entrusted by the previous team members and is responsible for planning the team's future projects and facilitating connections between various departments. Additionally, the first-generation members who have graduated voluntarily formed an advisory group to assist the second-generation team in adapting quickly.

The second-generation Human-Powered Submarine Team is mainly composed of five departments. The Hull Design Department calculates the hull, rudder surface, and hydrodynamic analysis. The Power System Department is responsible for propulsion and structural analysis. The Mechatronics Design Department focuses on watertight design and modular electromechanical control. The Administrative Department, responsible for team registration, record-keeping of expenses, and reimbursement. The Marketing Department is responsible for writing posts and promotes the team. Clear division of labor within the team not only accelerates independent progress but also facilitates targeted cross-departmental collaboration. Additionally, many enthusiastic students, professors, and diving partners provide timely assistance to the team.

✧ Team Members

POSITION	NAME
Captain	WANG, DAN-SYU
Hull Design Department	HSU, CHUN-YEN、HSIAO, TZU-YU、CHEN, CHUAN-JEN、LIN, MING-JING、HUANG, SHI-ZHEN
Power System Department	YANG, YU-CI、WANG, DAN-SYU、SHEN, KUAN-HUNG
Mechatronics Design Department	CHEN, YI-ZHEN、WANG, CHONG-EN、GUO, TING-WEI
Administrative Department	SHI, YI-YING、WANG, LI-YUAN
Marketing Department	CHEN, HSUEH-YING、XIAO, ZHU-TING
Advising Professor	CHEN, ZHENG-HONG
Advisory group	WANG, PI-CHENG、HSUEH, HAO-CHENG、WEI, HENG-YU、HAN, YUN-HAO、HSU, WEI-JEN

Table 1 Team work distribution

New Goal

With the experience of the first submarine, we have three major goals in preparing the second human powered submarine. First, we want to make our submarine lightweight, more comfortable and have a better buoyancy in engineering. If the pilot feels safe in the submarine, he or she will have a better performance while driving. In terms of design, we need to make a trade-off between speed performance, maneuverability and pilot's comfort inside. Second, we make everyone have their own project and conduct in-depth research and development on their respective projects. Every team member has schoolwork, so we hope this division of labor will enable the project to be promoted efficiently. From reorganizing the team to manufacturing a submarine which can be controlled to sail the specified track, we only have about two years. We need to make our plan on schedule and use time effectively. Third, our team are not just made of the students from the Department of Systems & Naval Mechatronic Engineering. There are also some students from the Department of Accountancy, Industrial Design and Hydraulic and Ocean Engineering.

Hull

✧ Shape

I. Design

The overall shape of the hull is designed to mimic the symmetrical profile of airfoils found on Airfoil Tools, ensuring that the hull generates no additional lift or buoyancy during navigation. The top view is based on the NACA 16021 airfoil, while the side view is based on the Griffith 30 symmetrical suction airfoil. Additionally, the curvature of the stern is adjusted to prevent rapid contraction of the hull, which could lead to boundary layer separation and generate additional viscous pressure drag.

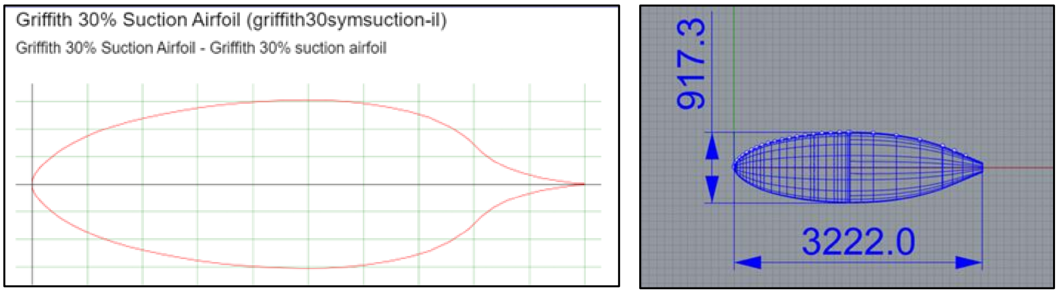

Figure 2 Shape of the hull

The cross-section is elliptical, aimed at mitigating some of the rolling caused by propeller rotation. The dimensions are determined based on the experience of the previous iteration, where space was limited, and with the aim of enabling every member to pilot the vessel. Therefore, the dimensions are set to be 3.22 meters in length, 0.91 meters in height, and 0.7 meters in width.

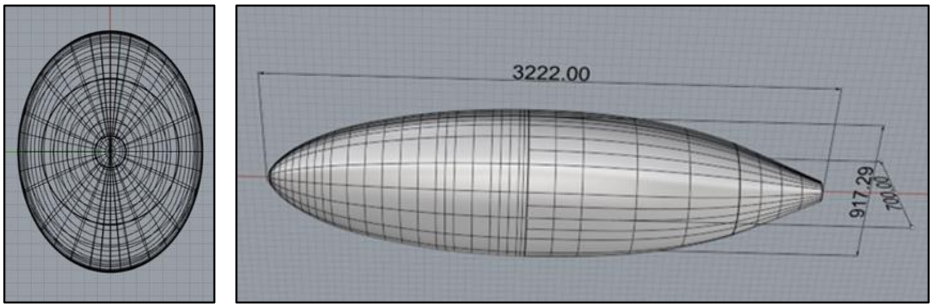

Figure 3 Dimensions of the hull

II. Analysis

We used Ansys Fluent to simulate the resistance of our hull moving in a straight line. During the design phase, we assumed that the ship's speed could reach 3 meters per second. In the flow field, the hull was positioned 2 meters from the water surface, 2 meters from the ground, and 3 meters from the walls on both the port and starboard sides. The mesh size of the flow field was set to 0.15 meters, and the grid size of the hull was refined to 0.035 meters, with a total mesh number of 860 thousand. After iterative calculations, the resistance was found to be 121.02 Newtons. The velocity distribution around the hull at this speed is shown in the following figure:

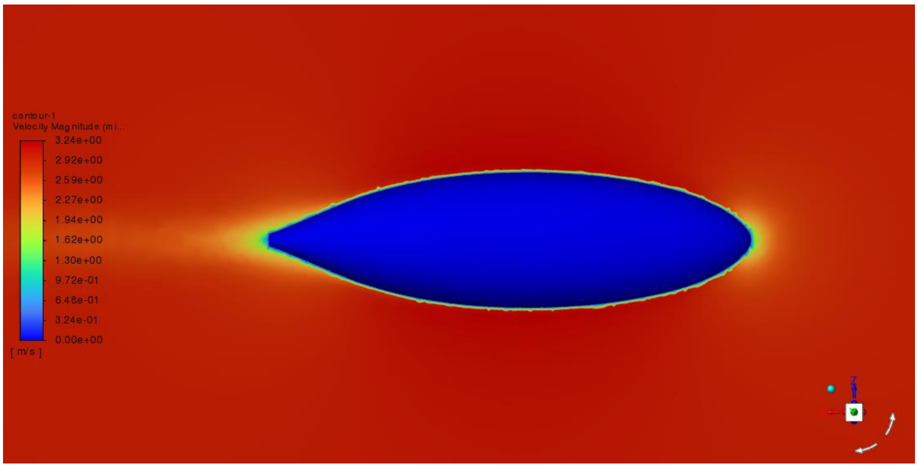

Figure 4 Velocity distribution around the hull at 3(m/s)

However, during underwater testing, we found that the ship's speed could only reach about 2 knots. Therefore, we conducted the simulation again, changing only the speed to 1.03 meters per second while keeping all other conditions unchanged. The calculated resistance was 17.457 Newtons. The velocity distribution is shown in the following figure:

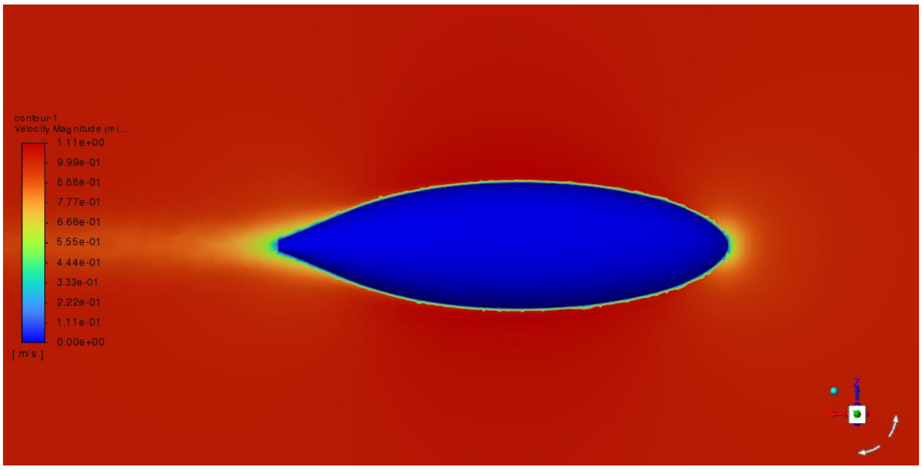

Figure 5 Velocity distribution around the hull at 2(knots)

✧ Bow Cowl

I. Design

Considering that most teams' bow covers are simply conical in shape, we aim to be innovative in both appearance and visibility. In terms of design, we aim to showcase determination on the competition field. We incorporate the side profile of ancient Greek helmets and draw inspiration from vehicle headlights and aircraft cockpit windows. Emphasis is placed on forward and lateral visibility, with a design featuring slanted sides to increase visibility to the sides and allow the driver to have a clearer view all around.

Regarding visibility, due to the smaller size of the first bow cover and previous incidents of hitting swimming pool walls, we focus on increasing visibility to the sides, enabling immediate response to signals from dive guards. Initially considering adding skylights for illumination in deep water, we abandoned this idea due to structural concerns with the sides of the bow cover. Instead, we emphasize a protrusion at the bottom to increase the area for mechanism installation, avoiding stress concentration and incorporating rounded corners. The final design style is determined by considering design aesthetics, practicality, and ease of construction (mold release).

Figure 6 Design of submarine

The locking mechanism uses 12 rounded-head screws with washers to reduce resistance and ensure firmness, adding an industrial style to the appearance. Combined with the aluminum panels on the hull, we consider both appearance and convenience for replacing the bow cover. The material for the bow cover is PETG, known for impact resistance, thermoformed and welded into two pieces, front and back. Upon launching, it was found to be transparent on land, significantly increasing visibility. Not only can the driver see the external environment, but dive guards can also observe the position of the bow mechanism and buoyancy materials, ensuring the driver's condition is normal.

✧ Hatch

I. Design

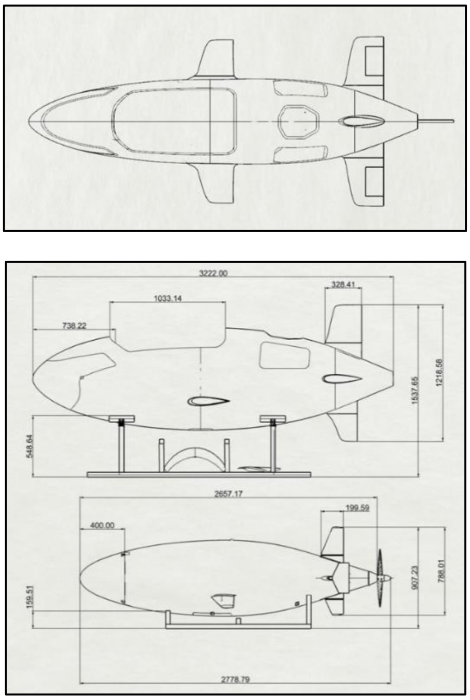

Figure 7 Sizes of various hatches compare with the previous generation

i. Main Hatch Cover

The goal is to facilitate easier entry and exit for the driver, considering the convenience of the driver gripping on both sides when entering. Therefore, the surface area of the hatch is increased. Additionally, a transverse hole is cut at the leading edge. Due to the increased weight, it is necessary to design for easier lifting, so a metal handle is securely attached in the middle. Both the hole and the handle have been measured to be accessible even when wearing diving gloves. The bottom locking components do not protrude beyond the lower edge of the hatch, making it convenient for upright drying. The overall length has been extended from 73.5 cm, the length of the “Sat-bȧ k-hî”, to 90 cm.

In terms of design, it aligns with the style of ancient warriors, incorporating octagonal lines with rounded corners to create a shield-like shape. The front end protrudes towards the bow of the boat to prevent collisions when the driver enters and exits. The exterior side lines are seamlessly connected from front to back, complementing the modified slanting design of the bow cover. The overall area is also larger compared to the first iteration.

Regarding locking mechanisms, it is similar to that of the “Sat-bȧ k-hî”, but two L-shaped iron pieces are used at the rear. The front locking mechanism adopts a simpler door lock, reducing the risk of accidental locking due to misoperation. Currently, dual nylon cords are used as external switches and internal emergency switches.

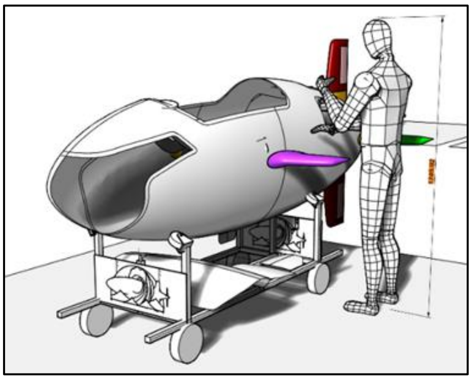

Figure 8 Simulation diagram

ii. Maintenance Hatch Cover

- Positioning and Design

Based on the review after last time of competition, it was decided to add a mechanism for balancing buoyancy in the water and facilitating onshore maintenance of the power mechanism. Therefore, it is located next to the mechanism and enlarged for easier maintenance access. With a three-point fixed lip edge, the size of the opening is approximately larger than that of a personal laptop, making it convenient for engineers to perform maintenance. Additionally, a 3D simulation of a human dummy was conducted to match the height of transport carts, allowing maintenance personnel to work without bending over frequently and serving as a point of force during transportation, while also improving ventilation and lighting during construction.

- Locking Mechanism

Initially, industrial-grade Velcro commonly used by racing teams was considered, but it was found to be prone to dust accumulation in factory settings, reducing adhesiveness and precision placement. Therefore, a door lock mechanism was adopted. For the rear, similar to the main hatch cover, two L-shaped iron pieces were hammered into an S shape and bonded with structural adhesive, while for the front, screws were used to secure the lock to prevent accidental detachment due to water flow during navigation. Since the unmodified hatch cover itself has positive buoyancy, it was discovered during the initial launches that this locking mechanism caused the cover to float slightly.

iii. Escape Buoy Hatch Cover

To complement the overall design style, we introduced a shield-shaped design and enlarged the surface area. Additionally, we adjusted the proportions to increase the lateral dimensions in line with the circular size of the buoy. Initially, we considered using a circular shape, but it was challenging to attach corner chains around it. Therefore, we opted for the same right-side locking mechanism for opening.

iv. Drainage Hatch Cover

After completing training in the pool, it's necessary to quickly reduce the water level inside the compartment during manual handling to facilitate transportation and maintenance. The drainage hatch cover of the " Sat-bả k-hî" is a simple rectangular shape, which is effective for drainage. Therefore, there haven't been many changes in the design this time. Our focus is on making it easier to open during social visits to prevent injuries to personnel.

This part is designed for maximum functionality. It is located at the lowest point of the boat's horizontal perspective, prioritizing functionality. The edges are rounded for ease of construction. Upon launching, it's observed that tilting the boat can discharge most of the water, and when it's on the support, drainage can continue through the hatch cover.

II. Materials

i. Main Hatch Cover

The main hatch cover will be closed after the driver enters the cabin in the water. In order to facilitate the assembly in the water, the buoyancy of the hatch cover should not be too high. But because the main hatch is located in the middle and above, some buoyancy needs to be provided for stability. We use fiberglass veneer (two layers) with three 10mm thick cores in the middle.

ii. Maintenance Hatch Cover

Because the maintenance hatch is located behind where there are more power systems and heavier weight, a sandwich structure (PVC 10mm and two layers of glass fiber at the top and bottom) is used to provide buoyancy.

iii. Escape Buoy Hatch Cover

The hatch cover needs to be light enough that the float can lift the hatch cover and float out by relying solely on its own buoyancy, but not so light that its density is less than that of water. Two layers of fiberglass veneers are used.

iv. Drainage Hatch Cover

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III. Manufacturing

These hatches are made of fiberglass and are made by hand lay-up technique.

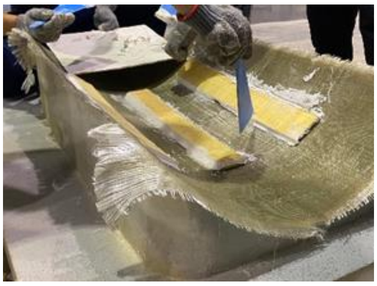
		
Waxing	Hand lay-up the fibers	Glue the core
		
Trim the edge	Semi-finished products	Release from the mold
		
Sand off mold and wax	Putty filling and polishing	End products after painting

Figure 9 The manufacturing of hatches

✧ Hull Manufacturing

I. Layer Configuration

The process of constructing the hull for the human-powered submarine involves considerations of both structural integrity and weight. The previous hull design, which utilized the hand lay-up method and consisted of five layers of fiberglass (m300, Lt600, db800, PVC core, db800, Lt600), was robust but heavy, impacting the submarine's acceleration capabilities.

Furthermore, the inclusion of buoyancy materials to achieve neutral buoyancy compressed the available space for the driver and other equipment.

In response to these challenges, the team plans to transition to carbon fiber and employ Vacuum Assisted Resin Transfer Molding (VARTM) to reduce weight without compromising strength. This decision was made following consultations with sponsors, extensive research on composite materials, and consultations with experts such as Professor Luo, Guang Min from the National Kaohsiung University of Science and Technology. The new hull design will feature a sandwich structure comprising four layers (m300, Lt600, PVC core, Lt600) and will utilize the VARTM technique, which has been optimized to enhance both strength and weight reduction.

II. Hull core material thickness configuration

Considering the gravity and buoyancy of each area, design the distribution position of 5mm thick, 10mm thick and 25mm thick PVC the core material in each area, so that the submarine can achieve a state of more buoyancy than neutral buoyancy and facilitate trimming. According to the position of the hatch cover and the location of the internal equipment, divide the submarine hull into four upper and lower parts to evaluate stability.

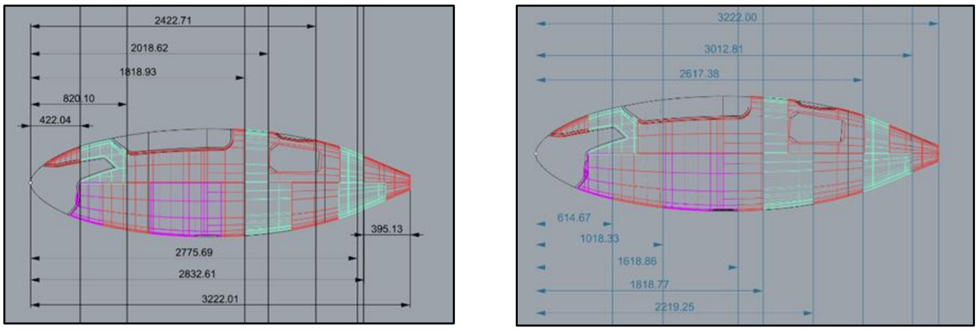


Figure 10 Distribution position of different core thickness

(Purple: 5mm; Red: 10mm; Green: 25mm)

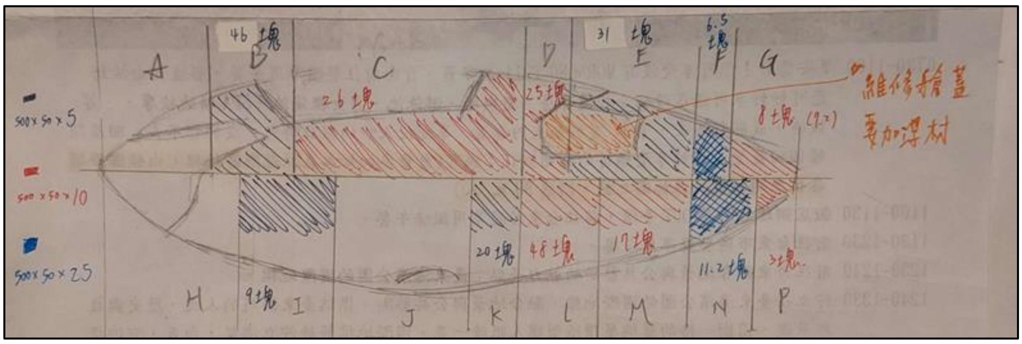


Figure 11 Design diagram

section NO.	Core material volume (m^3) approx.	Core material weight (kg)	hull area (m^2)	Board thickness (m)	Board weight (kg/m^2)

upper1	0.001141566	0.068493976	0.363155236	0.00159	2.81
below1	0.000559719	0.03358316	0.432902334	0.00159	2.81
upper 2	0.00661539	0.396923378	0.6479533	0.00159	2.81
below 2	0.001253138	0.075188265	1.19983415	0.00159	2.81
upper 3	0.004327073	0.259624351	0.455040004	0.00159	2.81
below 3	0.008994539	0.539672348	0.724308994	0.00159	2.81
upper 4	0.005896804	0.435318276	0.558987415	0.00159	2.81
below 4	0.007670898	0.599833254	0.55827205	0.00159	2.81

Table 2 The calculation of hull core material

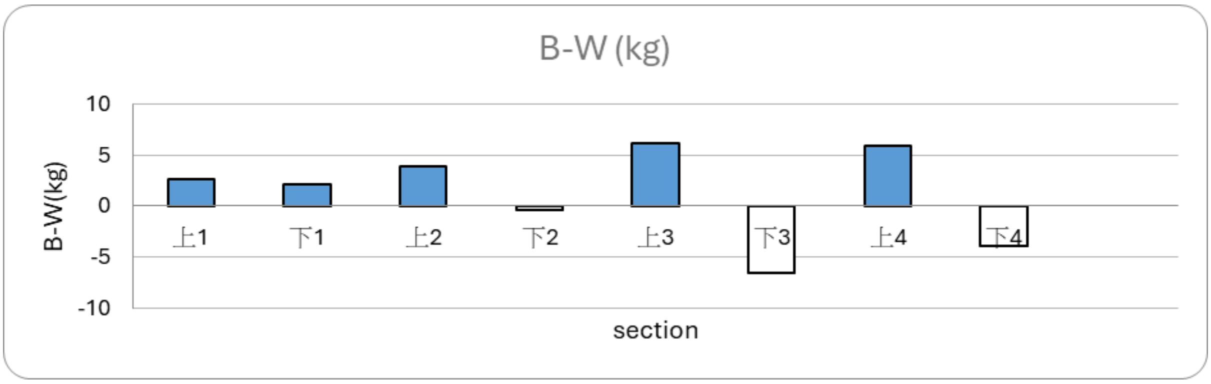


Figure 12 The buoyancy minus the weight of each part

III. Mold flow test

We made a mold flow test to understand the actual speed, so that the pipeline can be designed and the speed at which the resin reaches each area will not differ too much when the vacuum is actually evacuated.

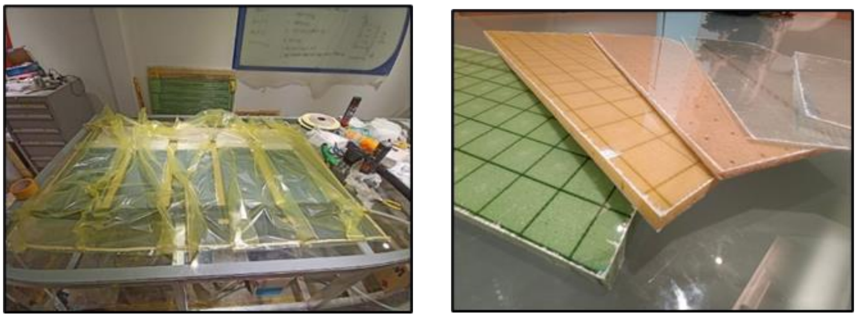


Figure 13 Testing process and end product

Result:

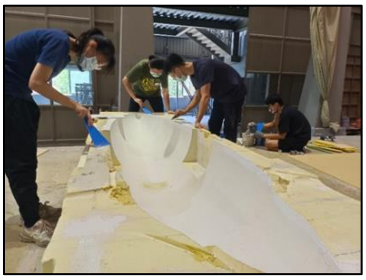
Layer	Two layers of fiberglass	Four layers of fiberglass	Two layers of fiberglass with 5mm core	Two layers of fiberglass with 10mm core	Two layers of fiberglass with 25mm core
Time	7min30sec	12min10sec	5min22sec	2min27sec	2min10sec

Table 3 The result of mold flow test

IV. Production

The computer-aided design software Rhino was used to divide the designed ship shape into upper and lower hulls, and then Boolean calculate was used to create the design diagram of the hull and hatch covers.

Glue standard-sized PU cuboids with structural adhesive until they are of sufficient length. Horizon Yacht was entrusted to use a five-axis processing machine to CNC the PU mold accurately according to the drawings to obtain the cavity plate. The rudder surface of the lower mold is not suitable for milling with a five-axis CNC machine due to its angle, so it is made as a sliding block which was milled with a three-axis CNC machine and being glued to the lower mold.

	
Gluing PU block	Mold preparation completed
	
Brush the mold with resin	Fill with putty
	
Polish and smooth the mold surface	After spraying the gel coat

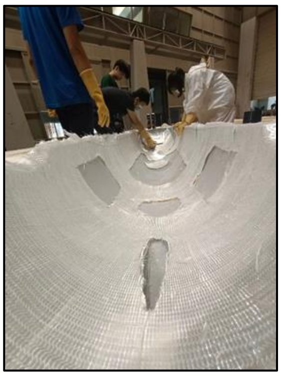
		
Laying fiber	Cut and lay the core material	Consumables & pipelines
		
Setting up vacuum bags	Vacuum infusion	After mold release

Figure 14 The manufacturing of hull

In the actual pipeline layout, there is a pipeline vertically at the bottom. The resin is injected first, and a feed pipe is circled in the middle. It will be opened after the vacuum is halfway through and the resin is pumped to the middle pipeline, allowing the resin rises evenly like water in a bowl, avoiding encapsulation.

- Assembly

  Glue a PVC flange inside and wrap it with fiberglass to increase the bonding area. Assemble the upper and lower hulls together with structural adhesive.

Figure 15 Increase the bonding area

- To trim exterior surfaces

  i. Smooth the edge and apply resin to the exposed areas of the PVC core material to avoid subsequent water immersion and increased weight. Use putty filling and polishing to make the overall shape streamlined and consistent with the hatch cover. After sanding the sandpaper from 60, 80 to 120, spray it with white modeling primer.

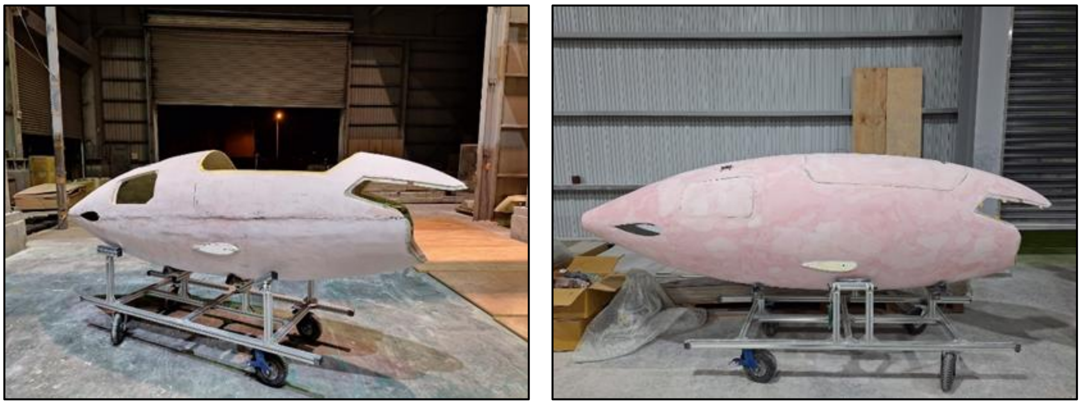


Figure 16 Smooth the edge

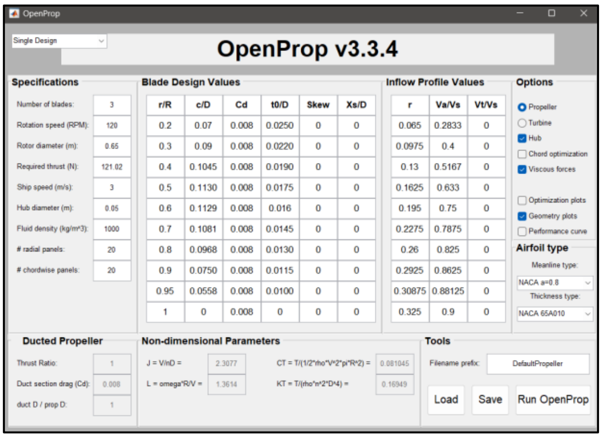
After smearing with black ink, you can see more subtle defects. Use putty to repair the concave areas, and sand the entire ship with No. 120 and 400 sandpaper to make the whole ship more streamlined. Finally, spray the PU topcoat and use paint protection film to protect and decorate the hull.

Figure 17 Spray the PU topcoat and use paint protection film

Propeller

✧ Shape & Design & Manufacture & Material

The propeller was designed by the open-source software OpenProp in MATLAB, where parameter adjustments are made to generate a three-dimensional model. Subsequently, the obtained three-dimensional coordinate points are exported as a text file and imported into 3D modeling software to create the propeller blades. The parameters set and its performance are shown in the following figure:



r/R	c/D	Cd	t0/D	Skew	Xs/D
0.2	0.07	0.008	0.0250	0	0
0.3	0.09	0.008	0.0220	0	0
0.4	0.1045	0.008	0.0190	0	0
0.5	0.1130	0.008	0.0175	0	0
0.6	0.1129	0.008	0.016	0	0
0.7	0.1081	0.008	0.0145	0	0
0.8	0.0968	0.008	0.0130	0	0
0.9	0.0750	0.008	0.0115	0	0
0.95	0.0558	0.008	0.0100	0	0
1	0	0.008	0	0	0

r	Va/Vs	Vt/Vs
0.065	0.2833	0
0.0975	0.4	0
0.13	0.5167	0
0.1625	0.633	0
0.195	0.75	0
0.2275	0.7875	0
0.26	0.825	0
0.2925	0.8625	0
0.30875	0.88125	0
0.325	0.9	0

Figure 18 Parameters set

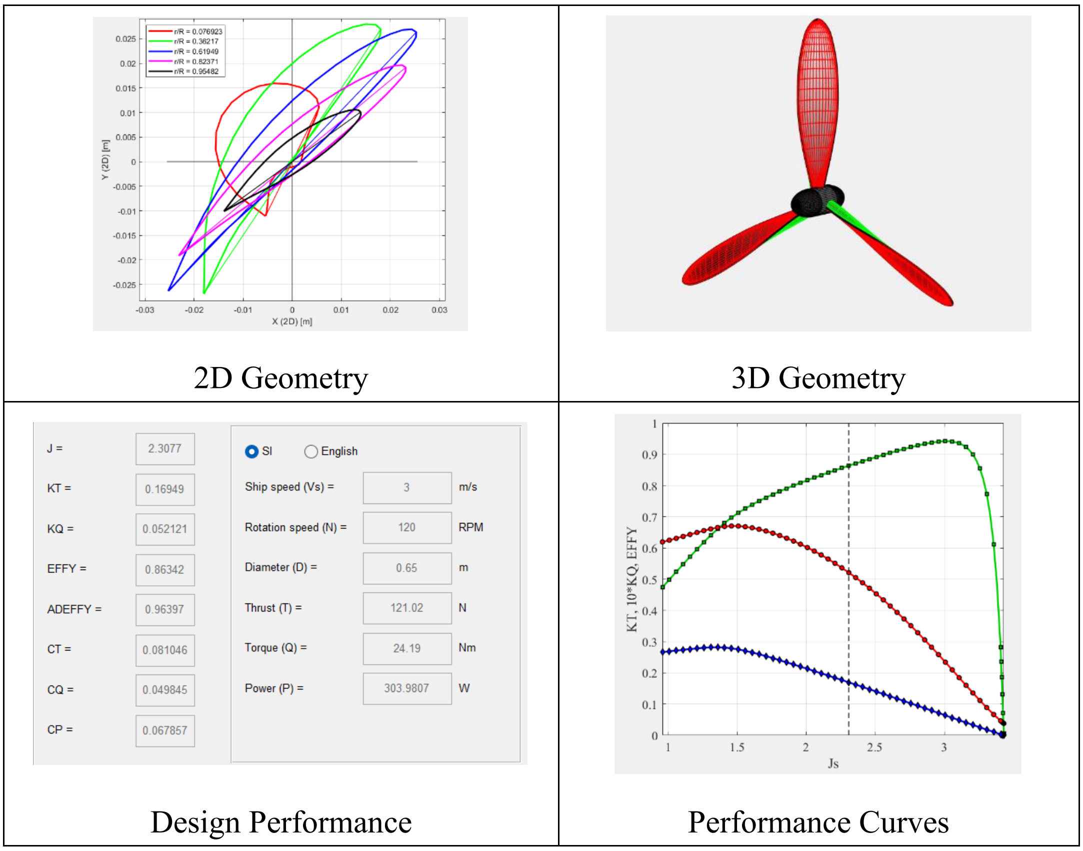


Figure 19 The analysis of propeller

To ensure smooth curvature between the stern and the propeller hub and to consider the convenience of blade replacement, a modular design approach is adopted. Additionally, 3D printing is planned for manufacturing.

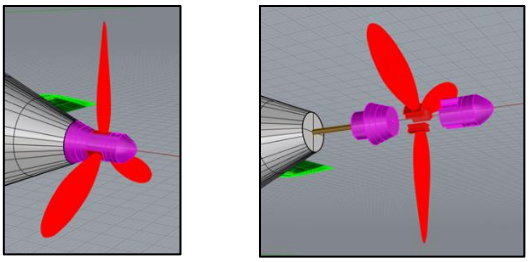


Figure 20 Propeller module

Fin

✧ Design

To avoid ambiguity during maneuvering and for ease of positioning during manufacturing, we have opted against the idea of an X-shaped rudder and instead chosen a cross-form rudder.

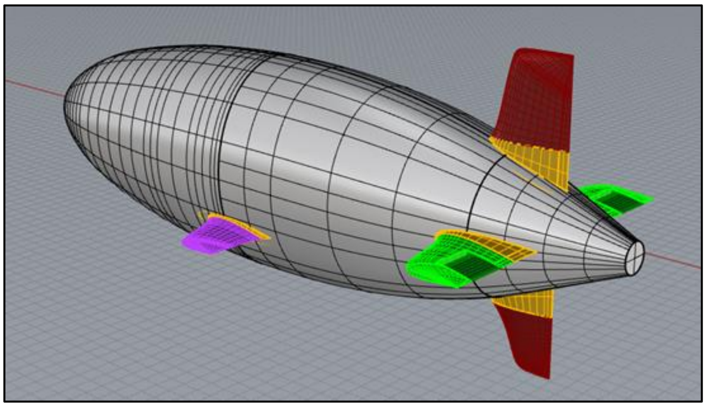


Figure 21 Submarine fins

All the control surfaces as well as their bases were generated by NACA 0021 airfoil. This is a symmetrical airfoil profile, ensuring that no additional lift is generated during straight-line navigation. To reduce horseshoe vortexes and the connection flow resistance generated at the junction of the control wing surface and the hull, a leading-edge strake has been designed to mitigate separation phenomena.

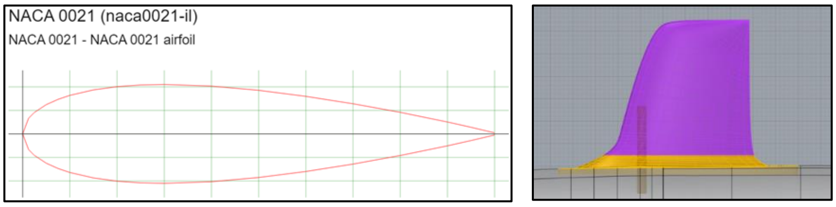


Figure 22 NACA 0021 airfoil

Additionally, referring to the document *Aircraft Design: A Conceptual Approach*, the pivot axis was positioned at 0.25 times the mean aerodynamic chord length.

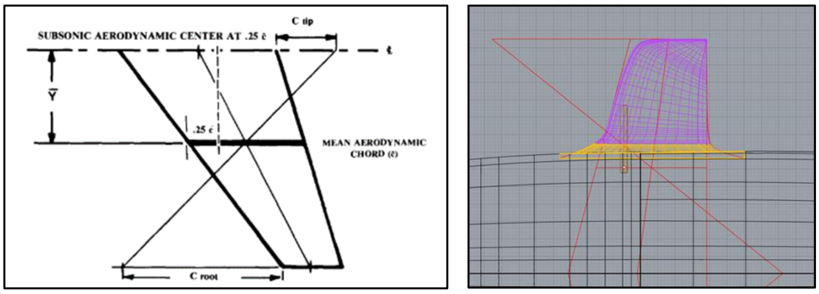


Figure 23 Position of the axis

✧ Planes & Rudders

I. Hydroplanes

The hydroplanes are positioned at the center of mass of the hull to reduce the turning radius and assist in vertical height adjustments of the vessel. They are placed lower to prevent the downstream flow from affecting the rear wing surface.

II. Stern Planes

The stern planes are positioned on both sides at 15% of the hull length from the stern. Since maintaining a certain depth is sufficient during the competition's maneuvering process, they are designed as partially rotating flap mechanisms to assist in fine-tuning the vertical stability of the vessel.

III. Rudders

The rudders are positioned both above and below at 15% of the hull length from the stern. Sensitivity in changing the navigation direction is crucial for the outcome of the competition. Therefore, they are designed with the entire wing surface capable of rotation to increase the area affecting fluid dynamics. However, to avoid bottoming out during navigation, the size of the lower rudder is reduced.

✧ Analysis

Similarly, we used Ansys Fluent to simulate the drag and lift of all the planes and rudders at attack angles of 0, 5, 10, and 15 degrees. The mesh size of the flow field was set to 0.035 meters, and the mesh size of the planes and rudders was refined to 0.02 meters. The total mesh counts for the Higher Rudder, Lower Rudder, and Stern Plane were approximately 980,000, 920,000, and 930,000 respectively. Under the condition of a speed of 2 knots, the iterative calculation yielded the following drag and lift values. The lift direction of the Stern Plane is vertical, and the obtained values include gravity, so the attack angle of 0 degrees was used as a baseline for modification.

		0°	5°	10°	15°
Higher Rudder	Drag(N)	1.07	1.46	2.71	4.37
	lift(N)	-0.05	-11.69	-22.74	-30.79
Lower Rudder	Drag(N)	0.56	0.78	1.49	2.58
	lift(N)	0.019	-6.21	-11.64	-16.68
Stern Plane	Drag(N)	1.47	1.57	1.72	2.17
	lift(N)	30.99	29.81	27.38	25.60
	Modified(N)	0	-1.19	-3.61	-5.40

Table 4 Drag and lift force of fins at different attack angles

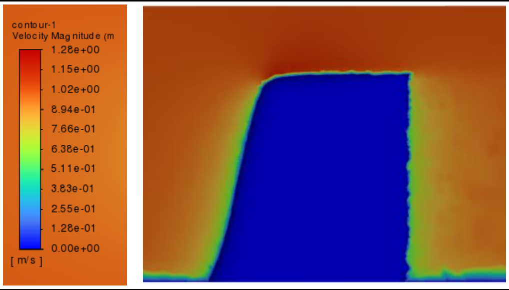
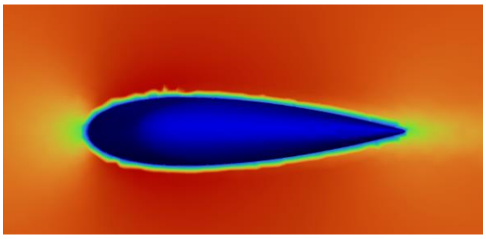
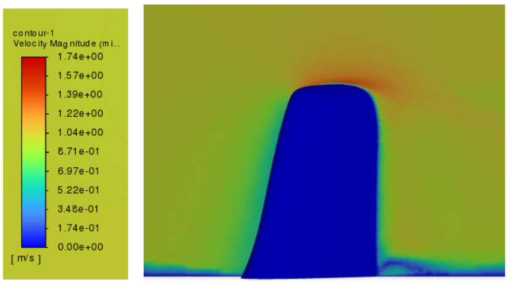
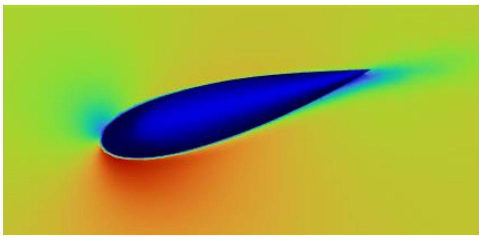
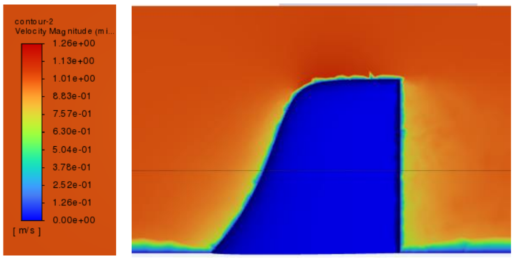
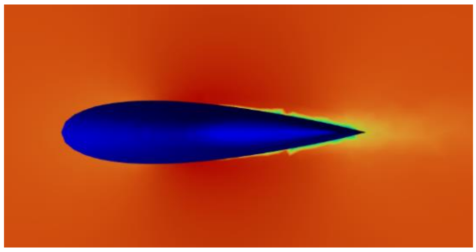
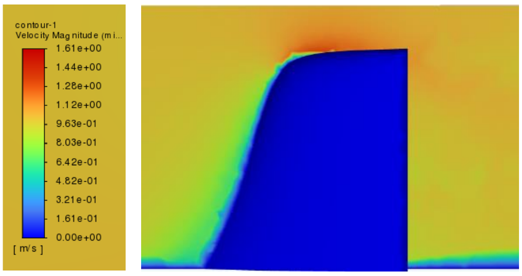
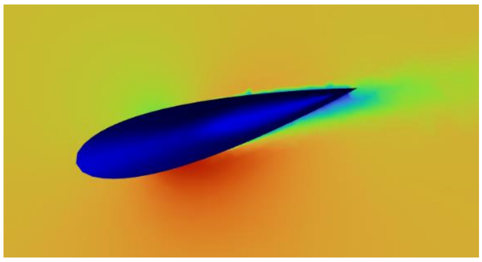
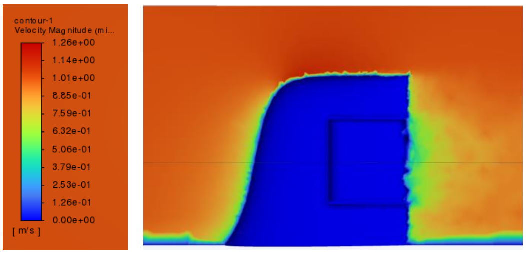
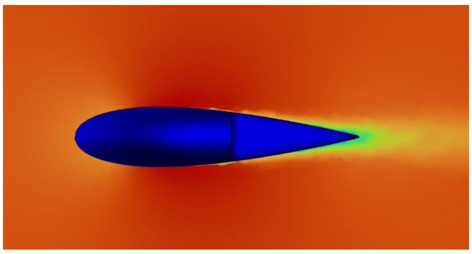
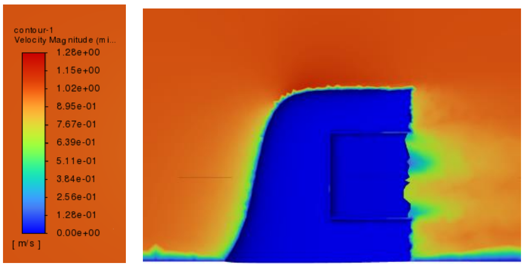
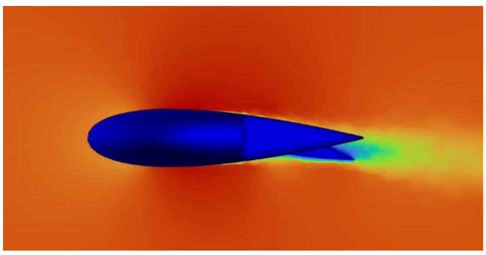
Higher Rudder	0°		
	15°		
Lower Rudder	0°		
	15°		
Stern Plane	0°		
	15°		

Figure 24 Velocity magnitude of fins at different attack angles

✧ Manufacture & Material

The control surfaces are planned to be manufactured by 3D printing technology. To facilitate easy replacement, a modular design approach will be adopted. Considering the size limitations of the 3D printing machine, the components will be divided into separate parts for printing. The assembly method is showed in the diagram below.

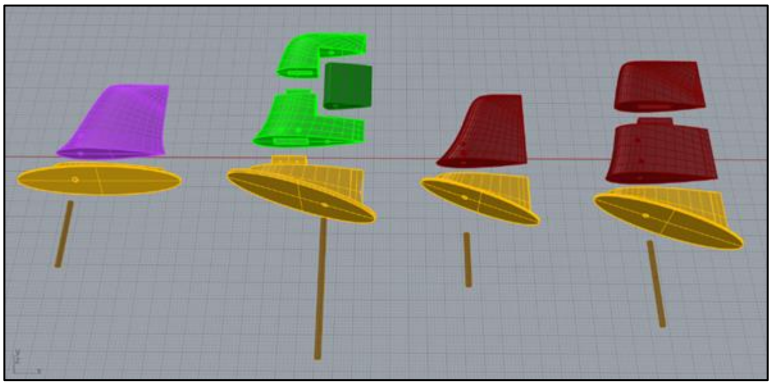


Figure 25 Fin modules

Rudders & Planes support structure

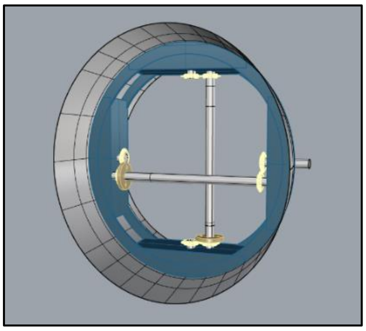
✧ Design

Rudder & Plane support structure is designed to support rudders, the planes and the mechanical control system. It's installed at the stern of the submarine, and adjusted to match the position of rudders and planes. There are four main ideas behind the support structure. First, to overcome the problem of transmission shaft collision. Second, to align the stern planes and rudders coaxially. Third, to minimize weight to avoid submarine trim issues. Last but not least, to consider the convenience of installation and positioning.

Regarding the issue of transmission shaft collision, we used multiple shafts to solve this problem. The initial design (see Figure 1) aimed to address the collision between the transmission shafts of the stern planes and rudders and the propeller shaft. However, due to changes in hull design, the stern planes and rudders are not on the same cross section. Thus, only the collision with the propeller shaft needs to be considered. Therefore, we used shafts and gears to stagger the transmission shafts of the rudder and propeller, avoiding collision. This also ensures that the stern planes and rudders are coaxial, improving transmission efficiency.

Next, to achieve lightweight design for the overall structure, we hollowed out the middle sections of various aluminum plates as much as possible without compromising structural strength. Additionally, for safety considerations, we designed to use a combination of aluminum alloy and stainless steel to manufacture different parts of the structure. As shown in Figure 2, where the purple sections represent stainless steel and the yellow sections represent aluminum alloy.

Finally, regarding the convenience of installation and positioning, we separated all structures in parts. As shown in Figure 2, the blue sections represent screw nuts. We welded them onto the stainless-steel structure to simplify the installation process. Therefore, we can install the entire support structure from front to back without being constrained by space. Moreover, we designed two structures under the lower part of the main structure that can be locked onto the hull. This allows the screws to lock in place during installation first, and then the remaining parts can be assembled. As a result, we could have easy installation even in relatively narrow stern sections.



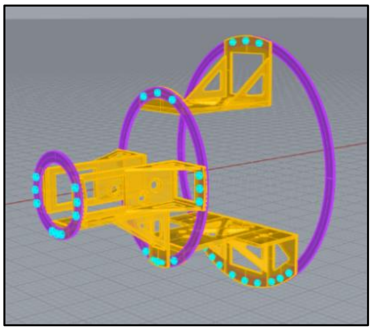


Figure 26 Initial design (left picture) and final design (right picture)

✧ Manufacture & Materials

As mentioned above, to achieve lightweight design for the overall structure, we have endeavored to use a combination of aluminum alloy and stainless steel in different parts of the structure without compromising structural strength. However, due to the use of different materials in the structure, directly welding is not feasible. Therefore, the most common method applied during the process of manufacturing involves drilling and tapping holes, followed by securing with screws.

For the installation of the shafts, we opted for watertight bearings coupled with C buckles for fixation. We also used spur gears to interconnect and facilitate rotational movement of the shafts. Regarding the selection of spur gears, due to the proximity of the shafts, conventional gear sizes were too small to accommodate keyways for secure attachment. The solution involved drilling holes in the gears and securing them onto the shafts using set screws. The finished products are depicted in the diagram (Figure 3 and Figure 4) below.

Figure 27 End product (left picture) and gears of shafts (right picture)

Transmission System

✧ Drivetrain

I. Design

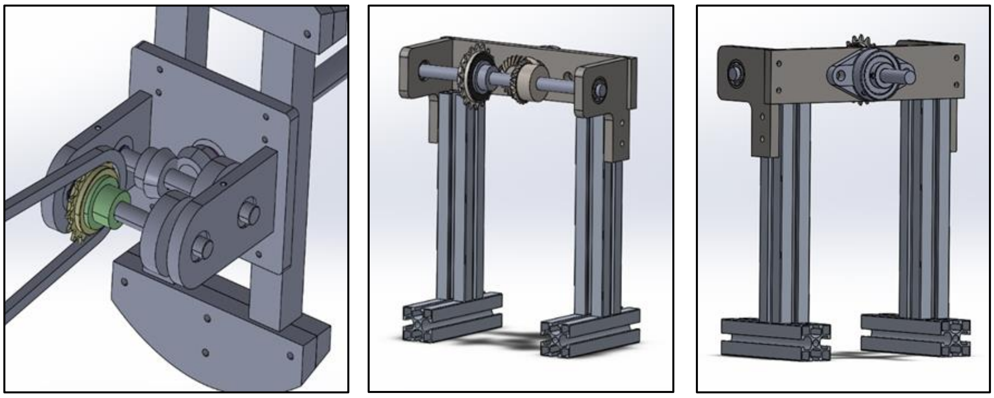
We have two ideas for the transmission part. The first idea involves implementing a shaft drive system. Pedaling causes the rotation of a bevel gear, which in turn drives another bevel gear mounted on the propeller shaft. Another idea is to use a chain drive system. When the rider pedals, the chain transfer power from chainwheel to flywheel. Bevel gear and flywheel shared the same transmission shaft, causing them to rotate together. The bevel gear then drive another bevel gear mounted on the propeller shaft. The first method is simpler, but the pedal may be driven by the propeller. If the foot gets stuck, the pedal will continue to rotate, which causes a danger condition. Therefore, we chose the second method. When pedaling backwards, the flywheel will idle, preventing the propeller from rotating.

Next is the design of the gearbox. The oversight in the previous gearbox was related to neglecting the size of the flywheel. This led to a collision between the flywheel and the back plate when it was mounted on the transmission shaft. This necessitated the addition of an extra transmission shaft to separate them. Also, the limited space at the stern makes disassembly and assembly difficult. Therefore, our goal this time is to reduce the volume and facilitate disassembly. We use two side plates to fix the transmission shaft, which carries both the bevel gear and the flywheel. The original idea was to mount two bevel gears on the shaft, one for rotation and the other as an idler. The idler can counteract the lateral forces when the bevel gear rotates, thereby providing stability. However, due to the need to keep the chainwheel and the flywheel in a straight line, and the addition of another bevel gear would increase friction and energy loss, we had to abandon the original idea. Another problem is that the flywheel's bore is larger than the transmission axis. We designed a flywheel coupling to fix it on top and prevent it from coming off due to rotation. There is extra space between the back plate and the transmission shaft this time, allowing room for the flywheel and chain to rotate.

The original support for the transmission shaft was to place a bearing in the front and a pillow block bearing at the stern where the rudder bracket is located. To make the shaft rotation smoother, we added a pillow block bearing to the back plate. However, we later found out that adding pillow block bearing restricted the system. Since two points can determine a straight line and adding extra pillow block bearings would increase energy loss, we had to choose between the bearing and the pillow block bearing. Choosing a bearing has the advantage of being lighter, but it produces sliding between the bearing and the transmission shaft, affecting transmission efficiency. This is because we use clearance fits rather than interference fits for easy disassembly. Using pillow block bearing also has sliding issues. Since it has screw holes, we can tighten the transmission shaft. Also, the pillow block bearings axle center can be adjusted which provides installation flexibility. Therefore, we decided to remove the bearing.

The entire gear assembly will be fixed on two vertical aluminum extrusions mainly because aluminum extrusions are lightweight and easy to assemble. The holes in the side plates are the positions for screw fastening, and the protruding part of the back plate will rest on the top of the aluminum extrusion to reduce the weight borne by the side plate screws.

The chainwheel has 48 teeth, the flywheel has 18 teeth, and both bevel gears have the same number of teeth. Therefore, the overall gear ratio is 24:9. In water, the estimated pedal rotation speed is 60 rpm, and the reasonable estimated propeller rotation speed is 160 rpm.



(a) (b) (c)

Figure 28 (a)Previous gearbox, (b)Gearbox front side and (c)Gearbox back side

II. Analysis

Assuming the transmitted force on the transmission shaft is 800N, the gear seat at both ends is subjected to a force of 400N each. After conducting an Ansys analysis, it was determined that the maximum strain is 8.0468×10-5 m/m, and the maximum deformation is 8.798×10-6 m. Both values fall within the acceptable range.

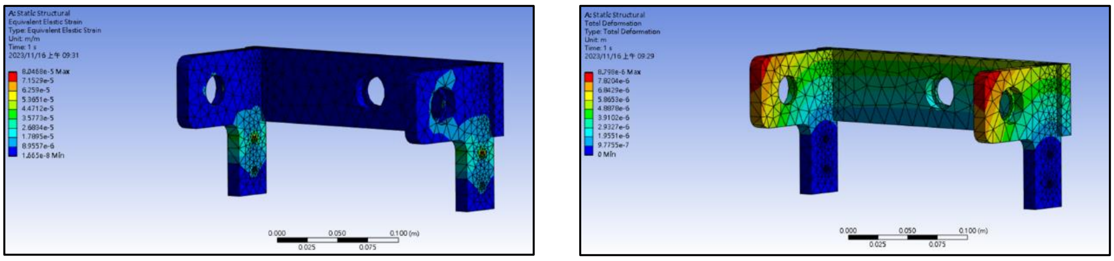


Figure 29 The result of Equivalent Elastic Strain (left picture) and the result of total deformation (right picture)

III. Manufacturing

To reduce weight, we have opted for aluminum alloy as the material for the gearbox. Since the transmission shaft is responsible for transmitting power, stainless steel is chosen to prevent deformation due to torque. There are C-shaped buckles on both sides of the transmission shaft to prevent the bearings from falling out and ensure axial stability. The bevel gears and flywheel coupling are fixed with keyways to allow rotation along with the transmission shaft. The size of bevel gears must be taken into consideration. Larger bevel gears could lead to collisions with the flywheel, but smaller one come with smaller bore diameter. We decided to counterbore the bevel gear to match the diameter of the transmission shaft.

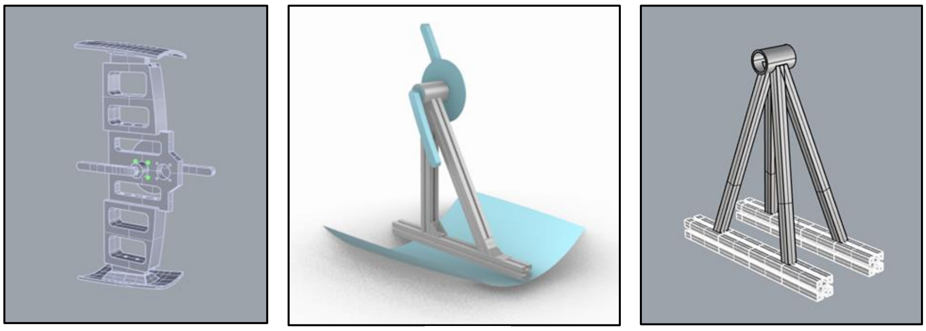
✧ Pedal Bracket

I. Design

Regarding the design aspects of the Pedal bracket, there are two main considerations: firstly, lightweight structure, and secondly, designing it to be adjustable in distance to accommodate the height of the pilot.

In the initial design, the Pedal bracket was too heavy, resulting in uneven weight distribution at the stern of the submarine. This made trim adjustment difficult, necessitating the addition of numerous buoyancy aids at the stern. Additionally, the fixed structure did not allow for distance adjustment, making it challenging for different pilots to find an appropriate pedal position and thus limiting maximum efficiency.

To address these issues, we implemented a design where the support is "fixed only at the bottom", reducing weight and allowing for distance adjustment by securing it with screws onto an aluminum extrusion rail. However, in the previous design, there was only one aluminum rail and two fixed points. Concerns arose about potential swaying of the support caused by the pilot's lower body movement while pedaling, leading to the final design incorporating dual rails and four fixed positions for increased stability. The point in the final design that the angle between each pair of front and rear cylindrical structures should not exceed 10 degrees (estimated), as this could result in pedal collision with the structure, impeding pedal movement.



(a) (b) (c)

Figure 30 (a)Previous version, (b)Initial design and (c)Final design

II. Manufacturing

To achieve lightweight construction, we opted for aluminum alloy as the material. However, during fabrication, the primary challenge we encountered was the difficulty in welding the four aluminum columns that comprise the support structure. Therefore, the manufacturer suggested using L-shaped aluminum bars instead, which would be easier to fabricate. The crucial aspect of fabrication lies in aligning the four support positions in pairs to ensure smooth adjustment of distance. Conventional welding techniques may not achieve such precision, so we sought out a manufacturer capable of precision laser welding for fabrication.

In the hollow cylindrical portion above, where the bicycle crankshaft and pedals need to be installed, we tapped the hollow circular section of the support structure. This serves as the bottom brackets for the bicycle's crankshaft. Once the support structure, pedals, and crankshaft are assembled, the chain is connected to the rear flywheel, completing the assembly.

(a)

(b)

Figure 31 (a)End product and (b)Pedal bracket and gearbox

Mechanical Controls

✧ Mechanical Control

We designed a joystick to control the rudders and stern planes. It features two independent directions of control. Our goal is to achieve precise control while ensuring that the joysticks can withstand the pulling forces.

We considered several materials for the control cable: brake cables, guy ropes, and curtain bead chains. The advantage of brake cables lies in their solidity and precise control. However, they require tensioning and are less maneuverable in tight spaces due to their rigidity. Guy ropes offer more flexibility and are easier to mount. Yet, they tend to elongate under force, leading to imprecise control. We also entertained the idea of using curtain bead chains for their feedback to the pilot. The beads can enable the pilot to feel the degree of turning. However, we are concerned about their strength and are also unfamiliar with tightening and wiring them. After carefully weighing the pros and cons, we ultimately decided to choose brake cables as our control cable.

The two rollers on the joystick control pitch and yaw. There are also two rollers on the rudder support structure corresponding to the joystick's rollers. The brake cables are clamped onto the rollers by screws and washers, allowing the joystick's roller and the rudder support structure's roller rotate simultaneously. Each roller has two brake cables attached to it for forward and reverse rotation. Brake cable tubes are used to allow the brake cables to move along a non-straight path. They can also keep dirt out of the brake cables, ensuring smooth movement. Brake cable stoppers are placed at the end of the brake cable tubes to prevent the brake cable tubes from moving. Motion can only occur on the brake cables not on the brake cable tubes. Otherwise, the turning angle will be less than expected. We use stick-on brake cable guides to fix the brake cable tubes on the side of submarine, making brake cable wiring clear and easy to manage.

We placed a spring in the middle of joystick to provide feedback to the pilot. The main part of the handle is made of alloy since turning require a lot of force. To provide the pilot with a comfortable grip, we designed a 3D printed object attached to the handle.

The material of joystick is aluminum alloy. Its strength meets the requirements, and it is lighter than stainless steel. While 3D printing is readily available, it tends to be more fragile and does not offer the same smooth motion as aluminum alloy.

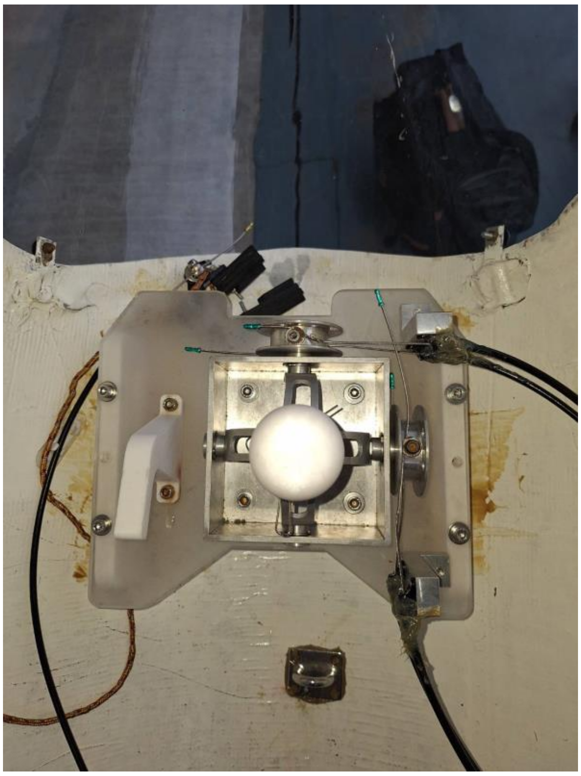


Figure 32 Joystick

Electrical Controls

✧ Electrical equipment

I. Joystick

PWM control signals are generated in the water by the driver controlling the x and y axes. This signal is transmitted to the microcontroller and processed into a control signal and a digital signal is generated using push buttons. Based on the last experience, a special waterproof design will allow it to be used underwater.

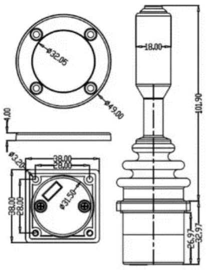


Figure 33 Engineering diagram of joystick

II. Step motor

The control signals from the lever are processed by the microcomputer and then exported to the driver, which is then configured with the relevant settings. The specification is used to control the digital motor to rotate the motor to generate torque to manipulate a series of power transmission devices. The rudder angle is controlled by the rudder position.

Performances	Stepping Motor	Servo Motor
Knowing the current direction	Combined drive	Combined Encoder
Maneuvering Difficulty	Easy	Difficult
Price	Cheap	Expensive
Torques	Small	High

Table 5 The comparison of motors

After trying to program the Encoder, we found that it was difficult to use a microcomputer to control it. We use stepper motor（OK57STH108-FS 57HY108-3004）.

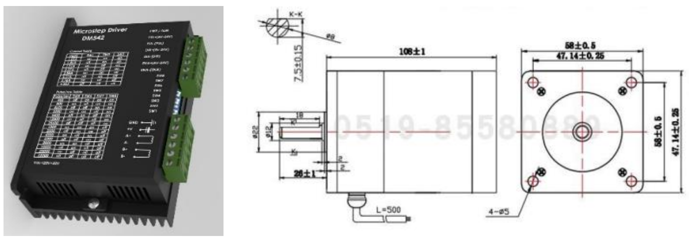


Figure 34 Stepping motor engineering diagram and the stereo view.

III. Step motor driver

It is used to output pulse, direction and brake signals to control the rotation of a stepper motor. It also protects the motor from abnormal output voltage. By controlling the specifications of the driver, it is possible to control the operating current of the motor, its speed and its output voltage.

IV. Panel

It is used to display data text and pictures. By connecting a micro controller, it can display information from other sensors or stepper motor control signals and data. The signals and data are processed and displayed on the panel. The panel is the largest TFT-LCD display in the market.

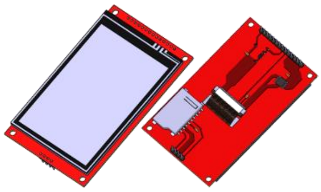


Figure 35 ILI9488 Panel

V. Microcontroller

i. Arduino Mega

It is used to process the gyroscope calibration and control the stepper motor operation, and the microcomputer has high processing power. Performance, memory, and other advantages are further selected to handle the huge amount of computational calibration.

ii. ESP8266 NodeMCU V1.0 ESP-12E Wi-Fi Module

After processing each sensor signal, the control board outputs a display signal to the panel. A wireless signal can be used to communicate with the outside of the watertight box to facilitate data processing for subsequent simulations. A joystick signal is processed into an actuation signal that is transmitted to the power unit.

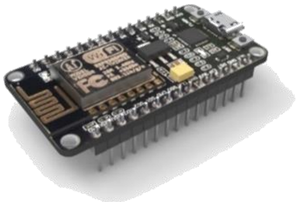


Figure 36 NodeMCU V1.0

VI. Watertight enclosure

The waterproof junction box ensures that the electrical and mechanical equipment is completely and safely protected in a closed and dry environment to support the stable operation of the equipment. The silicone O-ring in the lid prevents water from entering the box and damaging the device.

Four IP68-rated waterproof junction boxes are installed inside the submarine's cabin, taking into account the available space. The waterproof rating of IP68 means that it is completely dustproof and can be immersed in water up to a depth of 1m. The material is PC (Polycarbonate), a thermoplastic material. This material was chosen for its high degree of transparency, which enhances the driver's visibility of the panel.

Figure 37 Waterproof Junction Box

VII. Waterproof joint

According to the installation location will use two types of waterproof connector, only the size difference, because with the waterproof junction box, choose the waterproof level of the same IP68 model, detailed specifications are as follows.

Figure 38 Waterproof joint

The connector is a pull-out type connector for quick removal when adjusting the mechatronic device. O-rings are provided at each joint, including the gap between the connector and the box, to effectively prevent water ingress.

VIII.Gyroscope

The sensor combines a 3-axis angular accelerometer, a 3-axis accelerometer and a 3-axis magnetometer with a motion processor unit to provide accurate 3-axis attitude and motion tracking data.

Figure 39 BNO055

During use, environmental noise can lead to inaccurate values, so mathematical calibration is needed to ensure the accuracy of the values, in the human-powered submarine because of the need to use three-axis angular accelerometers and axial accelerometers need to be calibrated separately for these two:

- Angular Accelerometer Calibration

  The deviation correction utilizes a reference angle to numerically correct the measured value to the desired rotational matrix.

$$w_{measure} = R_{gyro} w_{idea} + w_{bias} + n_{noise}$$

$$Where \quad w = \left[w_x w_y w_z \right]^T, \quad R_{gyro} = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix}$$

$$w_{idea} = R_{gyro}^{-1} (w_{measure} - w_{bias} - n_{noise})$$

- Accelerometer Calibration

  Solve the calibration matrix using the sensor model with the sum of squares of the three-axis outputs and using Gaussian Newton's method.

$$A_{measure} = SA_{real} + B_{bias}$$

$$g^2 = a^2{}_{rx} + a^2{}_{ry} + a^2{}_{rz}$$

$$X_{k+1} = X_k - \alpha\left(\nabla^2 E(X)\right)^{-1}(\nabla E(X))$$

✧ Systematic operation

I. Control System

With the Arduino system as the signal control core, users can manipulate the related equipment to realize the control of the submarine rudder. Take the forward direction of the submarine as the target. Starting the NodeMCU board, giving the joystick DC5V after receiving two manipulation of digital signals to the NodeMCU and sending to another Arduino-mega board for controlling the stepper motors, which encountered NodeMCU can only be input to the signal below 3.3V, also only one analog channel and with other issue, which we uses a voltage regulator board and then divide the voltage, with four digital signals to switch between the multiple channels to solve those problems.

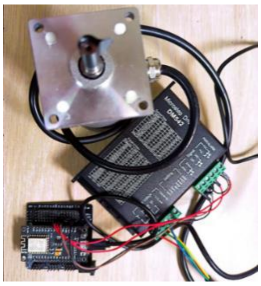


Figure 40 Stepping motor and its driver

II. Display System

The corresponding signals from the NodeMCU board enables the screen to update the resolution, and then the screen can update the resolution via the NodeMCU board. Data and pictures are displayed by overlapping patterns. In the first stage, we tried to use a touch screen. However, due to the difficulties of the underwater environment, with joystick interaction was finally used. In addition, after many tests, the panel can not only display text data, but also pictures, and slice and dice the pictures. The panel can also display small animations such as gifs, etc. The basic display interface has been structured, and a more humanized interactive interface will be considered in the future.

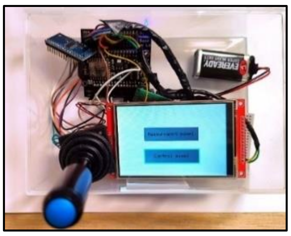


Figure 41 Control system basic model

III. Sensor System

The gyroscope mainly provides the attitude information of the submarine including the angular acceleration of x, y, z-axis, which can correspond to the Yaw-Row-Pitch of the human-powered submarine to provide the reference basis for the driver to control the submarine, and avoid the risk of the hull floating to the horizontal plane or sinking to hit the ground. Three-axis accelerometer can provide x, y, z-axis acceleration, through the integration can get the current human submarine current speed, can make the driver control the power output to avoid too fast to make the submarine out of control, the speed of the submarine again can get the current position of the submarine integration of this data is mainly used for the navigation system reconstruction, to reproduce the ship's sailing record and presented in the simulation system.

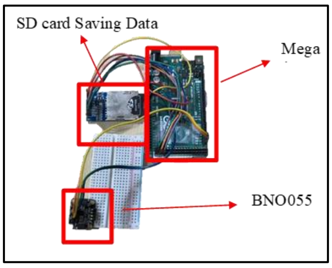


Figure 42 Actual Wiring

IV. Power System

Three 3.7V rechargeable batteries are connected in series to provide 12.1V power to the NodeMCU board. Each waterproof stepper motor is powered by a 22.2V lithium battery.

V. Watertight devices

By combining the above watertight devices with appropriate diameter cables, two Deli E&M systems can be connected: the main control system watertight device and the escape float warning system, each with independent power supply. The overall watertight design can be seen in the diagram below.

● Master Control System Watertight Installation

Equipped with a control system to control the servo.

✓ Box1: Loaded Panel, NodeMCU Hosting, W*H*D=20*20*10(cm)

✓ Box2: Loaded servo, Mega mainframe, gyroscope, W*H*D =20*20*10(cm)

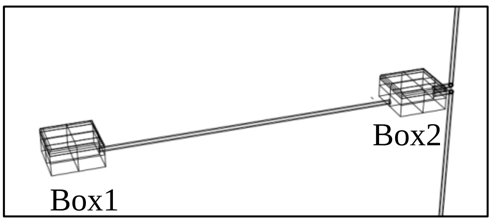


Figure 43 Integration of watertight devices in the main control system

● Escape Float Warning

Detecting the activation or deactivation of the escape mechanism

✓ Box3: Loaded Reed Switch, W*H*D = 4.5*6.5*7(cm)

- ✓ Box4: Loaded Battery, Led Lights, Resistance, W*H*D = 8*11*7(cm)
- ✓ Magnet: used to trigger reed switches

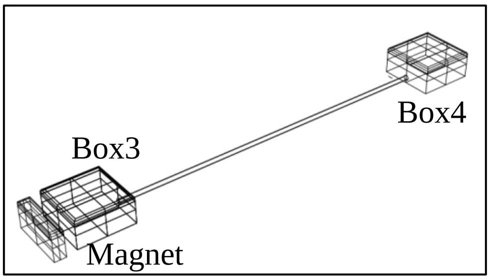


Figure 44 Escape Float Warning System

✧ Watertightness Test

I. The Water Chamber Test

Using the water chamber of the museum to do pressure test on the watertight box aims to be able to withstand a water depth of 10 meters, so the default withstand pressure value is 2.0kg/cm^2.Therefore, the preset withstand pressure is 2.0kg/cm^2. Inside the watertight box, we put materials that can easily identify the water absorption (e.g. toilet paper, test paper ....).The experimental results after pressurization by the water chamber showed that the watertight box can effectively achieve waterproof effect at 10m underwater.

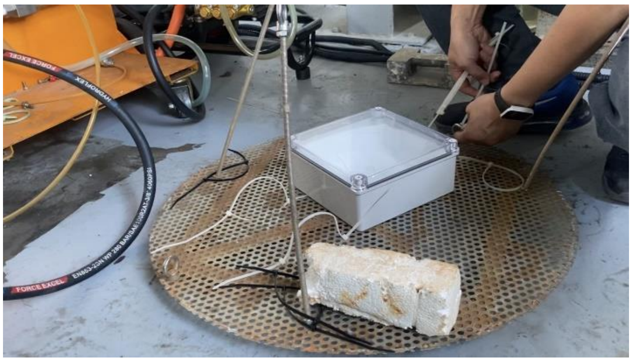
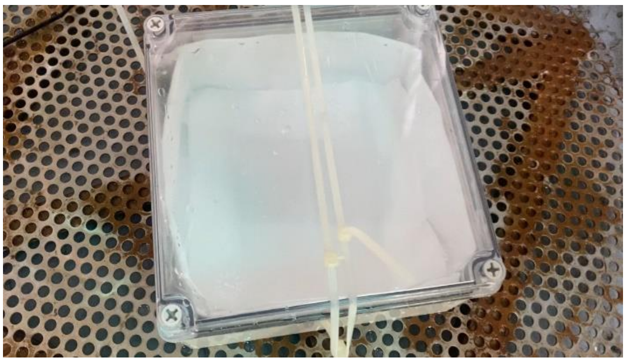
	
STEP1: Fixed to the underwater network	STEP2: Vacuum
	
STEP3: Water filled and pressurized to 2.0kg/cm^2	STEP4: Checking for water leakage

Figure 45 Water pressure test of watertight box

II. Actual Underwater Test.

After the holes were drilled, the waterproof junction box was brought into the practice pool for testing, and the results of the initial stand-alone box test were as follows.

Test Depth: 3m.

Test Temperature: 24℃

Soak Time: 20min.

Waterproof Junction Box Size (cm)	20 x 20 x 10	8 x 11 x 7	4.5 x 6.5 x 7
Water intake or not	Yes, from the lid.	No	No

Table 6 The result of actual underwater test

Upon submerging four independent waterproof junction boxes, it was found that the two larger boxes leaked due to insufficient locking points on the covers, while the smaller boxes remained watertight. To fix the issue without compromising the boxes, C-type clamps will be added on all four sides to improve the seal. The joints will be filled with silicone to provide double protection. The completed wiring of the escape system and the two small watertight boxes were tested in a swimming pool (depth: 3m, temperature: 24°C) and were able to run steadily for over an hour without any water ingress.

Figure 46 C-type fixed clamp (Image Source:親淨科技)

✧ Problem

After several underwater tests, we found achieving watertightness is more complex than expected. Large watertight boxes, lacking middle locking screws, allow air to expand and compromise the seal. Despite using C-type clamps, joystick holes in Watertight Box 1 remain vulnerable. Testing with batteries and other explosive components underwater is unsafe. After two hours at a three-meter depth, water droplets appeared inside. Although the system worked well on land, using Li-po batteries in the competition is too risky due to potential water exposure.

Safety System

✧ Buoyancy Warning System

The Buoyancy Warning System consists of an escape handle, buoy, rope, and buoy holder. It is designed to assist submarine pilots in notifying the shore-based security guards promptly when encountering dangerous incident.

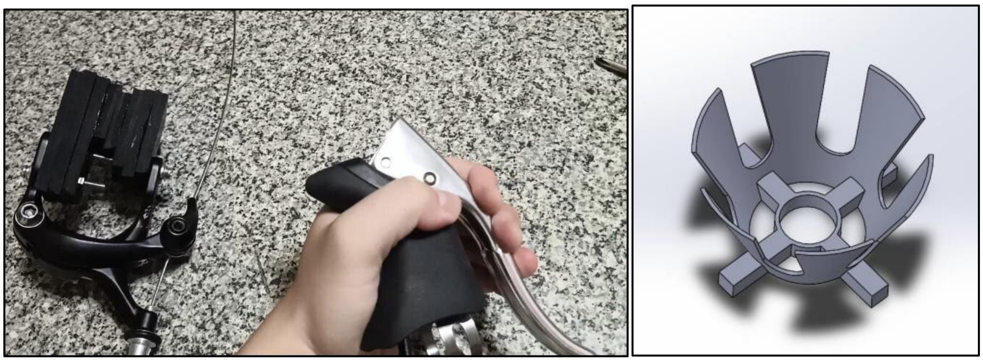


Figure 47 The buoyancy warning system

✧ Safety Belt & Pilot's Wearing

Because the driver is completely suspended under buoyancy when driving, the purpose of installing a safety belt is to ensure that the driver can maintain a certain position and not rush forward with sudden braking, without hindering the driver's normal driving, and can operate the submarine safely. The main structural design is to install two safety belts to the cabin side, so that the driver's shoulders can be supported and cushioned during sudden braking. The material is selected from common safety belt materials, which are lightweight and durable to ensure sufficient impact support underwater.

The design of the driver's straps is to fix the spare gas cylinder on the driver's back and prevent the gas cylinder from moving at will during driving, which will cause the driver's operational mistakes. As a whole, the straps are mainly made of lightweight and durable materials, such as nylon polymers like seat belts, to ensure the durability and comfort of the straps. Considering the principle of ergonomics, an adjustable strap is designed to adapt to different drivers' body shapes and operating preferences. Designed as a vest, it increases the area of the driver's back to disperse the weight of the gas cylinder and increase the stability.

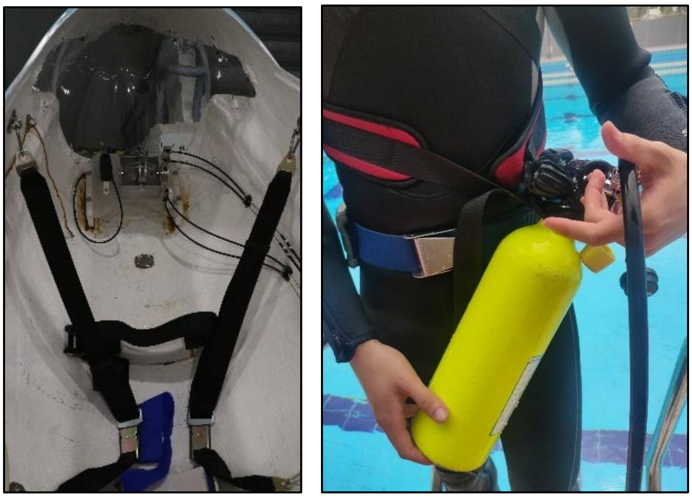


Figure 48 The safety belt and the pilot's wearing

Team Finances

✧ Sources of funding

Our major source of funding comes from Yen Tjing Ling Industrial Development Foundation and Karmin, they both contributed NT$500,000 to our group, while the ministry of education subsidized us with NT$300,000. In addition to direct financial contributions, we also got sponsorships in terms of equipment. For example, Problue gives us five sets of diving equipment, Tanko provides us with tool carts and storage boxes, and other processing manufacturers like Wild-force, Tong-chi, Hondar offer us discounts. Although some discounts are not that much, they still provide us with significant assistance.

✧ Statement of cash flows

The following is the statement of cash flows for our submarine team during the construction, computed using the direct method format :

National Cheng Kung University Human Powered Submarine Team
Statement of Cash Flows
For Period From September 1, 2022 to May 31, 2024

Cash Received from Sponsor-Karmin	NT$500,000
Cash Received from Sponsor-Yen Tjing Ling Industrial Development Foundation	600,000
Casd Received from Ministry of Education Republic of China (Taiwan)	300,000
Hull	(216,976)
Electronics	(22,764)
Mechanical Components	(93,912)
Tools	(10,714)
Freight(air and sea)	(350,000)
Airfare	(500,500)
Diving Expense	(130,679)
Personnel Expense	(126,963)
Marketing Expense	(29,090)
Administrative Expense	(1,398)
Miscellaneous Expense	(4,190)
Net change in cash	(87,186)
Cash , beginning of period	20,000
Cash , end of period	NT$(67,186)

Table 7 National Cheng Kung University Human Powered Submarine Team Statement of Cash Flows

✧ Sponsors