Singapore Institute of Technology Human Powered Submarine

MAKO

Design Report

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1. Executive Summary

This report presents the comprehensive development and preparation process of the SIT Nautical Knights' first-ever human-powered submarine, crafted for participation in the European International Submarine Races (EISR) 2024. Our team, consisting of ten dedicated students from the Naval Architecture, Marine, and Offshore Engineering (MNO & NAME) programs at Singapore Institute of Technology (SIT), is pioneering Singapore's entry into this biannual engineering and sporting competition.

Key Components and Design Strategy
The development of our submarine was segmented into three major phases:

1. **Design and Planning**: Extensive brainstorming sessions and technical meetings were held to conceptualize the submarine's design. Emphasis was placed on ensuring feasibility, compliance, and performance. The submarine was divided into four primary subsystems: propulsion, control, safety, and hull.
2. **Fabrication and Integrations**: With the support of our technical sponsors, we utilized specialized fabrication facilities to construct and integrate the various submarine subsystems. For many of us, this was our first experience with hands-on fabrication techniques. This phase involved learning new skills, overcoming technical challenges, and ensuring seamless integration of all components.
3. **Testing and Preparations**: The final stage involved integrating all subsystems and preparing the submarine for the race. This included rigorous testing, final checks, pilot training, and logistics planning for the race in Gosport, UK.

Challenges and Solutions
Throughout the project, our team encountered several challenges, including:

- **Resource Limitations**: Limited online resources on human-powered submarines required us to approach the design process innovatively, taking inspiration from ships, planes, aquatic life and conventional underwater vehicles.
- **Balancing Academic Commitments**: As students, balancing our academic responsibilities with the project's demands was challenging. We overcame this by maintaining clear communication, setting realistic deadlines, and supporting each other.
- **Technical Hurdles**: We faced various technical hurdles, from design complexities to manufacturing constraints. Collaboration with industry experts and continuous testing helped us address these issues effectively.

Benefits and Implications
The successful development and participation in the eISR 2024 offer multiple benefits:

- **Educational Impact**: This project has given us practical experience in engineering design, project management, and teamwork.
- **Industry Collaboration**: Working with industry partners has enhanced our understanding of real-world engineering challenges and solutions.
- **National Representation**: As the first Southeast Asian team to participate in the EISR, we proudly represent Singapore on an international platform, showcasing our country's capabilities in innovation and engineering.

Conclusion
The SIT Nautical Knights are ready to compete in the eISR 2024 with a meticulously designed and tested human-powered submarine. This project exemplifies the synergy between academic learning and practical application, setting a precedent for future engineering challenges. We are confident that our efforts will make a mark in the competition and inspire future generations of engineers.

2. List of Abbreviations

3D	3 Dimensional
2D	2 Dimensional
CFD	Computerised Fluid Dynamics
CAD	Computer-Aided Design
EISR	European International Submarine Races
SMB	Surface Marker Buoy
MNO	Marine, Naval & Offshore Engineering
NAME	Naval Architecture & Marine Engineering
SIT	Singapore Institute of Technology
LED	Light-Emitting Diode
RPM	Rounds per Minute
PLA	Polylactic Acid
HDPE	High-Density Polyethylene
PE	Polyethylene
V	Velocity
L	Length
Lf	Forebody Length
Lm	Midbody Length
La	Aftbody Length
A0	Expanded Area
Aw	Waterplane Area
R	Resistance
Rvp	Viscous Pressure Resistance
Rf	Frictional Resistance
D	Diameter
D1	Pilot 1
D2	Pilot 2/ Support Diver
D3	Dive Leader
D4	Support Diver (port)
D5	Support Diver (starboard)
D6	Support Diver (stern)
NDU	Naval Diving Unit
CO2	Carbon Dioxide
ROV	Remotely Operated Vehicle
COG	Centre of gravity
MoSCoW	Must-have, should-have, could-have, and won't-have, or will not have right now

3. List of Tables

4. List of Figures

5. Table of Contents

6. Introduction

This report aims to detail the journey and experiences of the SIT Nautical Knights team in the design, fabrication, and testing of a human-powered submarine for the European International Submarine Races (eISR). This project has been undertaken by a team of undergraduate students from the Singapore Institute of Technology (SIT), driven by a passion for engineering, innovation, and underwater exploration.

Team Formation and Motivation
The SIT Nautical Knights were formed through a shortlisting process in September 2023. The selection culminated in a 'proposal night' where candidates presented their initial research, vision, and concepts for a human-powered submarine. This event served as a platform for team members to demonstrate their commitment and innovative ideas.

The team was motivated to participate in this prestigious competition due to the unique opportunities it presented, such as international exposure, learning new skills and hobbies, and the challenge of working on a dynamic and multifaceted project. The competition also offered a chance to delve into a new and exciting sport.

Team Members and Roles
- Ryan: Final Year, Captain and Dive 2IC
- Karthik: Final Year. Vice-Captain and Dive IC
- Jolyn: Final Year, Team Manager and Secretary
- Xavier: Second Year, Controls and Technical Lead
- Jacob: Final Year, Hull Lead and Public Relations
- Matthew: Final Year, Propulsion and Logistics
- Dong: Second Year, Fabrication and Support Diver
- Irfaan: Second Year, Fabrication and Pilot Assistant
- Jun Rui: Second Year, Safety Lead and Pilot
- Chester: Second Year, Controls and Pilot

Project Timeline
- Project Kick-off: 23rd October 2023
- Beginning of Fabrication: 31st January 2024
- Testing Phase: 2nd May 2024
- Shipping Out Submarine: 15th June 2024

Support and Mentorship
The team received invaluable advice and support from their professors and industry professionals, who acted as technical sponsors. SIT provided institutional support in the form of financial assistance, venues, and after-office-hours access to facilities. This support was instrumental in overcoming many hurdles the project faced.

Vision and Long-Term Goals
The team's vision and long-term goals include:
- Attracting young people to the underwater world and fostering an interest in engineering.
- Creating a learning space for engineering students through future participation in submarine races.
- Participating in other international submarine races besides the eISR.

Professional and Personal Growth
This project has elevated the team's understanding of human-powered submarines, manufacturing techniques, mechanical systems, and hydrodynamic behaviour. Professionally, the team has developed skills in project management, problem-solving, critical thinking, professional networking, and presentation and communication skills.

In conclusion, the SIT Nautical Knights are proud to present their journey in this report, showcasing the dedication, hard work, and learning that have gone into preparing for the eISR competition. The team is excited to represent Singapore on this international stage and to continue advancing in the field of human-powered submarines.

7. Design Philosophy

"In naval architecture, the simplest solution is often the best one, balancing form, function, and practicality."
— Howard I. Chapelle

Our team's design philosophy is rooted in analysis and discussions concerning the race requirements, team objectives, and constraints of designing a competitive submarine for racing. The MoSCoW technique has been instrumental in prioritizing these elements.

Race submarine design requirements
The submarine must satisfy all stipulated requirements outlined in the rule book, specifically Rule No. D1 – D46. The key requirements for defining the design parameters are detailed below.

Table 7-1 Design Requirements

Rule No.	Requirements	Categories
D3	Operated by one or two pilots.	**Must have**
D4	Length <= 5.5 m	**Must have**
D5	Width <= 1.5 m	**Must have**
D7	CoG (w/o water) between 2.1 and 3.1 m from the bow or stern	**Must have**
D12	Propulsion system must be directly coupled to the pilot(s)	**Must have**
D16	The energy used for propulsion is produced by the pilot(s)	**Must have**
D31	The submarine pilot's face must be visible from outside the submarine	**Must have**
D32	The submarine must be equipped with a high visibility emergency pop-up (surface marker) buoy.	**Must have**

As can be seen above, the race rules provide extensive latitude in design to foster flexibility and encourage innovation.

Team objectives
A vote was conducted to determine team priorities, and the outcomes were categorized using the MoSCoW method. The summarized results are as follows.

Table 7-2 Team Objective

Team Objectives	Votes (✔)	Categories
Safety	✔✔✔✔✔✔✔✔✔ ✓✔✔	**Must have**
Overall winner (First & Runner up)	✔✔✔	**Could have**
Week's Top speed 24th June – 5th July	✔✔✔✔✔✔✔✔✔	**Should have**
Agility & Endurance	✔✔✔✔✔	**Could have**
Award for Innovation		**Will not aim**
Best Communication	✔✔✔✔✔	**Could have**
Sustainability		**Will not aim**

Constraints
The analysis above has guided us in defining our design parameters and priorities. Additionally, the team encountered two significant constraints.

- The SIT Subrace project commenced in October 2023, allowing us approximately three months for the design phase. Being newcomers to the competition, we initially had limited inputs for the design. Thus, the tight schedule presented one of our primary challenges.
- At the project's outset, we lacked sponsorship and faced considerable uncertainty regarding the budget. Therefore, the design needed to prioritize cost-effective solutions, utilizing fabrication equipment available in the university workshop.

Design principle and Workflow
Based on the above analysis and considerations, the team has established a design principle aimed at achieving a simple and practical solution for the submarine. Departing from the traditional naval architecture design spiral, we opted for a straightforward sequential design process. This decision stems from the fact that a human-powered submarine, unlike commercial or naval ships, features fewer system components and simpler interactions among them. Therefore, it is feasible to optimize each subsystem sequentially, emphasizing efficiency and avoiding iterative design loops, which is crucial for project success.

The design workflow is outlined below. Given that achieving maximum speed ranks as a primary objective for the team, hull form optimization was prioritized immediately after selecting the hull concept and pilot position. Subsequently, the propulsion system and propeller design will be tailored to complement the optimized hull form, ensuring they operate efficiently within the spatial constraints of the hull. Similarly, the optimization of control and safety systems will be conducted while adhering to the parameters established in earlier design stages.

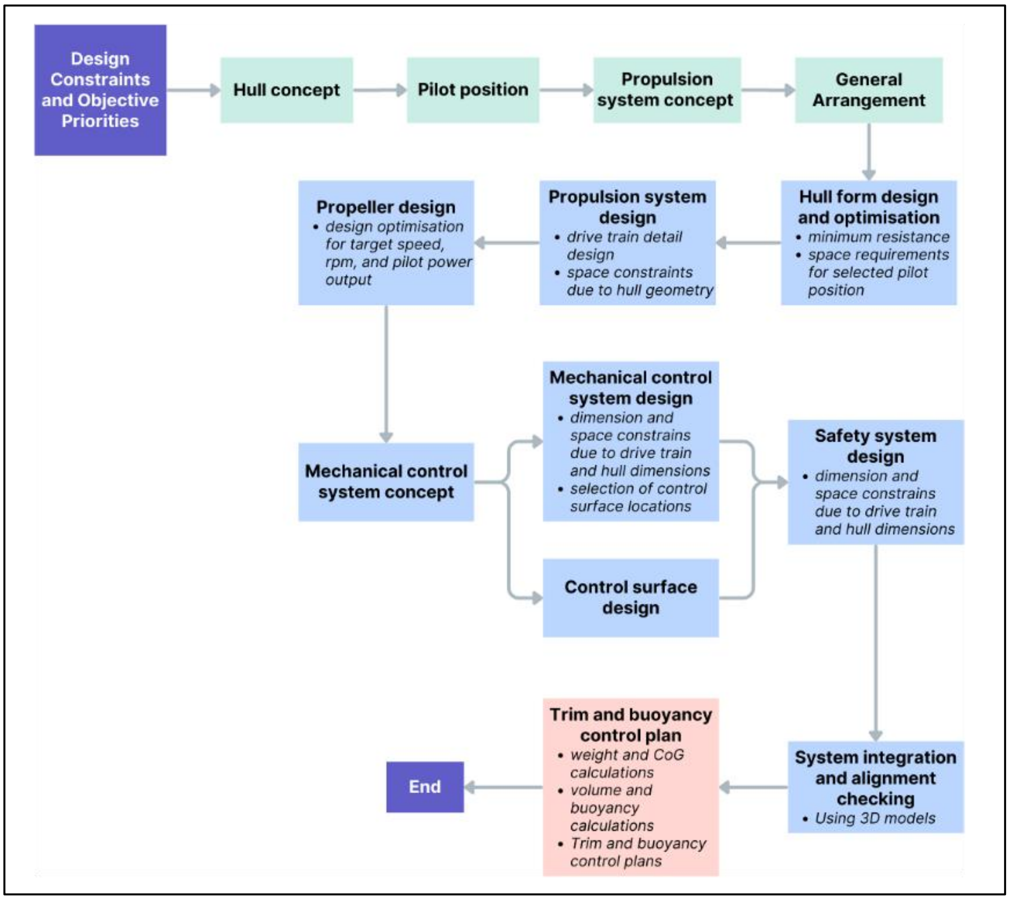


Figure 7-1 Design Flowchart

8. Design Options

8.1. Hull Shape

In our case the total resistance of a fully submerged submarine is composed of frictional resistance and viscous pressure resistance, whilst wave resistance is negligible due to our operating area being Qinetics Basin. A Research Article discussing CFD Analysis of the bow shapes of submarines, which also used these assumptions, allowed us to narrow down the selection to 3 shapes; Cylindrical, Elliptical and Conic-Elliptic.

Table 8-1 Main assumptions of models

V (m/s)	L (m)	L_f (m)	L_m (m)	L_a (m)	D (m)	L/D	Bow Shape
10	6	3	1	2	1	6	Different for each model

Table 8-2 Models of Stage A

	Bow shape Profile	Aw	A0	Volume
A1	Elliptical	13.87	0.785	3.53
A2	Conic-Elliptical Bow	14.41	0.785	3.03
A3	Hemisphere	15.8	0.785	3.53

Table 8-3 Resistance components of Models in Stage A

Bow shape	R	Rvp	Rf	Rvp/R
Elliptical	2336	620	1716	26.5
Conic-Elliptical Bow	2416	608	1808	25.2
Hemisphere	3280	1360	1920	41.5

In summary of the above results,

Table 8-4 Summary of results

Elliptical Bow	Conic-Elliptical Bow	Hemisphere Bow
Has the best acceptable results in terms of resistance coefficients and hydro-volume efficiency (ratio of resistance to volume)	Consists of a conic section capped with an elliptic curve, tangent to each other. Has similar and almost optimal results as the elliptical bow in terms of resistance and hydro-volume efficiency.	Has the highest overall resistance however, while it lacks in hydrodynamics it provides the largest internal space. Most naval submarines and ROVs have a cylindrical parallel middle body shape.

Thus, the elliptical and conic-elliptical bow shapes emerge as the most hydrodynamically efficient designs when paired with a cylindrical middle body, based on the CFD analysis and comparisons presented in the search results. The Conic-Elliptical Bow was ultimately selected due to the additional internal space it provided.

8.2. Control System (Electrical vs Mechanical)

8.2.1. Comparison of Pilot Controls

During the initial design phase, we planned to implement electrical and mechanical control systems. However, the team needed to decide which system would be our primary control method. When comparing the two options, we considered several factors, including space constraints, potential design conflicts with other components, such as the drivetrain, and the placement of our control system. Furthermore, because we were less experienced in dealing with mechanical systems, we felt more comfortable designing an electrical system. Ultimately, we concluded that an electrical system would be more advantageous and more accessible to implement due to its greater flexibility, modularity, and more straightforward internal layout.

The significant benefit of choosing the electrical system includes increased accuracy and control over the submarine's pitch and yaw, the ability to implement a human-machine interface (HMI) for pilots to monitor speed, position, and the angles of yaw and pitch, and the capacity to incorporate code that autonomously combats rolling motion. These features are essential for reducing the pilot's physical and mental load, especially when navigating the slalom obstacle course.

However, the electrical system presents a critical failure point when operating electrical components in a 5-meter pressurized wet environment. Therefore, we decided to integrate electrical and mechanical systems into the submarine, with the mechanical system as a backup.

Table 8-1 that shows a clearer overview of the differences of Mechanical vs. Electrical control system and highlights the additional benefits & drawbacks of each system.

Table 8-5 Mechanical vs. Electrical control system

	MECHANICAL	ELECTRICAL
Cost	Low	High
Reliability	High	Average (Reliable only when properly waterproofed)
Yaw and Pitch accuracy	Low	High
Maintenance	Low	Low
Weight	Heavy	Light
Complexity	High	Low
Ease of Implementation	No	Yes (Since components can be shifted around without many constraints)
Modular	No	Yes
Pilot's Fatigue	Increased	Reduced
Sensor Feedback	No, however Pilot can gauge angle of attack based on feel	Yes, Pilot can see the angle of attack and more information on the LED Screen
Benefits	NIL	1. Ability to autonomously combat roll
Drawbacks	NIL	1. Critical Failure point: Water ingress to any electrical components 2. Electrical Safety Hazard (Risk of short-circuit)

Below is an in-depth explanation of why and how we implemented and integrated both the Electrical and Mechanical Control Systems into the submarine.

Backup Control System:
Due to the numerous advantages of the electrical system over the mechanical system, we decided to make the electrical system our primary control system and the mechanical system our secondary control system. The mechanical control system is designed as an add-on to the existing electrical system backbone, eliminating the need to swap any components if we need to switch to the mechanical system. This integration is crucial for a pioneering project like this, allowing us to focus on one system while ensuring a backup is in place. If the chosen system fails during the race, having a backup ensures we can still participate in other races that day.

Simplicity:
For the electrical system, we designed a direct drive control for the four fins, with a 3D-printed custom enclosure box for mounting and waterproofing the servos. For the mechanical system, the four fins are controlled using three levers connected through multiple linkages.

Modularity & Ease of Maintenance:
The electrical system is highly modular, allowing us to foresee and manage maintenance efficiently. Faulty components can be swiftly replaced by unplugging the dry mate connector, removing the faulty component's box, installing a new component's box, and reattaching the dry mate connector. The mechanical system, while not modular, includes a linkage that can extend and retract slightly, allowing for minor adjustments to calibrate both the control lever and the control fins to a neutral position in case of manufacturing discrepancies in the connecting rods.

Waterproofing of the Electronic Components:
We encased one Arduino board, four servo motors, one 7000mAh battery, and one "Power Cutoff" switch in an IP68 waterproof enclosure, sealing any potential water ingress points with marine-grade sealant. Additionally, we added water-ingress protection for the servo motor by applying marine-grade grease to the shaft's opening. Despite these measures, achieving consistent 100% waterproofing for all electrical components remained a significant challenge and proved to be the Achilles heel of the electrical control system.

8.3. Propulsion System

8.3.1. Transmission

Shaft vs Chain Transmission
A comparison was made between shaft and chain transmissions, considering factors such as cost, maintenance, efficiency, weight, complexity, availability, and suitability for the current application. The analysis showed that a chain transmission was more advantageous due to its lower cost, higher efficiency, lower weight, lower complexity, and better suitability for the submarine's requirements. (Table 8-2)

Table 8-6 Comparison of shaft vs chain transmission

	Shaft transmission	**Chain transmission**
Cost	High	Low
Maintenance	Low	Moderate (need to clean and lubricate)
Efficiency	Moderate (20-25% loss)	High (1-4% loss)
Weight	High	Low
Complexity	High	Low
Easily available	No	Yes
More suited to current purpose	No (Requires high torque applications)	Yes

Gear Types
Different gear types, including spur gears, helical gears, and bevel gears, were evaluated based on their characteristics, such as application, benefits, and drawbacks. We do have a dilemma between helical gears and bevel gears. However, the team believes that bevel gears were more accessible and easier to work with, which aligns to our objectives. (Table 8-3)

Table 8-7 Comparison of characteristics of different types of gears

Characteristics	Spur Gears	Helical Gears	Bevel Gears	Worm Gears
Application	Low-Medium Speed (3600 RPM)	High Speed Applications	Transmit power at an angle (Usually 90°)	Transmit power at 90° angle/ non intersecting shafts
Benefits	Cheap Production Simple Design Easy Maintenance	Can carry more load compared with spur gears Smoother operation Quieter operation	Efficient power transfer between non-parallel shafts.	"Produces thrust load" Good for high shock load applications
Drawbacks	Efficient at power transmission, biggest losses will be due to friction	Similar to Spur Gear, more complex design and fitting	Similar to Spur Gear	Lowest Efficiency and other stresses

8.3.2. Propulsion

In terms of choosing the most suitable propulsion, the team came up with several options, but we narrowed it down to two options. One of which uses the Contra-Rotating Propeller, and the other uses the Single Screw Propeller. Based on past subrace teams we were able to understand the mechanism of the contra-rotating propeller. However, due to time constraints, we went for a simpler approach. Therefore, the decision was straightforward, and we went for a single-screw propeller concept.

8.3.3. Material Selection

As we design the drivetrain, we aimed to achieve a balance between lightweight construction and reliability, and cost efficiency, especially considering the underwater operating conditions. Therefore, we strategically integrated mainly aluminum and stainless steel throughout the drivetrain components.

Usage of Aluminum

Aluminum was chosen as the primary material due to its lightweight properties and corrosion resistance. Therefore, aluminum extrusion profiles were used to form the frame to mount multiple systems. In addition, we also utilized aluminum plates to provide a foundation to integrate the pillow blocks. To further reduce the weight, cutouts were done wherever possible, without compromising the structural integrity.

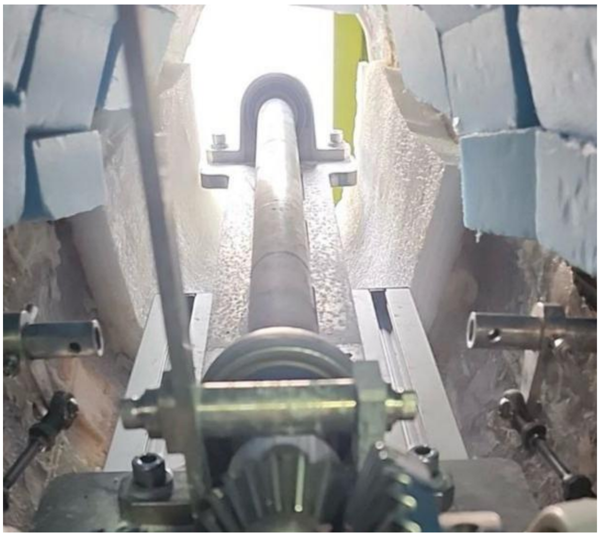


Figure 8-1 Aft of the drivetrain

Stainless Steel Usage

While aluminum provided the lightweight foundation, we incorporated stainless steel in critical areas or high-stress components requiring additional strength and durability, while still maintaining space efficiency. Some key areas namely:

- Bevel gears
- Propeller shaft
- Chain and sprocket
- Bottom bracket
- Crank arms
- Shoulder brace
- Gusset plate
- Mounting plate of control mechanism
- Mechanical rods for control system (Minimal flex and less likely to undergo plastic deformation)

This hybrid approach to material selection, combining the lightweight properties of aluminum with the strength and durability of stainless steel, allowed us to create a drivetrain that is both lightweight, yet reliable. However, we also explored alternative materials to enhance cost efficiency. Utilizing nylon pillow blocks helps maintain lightweight characteristics and anti-corrosion properties. Most importantly, nylon pillow blocks are more cost-effective compared to using entirely stainless-steel pillow blocks.

8.3.4. Material Selection of Propeller

Various materials were considered for the propeller fabrication. Our focus was to create something that was light and easily accessible. This easily narrowed down our options to either Polylactic Acid (PLA) or Aluminum. We decided to work with 3D-printed propeller due to the following reasons:

- Cost-effective
- Customization
    - We were able to control the propeller's weight, enabling us to improve efficiency and performance by reducing it.
- Rapid prototyping
    - This method allowed us to produce numerous propellers for testing in a short period of time, facilitating the iterative process of refinement and optimization.
    - In addition, we were able to easily create spares in case it gets damaged, which significantly reduces our downtime and maintenance costs.
- Experience
    - Some of our team members have experience with 3D-printing which boosts our confidence and its reliability
    - We have existing connection who have experience in production of 3D-printed propellers

9. Engineering Aspects & Design Details

9.1. Hull

9.1.1. Hydrodynamics

To determine the parameters of our submarine, we used an optimal fineness ratio of 6 as a benchmark. The fineness ratio (L/D) is defined as the ratio of the total length to the maximum diameter of the body. According to Figures 3 and Figure 4 from the referenced paper, it can be observed that as the fineness ratio increases, the drag decreases up to a certain point. Beyond this point, the drag force starts to increase. This occurs because, as the fineness ratio increases, the body becomes more streamlined, reducing back-pressure. However, as the fineness ratio increases and the diameter remains fixed, the overall surface area also increases, which in turn increases surface friction. Therefore, the fineness ratio at which the total drag is minimized is 6 for conical, elliptical, and ogive-shaped hulls. For a submarine with a parallel midbody hull shape, the optimum fineness ratio is 7.

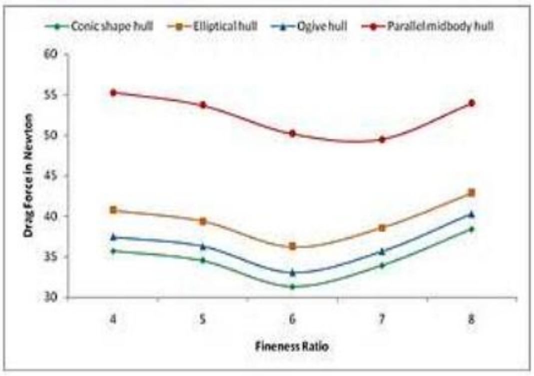


Figure 9-1 Optimum Fineness ratio for different shapes

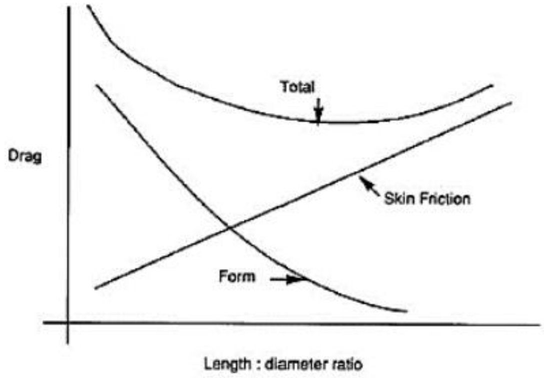


Figure 9-2 Fineness Ratio Relation to Drag

The bare hull design is done by using the bow form equations called hull envelope equations. The total length of the hull is divided into forebody (Lf) and the after-body (La) as shown in Figure 5

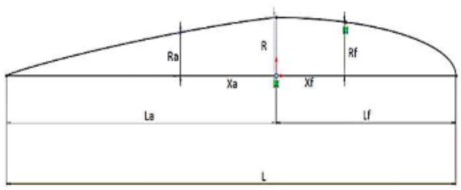


Figure 9-3 Bow Form

The curve of the fore body is elliptical and that of the after body is conical. The length of the fore body is 40% of the total length and the aft body is 60% of the total length. The equation of the for the fore and aft body curves are determined by 2 parametric equations as follows.

$$R_f = R\left[1 - \left(\frac{X_f}{L_f}\right)^n\right]^{\frac{1}{n}}$$

$$R_a = R\left[1 - \left(\frac{X_a}{L_a}\right)^n\right]^{\frac{1}{n}}$$

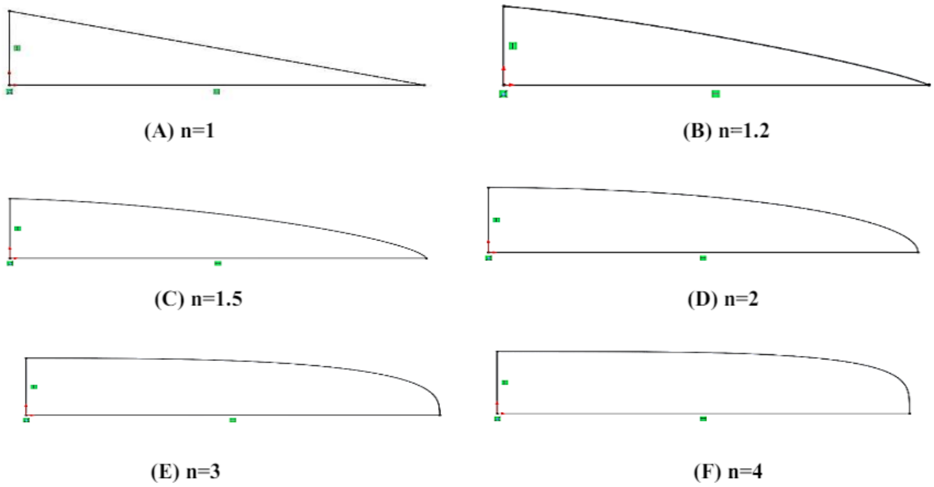


Figure 9-4 Variation of Shape in accordance with 'n'

By adjusting the parameter 'n' in equations (1) and (2), we can manipulate the shape of the resulting curves. As the value of 'n' increases, so does the degree of the curve. When 'n' is between 1 and 1.5, the curve resembles a cone, while a value of 2 produces an elliptical curve. The figures above illustrate the various curve shapes obtained for different values of 'n'. Utilizing the above equations allowed us to illustrate the desired shape using the points generated.

Table 9-1 Curve line Coordinates

x	y	z
3.59	0.00000	0.00000
3.63	0.00172	0.00187
3.43	0.04373	0.04770
3.23	0.07662	0.08358
3.03	0.10616	0.11582
2.83	0.13345	0.14558
2.63	0.15893	0.17338
2.43	0.18281	0.19943
2.23	0.20517	0.22382
2.03	0.22599	0.24653
1.83	0.24510	0.26738
1.63	0.26207	0.28589
1.43	0.27500	0.30000
1.23	0.27043	0.29501
1.03	0.25624	0.27954
0.83	0.23067	0.25164
0.63	0.18914	0.20634
0.43	0.11559	0.12609
0	0	0

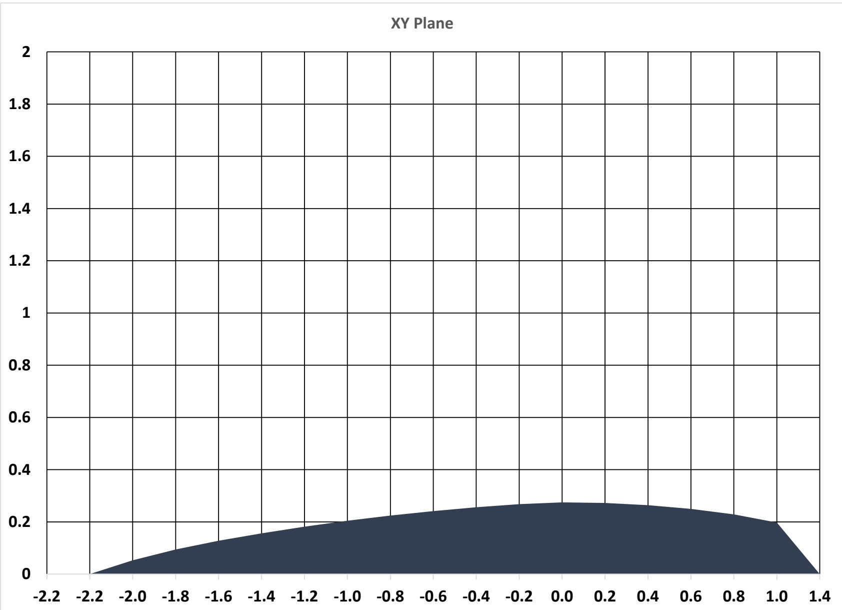


Figure 9-5 X-Y Curve Coordinates

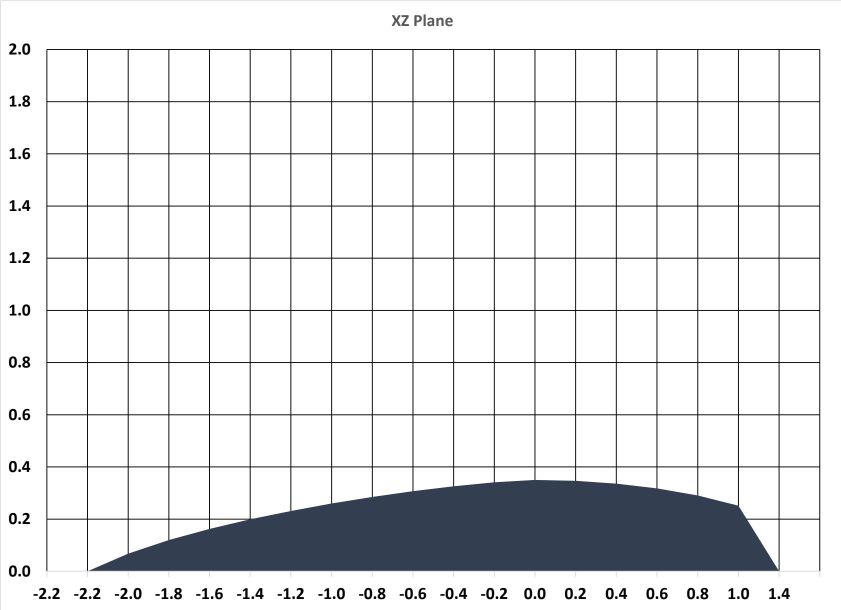


Figure 9-6 X-Z Curve Coordinates

Finally, the curve coordinates were imported into SOLIDWORKS, enabling us to generate a 3D model of the hull. This model served as the foundation for iterative refinement through CFD simulations. By leveraging the advantages of a digital twin, we were able to precisely adjust the hull's geometry and optimize its hydrodynamic performance by analysing fluid flow around the hull, identify areas of high drag, ensuring that the design met all necessary specifications.

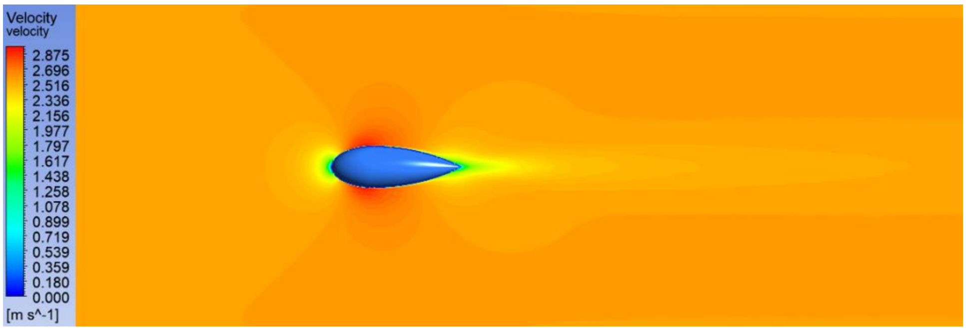


Figure 9-7 CFD Iteration 1

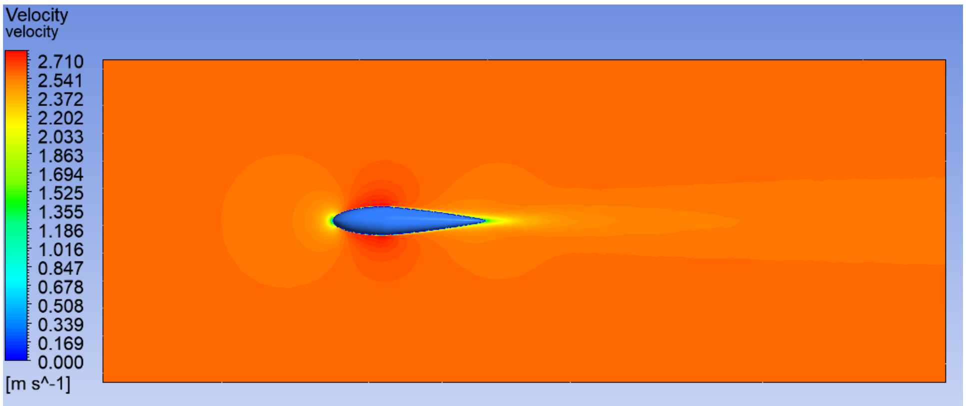


Figure 9-8 CFD Iteration 2

9.1.2. Hatches

Pilot Hatch
A general pilot hatch designed to fit the size of our pilots.

- provides a very large hatch giving ideal accessibility to the pilot in an emergency
- Main access hatch, which is used by the pilot to get in and out of the submarine, is locked using a mechanical latch.

Maintenance Hatch
An additional larger removable hatch on the top half of the submarine, was implemented into the design to allow easier access for maintenance whilst the submarine is submerged. There are also 2 smaller hatches on the rear section of the bottom half of the hull for ease of access when trying to work on the servo motors.

9.1.3. Materials

For the primary material of the hull, fiberglass was selected as the most suitable option. This decision was driven by two key factors:

Availability of Manufacturing Resources: Unlike carbon fiber, which has limited manufacturing capabilities in Singapore, fiberglass is widely available and supported by local manufacturers. This accessibility ensured a reliable supply chain and reduced logistical challenges during the construction process.

Ease of Maintenance and Repair: Compared to wood, fiberglass offers significant advantages in terms of maintenance and repair. In the event of any hull damage, fiberglass can be readily repaired or patched, using putty or resin, ensuring the structural integrity of the hull is maintained throughout the submarine's operational life. Wood, on the other hand, presents greater challenges in terms of repair and maintenance, particularly in a marine environment.

By selecting fiberglass as the primary hull material, we aimed to strike a balance between performance, cost-effectiveness, and long-term maintainability. This choice not only facilitated the initial construction process but also ensured that the submarine could be effectively maintained and repaired as needed, extending its operational lifespan and minimizing downtime.

9.1.4. Manufacturing Method

Initially, we wanted to get a negative Mold for the construction of the hull so that we would be able to build it more accurately and easily, however it was very expensive and the duration to create the Mold & build our hull would exceed our deadline hence after some intensive research and advice from professors that we consulted. We decided to build the hull by ourselves using resin and fiberglass. Firstly, we built portions of the submarine bulkheads in wood and layered chicken wire to hold the bulkheads together, it also acts as a reinforcement to the hull body and provides a foundation to lay the fiberglass before pouring resin to saturate with the fiberglass. We have a total of 4 layers of fiberglass where each layer can only be done one at a time and we had to wait for the resin mixture to harden and dry for the next layer, because we were inexperience with building the hull using fiberglass and resin, the surface of the hull was uneven. Hence, we used car fillers and putty to smoothen the hull form, then we spent another 3 days sanding down the hull to 1800 grit to match the requirements before we sent it out for painting.

We created a mould using half-body wooden sectional cut outs of the hull, then layered chicken wire over it to create an initial shape. Fiberglass reinforced resin was then applied over the mould to create the first layer. Once cured, the half body was flipped over to allow a second layer of fiberglass to be applied on the inside, creating the second layer of fiberglass.

This was repeated for the second half body of the submarine. Patching and sanding of the hull was required to ensure there were no holes or uneven patches on the surface.

We created a mould using half-body wooden sectional cut outs of the hull, then layered chicken wire over it to create an initial shape. Fiberglass reinforced resin was then applied over the mould to create the first layer. Once cured, the half body was flipped over to allow a second layer of fiberglass to be applied on the inside, creating the second layer of fiberglass. Sanding was performed to also prepare the hull for the next step.

Figure 9-9 Laying chicken wire

This was repeated for the second half body of the submarine. Patching and sanding of the hull was required to ensure there were no holes or uneven patches on the surface.

Figure 9-10 Fairing compound

Once the submarine has been sanded, we shipped the submarine over to ICS further body work and painting. At ICS, we used Awlfair, a fairing compound, to even out the surface of the submarine. It was also during this process that we also decided to make the submarine hull an aerofoil as well. Understanding that the racecourse has mostly left turns, it would be ideal to make the hull assist us to turn left. However, some restraint needed to be exercised to ensure that it is not overdone and hence start veering the submarine aggressively to the left.

Figure 9-11 Sanding of Hull

In between the application of the fairing compound (2 layers) and 1 layer of patch work, we had to hand sand the hull, to achieve a uniform curve throughout the whole hull. This was done with 80grit sandpaper on a long wooden board and sanded in a diagonal fashion. Doing this also meant that the work done was extremely labour intensive and that fatigue level had to be managed. After sanding, an acetone wipe down was performed to remove any dust that will affect the next step, painting.

Figure 9-12 Hull before and after Painting

For painting, we pushed the submarine into a dedicated room for painting. This was necessary as dust and debris can get stuck on the hull, which will affect the quality of the paint work. Taping and covering up the areas that we did not want to be painted was also essential as these would affect the components, by locking them up, if it gets a layer of paint over. Once that was done. we applied some primer, then gelcoat for the white colour. Once this was done, we carefully taped up the sections which we would like to spray it black and then applied the black paint over. After the drying process, we had to lightly sand and wipe with acetone to ensure that the surface was smooth and clean.

9.1.5. Additional Design Elements

To enhance the submarine's stability and structural integrity, we implemented two key design elements:

Foam Sheet Layer: A layer of foam sheets was strategically added to the top of the submarine's hull. This lightweight yet buoyant material serves a dual purpose:

1) Roll Stabilization: The foam sheet layer acts as a counterbalance, effectively combating the rolling motion that can occur during underwater operations. By distributing buoyancy along the top of the hull, it helps maintain a stable and level attitude, improving manoeuvrability and control.
2) Structural Reinforcement: This layer also provides additional structural reinforcement to the hull's topside. This reinforcement helps distribute loads evenly and mitigates the risk of deformation or damage, particularly in the event of accidental impacts or collisions.

Fiberglass Rod Reinforcement: To further bolster the structural integrity of the hull's underside, we incorporated five fiberglass rods along the bottom. These rods serve as reinforcing elements, providing the following benefits:

1) Load Distribution: The fiberglass rods distribute the weight of the submarine evenly along the hull's bottom, preventing localized stress concentrations and potential deformation.
2) Mounting and Penetration Support: The underside of the hull will frequently accommodate mounts, hatches, and drainage holes. The fiberglass rods offer localized reinforcement in these areas, ensuring that the hull maintains its structural integrity despite the presence of penetrations.

By implementing these design features, we have effectively addressed the submarine's stability requirements and enhanced its overall structural robustness. The combination of the foam sheet layer and fiberglass rod reinforcement ensures a well-balanced and durable hull capable of withstanding the rigors of underwater operations.

To achieve neutral buoyancy at a depth of 3-4 meters, we initiated the process by performing a simple calculation using the overall weight of the submarine to estimate the amount of foam required. Closed-cell foam was selected due to its water resistance properties.

Figure 9-13 Polyethylene foam cut to match hull's internal curvature

Initially, we utilized polyethylene foam, which we scored to allow it to conform to the curvature of the hull before integrating it into the hull with resin. However, during testing, we encountered a significant issue. The polyethylene foam began compressing underwater, causing the air trapped within the foam to be pushed out, thereby removing its buoyant properties.

Figure 9-14 Polystyrene Foam layered inside hull

Recognizing the limitations of polyethylene foam, we promptly made the decision to swap to a much higher-density polystyrene foam instead. This change ensured that the foam would maintain its structural integrity and buoyancy under the pressure encountered at the desired depth

9.2. Propulsion System

In this section, we discuss about the current implementation of the propulsion system. This consists of several key components, each meticulously designed and implemented to ensure performance and efficiency. An overview of these components as well as the highlighting the collaborative efforts with our technical partners and the modifications made to enhance the overall design can be seen below.

9.2.1. <u>Transmission Drive</u>

The transmission drive utilizes a hybrid transmission system, combining a chain and sprocket mechanism with a bevel gear drive. It is mounted onto aluminum extrusion profiles, which offer a lightweight yet strong framework for the drivetrain.

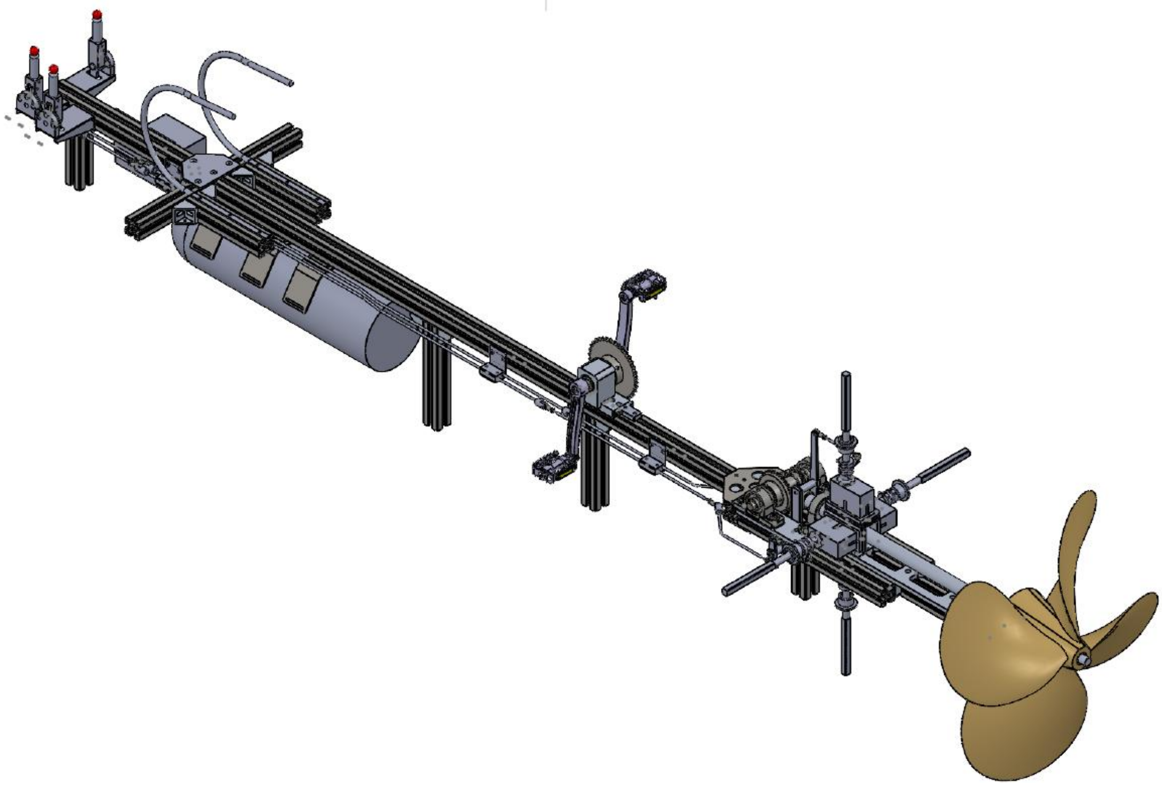


Figure 9-15 Propulsion System

9.2.2. Collaboration with Starlight Tool Precision Engineering

To refine our initial design, we collaborated with our technical partner, Starlight Tool Precision Engineering. Their expertise led to several key modifications. Such modifications included enhancing the overall strength, reducing the weight by creating cutouts without affecting the structural integrity and improving the design, resulting in a more integrated and efficient design, while reducing potential points of failure and improving reliability.

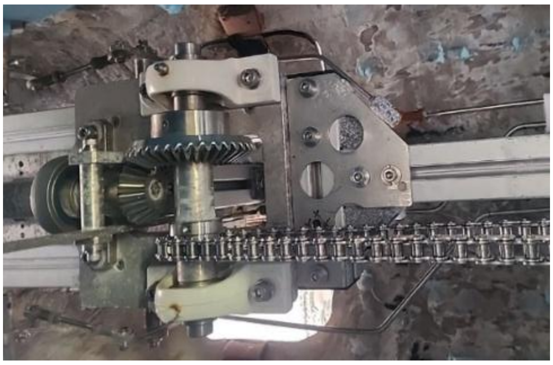


Figure 9-16 Transmission System -Aft

Figure 9-17 Transmission System - Forward

In addition, Starlight Tool Precision Engineering manufactured the entire drivetrain, ensuring high precision and quality in the final product.

9.2.3. Propulsor

The propulsor is a single right-hand screw propeller, designed to provide efficient thrust and manoeuvrability. Our approach to propeller fabrication involved close collaboration with our technical partner, Mencast.

9.2.3.1. Propeller Design and Fabrication with Mencast

Based on our initial design specification, we noticed that our propeller was unnecessarily big hence, we decided to scale down the CAD design. This design was later given to Mencast, who helped us optimize the blade profile to improve efficiency.

Figure 9-18 Propeller with boss cap

The propeller design process involved the following steps:

1) Approximating the propeller size using in-house software based on the submarine specifications.
2) Identifying the best type (series) for the design
3) Generating optimal parameters (blade area ratio, diameter, effective pitch) using software to achieve the highest theoretical top speed.
4) On another software, we generated 3D CAD model based on the parameters and proceed on to further optimize the design
5) A simple CFD (Computational Fluid Dynamics) simulation was done for the designed propeller to ensure the propeller's durability was suited for the race.

The CFD simulations included pressure distribution analysis on the propeller blades and eddy simulations (3D axial velocity field) to optimize the design

CFD Simulation: Pressure Distribution on Propeller Blade

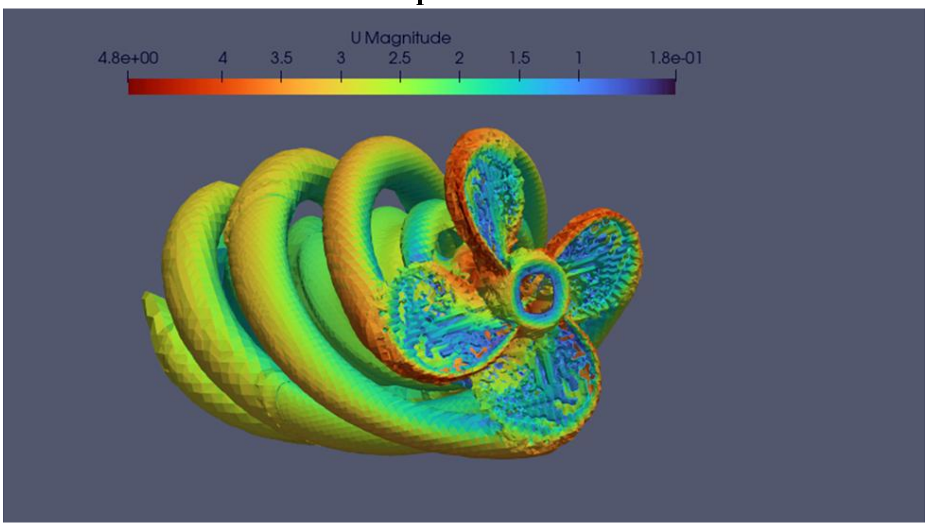


Figure 9-19 Pressure distribution on propeller blade

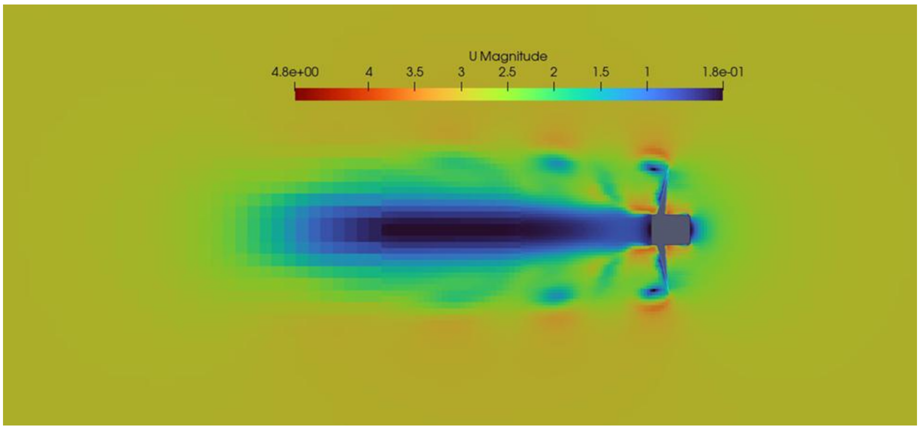


Figure 9-20 Eddy simulation 3D axial velocity field

Infill Pattern

We chose a grid infill pattern for the propeller. This pattern is widely used in 3D printing for its moderate strength and superior performance in the vertical direction, making it ideal for our application. Despite other infill patterns that could improve the overall strength, grid infill patterns enable us with a balance of structural integrity and faster printing time.

Achieving Neutral Buoyancy

While we aim for a neutrally buoyant submarine, we planned to create the propeller to be neutrally buoyant to minimize the extent of its effect as we try to fine tune the submarine to be neutrally buoyant. The weight of the 3D-printed propeller was a crucial parameter, adjustable through the print settings such as the infill percentage and the number of perimeter walls. These settings not only influence the weight but also the overall strength of the propeller. Therefore, we aim to find a good balance. To achieve the necessary weight for the propeller model prior to printing, we calculated the weight as follows:

Before deriving the weight, we multiplied the propeller's surface area with the water density. This would give us the buoyancy force which is key to finding out the weight required for neutral buoyancy. However, post-processing added complexity to this calculation. After printing, the propeller was lightly sanded, and several layers of polyester putty were applied to create a uniform surface and enhance the overall strength. Additionally, a couple layers of primer were used to improve waterproofing and reduce resistance. These steps further contribute to the propeller’s weight. As it is extremely difficult to fully achieve neutral buoyancy in this context due to various inconsistencies, we aim to keep it as close as possible. Therefore, an estimated weight was derived.

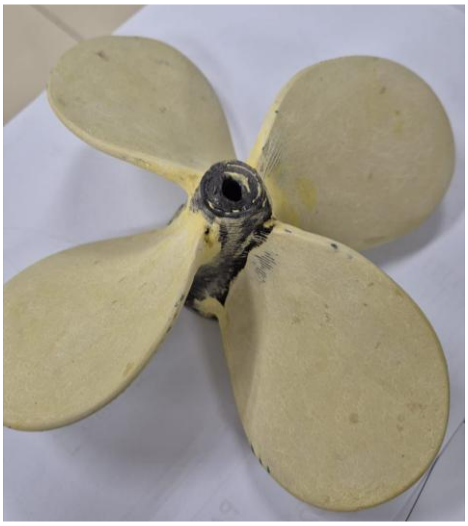


Figure 9-21 3D Printed propeller coating in progress

Integration of Propeller to Drivetrain

To integrate the propeller to our drivetrain, we went for a more conventional design concept which utilizes a tapered shaft to propeller connection. In addition, we implemented a key shaft to prevent the propeller from slipping, ensuring the propeller and shaft are rotating at the same speed. This was further supported by creating a boss cap, integrated with a left-hand threaded screw. The boss cap is screwed tightly to the end of the tapered shaft, pushing the propeller deeper, creating a more secure fit.

9.3. Trim, Hydrostatics & Stability

9.3.1. Weight Estimation & Volume Calculations

The combined weight of the submarine before system integration and cradle is 120kg and the weight of the cradle is estimated to be 30kg, leaving our hull weight as 90kg. Using Autodesk Fusion360 we are also able to determine the internal volume of our hull; 0.643m^3.

With SOLIDWORKS, we are also able to estimate the weight of our drivetrain excluding the propeller weight of 6kg.

Table 9-2 Drivetrain weight

NO	FILE NAME	ITEM	MATERIAL	WEIGHT(KG)	VOLUME (cm^3)
1	AP152-01-001		SUS+ALU	1.032	162.9
2	AP152-01-002A	PROFILE+GUSSET ELEMENT	ALU	7.942	2941
3	AP152-01-004	PLATE	ALU	2.1	791
4	AP152-01-005	SHAFT	SUJ	1.9	725
5	AP152-01-006	SHAFT	SUJ	0.55	70.5
6	AP152-01-007	SPACER	ALU	0.068	12.7
7	AP152-01-009	CONNECT PLATE	SUS	0.265	33
8	AP152-01-011	SHAFT	SUJ	0.335	42
9	AP152-01-012	CONNECT PLATE	ALU	0.5	182.4
10	AP152-01-014	COLLAR	SUS	0.036	4.4
11	AP152-01-015	COLLAR	SUS	0.032	3.92
12	AP152-01-018	BEARING HOUSE	ALU	0.552	200.6
13	AP152-01-019	CONNECT PLATE	SUS	0.389	48.6
14	AP152-01-020	L BRACKET	SUS	0.132	16.6
15	AP152-01-021	SPACER	SUS	0.004	0.5
16	AP152-01-022	SPACER	SUS	0.019	2.4
17	AP152-01-023	SPACER	SUS	0.038	4.8
18	AP152-01-024	SPACER	SUS	0.13	16.4
19	AP152-01-025	SPACER	SUS	0.061	7.7
20	AP152-01-026	SPACER	SUS	0.033	4
21	AP152-01-027	SPACER	SUS	0.02	2.7
22		BEARING HOUSE	PLASTIC	0.4	200
23		GEAR	SUS	1.13	141.6
24		KP006	ALU	0.82	103
25		SPROCKET	SUS	1.57	197.8
26		CHAIN	SUS	1.5	189.1
27		BEARING		0.138	17.4
28		PADDLE		0.374	47
29		ONE WAY CLUTCH		0.15	19
31				22.22	6188.02

9.3.2. Centre of Gravity & Buoyancy
For all NACA symmetrical air foil shapes, the Centre of Gravity occurs at approximately 0.3994 of the chord length which corresponds to the maximum height of our submarine at 40% of its length or 1.44m from the forward. The Centre of Buoyancy is located directly above the Centre of Gravity at the same longitudinal point.

9.3.3. Stability Assessment
In our stability analysis, we adopted a conservative approach by neglecting the effect of the pilot's presence. The human body is nearly neutrally buoyant, thus by excluding the pilot's buoyancy from our calculations, we ensure a margin of safety that can accommodate final adjustments.
A more significant factor influencing the submarine's stability during operation is the changing volume of the scuba tanks. As the compressed air is consumed, the tanks become lighter, gradually altering the position of the centre of gravity. This progressive weight reduction causes the submarine to experience increased buoyancy over the course of the race.

9.4. Controls Surface & Profile
The design methodology of the control systems, consisting of Control surfaces, Actuators, controllers and the ancillary components were adapted from the rudder design methodology in Practical Ship Hydrodynamics (2012) by Volker Bertram.

Hence, the controls team decided the overall design process and strategy; to first focus on the control surface design.

9.4.1. Control Surfaces
Pitch & depth control, control surfaces, design of rudders & hydroplanes, design of fixed planes, materials

As with all and any design process, the design requirements must first be established. To establish this. The team considered the available tools and options to derive said requirements.
Utilizing Desmos, the team plotted the racecourse accurate to the information per the rulebook and briefing packets provided. Notably, the focus was on yaw, as the racecourse does not entail pitch adjustments. This detailed breakdown enabled the team to effectively strategize and optimize our approach for navigating the course with precision. This also allowed the simplification of the reference frame to be purely in the x and y axes and Ψ (Yaw) for the purpose of simplified analysis.

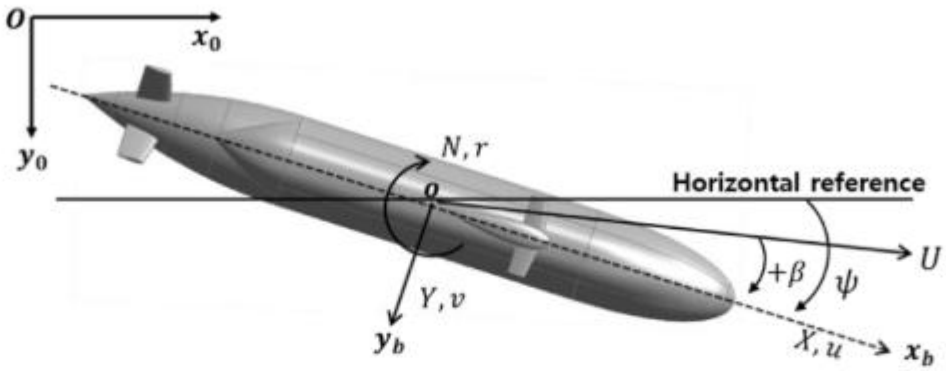


Figure 9-22 Reference frame used

Establishment of empirical formulae for hydrodynamic derivatives of submarine considering design parameters Thi Loan Mai a , Myungjun Jeon c , Anh Khoa Vo a , Hyeon Kyu Yoon b, * , Seonhong Kim c , Jooho Lee c

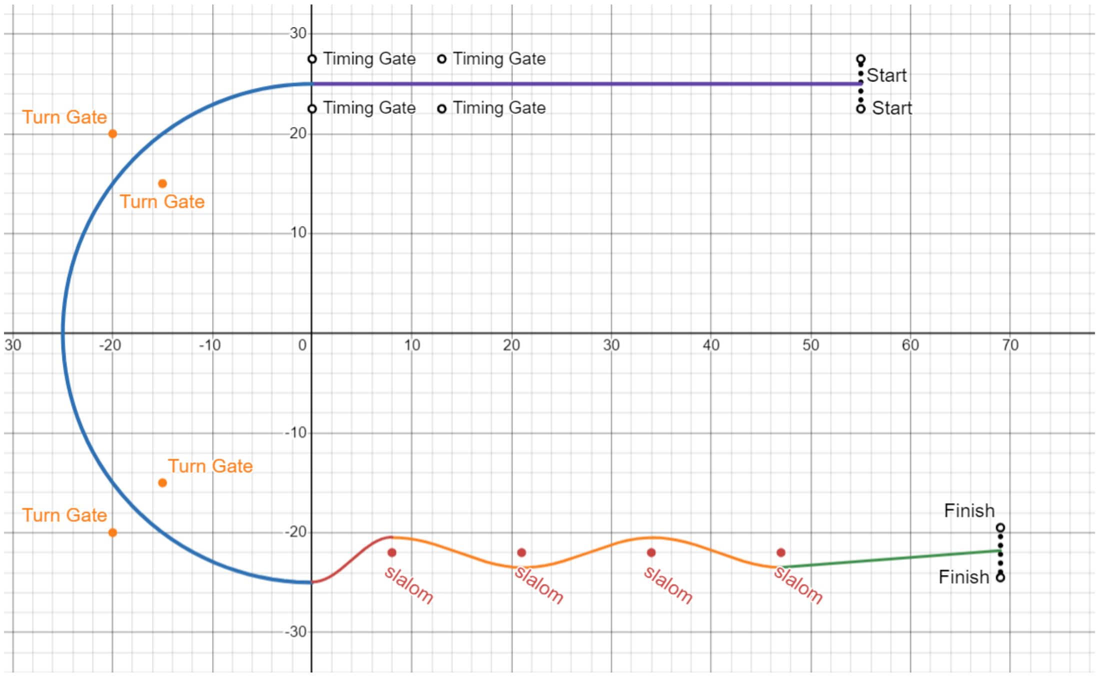


Figure 9-23 Graphical plot of racecourse

Further to this, the controls team subsequently conducted a mathematical analysis to ascertain the maneuvering requirements. This was an empirical approach using the first derivative of the functions for each curve, specifically, the first left turn, the approach into the slalom section and the slalom section itself. The objective was to determine ΔΨ, the change in heading.

First, the investigation for the semi-circle was conducted. Following the graphed equation:

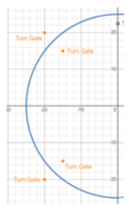
Semi-circle R=25m	Curve	Dy/Dx
	$x=-\sqrt{25^2-y^2}$	$-\dfrac{x}{\sqrt{625-x^2}}$

Figure 9-24 Equation used to map semi-circle

Table 9-3: investigation for tuning angle & distance (Semi-circle)

when x =	**1st deriv dy/dx =**	**turn angle Ψ; tan^-1(dy/dx)=**	ΔΨ/m (1step)	ΔΨ/m (average)
0	0	0	0	0
-2.5	0.1005	5.74	2.296	2.296
-5	0.20412	11.54	2.32	2.308
-7.5	0.31449	17.46	2.368	2.328
-10	0.43644	23.59	2.452	2.359
-12.5	0.57735	30	2.564	2.4
-15	0.75	36.87	2.748	2.458
-17.5	0.98019	44.43	3.024	2.538857
-20	1.3333	53.13	3.48	2.6565
-22.5	2.06474	64.16	4.412	2.851556
-25	inf~	inf~	-	-

Next, the investigation for the approach into the slalom section:

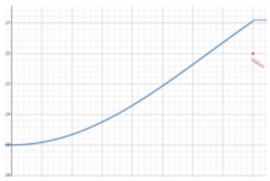
Turn into Slalom	Curve	Dy/Dx
	$y=-3\cos\left(\frac{\pi}{13}x\right)-22$	$\frac{3\pi}{13}\sin\left(\frac{\pi x}{13}\right)$

Figure 9-25 Equation used to map approach into slalom

Table 9-4: investigation for tuning angle & distance (Approach into slalom)

when x =	1st deriv dy/dx =	turn angle Ψ; tan^-1(dy/dx)=	ΔΨ/m (1step)	ΔΨ/m (average)
0	0	0	0	0
0.5	0.087387	5	10	10
1	0.1735	9.84	9.68	9.84
1.5	0.2571	14.42	9.16	9.613333
2	0.3369	18.62	8.4	9.31
2.5	0.4118	22.38	7.52	8.952
3	0.481	25.69	6.62	8.563333

Next, the investigation of the slalom section:

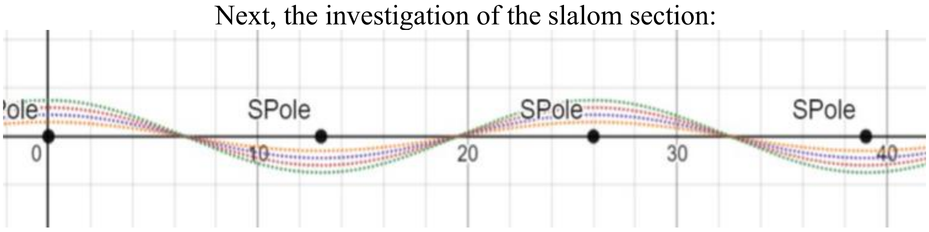


Figure 9-26 Mapping the slalom section

With the assumptions:
1. Assume biggest arc A=1.5
2. Focusing on turns around slalom pole; range of +/-3units X axis at 0.5 steps
3. note that bigger Amp will result in sharper turn

Table 9-5 Investigation for tuning angle & distance (slalom)

when x =	**dy/dx =**	turn angle thetaΨ; tan^-1(dy/dx)=	ΔΨ/m (1step)
10	-0.24	-13.5	3.74
10.5	-0.2059	-11.63	4.14
11	-0.1685	-9.56	4.48
11.5	-0.1285	-7.32	4.72
12	-0.0867	-4.96	4.92
12.5	-0.0437	-2.5	5
13	0	0	0
13.5	0.0437	2.5	5
14	0.0867	4.96	4.92

14.5	0.1285	7.32	4.72
15	0.1685	9.56	4.48
15.5	0.2059	11.63	4.14
16	0.24	13.5	3.74

Hence, we determined that at minimum, in the ideal scenario, the rudders would have to enact a change in heading of 10° or 0.17453 radians. Subsequently, by multiplying with desired speed, we can determine the base yaw requirements to be:

Table 9-6 Calculation for base Yaw requirements

Find:	Method:	Ψ(rad)	V(Knots)	V(m/s)	Result	Remarks		
ω Angular Velocity	Ψ x Speed V	0.17453	5	2.5722	0.448926066	Rad/s	25.722	Deg/s
		0.17453	6	3.0867	0.538721751		30.866	
		0.17453	7	3.6011	0.628499983		36.01	

During this preliminary stage, we also considered the margin of error allowable to factor into calculations. This was done also through mathematics and graphical plotting of potential error trajectories.

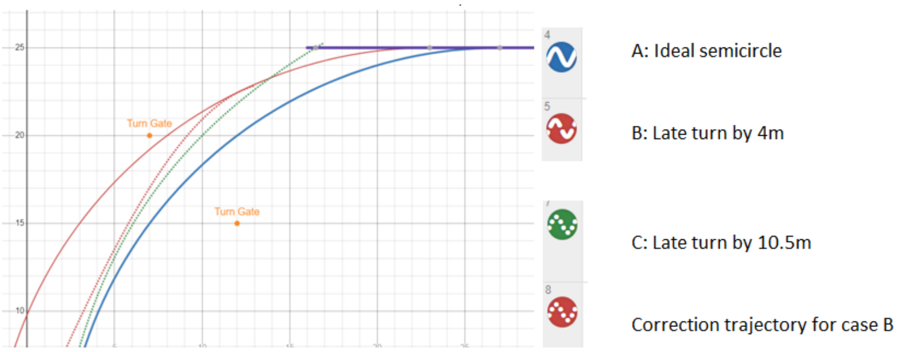


Figure 9-27 Mapping Scenarios of imperfect trajectories

Whilst considering such non-ideal trajectories for the submarine, we also noted that the design should be designed to the ideal conditions, with some allowable margin for error and not to design for these error trajectories, as doing so would lead to overengineering, an imbalance in the other aspects of the submarine, and potentially a costly major redesign.

Preliminary numbers for Reynold's and Froude were also established with some assumptions to understand the operating environment for the submarine. The density of water at 17°C was also factored into consideration.

$$Re = \frac{\rho * V * L}{\mu} \qquad Fr = \frac{U}{\sqrt{gL}},$$

During this stage, manufacturing methods were also listed and considered. Due to budgetary constraints, we looked to fabricate the control surfaces in-house. As such, materials such as fiberglass and foam composite were rejected due to the intricacy required for control surfaces. The ability to quickly enact modifications to the design for fabrication was also deliberated. Due to these considerations, the controls team settled on 3D printing using PLA for the fabrication of control surfaces.

Table 9-7 Justification of fabrication methods

Consideration	**Fabrication Method**			
	Weightage	**3D Print (In-house)**	**Fiberglass (In-House)**	**Foam composite (In-house)**
Lead Time	10	3	2	1
Cost	9	3	1	2
Ease of Manufacture	8	3	2	1
Weight	7	2	1	3
Drag/Surface	6	2	1	3
Strength	5	1	3	2
Total		14	10	12

9.4.2. Control Surface Geometry

The team conducted multiple literature reviews for knowledge due to our relative inexperience, to source for formulas, from class societies Det Norse Veritas, Turk Loyds, and many other sources. It was decided that each control surface area was to be 7% to 8% of the 2D plane area.

Originally, based on literature, it was decided that the effective aspect ratio $\frac{b^2}{A}$; where b = span, A = Control fin area would be 2.2. Due to 3D printer size limitations, we had to change the aspect ratio from 2.2 to 1.7 for the print to fit within the 3D printer max specifications.

A 2-piece design print was considered but rejected due to the required management of the **hygroscopic** properties of 3D prints and more importantly, the structural integrity.

9.4.3. Control Surface Profile

Research was made into the optimal control profile. Profiles such as NACA, IFS, HSVA, Fishtail, Becker-Rudder were investigated. Originally, the controls team had opted to go with the IFS58TR15, due to it striking a good balance of the various criteria, having a high $\frac{C_L}{C_D}$ slope at low α (Angle of Attack), a larger stall angle, and optimal chord thickness.

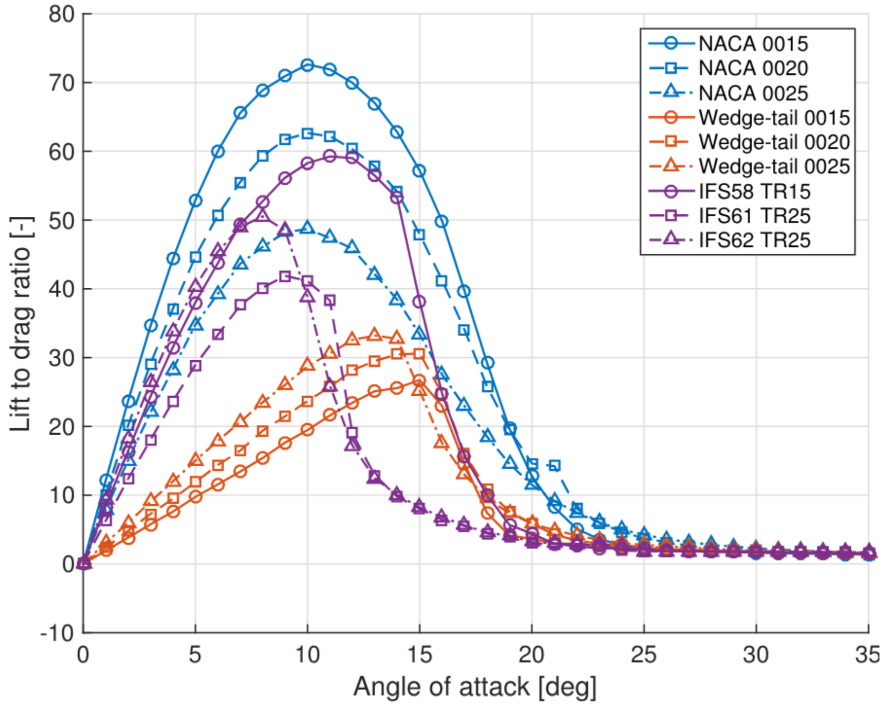


Figure 9-28 Comparison of Lift to drag ratio and Angle of attack

However, upon executing the preliminary CAD design of the airfoil, we noticed that the coordinates provided by literature were insufficient, ie. The number of coordinates were too little, resulting in a curve that was not smooth. Hence, the decision was made to move to the next best option, the NACA0018 following the same balance of factors mentioned above.

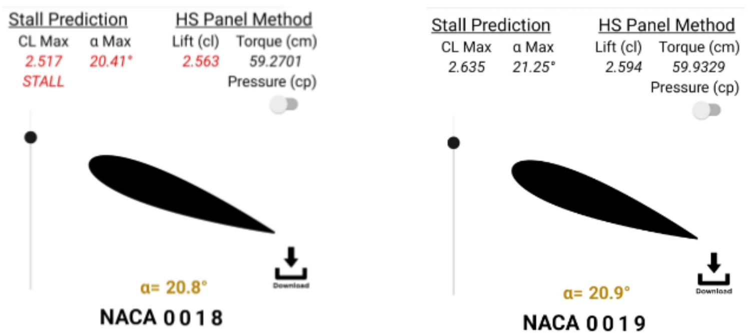


Figure 9-29 Rudder Profile -2

9.5. Control System (Mechanical System)

9.5.1. Pilot Control

During our initial design phase, we considered both Electrical and Mechanical control systems. However, due to challenges in achieving consistent 100% waterproofing for the electrical components, we decided to focus more on the mechanical control system. Our mechanical system features three levers instead of four to control all the fins individually. This design accommodates the rulebook requirement for our pilot to keep their left hand constantly on the Deadman switch.

Figure 9-30 Cockpit view showing the Pilot Mechanical Controls

We designed one control lever to manage the pair of vertical stabilizers (yaw) and two individual levers for the port and starboard stabilizers (pitch). This configuration reduces the pilot's workload by minimizing the number of levers they must handle while still enabling them to counteract any rolling motion by adjusting the port and starboard stabilizers. Additionally, the custom-made levers incorporate an auto-locking mechanism, eliminating the need for the pilot to exert continuous force to maintain the stabilizers' positions. To manoeuvre the submarine, the pilot simply applies a small downward force on the top red part of the control lever to unlock it.

9.5.2. Transmission

Initially, for the Electrical Control System, we transmitted the joystick control signal via wire rather than wirelessly because a single transmitter (Arduino UNO) cannot send signals to four receivers (four servos).

The system included two intermediary shafts between the servo and the fins, with the servo shaft directly coupled to a fin shaft. We initially planned for a shaft coupling to allow for tolerance in case the servo shaft did not perfectly align with the drilled hole. However, we removed this due to space constraints when integrating the mechanical control system. Each fin shaft also has a load bearing on the hull to prevent stressing the servo shaft with load.

The mechanical control system is meticulously designed with three control levers connected to three different connecting rods via linkages. These linkages are integrated into a custom-made 'shaft rod linkage,' which is affixed to the shaft rod. The custom 'shaft rod linkage' and the shaft rod are secured together by an aligned through pin hole, locking the entire assembly in place. This shaft rod is directly connected to the control fins, facilitating control of the submarine. Additionally, a custom-made bushing is mounted onto the drivetrain profile. This bushing supports the connecting rods, preventing any vertical or horizontal movement from the front perspective of the submarine and ensuring efficient transfer of pressure from the control lever to the control fins.

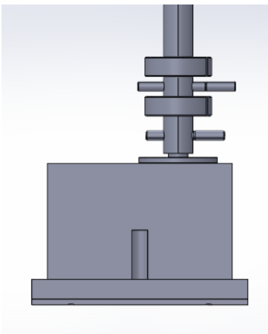


Figure 9-31 Servo Motor + Shaft Rod + Custom-made "shaft rod linkage"

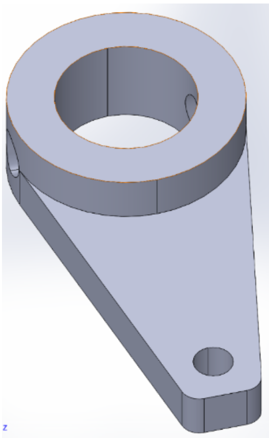


Figure 9-32 Custom-made "Linkage" to connect shaft rod linkages with connecting rods

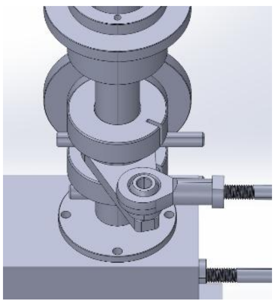


Figure 9-33 Overview of the Mechanical linkage with the through pin

9.5.3. <u>Control fins bearing support and mounting bracket</u>

The hexagonal mounting bracket was initially designed to accommodate both the electrical and mechanical systems while maintaining compatibility with most of the high-torque servo motors. However, space constraints emerged when attempting to install the bearing support. To address this issue, we redesigned the

bracket into a smaller rectangular mounting bracket which was much smaller, specifically designed to match our chosen servo motor. This new, smaller mounting bracket was designed to maximize available space, allowing for the installation of the control fin bearing support.
The bearing support plays a critical role in enhancing the structural integrity and reducing the bending moment experienced by the shaft rods. This ensures a robust and efficient transmission system, capable of withstanding high pressure and bending moments.

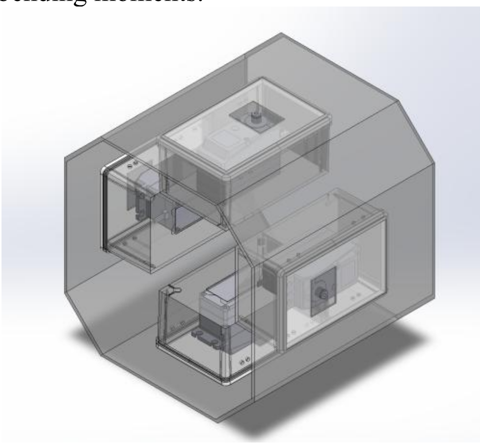


Figure 9-34 Hexagonal Mounting Bracket

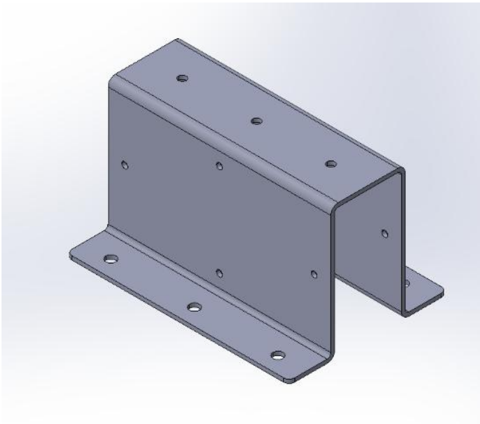


Figure 9-35 Rectangular Mounting Bracket

9.5.4. Manual system design and manufacture

All the components were made in stainless steel to prevent corrosions as the mechanical system consists of numerous moving parts, and it would be disastrous if any of the moving parts were corroded, which meant additional resistance. Using a mechanical system is already poses fatigue on the pilot as the pilot requires strength to control the lever to manoeuvre the submarine, additional resistance will further increase the fatigue level of our pilot and may not allow our pilot to fully focus on the racecourse. After we designed the mechanical system in Solidworks, we then sent it to Starlight for production. During production phase, changes were made to further enhance the structural integrity by adding more bushing brackets for the connecting rods.

9.6. Ergonomics & Pilot Biomechanics

The design of our human-powered submarine prioritizes the pilot ergonomics and biomechanics to optimize performance and comfort. Drawing from the research based on a study on human power generation in an underwater environment, we have implemented key features to accommodate various pilot physiques and maximize efficiency.

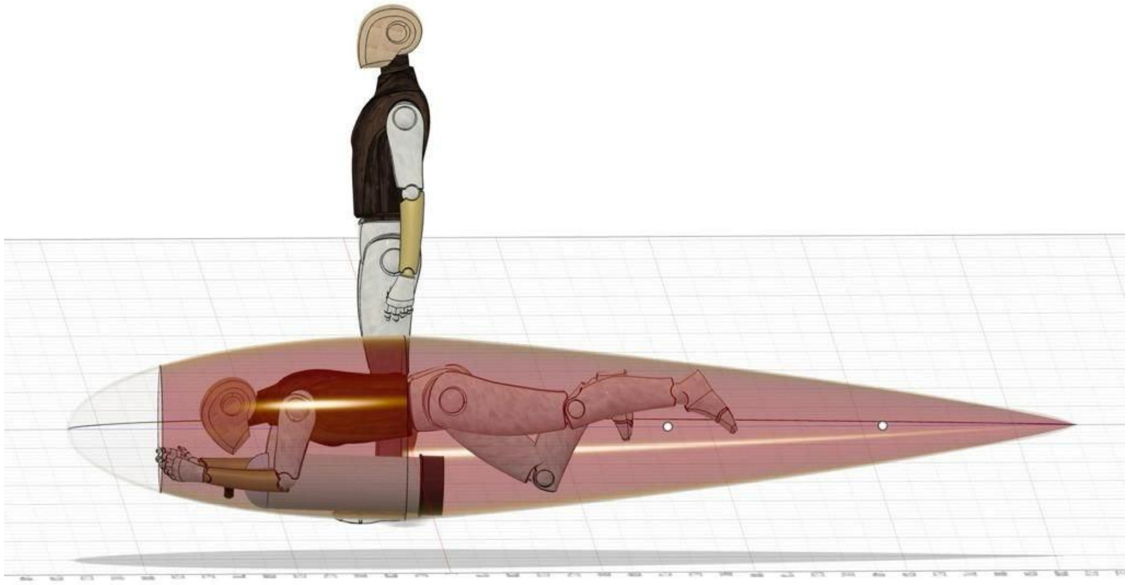


Figure 9-36 Pilot position

Our submarine's drivetrain incorporates adjustable components, in this context, primarily focusing on the shoulder braces and pedals. These are mounted on extrusion profiles, allowing for easy customization to each pilot's ergonomics and comfort. This adaptability is crucial. Based on our research, it has shown that proper positioning can significantly impact power output and reduce discomfort during operation. The hybrid transmission system, combining chain and sprockets with bevel gears, maintains optimal functionality even when adjusting the crankset position, as the chain length can be easily modified.

Pilot testing has also revealed cadence output from 83-97 rpm in air. However, it is important to note that underwater conditions significantly affect the pedalling performance. Studies have shown that the underwater pedalling cadence is considerably lower than on land, with research participants achieving peak power output at around 50 rpm. This reduction is due to the increased resistance of water and the physiological demands of operating in an underwater environment. Our design takes this into account, aiming to balance the pilots' cadence on land with the optimal underwater pedalling rate to maximize efficiency and sustained power output.

When it comes to the position of the pilot, we have concluded that the prone position was our best approach. A prone positioning system has proven that it was a popular choice for underwater propulsion. This position offers several benefits, including improved hydrodynamic efficiency, better power transfer during pedalling, and natural alignment with our streamlined hull form. Based on our research, it is evident in the various tests, showing that the research participants in a recumbent position can generate an average useful power output of 0.12 HP at an optimal cadence of 50 rpm in underwater conditions. Additionally, a study conducted at the U.S. Naval Academy found that four out of six research participants produced more power and consumed less air in the prone position compared to the supine position while breathing SCUBA. As the studies have shown that majority of the participants felt less tired after pedalling in the prone position than when sitting.

While the prone position presents some challenges such as potential neck strain, in order to counter this issue, we made some modification by including an EVA foam. This foam elevates the chest. This enables the pilot to have a more natural and better field of vision.

9.7. Safety Aspects (Karthik)

For our safety system and aspects, it consists of multiple components/ sub-systems. These are namely the pop-up buoy, the release system & stowing mechanism and pilot hatch latch.

Figure 9-37 Pop-up buoy

For the pop-up buoy, we have used an H-shaped plastic buoy, originally used for fishing. It can withstand the water pressure and prevent water ingress which will affect the buoyancy of the buoy. We chose this item to be our buoy for the following reasons: shape, cost, and it established use in water. The shape allows us to easily anchor down the buoy via a simple knot, which is also in the middle. This results in a centralised mounting and hence a lesser chance of the line getting caught on the edges of the hull as the buoy is released. Due to it being a compact design, it is also beneficial in the sense that the mechanism would only take up a small space yet be able to function as required. The cost is low, meaning that replacements and spares is easily affordable. Since it has already been established to work in the context of fishing, the pop-up buoy would not have an issue with buoyancy to be used in our context.

Release system & stowing mechanism

Figure 9-38 Brake system

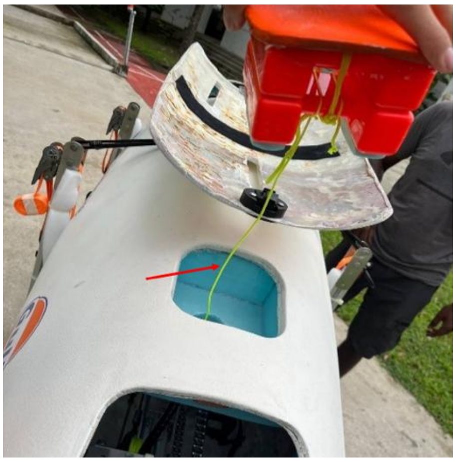


Figure 9-39 Surface Marker Buoy (SMB)

The safety system release system is operated via a bicycle v-brake system. The handle that the release mechanism (dead man switch) is mounted on is port side horizontal stabilizer, resulting in the pilot always having his left hand on the port-side horizontal stabilizer when he is in the submarine and will have to operate the starboard-side horizontal stabilizer and the vertical stabilizers with his right hand. It has been tested and established that this mechanism and method of controlling and releasing the dead man switch works. In addition to this, the dead man switch is locked in place with the use of a Velcro binder. It works well underwater and is easily removable and re-engaged when the pilot has entered the submarine and before he exits the submarine accordingly. We chose this option as it is cost-effective, simple, and does not have a large space requirement. From the dead man switch, it is connected to the braking mechanism via a brake cable, carefully tucked into the aluminium extrusion frame of the submarine. This braking mechanism is located behind the crankarms to prevent any tangle of lines within the chain. The braking mechanism housing the reel of line that is connected to the pop-up buoy. When the dead man switch is engaged, the braking mechanism is holding onto the reel and prevents the pop-up buoy from prematurely being released. However, in the instance of an emergency, the dead man switch is disengaged, leading to the reel being unrestrained, and hence the buoy being released. An additional cable housing is added to prevent the line from getting caught on the edges of the hull, openings, and getting tangled up. This system was selected as it is cheap, easy to use, due to its existing use as a bicycle brake and that the parts are easily replaceable.

Figure 9-40 Pilot hatch, shoulder brace and gusset plate

The pilot hatch has the opening mechanism in the forward part of the submarine, directly above the back of the pilot's head, with the hinge in the mid-ship section of the submarine, directly above the pilot’s tailbone. This was designed and taken into consideration for the ease of hatch opening by the pilot in emergencies. In emergencies, the pilot will trace his hand from the side of his neck to the back of his head. From this position, he will reach upwards and locate the hatch lever. Once the lever is located, it will be disengaged from its locking position by pulling it towards the aft of the submarine and then a push towards the top of the submarine when it has been disengaged. In addition to this, the pilot hatch has ventilation holes to allow the air bubbles expelled by the pilot to escape the submarine, not affecting the buoyancy of the submarine. This doubles up as a visual check for the support divers to have a preliminary assessment of the pilot’s condition.

Pilot constraints

Figure 9-41 Pedal toe cage

Using the shoulder braces that the pilot will be using to support himself, there will be a relatively limited range of motion. This will mean that pilot entry will be something like fitting an AA battery into a remote, by slotting his legs into the submarine before the torso and arms enter the submarine. Similarly, the pilot is unable to slot his feet into the toe cages on his own. To counter this, a dedicated support diver will have to assist the pilot to do so. However, the pilot can autonomously disengage his feet from the toe cage, which is a necessary safety factor for the pilot to evacuate during an emergency. In addition to this, when we tested the submarine, the pilot was wearing a rash guard or wearing a 3mm wet suit. What we noticed was that when wearing a 3mm wetsuit, the pilot had to be more careful when entering the submarine to prevent the suit from catching onto the hull and hinges. This means that when we will be wearing 5mm wetsuits and 3mm hoods (16mm thickness increase), the pilot must be more precise when entering the submarine as it will be a tighter fit and the exiting procedure. The pilot's arms will have some restrictions on his hands due to the narrowing of the hull in the forward section. In addition to this, the placement of the controls, the gusset plate, and the shoulder brace will also mean that the pilot will not have much space to move as these components would limit his movement. This is however essential as being secured in a position will allow the pilot to feel the submarine more effectively, allowing for more deliberate and precise control.

10.Test & Trials

Our first round of wet tests was conducted in Singapore Polytechnic (SP), using their pool.
We conducted a series of tests at SP pool, propulsion tests, controls test, buoyancy tests, pilot entry and exit procedures.

SP Pool Propulsion tests
Propulsion tests was conducted by fitting the propellor on the submarine, while still on the cradle and operating it. This test was to have a confirmation of the functionality of the drivetrain and propeller. We found out that the propeller and drivetrain was able to propel the submarine effectively, achieving our designed speed easily, with no vibrations, difficulties or issues faced by the pilot.

SP Pool Controls tests
Controls test was conducted by fitting the control surfaces on the submarine and performing a mini course within SP pool at the 2m depth section. When operating the control system electrically, we faced some obstacles as waterproofing was an issue as water kept coming in regardless of our efforts. Hence, we decided to switch to completely mechanical system for the control systems. We faced some issues, where the centre alignment between the control surfaces and the control handles were misaligned. We spent a fair bit of time and testing sessions due to our limited time frame as well as the rainy season, that prevented us to complete it quickly.

SP Pool Buoyancy tests
Buoyancy tests was conducted by adding polyethylene (PE) foam to the inside of the hull. It was attached with the use of resin and placed in a way that would not let the submarine be extremely prone to rolling, yet still nimble, by placing the chunk of the foam along the midline of the submarine. This proved to be effective as we were able to get the submarine to float (positively buoyant) relatively easily. However, the main issue faced was that when we brought the submarine under water to 2m dept, the PE foam compressed and hence our buoyancy was reduced as well. This proved to be challenging as theoretically, the amount of foam used was sufficient to let the submarine achieve neutral buoyancy, but the compressibility of the foam was an issue. The submarine kept rapidly diving downwards and proved to be an issue. We resolved the issue by using a high-density polyethylene (HDPE) foam and hot glue to stick it on, using our calculations to determine where and how much the foam is to be placed. Due to our time constraints, we tested the high-density foam in our 2nd batch of testing at Singapore Navy's Naval Diving Unit (NDU) pool.

SP Pool Pilot entry and exit procedures
At SP pool, we fine-tuned and got the flow of the taskings for each support diver, the pilot actions and emergency procedures. The we have a total of 6 divers; 5 support divers and 1 pilot. Divers (D) will be numbered 1 to 6 for ease of understanding. D1: pilot, D2: pilot support diver, D3: Dive IC, D4: submarine support diver (port), D5: submarine support diver (starboard), D6: submarine support diver (stern).

Pilot entry procedure.

- D2 will share his secondary regulator to D1 when descending.

- Meanwhile, D3 will open the pilot hatch while D4 – D6 will support the submarine, preventing it from moving or hitting the bottom.
- Once D1 and D2 have descended, D2 will signal D3 for confirmation before asking D1 to enter the submarine.
- Once confirmation is given, D2 will assist D1 into the submarine, looking out for D1's safety.
- Once, D1 has entered the submarine, he will signal "ok". D3 will respond with an "ok" signal and then D1 will proceed to take 3 deep breaths while on D2's secondary regulator, while counting with his fingers.
- Once D1 has taken his 3 deep breaths, he will switch over to the regulator in the submarine and again take 3 deep breaths while counting out.
- Once this has been completed, D1 will signal "ok" to D3, who will then signal "closing hatch" to D1, acknowledged by a "ok" signal. D3 will then signal "insert toe cage for pilot" to D2 while D3 closes the hatch.
- D2 will then insert D1's feet into the toe cage.
- Once done, D3 will check with D1 if all is ok and if so, to standby to move off. When ready to move off, D3 will signal D1 to "start pedalling", acknowledged with "ok".

Pilot exit procedure.

- Once we are done with the race, D3 will get confirmation first and then signal all the divers with the "cut exercise" signal so that they will be ready.
- D4 - D6 will support the submarine throughout this process.
- D3 will then signal "exit the submarine" to D1, acknowledged by a "ok" signal from D1.
- D1 will then open the hatch and D2 will standby pass D1 his secondary regulator.
- D1 will slowly come out of the submarine and the signal "ok" to D2, who will pass D1 his secondary regulator.
- D1 will then perform the same 3 deep breaths before changing regulator as what was performed in the entry procedure.
- When D1 is out and tethered to D2, they will slowly ascend, while D3 – D6 will shift the submarine to its appropriate holding area and then ascend when ready.

NDU pool buoyancy test

After replacing the PE foam with HDPE, we went to NDU to test out the neutral buoyancy of the submarine at 3.5m to 4m. We were able to successfully achieve the neutral buoyancy of the submarine and hence, able to start testing and fine-tuning out control mechanisms. To ensure that our submarine was neutrally buoyant, we left the submarine for some time and even gently nudged the submarine from time to time and from different locations of the submarine to ascertain the submarine's ability to hover in the desired depth. It was to our great pleasure to learn that the submarine can hover in said depths with and without the pilot. Buoyancy of such accuracy will allow the submarine to be nimbler, without rolling out of control during operation.

NDU pool controls test

Now that the buoyancy issue has been resolved, the controls testing was done to determine the accuracy of the controls, especially the accuracy and free play of the system. When conducting the controls test, it was difficult to do so as the space was limited, but we had to move at speed to be able to perform yaw and pitch controls. Therefore, we had to make do with the space by identifying a particular speed to operate submarine and running a mini racecourse. In doing so, we were able to understand and perform fine tuning of the controls to suit the needs and accuracy of the submarine. Based on our constraints, we were still able to get a decent understanding of the controls and how we expect it to perform in Qinetic's basin would be somewhat similar.

11.Construction Maintenance & Repair

The hull was built using fiberglass and resin. However, due to our financial constraint, we decided to build it on our own, learning how to do so as we embarked on this project. For safety while building the hull using fiberglass and resin, we used masks, gloves, coveralls, and covered shoes to prevent direct contact of resin with our skin. We also ensured that the venue was sufficiently ventilated to prevent the buildup of fumes from the resin. Fiberglass is ideal as it should not require repair, but in the instance that it does, resin and fibres can be easily attained to patch it up. For tools that is required, basic protective gear and the cup to hold the resin as well as the spatulas to spread and saturate resin in the fiberglass will be needed.

The drivetrain was precision-engineered with the help of Starlight tool and precision engineering. To significantly reduce the maintenance needs, we used stainless steel and aluminium to make up the components of the drivetrain, due to reduced corrosion by water. the accessibility to work on the drivetrain has multiple access points, from the pilot's hatch and three maintenance hatches (1x top, 2x bottom). We have accounted for some spares, those that have been identified to be a weak point. These would be mounting brackets, screws, nuts, and chain links. Tools for this maintenance also account for, using screwdrivers, Allen key set, rachet, and spanner sets, that we have brought along.

The control surfaces and propellor were 3D printed, either by us or by Mencast Marine Pte Ltd. Using 3D printed meant that the items could have a fast turnover time and that it was cheaper to have spares. As much as possible, we would use the spares, instead of repairing them. However, if the situation arises that repairs would need to be performed, we would be using sealant to seal the holes and to piece back any small broken parts. To seal it with sealant, a caulking gun, and spare sealant has already been accounted for as well.

12. Environmental Impact

In designing our submarine, we prioritized minimizing environmental impact throughout its entire lifecycle, from initial design through to eventual disposal. A key strategy in achieving this goal was the extensive use of 3D printing technology, which offers several significant environmental benefits.

<u>Design and Prototyping Phase</u>
During the design phase, we leveraged 3D printing for rapid prototyping, which provided substantial environmental advantages:

<u>Waste Reduction:</u> Unlike traditional prototyping methods that often result in significant material waste, 3D printing allowed us to create precise prototypes with minimal excess material. This additive manufacturing process used only the material necessary for each prototype, reducing overall waste generation.

<u>Energy Efficiency:</u> The printing process consumed less energy compared to conventional prototyping techniques. This efficiency was particularly notable in our iterative design process, where multiple prototypes were required.

<u>Lifecycle Considerations</u>
Our use of 3D printing technology extends beyond initial manufacturing, contributing to reduced environmental impact throughout the submarine's operational life and eventual decommissioning:

Repair and Maintenance: 3D printing enables on-demand production of replacement parts, potentially extending the submarine's operational life and reducing the need for complete component replacements.

Recyclability: The 3D printed components were designed with end-of-life considerations in mind, using materials that can be more easily recycled or repurposed. In our submarine design, we opted to use Polylactic Acid (PLA) for 3D printing certain components due to its environmental benefits. PLA is derived from renewable plant-based resources such as cornstarch, sugarcane, or tapioca roots, reducing our dependence on fossil fuels compared to traditional plastics. This choice aligns with our commitment to sustainability, as PLA production generally consumes fewer fossil fuels and emits less carbon dioxide compared to conventional plastics. Under specific controlled conditions, PLA is biodegradable, breaking down into harmless natural compounds. While this biodegradability occurs only in industrial composting facilities and not in normal environmental settings, it still offers a potential end-of-life advantage over non-biodegradable alternatives. Furthermore, our use of recycled PLA filament, where possible, has the potential to lower CO2 emissions by over 50% compared to virgin PLA material, further reducing the environmental impact of our manufacturing process.

By incorporating 3D printing technology throughout the submarine's lifecycle, from initial design to eventual disposal, we have significantly reduced its environmental footprint. This approach aligns with our commitment to sustainable manufacturing practices and responsible resource management in marine engineering.

13.General Arrangement

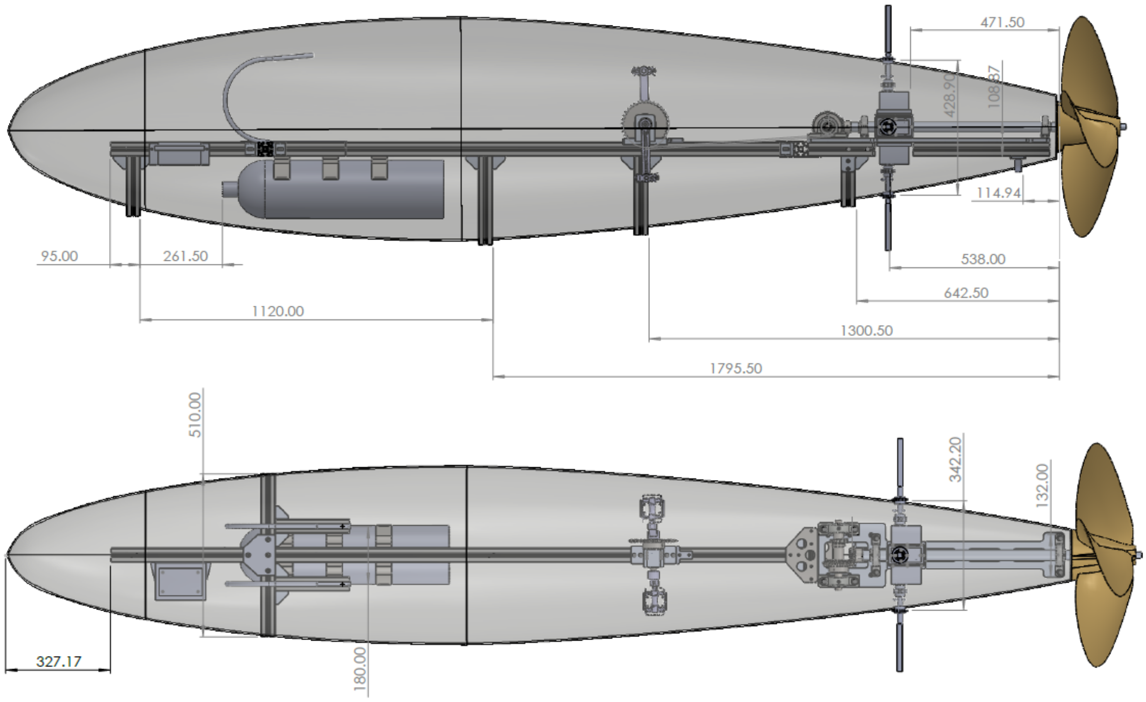


Figure 13-1 General Arrangement of the Submarine

14.Future Development & Lessons Learned

Through the course of preparing for the competition we faced numerous challenges, in both administrative and technical aspects.

As the inaugural team from Singapore to participate in this competition, we encountered significant challenges stemming from our lack of prior experience and the absence of established mentors in our region. This knowledge gap resulted in suboptimal team and resource management, particularly during the initial phase of our project. The first three months of our preparation were characterized by a steep learning curve and slower-than-anticipated progress. We struggled to efficiently allocate tasks, prioritize objectives, and effectively utilize our available resources. This experience highlighted the critical importance of knowledge transfer and the value of mentorship in such specialized endeavours. Moving forward, we recognize the need to establish a robust knowledge base and mentoring system for future teams, ensuring that subsequent participants can benefit from our experiences and avoid similar setbacks. Despite these initial hurdles, the challenges we faced ultimately fostered resilience and innovation within our team, compelling us to develop unique solutions and laying the groundwork for future advancements in Singapore's participation in this competition.

However, this infancy also led to technical failures such as the waterproofing of our electronic system. One of the key lessons learned is the importance of redundancy in waterproofing measures. Even with multiple layers of seals and protective coatings rigorous testing under simulated conditions is essential to identify potential failure points before deployment which we were not able to conduct. In addition, we learnt the importance of a modular design which allows for easier maintenance and replacement of faulty components. This approach also facilitates better sealing, as smaller units are easier to waterproof effectively.

15.Summary

The design of the SIT Nautical Knights' human-powered submarine successfully embodies the team's design philosophy, which emphasizes simplicity, practicality, and cost-effectiveness. By adhering to the MoSCoW

prioritization technique, the team effectively balanced race requirements, objectives, and constraints, ensuring a competitive and efficient design. The sequential design process, chosen over the traditional naval architecture design spiral, allowed for the optimization of each subsystem in a straightforward manner, crucial for the project's success given the limited complexity of a human-powered submarine.
The design's primary objective of achieving maximum speed was met through meticulous hull form optimization, followed by the tailored design of the propulsion system and propeller to complement the optimized hull. The use of fiberglass for the hull, driven by its availability and ease of maintenance, ensured a reliable and practical construction process. The integration of advanced manufacturing techniques, such as 3D printing, not only facilitated rapid prototyping and reduced material waste but also allowed for precise adjustments and enhancements to the submarine's components.

Collaborations with industry partners, such as Starlight Tool Precision Engineering and Mencast, were instrumental in refining the design and manufacturing processes, resulting in a robust and efficient propulsion system. The implementation of a hybrid transmission drive and a carefully optimized propeller design further contributed to the submarine's performance and reliability.

Overall, the design of the SIT Nautical Knights' submarine meets the original objective of creating a competitive, human-powered submarine for the eISR competition. The team's approach, grounded in a clear design philosophy and supported by strategic collaborations and innovative manufacturing techniques, has culminated in a well-rounded and high-performing vessel, ready to represent Singapore on the international stage.

16.Bibliography

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17.Appendices

17.1.Compliance Matrix

Rule No	Rule	Met
G1.	The eISR Event is open to teams of university students and alumni. All members of the team must be over 18 years of age before the start of the Preparation Week.	✓
G2.	University professors and advisors are permitted to attend the eISR Event, however, they are not permitted to enter the water during the Preparation Week or the Race Week.	✓
G3.	All divers must be amateurs, i.e., they must not be paid to take part in the eISR Event.	✓
G4.	All divers must have the minimum dive qualification EN 14153-2 or ISO 24801.	✓
G5.	Teams must provide, a minimum of 4 weeks prior to the start of the eISR Race Event, the dive training organisation's rules they will be following.	✓
G6.	All divers must be qualified to dive independently, i.e., without an instructor, by an internationally recognised dive training organisations. Examples of internationally recognised dive training organisations and their EN 14153-2 equivalent certifications include: • BSAC – Ocean Diver. • PADI – Open Water Diver. • NAUI – Scuba Diver. • CMAS – 1 Star. • NASDS/SSI – Open Water Diver. • SDI – Open Water Diver.	✓
G7.	Each team must provide a Surface Liaison Officer (SLO).	N.A

Rule No	Rule	Met
D1.	If a submarine hull is being re-used, it must have only been used in one other eISR Race Event.	✓
D2.	If a submarine hull is being reused, it must have had a major refit, e.g., a new propulsion system.	✓
D3.	Submarines must be designed to be operated by one or two pilots.	✓
D4.	The submarine length, excluding appendages, must be 5.5 m or less.	✓
D5.	The submarine width, excluding appendages, must be 1.5 m or less.	✓
D6.	Any submarine appendage that extends beyond the maximum dimensions, as defined in D4 and D5, must be configured so that it can be attached and removed by the Support Divers when the submarine is in the water.	✓
D7.	The submarine's centre of gravity, when out of the water (dry or draining) must be between 2.1m and 3.1m from the bow or stern extremity of the submarine.	✓
D8.	The submarine must have a free flood hole or drain hatch opening sited on the underside of the vessel, close to the longitudinal centre of gravity position, with the following minimal dimensions: • I -pilot submarine: 117cm2 [18in2] • 2-pilot submarine: 233cm2 [36in2]	✓
D9.	The submarine's propulsion must be water coupled.	✓
D10.	The use of wheels or other mechanisms that generate movement of the submarine through friction along the bottom or the walls of the eISR racecourse are prohibited.	✓

D11.	The submarine may swap between propulsion and/or control options throughout the eISR Event, unless directed otherwise by the Head Judge at the start of the eISR Event.	✓
D12.	The submarine's propulsion system(s) must be directly coupled to the pilot(s).	✓
D13.	The use of clutches within the submarine's propulsion system is prohibited.	✓
D14.	Energy storage systems are permitted, only where all the energy is created, stored and dissipated during the Run itself, e.g., resonant elastic structures on oscillating biomimetic fins.	✓
D15.	Flywheels or other energy storage devices which can be loaded before the submarine crosses the start line of the eISR racecourse are prohibited.	✓
D16.	The use of hydraulic, pneumatic, or electric transmission systems are permitted, only if all of the energy used for propulsion is produced by the pilot(s).	✓
D17.	The use of any fluid other than water within the submarine's hydraulic system(s) is prohibited.	✓
D18.	The use of oil anywhere within the submarine, including within sealed watertight electronic component containers, and within the team's area in the Ocean Basin is prohibited.	✓
D19.	The submarine must only use water-resistant grease to lubricate boxed gearing.	✓
D20.	It is forbidden to use the pilot's onboard air supply (primary and backup) for any other purpose than life support.	✓
D21.	The submarine electric systems must not exceed 24V DC.	N.A
D22.	If fitted with batteries, the type of battery, the battery location and how the battery can be isolated must be detailed close to where batteries are fitted.	N.A
D23.	The use of expelled air from the pilot(s) to create thrust, in any direction, is prohibited.	✓
D24.	The tips of all moving parts and appendages extending away from the submarine hull must be high visibility orange in colour.	✓
D25.	All internal and external handles and release mechanisms used to exit the submarine must be marked with a high visibility orange patch, a minimum of 10 cm2.	✓
D26.	External handles and release mechanisms used to exit the submarine must be marked in high visibility orange with the word "rescue".	✓
D27.	All handles or release mechanism used to exit from the submarine must be readily accessible from both inside and outside the submarine.	✓
D28.	Each pilot must have a separate exit hatch.	N.A
D29.	For 2-pilot submarines, a visual indicator must be provided for each pilot that shows that either: • both pilot exit hatches are in place and shut, or • one or both pilot exit hatches are open.	N.A
D30.	All pilot restraints within the submarine, e.g., toe clips or shoulder straps, must have the release mechanisms clearly identified with high visibility orange material.	✓
D31.	The submarine pilot's face must be visible from outside the submarine when the pilot is in the submarine in the racing position, with the main hatch closed. In two-crew submarines, this applies to both pilots.	✓
D32.	The submarine must be equipped with a high visibility emergency pop-up (surface marker) buoy.	✓
D33.	The emergency pop-up buoy must have a net buoyancy (natural buoyancy minus weight) of at least 500 grams	✓

D34.	The emergency pop-up buoy must be attached to the submarine by 10m of floating, highly visible line.	✓
D35.	The emergency pop-up buoy (float) line must be stowed so that it cannot be a hazard to the Pilot(s).	✓
D36.	If the emergency pop-up buoy (float) line reel is inside the hull, the line between the reel and the stowed emergency pop-up buoy must pass through a tube so that it does not snag on any fitting when the emergency pop-up buoy is released.	✓
D37.	The emergency pop-up buoy must either form part of the hull or be contained in a fully flooded compartment inside the submarine hull.	✓
D38.	The emergency pop-up buoy must be secured to the submarine hull to prevent it from floating to the surface unless it is intentionally deployed.	✓
D39.	The emergency pop-up buoy must be deployed automatically should the pilot become incapacitated (e.g., “dead man’s handle”).	✓
D40.	In 2-pilot submarines, each pilot must have a release mechanism that automatically releases the emergency pop-up buoy should either pilot become incapacitated.	✓
D41.	Override mechanisms on the emergency pop-up buoy are permitted while the submarine is behind the starting line.	✓
D42.	Use of override mechanisms on the emergency pop-up buoy once the submarine has crossed the starting line is prohibited.	✓
D43.	All submarine hatches must be permanently attached to the submarine by means of hinges, straps, or other similar mechanisms.	✓
D44.	The mechanism permanently attaching the hatch to the submarine must not restrict the pilot’s ability to exit the submarine in any way.	✓
D45.	Drag reducing coatings on the submarine are permitted, so long as they are not able to slough off the submarine into the Ocean Basin.	✓
D46.	The use of drag reducing hull coatings must raised to the Head Judge during the design stage. Failure to do so may cause the team to be prohibited from entering the Ocean Basin. The Head Judge reserves the right to prohibit the use of the coating if it is considered there is a risk of contamination of the Ocean Basin	✓

Rule No	**Rule**	**Met**
B1.	A primary air supply for each pilot must be carried aboard the submarine with sufficient capacity to complete a run at speed and not fall below the minimum pressure specified in Rule B2.	✓
B2.	The pilot(s) must not allow the primary air supply to fall below 50bar (725 psi).	✓
B3.	The pilot’s air pressure gauge must be visible to the pilot when inside the submarine.	✓
B4.	With the pilot(s) in the submarine and all hatches closed, the pilot(s) must be able to communicate the pressure of their primary air supply to a support diver.	✓
B5.	Each pilot must carry a secondary independent air supply with a capacity of no less than 3 litres.	✓
B6.	The secondary air supply must not be used for tasks such as loading and preparing for a run, and its pressure must not be allowed to fall below 50bar (725psi).	✓
B7.	All support divers must be equipped with a spare second stage regulator (octopus), for safety and support, e.g., assisting pilots during submarine entry and egress.	✓
B8.	All divers must not let their air cylinders drop below 50bar (725psi) - Repeat low remaining pressure offences may result in the diver (pilot or support diver) being excluded from the competition. Air supply pressures will be checked on entry and exit from the water, and the Dive Supervisor has the ultimate authority to decide whether a	✓

	diver will be allowed into the water	
B9.	All breathing air must be supplied using an open-circuit SCUBA system, and use compressed normal atmospheric air. Special gas mixtures, e.g., nitrox, are prohibited.	✓
B10.	Re-breather systems are prohibited.	✓
B11.	The Team must provide evidence of qualified servicing of all first and second stage regulators within one (1) year of the end of the Event.	✓
B12.	All air cylinders must be correctly labelled in accordance with European Standard EN 1089-2, with a label displaying the green compressed-gas hazard diamond.	✓
B13.	All air cylinders must clearly display current hydrostatic test and visual inspection dates	✓
B14.	• All air cylinders must be CE certified to appropriate EN or BS Standards that are suitable for PPE/breathing apparatus. The current standards are: • EN 1964:2000 Transportable gas cylinders – Seamless Steel, • EN 1975:2000 Transportable gas cylinders – Seamless Aluminium, • EN 12245:2002 Transportable gas cylinders – Fully wrapped composite, • EN 12257:2002 Transportable gas cylinders – Seamless hoop-wrapped composite, • BS 5045-7:2000 Transportable gas containers – Seamless Steel, and • BS 5045-8:2000 Transportable gas containers – Seamless Aluminium.	✓

Rule No	Rule	Met
T1.	If a crate is used to transport the submarine and support equipment to the Ocean Basin, each laden crate must have a weight no greater than one (1) metric tonne (1000 kg).	✓
T2.	Once within the Ocean Basin facility, the submarine must use a trolley (cart) to transport the submarine between the team's working area and the launching lifts (elevators).	✓
T3.	The trolley (cart) must be strong enough to take the weight of the submarine and any water contained within it during the process of lifting the submarine out of the water.	✓
T4.	The draught of the submarine and the trolley (cart) must not exceed 1.2m.	✓
T5.	The trolley (cart) must be, at max, 5kg negatively buoyant	✓
T6.	The trolley (cart) must secure the submarine so that it does not float off the trolley (cart) in 1.2m of water.	✓
T7.	The transverse distance between the wheels of the submarine trolley must be between 500mm and 750mm.	✓

Rule No	Rule	Met
O1.	Pilots must indicate an abort by releasing an emergency pop-up buoy:	✓
O2.	Accidental release of the emergency pop-up buoy after the Start Gate will automatically abort a run.	✓
O3.	After the emergency pop-up buoy has been deployed, whether intentionally or by accident, the pilot(s) must follow the Abort procedure.	✓

O4.	If the command "[Submarine Name] STOP STOP STOP" is given, the Abort procedure must be followed.	✓
O5.	On intentional release of the emergency pop-up buoy, the pilot(s) must immediately undo any restraint systems, switch to their secondary air supply, exit the submarine, remain with their submarine, and await rescue.	✓
O6.	The pilot must retain their weight belt, keep mask on and regulator in the mouth, until secured by the rescue boat at the surface.	✓

Rule No	**Rule**	**Met**
P2.	All team divers must attend the Ocean Basin Safety Brief before entering the water.	✓
P3.	All team divers must have had their dive logbook checked by the identified member of the eISR Race Committee or delegate before entering the water.	✓
P4.	On successful completion of P2 and P3, all team divers must undertake a Basin Familiarization Dive as specified in the Ocean Basin Safety Brief.	✓
P5.	The Dry Inspection must be successfully completed before teams are permitted to commence the Wet Test procedure.	✓
P6.	The Wet Test procedure must be successfully completed before teams are permitted to attempt Runs.	✓
P7.	Teams must have their submarines main hatch inspected by the rescue divers before being permitted to attempt Runs.	✓

Rule No	Rule	
R1.	The team must produce a single page document that provides the principal parameters of their submarine in accordance with Section 3.1.	✓
R2.	The team must produce a Design Report that follows the template provided in 3.2 .	✓
R3.	The Design Report must include a Compliance Matrix verifying that all the Design Rules have been met.	✓
R4.	The Design Report must include calculations that demonstrate the primary air supply carried by the pilot complies with Rule B1. It should be noted that sports diving consumption rates at depth must be used.	✓