OMER 9

Final Design Report
13th ISR

ÉTS
Le génie pour l'industrie

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2 INTRODUCTION

2.1 ABOUT US

The OMER club was established in 1990 and has been designing and fabricating human propelled submarines ever since. Our years of experience has given us a notorious reputation in the submarine world and each year the club aims without a doubt to surpass our previous prototypes with the intentions of a first place position in the competition we partake in. Not only are we all active students of the University of Superior Technology, « l'École de Technologie Supérieure » (ÉTS) but also passionate and motivated volunteers. The club allows each member to evolve in their specialization by applying the theoretical to the practical along with each individual's technical background and creativity. The level of implication of each member is as much technical as it is human relations. The OMER club is a tight woven family that learns from one another and in turn, is constantly trying to surpass one another.

The different stages of design and fabrication of the submarine is distributed among the members of the club and weekly meetings allow for the unison of the team and an up to date log of the progression of one another's advancements. It is a great pride for us to be able to design and build our own submarine, using the equipment lent by our school, such as shops, CNC machines, and the crude materials given by our partners, such as aluminium or basalt fiber. More than just a competition, OMER is without a doubt an out of the ordinary experience.

2.2 ÉTS

Constituent of the University of Quebec, ÉTS is renowned for developing engineers and researchers recognized for their practical approach and sense of innovation. Specialized in teaching and hands-on research, the school maintains a tight partnership with companies in the industry.

Very meticulous to the blossoming of their students, ETS dedicates a large budget to the development of the school clubs. A complete department was created to manage the clubs, as well as their office space and workshop. Professors and technician are always available for student and club consulting.

The current population of the school is currently 6700 students. It is situated since 1997 at 1100 Notre-Dame West, Montreal, QC.

2.3 THE PROJECT

Since OMER 5's debut in 2004, at its first competition, it propelled ÉTS to a world class position in the category ''two persons with propeller'' for a record speed that has yet to been beaten. OMER 9 was conceived with the intention to beat this record. New fabrication methods were implemented, a new electronic management system to control the propeller and an optimized design profile to enhance the performance. The positive outcome of the 2014 competition motivated the OMER club to represent OMER 9 in the 2015 competition. Improvements on the blades and the hull are currently in progress. Due to these new enhancements, OMER 8 has lastly set a new world speed record of 7.282 knots, with a first place Overall award, first place Absolute Top Speed award and a first place Top Speed 1 person, Propeller. Moreover, the team takes great pride in also taking home the third place Innovation award

for developing a mono blade, which left the juries rather shocked and surprised. OMER 8 had achieved one of the best recorded times at the competition while the mono blade was installed on the submarine.

With the new and improved OMER team in full swing, we are motivated to start a new journey, with the design and fabrication of OMER 9. The project will see light as of 2014; the first prototype pieces will be machined. The category chosen by OMER to part take in is two people with propeller, with every intention to win a new title. The key innovation points for this prototype will be focused on the methodology of the design of the submarines shell, the pneumatic systems, the blades and an electrical guidance system.

2.4 More than 20 years of human-powered submarines

1

3

OMER 1 - 1993 -Competition of Fort Lauderdale, FL (44 teams)

- ✓ Single seater
- ✓ On-board pc
- ✓ Variable pitch
- ✓ Propeller
- ✓ Best innovation by a university team
- ✓ Best international innovation
- ✓ Best instrumentation

OMER 3 - 1998 - Competition of San Diego, CA (16 teams)

- ✓ Single seater
- ✓ Wireless communication
- ✓ Propeller
- ✓ First place for speed
- ✓ first place for presentation
- ✓ Speed : 6.977 knots

1995 **2000**

OMER 2 - 1996 -Competition of Bethesda, MD (16 teams)

- ✓ Single seater
- ✓ Assisted Direction
- ✓ LCD screen
- ✓ Propeller
- ✓ World speed record over 10m (6.977 knots)
- ✓ World speed record over 100 m (6.291 knots)
- ✓ First place position for speed
- ✓ Prize for best design

OMER 4 - 2001 -Competition of Fort Lauderdale, FL (19 teams)

- ✓ Single seater
- ✓ Direction électrique
- ✓ Propeller
- ✓ World speed record (7.192 knots)
- ✓ First place position for use of composites

2

4

OMER
SOUS-MARIN A PROPULSION HUMAINE

5

7

OMER 5 - 2003 -Competition of Bethesda, MD (22 teams)

- ✓ Two seater
- ✓ Complete System
- ✓ Propeller
- ✓ World speed record (8.035 knots)
- ✓ First place over all position
- ✓ First place position for absolute speed

OMER 7 - 2009 -Competition of Bethesda, MD (22 teams)

- ✓ Two seater
- ✓ Complete System
- ✓ Without Propeller (wings)
- ✓ World speed record (5.133 knots)
- ✓ First place over all position
- ✓ First place position for absolute speed

2005 2010

5 6 7 8

OMER 6 – 2006 -Competition of Bethesda, MD (22 teams)

- ✓ Single seater
- ✓ Without Propeller (wings)
- ✓ World speed record (4.642 knots)
- ✓ First place over all position
- ✓ First place position for speed in its category
- ✓ Special mention for innovation
- ✓ Special mention for design

OMER 8 - 2013 -Competition of Bethesda, MD (19 teams)

- ✓ Single seater
- ✓ Electrical variable pitch
- ✓ Propeller
- ✓ New World speed record (7.282 knots)
- ✓ First place over all position
- ✓ First place over all position for speed (7.282 knots)
- ✓ Third place Innovation award

6

8

OMER
SOUS-MARIN A PROPULSION HUMAINE

3 AIM

The OMER 9 submarine is the ninth generation of record holding submarines. The goals and expectations are very high. This family of submarine respects all the criteria of traditional submarines. It is influenced by human realisation like that of airplanes that requires low drag profiles and is optimized to improve the speed of the submarine.

Before thinking about how to build a new submarine, we had to acknowledge the physical constraints involved. These constraints specify the path to take during the design and the fabrication of this interesting project. They also influence the design of the internal mechanisms of our submarine and their components. The elements that characterize the OMER 9 submarine are the following:

It is clearly specified in the rules that the submarine has to be human powered. This first information restricts us to use a mechanism that is not influenced or enhanced by any other source of energy than human energy itself. The second element is the environment in which the submarine will be placed. The submarine has to be fully submerged in water and filled with it to increase stability. This environment factor is decisive in the choice and classification of the material used for the fabrication of all the mechanisms of the submersible vehicle. The other important design criteria are the security restrictions that must be respected. Outside of those major constraints, we had complete freedom to design the submarine.

Our first step was to gather information and evaluate the human and material resources available. The initial part that had to be designed and built was the hull, because all the internal components depend on the shape of it. From this point, a design and fabrication procedure was created. This procedure helped us build, step by step, the submarine and organize the multiple tasks.

With the experience we learned throughout the years, a variety of things we are making are function of what has been made some years before. Sometimes we try to simplify the good systems, automate or improve the others and try to innovate within each new project. The design philosophy of every system in the OMER 9 submarine is speed, safety and efficiency. Consequently, the hydrodynamics of the hull, the fins and the propeller are very important. All the electronic systems have to be efficient, not only to improve the mechanical systems but also to improve the safety systems, such as the pop-up buoy and strobe light.

The aim of this report is to describe the design of all the systems we implemented into the submarine. Moreover, its goal is also to show how we manufactured it at our school.

4 EXISTING HULLS LESSONS LEARNT

4.1 CHANGES FROM PREVIOUS DESIGN, WITH REASONS FOR MAKING THE CHANGES

As said in the previous part of this report, OMER has in its story build 8 submarines in the past 20 years. Because of that, it has been possible for us to observe and study the different hulls of these submarines in order to improve our design. However, since part of the team worked on OMER 8 during the past few years, it is this one we used as an inspiration. OMER 8 has the last hull made by our team, which is known to be the smallest submarine ever made in any category. The approach was a minimalist approach, which means that there was only the minimum necessary to propel the submarine and ensure pilot safety. Since OMER 9 is a 2 pilot submarine, the hull is way bigger, but the approach remains the same. Actually, the main restriction we observed on OMER 8 hull was the height of the hull; the pilot was touching the bottom with his knees and with the 3 bottles under the chest, entering and exiting the hull was tricky. This helped us to create the smallest hull possible, but this only allowed us to use only one person as pilot. In order to avoid those effects, we have decided to really work on that problem and try to optimize the height of the submarine for 5'10'' pilots, which allow us to use several pilots in function of their physics conditions.

Another problem encounter in the fabrication of OMER 8 was the manufacturing process. Indeed, OMER 8 is a submarine that has been manufactured in quite a short period of time, so the finish was not as nice as we wanted it to be. What's more, the hull is too thin, which causes the submarine to be breakable. Because of that, we decided to inspire ourselves from the manufacturing of OMER 7, which is one of the most beautiful human-powered submarine ever made, with a carbon finish that is very impressive.

To inspire ourselves from the modeling methods used with the older submarines, different 3D models were consulted, in particular those of OMER 5, 7 and 8. The method used for OMER 7 and 8 seemed pretty simple and effective. This method is to take several aerodynamic profiles and generate a surface from these splines. Then, in order to have a perfectly symmetrical hull, the surface generated is just a fourth of the hull, and then repeated. The method used to design our new hull will be fully explained in the next section.

5 NEW HULLS DESIGN PHILOSOPHY DESIGN AIMS

5.1 THE UNDERLYING AIMS INFLUENCING THE DESIGN

The goal for OMER 9's hull is succeed in obtaining the most hydrodynamic model possible without compromising too much on the driver ergonomics. Several constraints were added to the challenge of designing a hull as good as the previous ones, in terms of design and hydrodynamics. The ergonomics of the pilot who must be able to pedal with all his power in the submarine is the main constraint. Then comes the propulsion system, the methods of manufacturing, the steering system and the door opening system. With all these constraints, the goal is still to produce the smallest hull possible. In this section we will present the approach of the OMER 9 hull design.

The design of the hull was performed in several stages. In this section, the different steps that were followed will be presented.

5.1.1 Modeling pilots

First, to get an idea of the footprint caused by the pilots, it took the model. To do this, a study has been conducted with the team. From the data collected for each member, a type pilot has been modeled with CATIA (the largest measurements have been used).

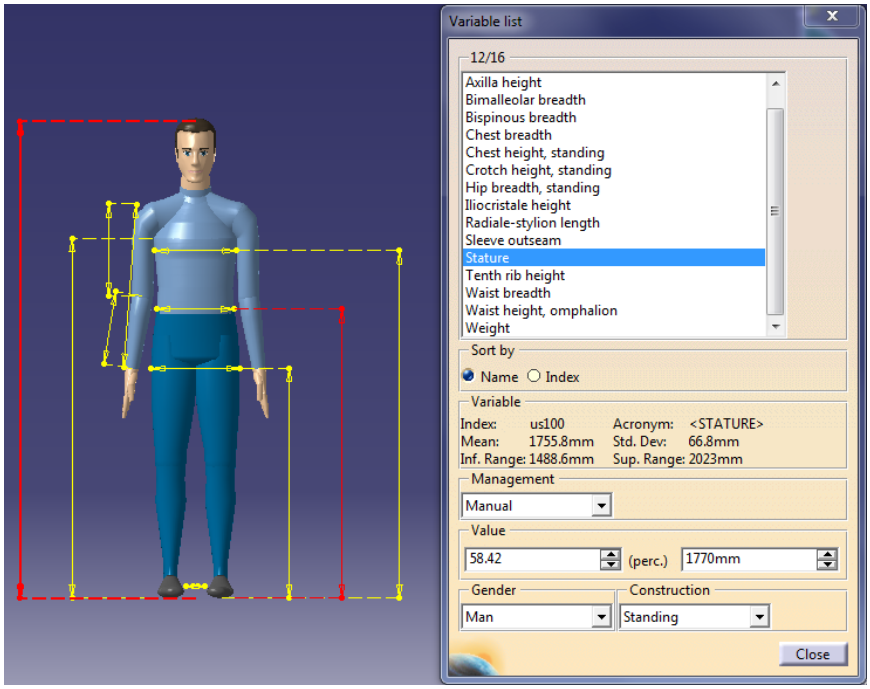


Figure 1 : Modeling the representative models of OMER 9 drivers in CATIA

5.1.2 Modeling scuba tanks and propulsion

Scuba tanks and propulsion are the elements which size is the most binding. To see what arrangement would be possible in the submarine it was necessary to model them. Knowing the number

and size of the bottles, it was easy to model simplified bottles. In terms of propulsion, the dimensions of the OMER 5 propulsion were identified and taken as design values of a simplified OMER 9 propulsion.

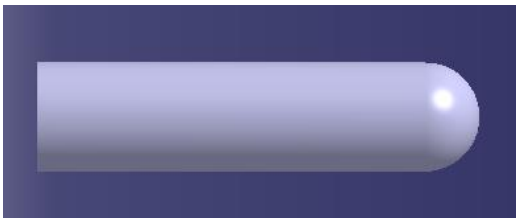


Figure 2 : Overview of modeling a scuba tank

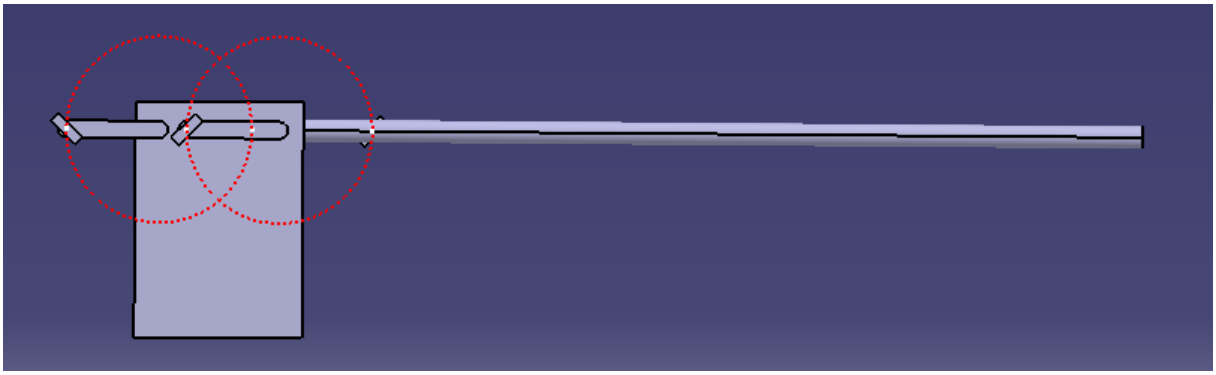


Figure 3 : Overview of modeling the propulsion system

Note:

Red circles in figure 3 show the path of pedals.

5.1.3 First modeling of the hull

From CATIA models of the drivers, the scuba tank and the propulsion system, it has been possible to design a first shell in order to get a good idea of the footprint. The vertical and horizontal profiles have been done ''by hand''.

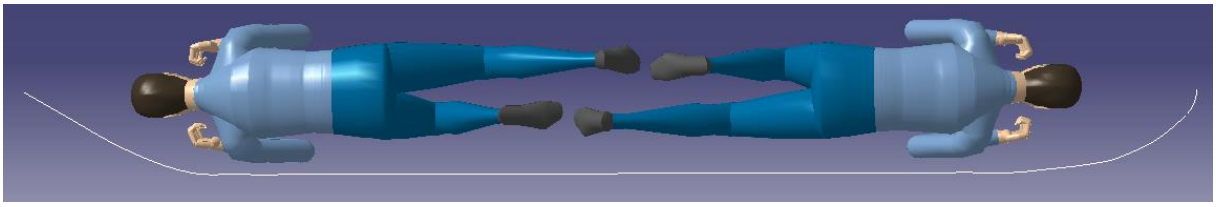


Figure 4 : Overview of the horizontal profile ''handmade''

As shown in figure 4, the most constraining points are located at the shoulders of the pilots. The front of the submarine was designed domed (aerodynamic shape). In the center, the profile remains law to avoid losing too much space. A front and rear space was left for the other systems (pneumatic, electric…)

For the vertical profile, the constraining points were at the drivers' knees. To properly size this profile the pilots were placed in the most restrictive position:

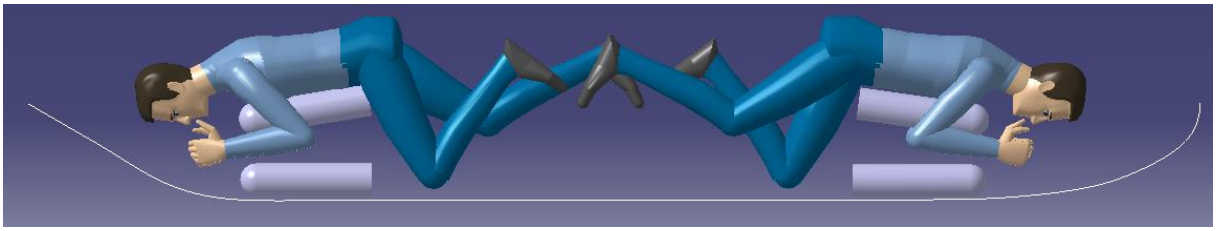


Figure 5 : Overview of the vertical profile ''handmade''

The design of these profiles was conducted so as to favor a maximum footprint while optimizing the wasted place. However, numerical studies made on the software Xfoil have shown that these profiles were not optimized in terms of hydrodynamics.

To select a profile that does not generate too much drag, we develop a Matlab code which perform the following operations:

- Selection of symmetrical profiles in a library of profiles
- Pilot the software Xfoil to perform a hydrodynamic study of each profile
- Sort profiles based on the drag it generated.

The NACA profiles seemed much more interesting. From our researches, two profiles emerged: the NACA 16-015 for the horizontal profile and the NACA 16-018 for the vertical profile. These profiles were not the best in terms of hydrodynamics but allowed us to meet the size constraints (mentioned above) without reaching a submarine total length too high. With these profile, a 4.25 meters chord length was sufficient and wasted space was limited.

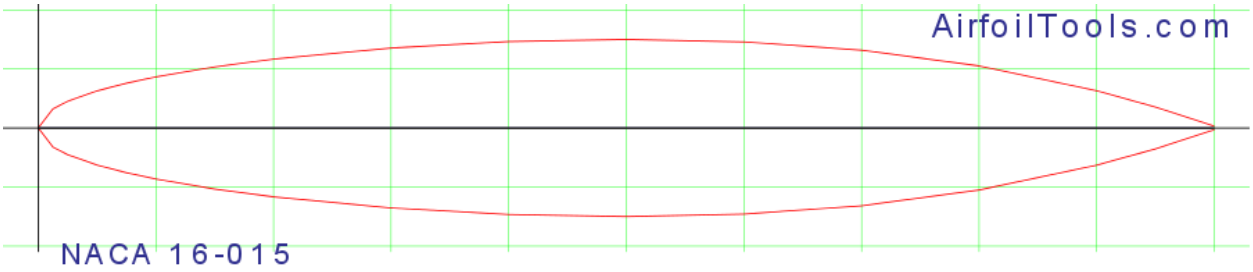


Figure 6: Overview of the NACA 16-015 profile

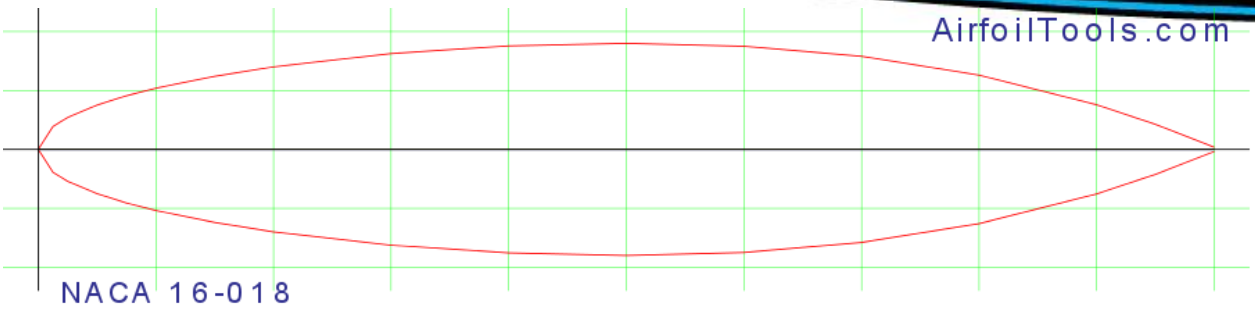


Figure 7: Overview of the NACA 16-018 profile

5.1.4 Improved modeling of the hull

Once selected, the profiles were imported into CATIA in dimensionless form. They were then forced against a geometrical parameter, called ''length''. With this, we can keep a check on the dimensions of the submarine throughout the design. This work was laborious since each point of the profiles had to be constrained. Once the length chosen and the new profiles generated, we had to integrate the profile of the tail cone, designed before. To do this, the horizontal and vertical profiles were somewhat modified. Note that the changes are minor are minor and have virtually no impact on the hydrodynamic profiles.

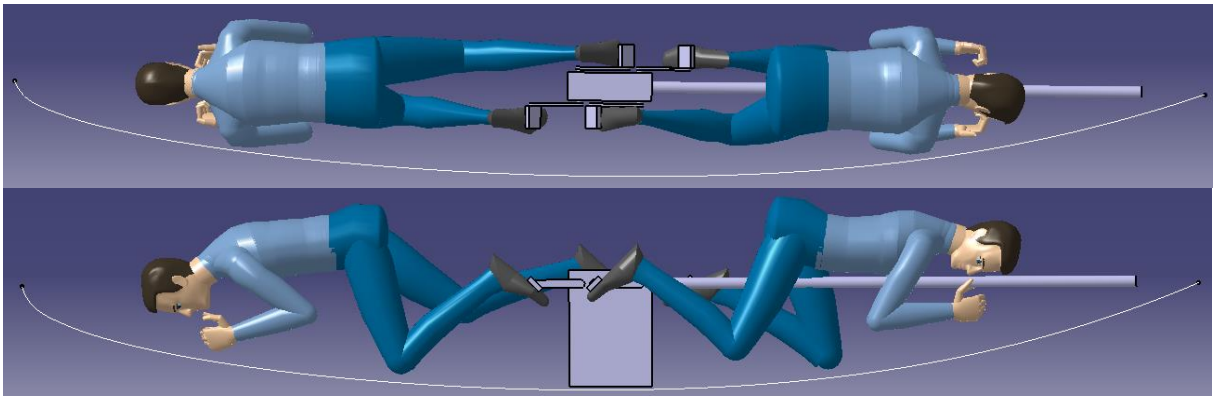


Figure 8 : Final profiles (top: horizontal profile; below: vertical profile)

Then, to generate the hull with the CATIA surface tool, we had to choose ''guide curves'' linking patterns between them. The base of the tail being a circle, we decided to use ellipses. In order for the generation of the surface to be as close as possible of the profiles, five guide curves were generated: one at 3%, 25%, 75% and 90% of the length of the submarine (from its nose). The equation which was used to generate those curves is:

$$\left(\frac{x}{x_1}\right)^2 + \left(\frac{y}{y_1}\right)^2 = 1 \;\Rightarrow\; \boxed{y = \sqrt{y_1\left(1 - \left(\frac{x}{x_1}\right)^2\right)}}$$

Where x_1 and y_1 are the semi-major axis and the semi-minor axis of the ellipse (cf. figure 4).

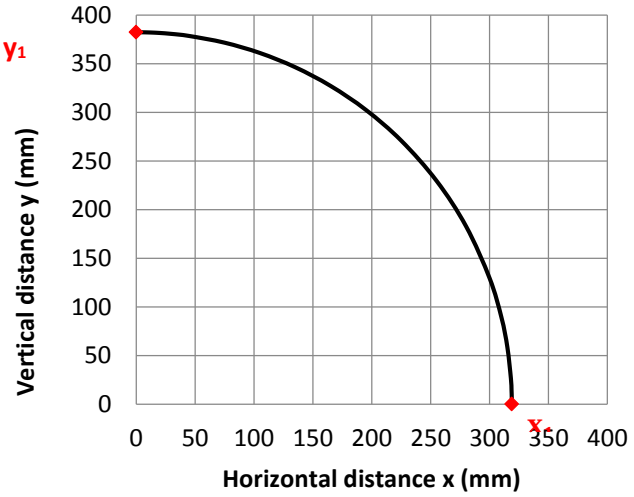


Figure 9 : Quarter profile of the ellipse plotted at half of the hull

Also note that x_1 is on the horizontal profile and y_1 on the vertical one.

Finally, the hull looks like as follows:

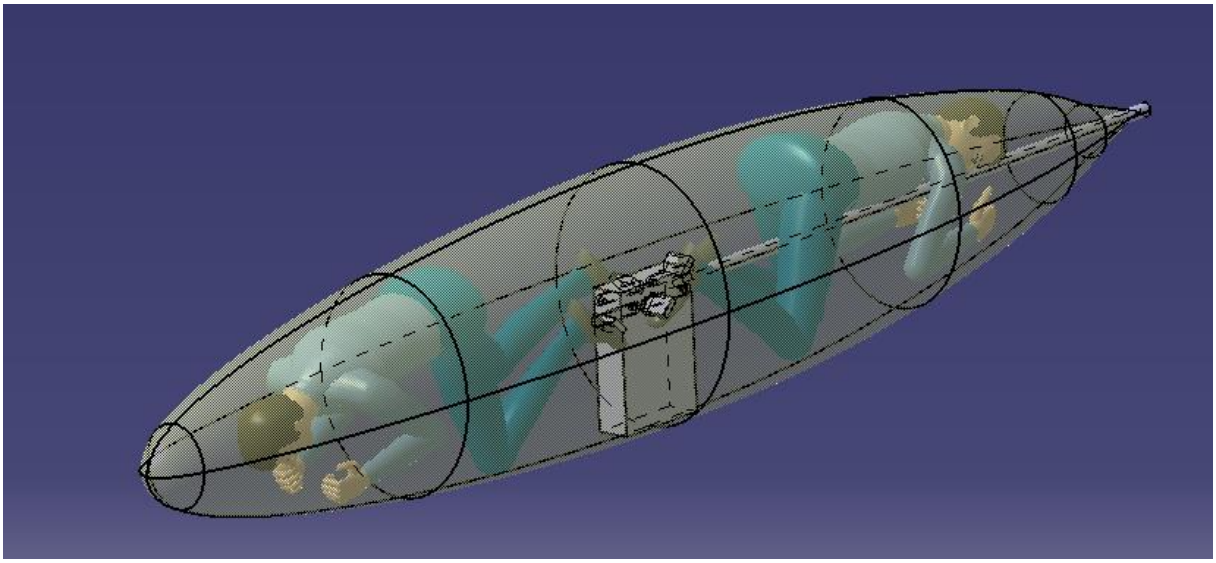


Figure 10 : Preview of the final hull with the tail cone

It is 4.25m long. Its maximum width is 616 mm and its maximum height is 764,5mm.

6 HYDRODYNAMICS

6.1 HULL RESISTANCE

After the creation of the geometry of the hull, we seek the drag that it generates. To do this, we will use the ANSYS Fluent software that allows us to perform simulations by the finite volume method. The numerical model used is based on the turbulence model SST-k-ω of Menter et Al (1993). This model is a fully turbulent two transport equation model. However, we use the transition SST-k-ω model that is not a fully turbulent model, which will give us a better accuracy in our results. Indeed, we do not know if the fluid is turbulent along the hull or only partially turbulent. This model will take into account the laminar region and the turbulent region, the estimation of the drag will be more realistic.

To simulate the behavior of the submarine in the water, we need to create a mesh. We use the ANSYS ICEM CFD software for creating accurate meshes. The parameters of meshing are defined by the choice of the numerical model we will use with the software ANSYS Fluent.

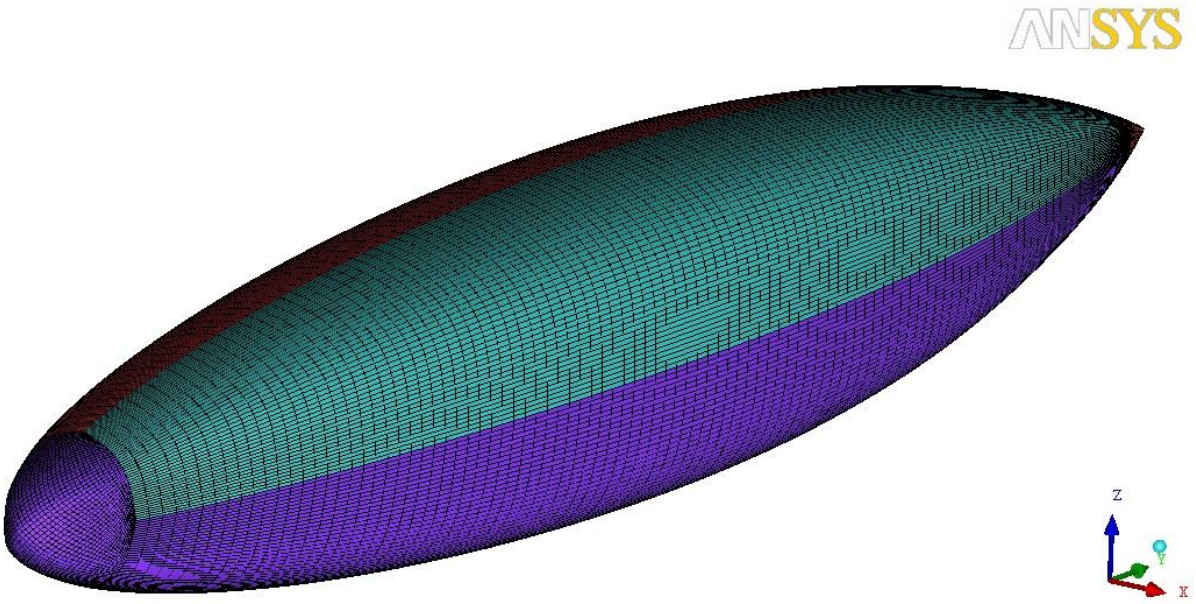


Figure 11 Mesh of the submarine hull

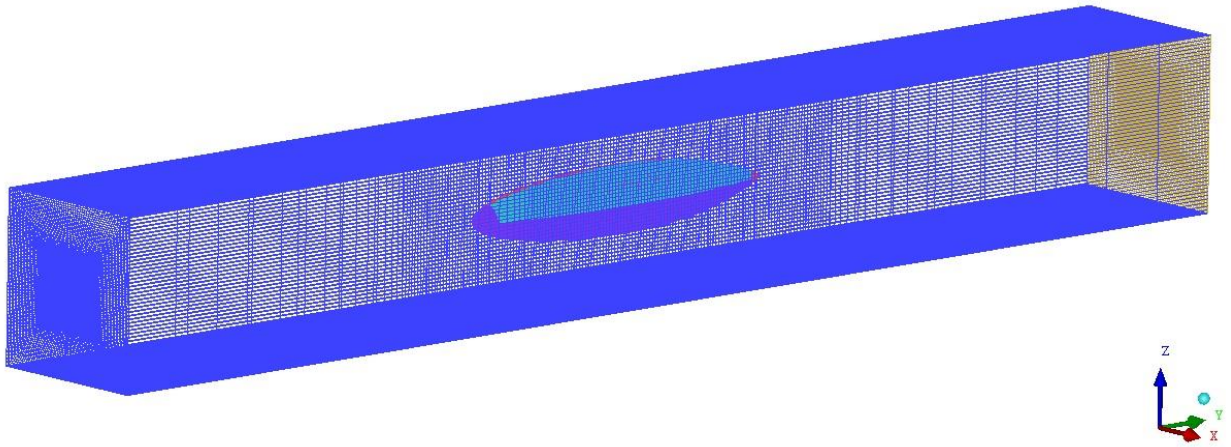


Figure 12 Mesh of the control volume

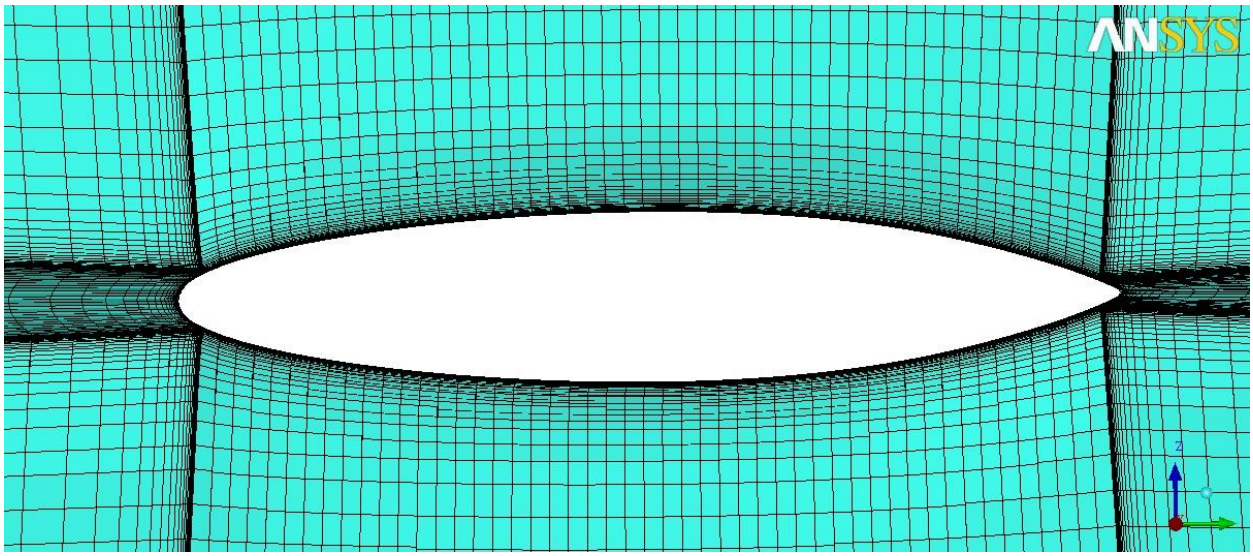


Figure 13 Cut plane of the control volume mesh close to the submarine hull

For the simulation with ANSYS Fluent, the boundary condition in the inlet is a velocity of 8 knots. The estimate coefficient of drag for the hull of Omer 9 is $6.924e^{-3}$. To calculate the drag force generated by the movement of water on the hull, we will use for formula follows:

$$F_{drag} = \frac{1}{2}.\rho.C_D.V^2.A$$

With A, the reference area. For a body like a submarine, the reference area is the projected frontal area.

$$A = \pi.D^2$$

With D is the maximal diameter of the submarine: 0.765m

C_d represents the drag coefficient of the hull calculated with ANSYS Fluent. V is the velocity of the fluid and ρ is the density of the water.

The resistant force generated by the water on the hull is 101.6N for a velocity of 8 knots.

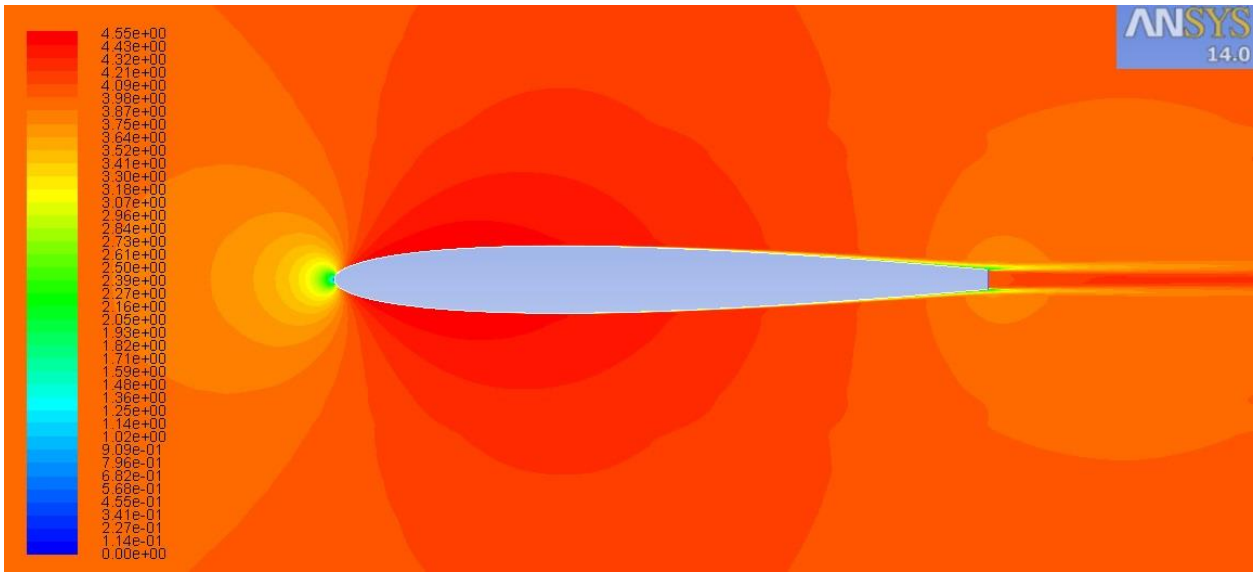


Figure 14 Velocity repartition around the hull of Omer9

On this figure, we can see the velocity repartition around the hull of the submarine after the hydrodynamic simulation with ANSYS Fluent.

7 PROPULSION SYSTEM

The propulsion system is designed to transfer the power of one person pedaling to the propeller. In the case of OMER 9, the main philosophy influencing our design was the efficiency, following that sentence: ''the simpler the better''. Doing so, we observed several two-person with propeller submarines, such as our previous OMER 5 and the latest submarine of the Florida Atlantic University, a two-person submarine called ''FAU-BOAT 2''. The main problem we saw in both design was the too high numbers of parts and gear, which increases the risks of mechanical failure and decreases the total yield of the submarine. You can see in the pictures below some overviews of the FAU-BOAT 2 and OMER 5 propulsion systems.

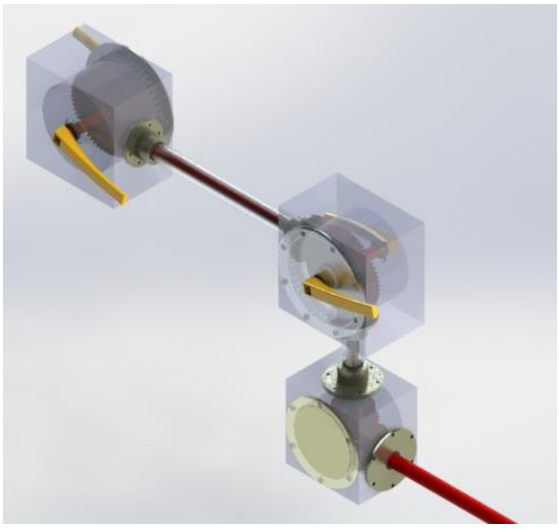


Figure 15: Overview of the FAU-BOAT 2 propulsion system

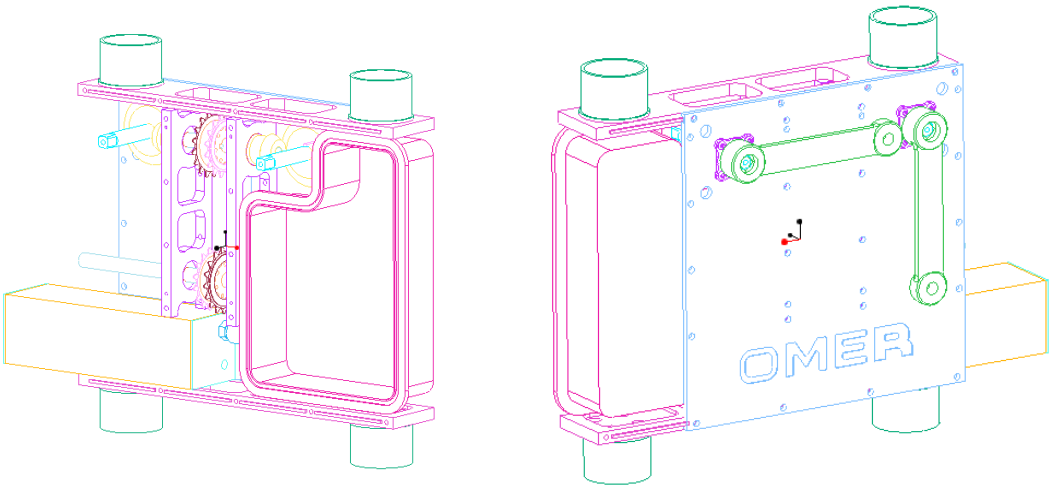


Figure 16: Overview of the OMER 5 propulsion system

Thus, we decided to use the same system as OMER 8 for the gearbox, but doubled in order to be able to use two pilots, which readjusts the rotation of a pedal board to a propeller. This choice was made considering that the gearbox of OMER 8 was optimal and a new design would be a waste of effort. Nonetheless, we designed a new propeller and the variable pitch of the new propeller. By doing so, we think that we can optimize their functioning compared to OMER 5 (2-person submarine with propeller). In the current section, we will explain the functioning of the propulsion system and all of its components.

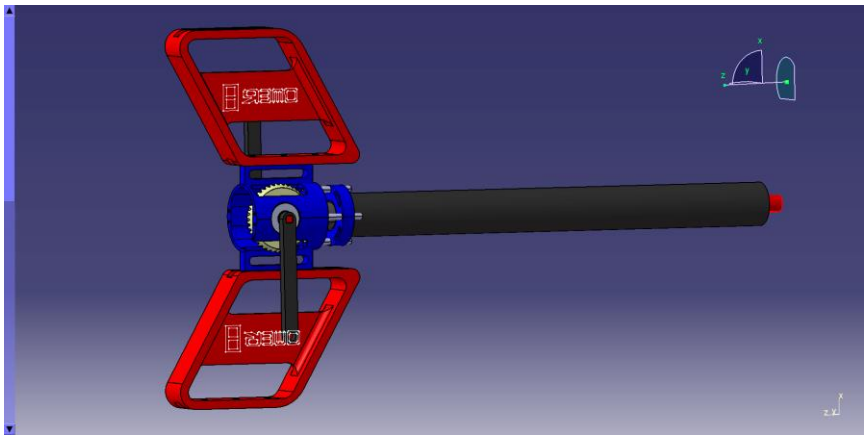


Figure 17: Overview of the OMER 8 propulsion system

7.1 PROPULSION SYSTEM DESIGN

The first thing that we did, before modeling in 3D, was to draw on a paper what the design will be globally. Some sketches were made to determine what parts are needed such as bearings, bevel gears, seals, motors, etc. After the global design is made, we began modeling with the software CATIA V5R19. All the parts needed were modeled. For some parts that we bought, the 3D cad file was downloadable online and then we can include these cads in our assembly model. If we don't have the cad file, we referred to specs sheet of the part and we modeled the part. For the modeling of the propulsion system, it's very important for us to have all the parts that will be present in the assembly. In the past, we learned that if the 3D model is not similar to what we want it to be in reality, there are chances that we have mismatches.

For the design, we began modeling the variable pitch. As it will be explained in another section, the variable pitch is designed to be in a conic rotor. The use of two bevels was decided before modeling and after we designed the rotor depending on the decisions in the preliminary design. During the modeling, we tried to fit all the parts needed in the rotor. The other thing was that we tried to make a design that will be simple and fast to assemble and disassemble the submarine. As a result, if there is a problem with the module, we can replace it very fast with another. The challenge in designing this module was to fit all the parts in the rotor as we said but also to make it waterproof because of the presence of electrical components.

For the modeling of the gearbox and all the parts connected to it, we used the 3D Cad files from the gearbox of OMER 4.The gearbox consists of an assembly of bevel gears connected to a driving shaft and a pedal board. With the gearbox, we modeled the other parts needed to fix the propulsion system in the submarine. In the next section, you will see the assembly of the gear and all of its parts.

7.2 DRIVE TRAIN

The propulsion system is designed to transfer the power of one person pedaling to the propeller. Because of the high efficiency we observed with that system on OMER 8, we decided to create a similar system for OMER 9, but adapted for a two-person submarine. Thus, we decided to use the same system as OMER 8 for the gearbox, which readjusts the rotation of a pedal board to a propeller. This choice was made considering that the gearbox of OMER 8 was optimal and a new design would be a waste of effort. Because of this choice, the goal was just to adapt the design for a two-person submarine. In the current section, we will explain the functioning of the propulsion system and all of its components.

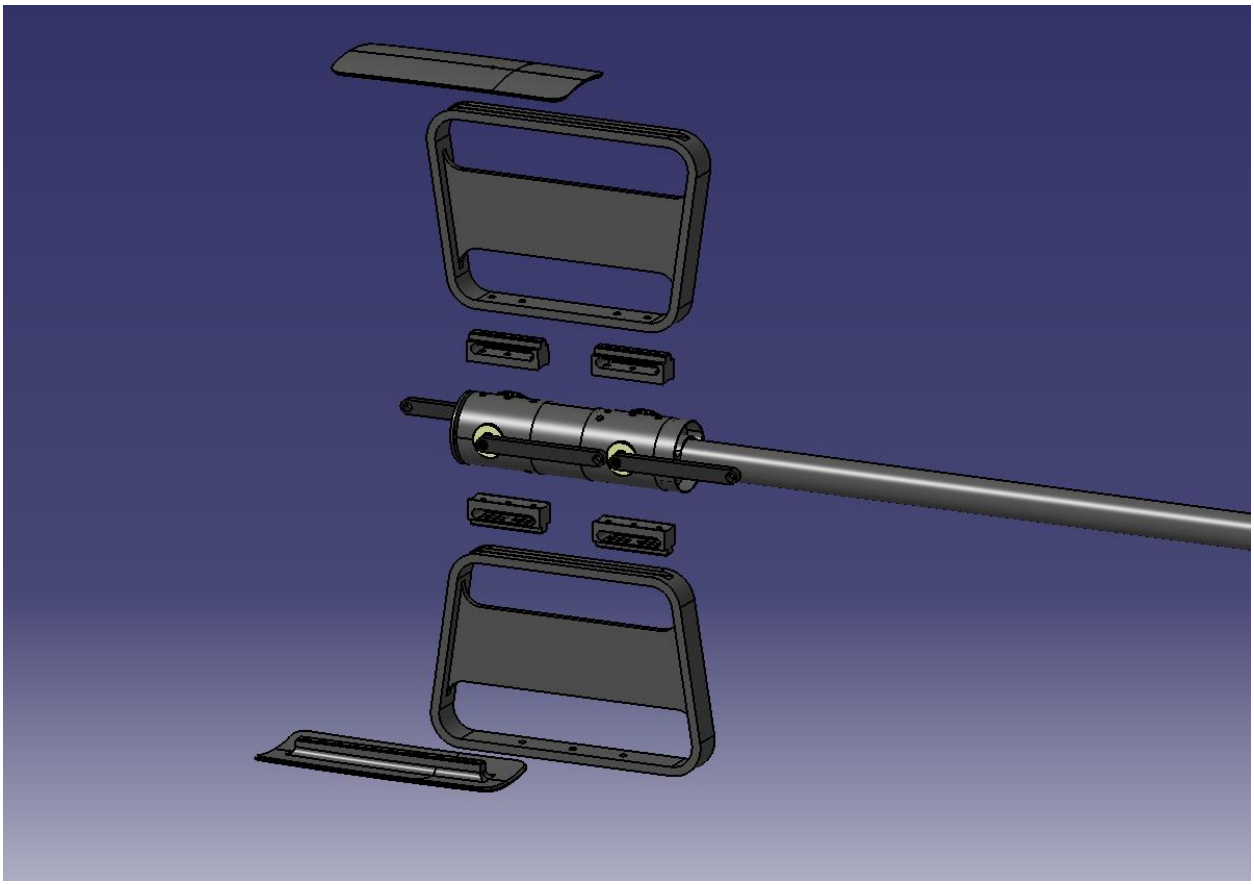


Figure 18: Propulsion system assembly

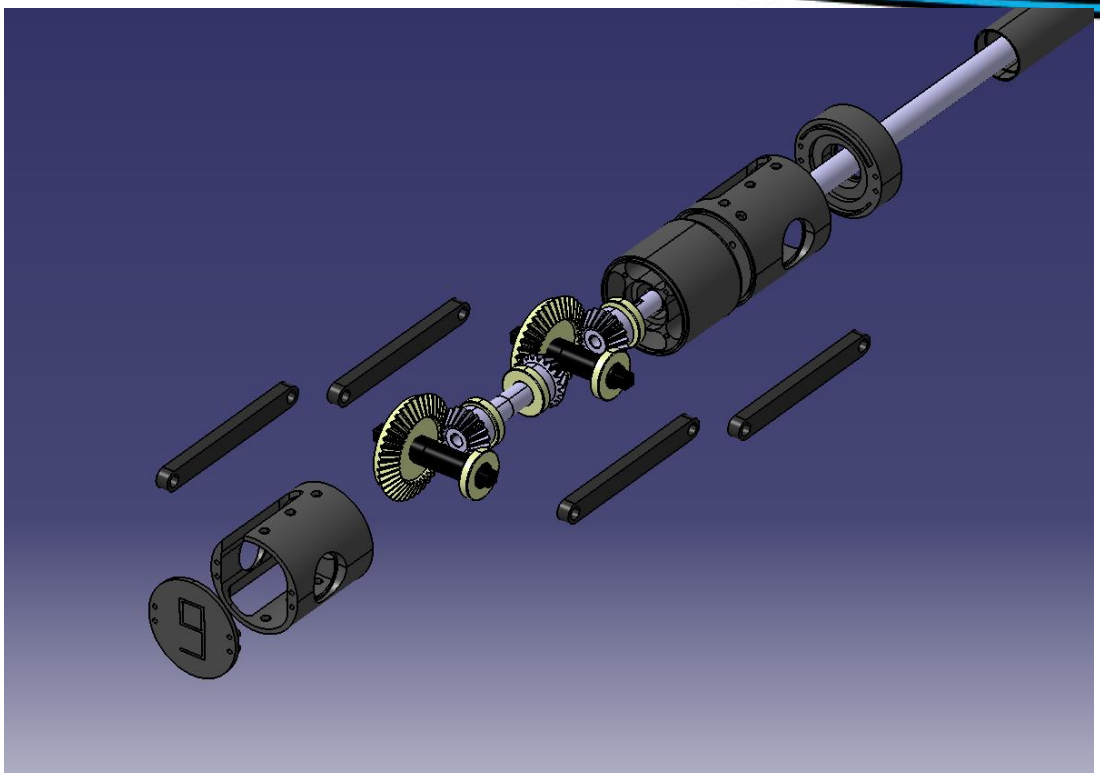


Figure 19: Gearbox assembly

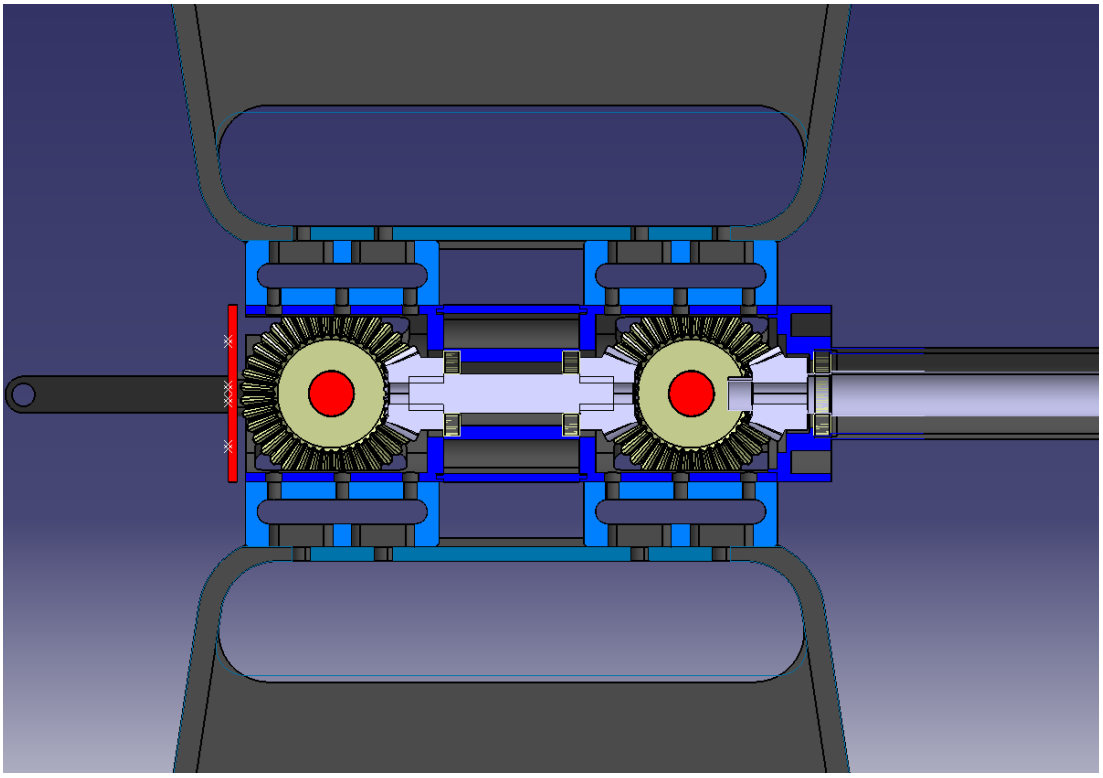


Figure 20: Rotation inside the gearbox

7.3 TRANSMISSION

The question of the transmission has been one of the great test in the OMER 9 design. As said before, our goal when designing the propulsion system was the efficiency. Observing the OMER 5 propulsion system that you can see in the Figure 15, we saw that they used a chain in order to transmit power to a lower shaft went all the way to the back and another chain to retransmit power to the propeller shaft.

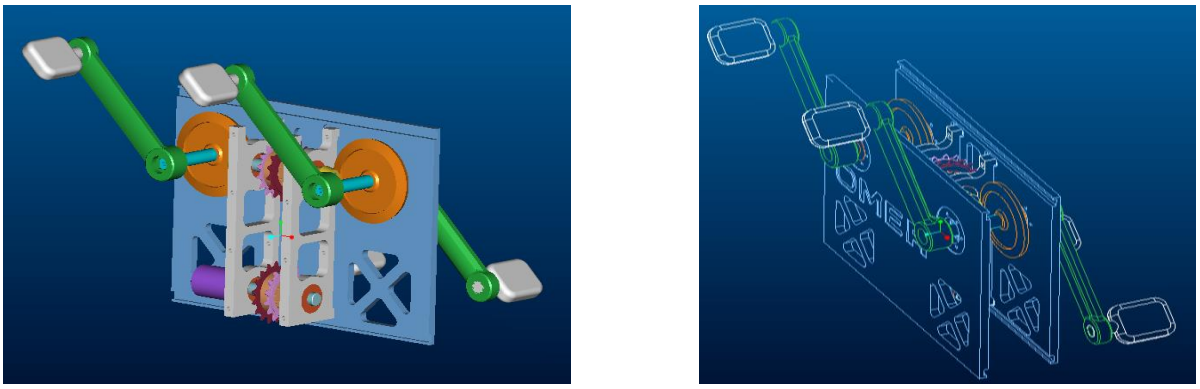


Figure 21: Overview of the OMER 5 propulsion system

Since OMER 5 holds the speed record we would like to beat in the future, we decided to design a system that would be more efficient: this would mean having a direct shaft covered by a pipe. At first sight, this idea seemed a bit crazy since the lower shaft of OMER 5 was made in order to give the second pilot a maximum of space to pedal, but while designing the hull, we decided to choose profiles that would help us implement that idea in the submarine. After some researches, we were finally able to create a hull that would allow us to use a direct shaft from the propulsion system to the tail cone in order to have a maximum efficiency in our system.

You can see the all system installed in our submarine in the picture below.

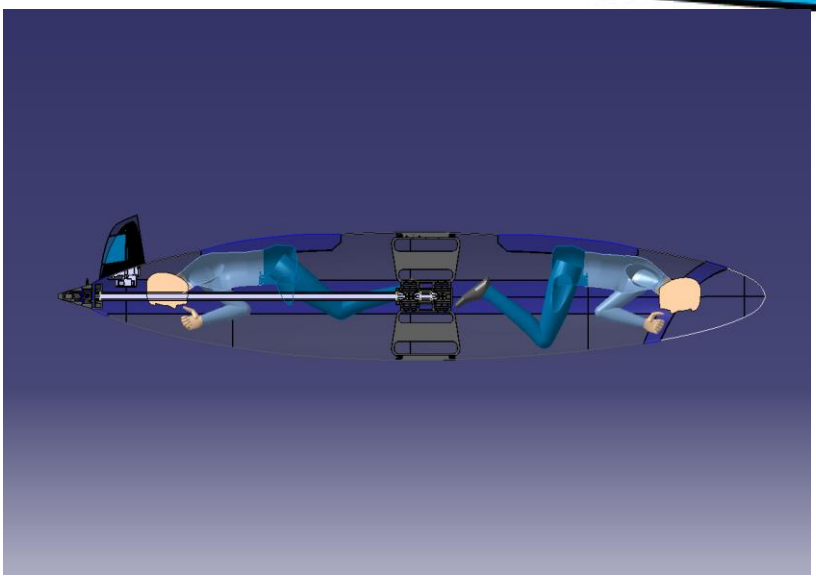


Figure 22: propulsion system installed in OMER 9

Doing so, the only requirements we had to follow was to have a pipe that would not be too big for not disturbing the pilot pedaling, such as on a bike.

This system will help us transmit all the power, with a maximum efficiency, from the pilot to the propeller, which is the subject of the next section in this report.

7.4 SIZING WITH ANSYS

As well as for the calculus of the hull resistance (drag), we used the ANSYS software during our design process. When considering the propulsion and the mechanics parts, the Workbench module was the one used to size the components. The geometries were imported from CATIA and we applied the forces that were acting on the component. After computing, the software was able to tell us the stress present in several positions. Here are several example of the parts we have tested in that software, such as the gears and the gearbox case.

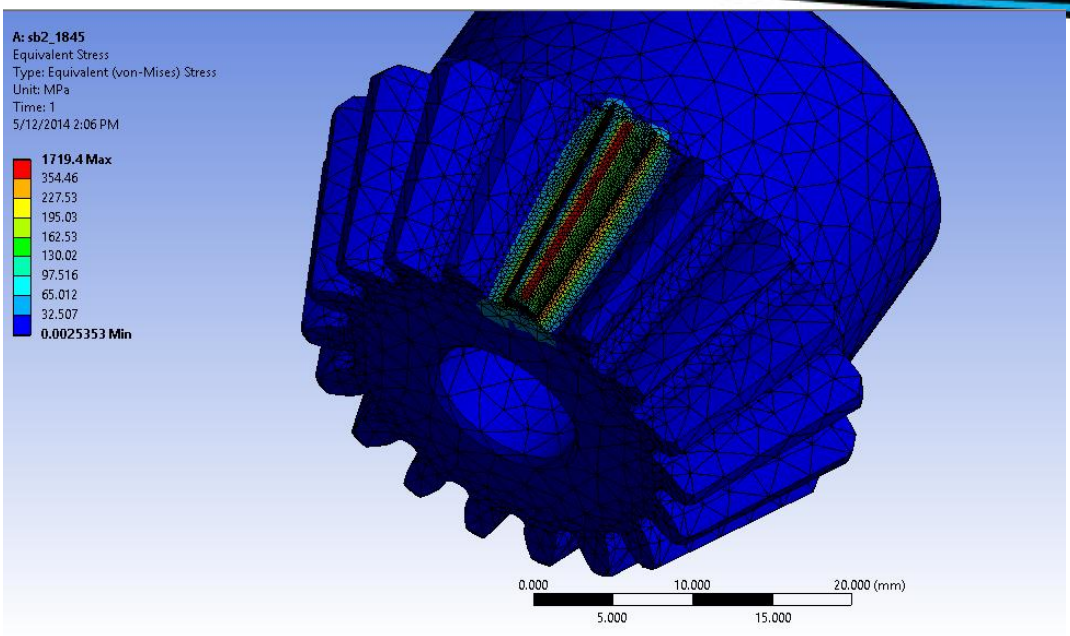


Figure 23: ANSYS sizing of a gear

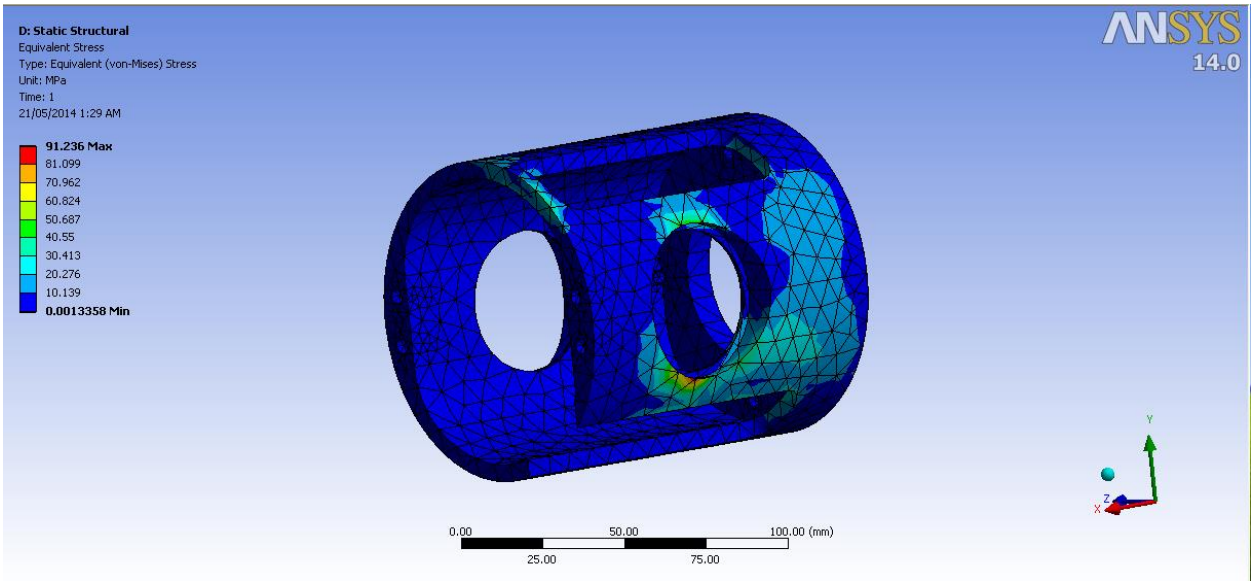


Figure 24: ANSYS sizing of the gearbox case

7.5 PROPELLERS

The blades of the propeller are designed with a MATLAB program that needs some parameters to produce a shape. The parameters are the rotation speed, the diameter of the

rotor, the resistance of the material used, the estimated power delivered by the pilot and the estimated drag of the hull and fins. Here is the list of the parameters and their values:

Table 1- Propeller design parameters

Rotation speed	200 Rpm
Diameter of the rotor	5.7 in
The resistance of the materiel	500 MPa (Tensile Strength)
The power delivered by the pilot	1.5 Hp
Estimated drag of the submarine	150 Newton

With the MATLAB program a type of airfoil is chosen and the angle and the length of cord of the airfoil is calculated throughout the blades length. Because the speed of fluid is higher the more you distance yourself from the rotor, the angle of the airfoil near the rotor is larger than the tip. The program also does an optimization of the length of the blade and the surface area. For the modeling, the MATLAB program produces points that represent airfoils disposed in 20 levels. Here are images of the points.

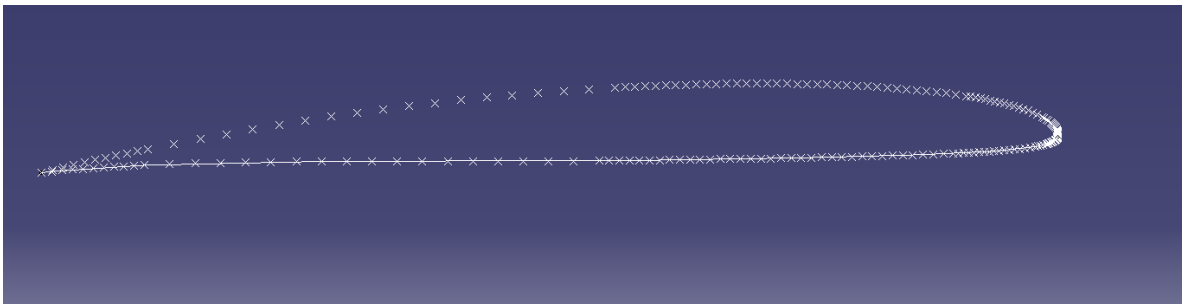


Figure 25- Points of an airfoil

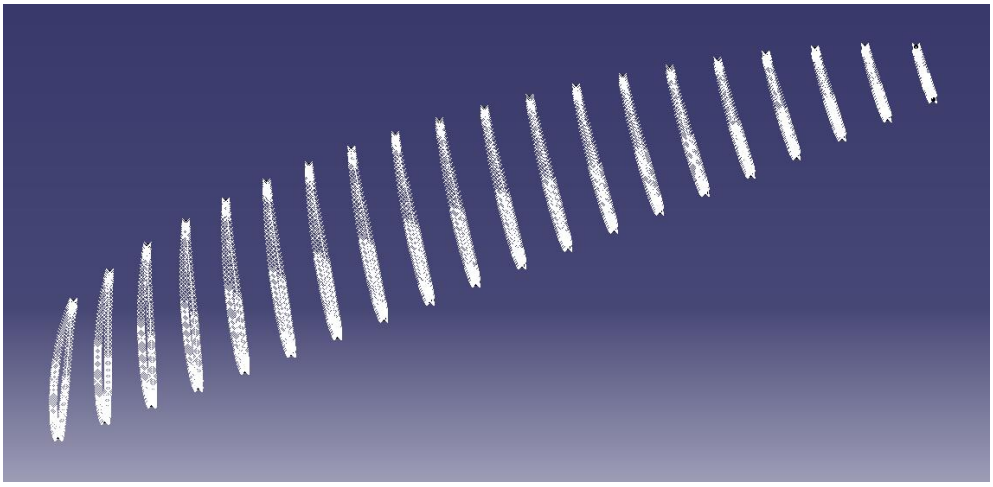


Figure 26- The airfoils on different levels

With the cloud of points, each upper and lower surface was drawn using a cubic spline going through the points. Once these splines drawn, a surface is generated. Then, work has been done so that the geometry fits as possible with the rotor surface. Moreover, the shape to connect the propeller to the variable pitch system was added.

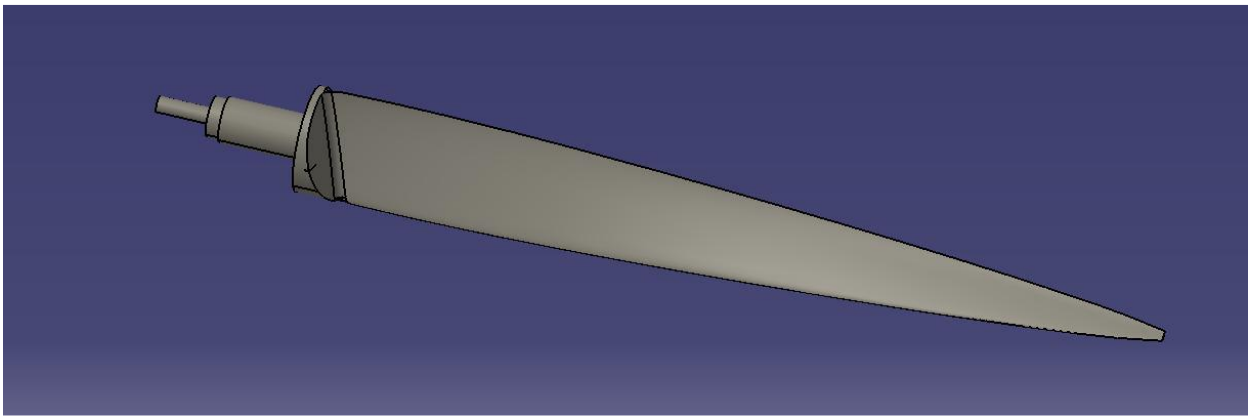


Figure 27- The 3D model of the propeller blade

Figure 28 illustrates the work done for the connection between the rotor and the propeller blade.

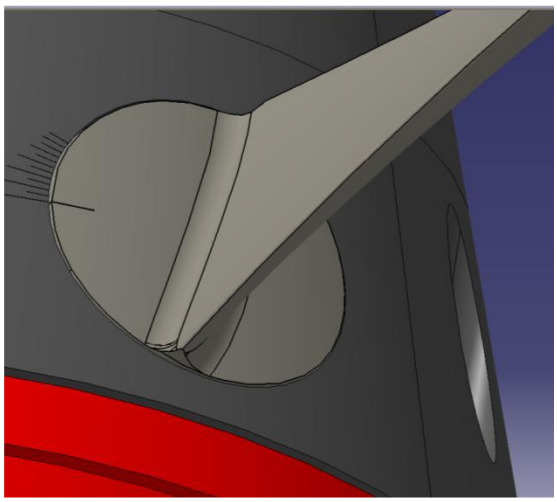


Figure 28: Connection between rotor and blade

7.6 VARIABLE PITCH

We call the variable pitch the module of the rotor, which handles the propeller. The purpose of the module is to rotate the propeller and to hold the two blades in a certain angle. The reason of a variable pitch is to keep the pilot pedaling at the more effective RPM. To make a system that adjusts the angle of the blades, there is not a lot of solution. The most common

used solution is a linear system controlled by an actuator. This system is used for the variable pitch of a helicopter and it has been used for OMER 4 and OMER 5. While seeking a more simple solution, we determined that we might be able to fit an electrical system in the rotor and it will be completely independent. Thus, it allows a simpler assembly and can be more precise. Furthermore, we wanted to simplify the assembly of the rotor to the propulsion system. In the other submarine, disassembling the rotor required disassembling all of the propulsion system. Since we put electrical components in the rotor and we wanted to make adjustments with the variable pitch program, we wanted the rotor to be disassembled very fast from the submarine.

The variable pitch is actually the rotor of the propeller with a mechanism for changing the pitch angle. This system is required to have a good acceleration from the start. This module is very similar to the one we used on OMER 8. This also helps to regulate the speed like an automatic transmission. In short, there are many ways to use a variable pitch in order to optimize the performance of the propulsion system.

To start, we decided to have a main part which accommodates the propellers and the mechanism, called the tail cone. Then we have another sealed part containing the motor and the electrical system, installed at the end of the cone that we call ''head cone''. Afterwards, we had to find a way to couple the cone to the transmission shaft. In order to the rotor to be quickly removable without having to remove the head cone, we implemented a turning plate fixed to the transmission shaft on which the cone will be fixed. Because of that part, we are able to remove the head cone to work on the electrical system without removing the propeller system, which is a bit harder to settle on the submarine. This assembly requires to have screw holes on the cone, which can affect the hydrodynamic efficiency of the propeller. Finally, we designed a hub to receive the transmission shaft. This hub will remain hooked to the sub, and bearing will be installed in order to allow the shaft rotation.

In figure 29, a view of the components described above. Looking at the assembly, the cover tube (5) of the driveshaft (6) is inserted into the hub (4). Afterwards, the turning plate (3) is connected to the driveshaft. On the turning plate, the rotor cone (2) is screwed on. In the end, the head cone (1) is screwed to the rotor cone.

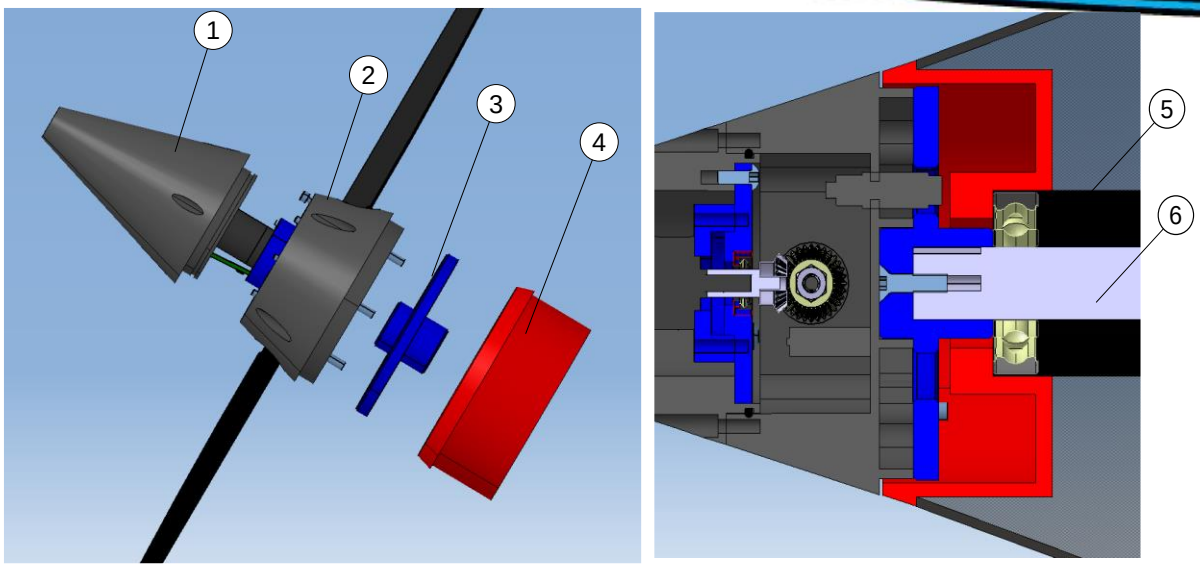


Figure 29- Components of the cone

Table 2: Components of the variable pitch

1	Head cone
2	Cone
3	Turning plate
4	Hub

Mechanics inside the rotor is pretty simple and compact given the limited space (see figure 30 and table 3). The motor and the circuit board are located above the blue parts which delimit what is contained into the head cone. These blue parts will be used for supporting the motor and sealing the head cone. The motor used is a MAXON (see appendix). This engine was chosen because of its high accuracy in that it has a gearbox with a large ratio. With an encoder that gives 16 pulses per revolution of the engine, we are able to have a good control on the pitch angle. Then, a waterproof connector (in yellow) is used for the connexion between the batteries and the Hall Effect sensor. A sealing washer is used at the motor shaft to protect all the electrical system from the environment. About mechanics, aluminium inserts are used to contain the bearings. The presence of these inserts is necessary in order to easily install the bearings. Small bevel gears are used and offer a ratio of 1.33 for 1, which increase the accuracy. The parts in green are sealing washers that help us having a sealed cone.

As it is shown, the hub is used to support the cover tube and is used to position the propulsion system. This part is fixed to the hull with glue so it is not moving. The turning plate is necessary to make the link between the driveshaft and the rotor cone. The reason why we do not directly connect the rotor cone to the driveshaft is that we want to be able to remove the entire rotor without disassembling the head cone and other components located in the rotor cone. Four screws hold the assembly, so it is really fast to disassemble. The rotor cone contains a lot of parts such as batteries, bevel gear bearings, bearing inserts and the blades of the

propeller. The main purpose of this part is to hold the blades of the propeller with the mechanism of the variable pitch. Connected to this part, we have the head cone, which includes the motor and electronics to control the mechanism of the variable pitch. In the next figure you can see the parts inside the rotor cone and the head cone.

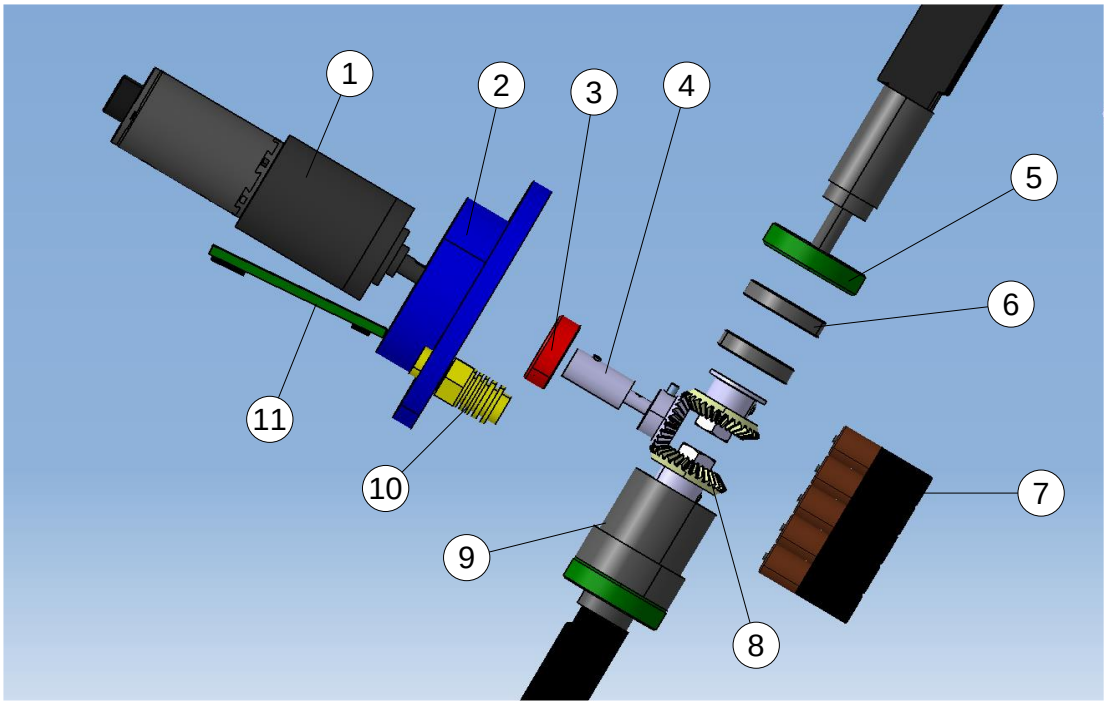


Figure 30-Components inside the rotor

Table 3 - List of the components inside the rotor

1-Electrical motor
2-Motor support
3-Seal of the head cone
4-Motor bushing
5- Seal of the rotor cone
6-Blade propeller bearing
7-Battery pack
8-Bevels gears
9-Bearing insert
10-Water proof connector
11-Electical board

For the design, the decision was taken to use a bevel gear assembly which performs exactly the movement required from the motor rotation. It means that both propellers should turn in opposite direction. In figure 32, you can see the rotation of the motor giving a clockwise rotation on the propellers. This rotation of the engine increases the pitch angle for more biasing

force. You should notice the arrows designating the front and rear of the submarine. The rotor always rotates clockwise, viewed from behind.

The mechanism inside the rotor, shown in the figure, controls the angle of the two blades. Those two blades are assembled in two bearings to hold them in place and allow their rotation. The bevel gears are also connected to the blades. For the design, we wanted to choose bevel gears with a high number of teeth in order to have better precision and to limit loose fits. Due to the rotor cone being relatively small, we were limited in choice of bevel gears. The gears that we decided to use for the design offer a ratio of 1 for 1.3 and 35 and 29 teeth. The ratio is not very high which offers less precision. However, we decided to use an electrical motor with an integrated gearbox that has a ratio of 1 for 256. This motor is installed on a support to be perfectly placed in the head cone. The seals in the assembly are necessary to keep the entire rotor waterproof. To make sure that there is no water that goes through the motor and the electrical board, we designed the head cone to be perfectly waterproof independently of the rotor cone. The rotor cone is designed to be waterproof too, although with the blades moving, we are not sure if the seals will be waterproof. Here is some more information of the variable pitch mechanism:

Table 4-Variable Pitch components information

Battery pack voltage	24 volts
Motor	Maxon, 100 watts, 24 volts
Bevels Gears	Cobalt
Weight	100 Kg
Number of parts	25 parts
Bearing	17mm(NSK6002), 15 mm (NSK6000)
Seal	SKF CR SEALS 6mm and 17 mm
Connector	Seacon Hummer 1.15 amps

7.6.1 Functioning of the variable pitch

As mentioned earlier, the mechanism of the variable pitch consists of controlling the angle of the blades mounted to the rotor. In the picture below we can see an example of the possible positioning of the propeller blades. The variation of the angle increases or decreases the propulsion to get maximum force out of the pilots pedaling, it`s like when you are changing speeds on a bicycle.

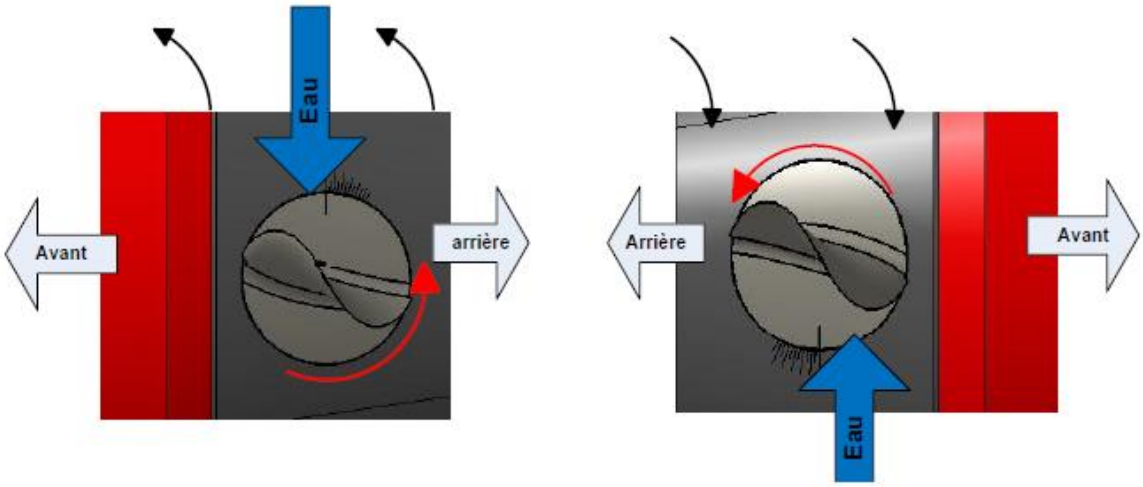


Figure 31- Different angles of blades

To simplify the explanation of the phenomenon we displayed the situation when rotor is turning in the image below. When the water hits the angled blade, it creates a force, which is decomposed in lift and drag. The lift pushes the submarine forward and the drag resists the rotation of the blade. The variation of the lift and drag is influenced by the rotation speed and the angle of the blade. To increase the lift you can keep the same rotor speed and just increase the angle of the blades. In our case a lower angle will give more lift. In the picture the blade drawn flat but in reality the blades are dimensioned with aeronautics airfoil. There are limits to how much you can increase the angle. For example, if you drag horizontally with and angle of 90 degrees the drag is a lot stronger then the lift, just like trying to push water aside with a flat hand. On the other hand, if the angle is near 0 degree the drag will be small but the lift will be close to zero, it`s like slicing through water with a sword. With our blade design, the maximal pitch angle (angle with which we get maximal lift/drag ratio) is about 20 degree. The designs of the blades of propeller are more detailed in the section 5.

The image below is an example of the variable pitch system decreasing the angle of the propeller to increase lift. We use bevel gears for the rotation of the two blades. During the rotation, the fluid on different sides hits the blades and thus must both be turned counter clockwise in order to get a better lift.

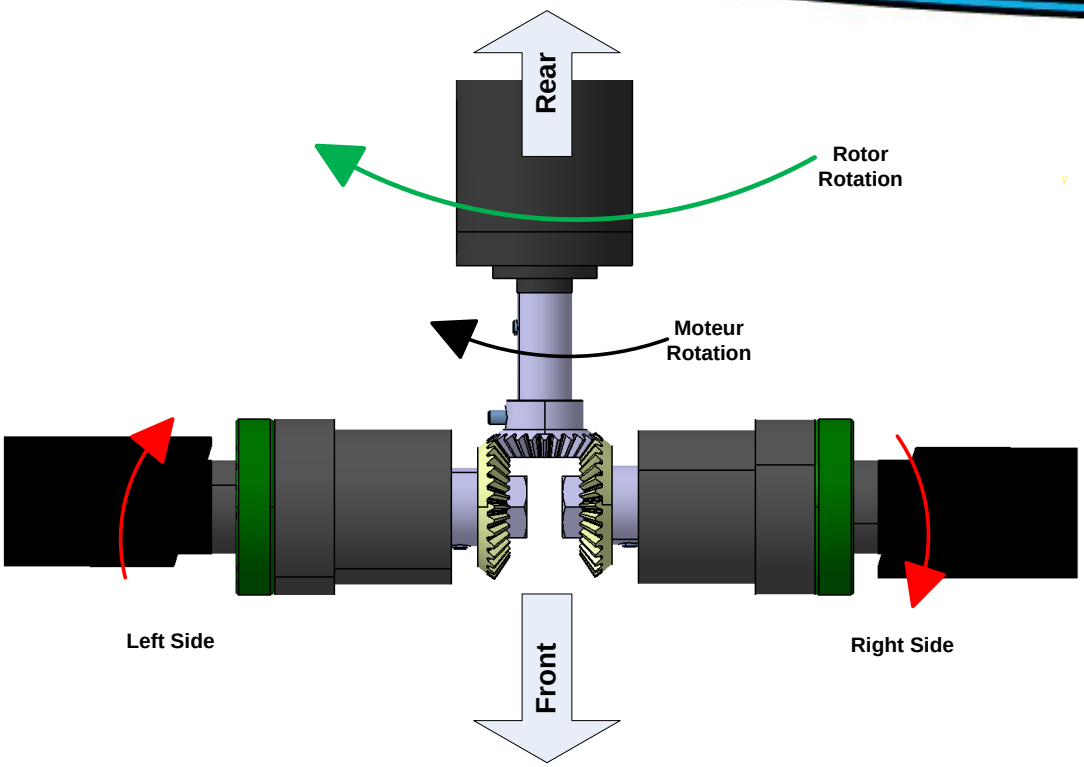


Figure 32- Rotation of the motor and the blades

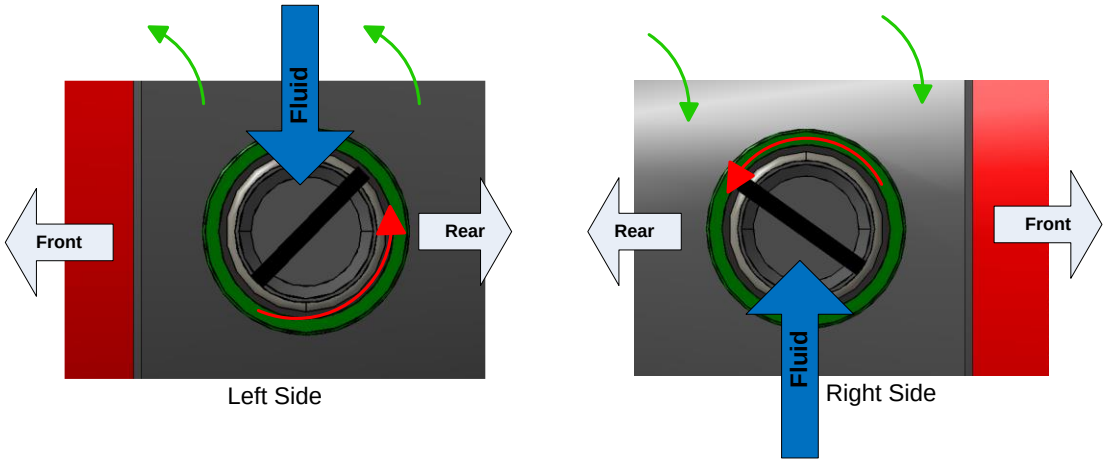


Figure 33 - Example of the variation of the angle

7.6.2 Fabrication

The fabrication of the propulsion system has mostly involved machining custom pieces designed in 3D on CATIA V5R20. For parts that need to be machined in a 3-axis numeric milling, we programmed the tools trajectories in CATIA with the manufacturing features and then we programmed it in a machine which then cuts out the piece. For cylindrical and conic parts, we use a numeric ladder called Mazak, which is already programmed in our machine, so all we have to do is input the dimensions wanted. We included some pictures of the machine and parts made from the ladder in the Appendix B.

To ensure a quality, every part is inspected to insure that it will fit in the final assembly. This inspection is made with micrometers and calipers to verify if the dimensions are within the tolerated variations.

Once the machining is finished, we pass to the assembly where we recheck every parts, to make sure it fits the 3D model, and that it is tight enough to fit and that it won't need constant tuning.

7.6.3 Electrical system

The variable pitch is controlled by an electrical system that changes the angle of the propeller blades. This system consists of a motor controlled by a programmed electrical board. The board will adjust the angle of the blades in function of the rotation speed. To evaluate the speed of the rotor a Hall Effect sensor is placed below the rotor cone and each time its passes of one of the reference holes the microchip will calculate the speed of the rotor using the time it took between two reference holes.

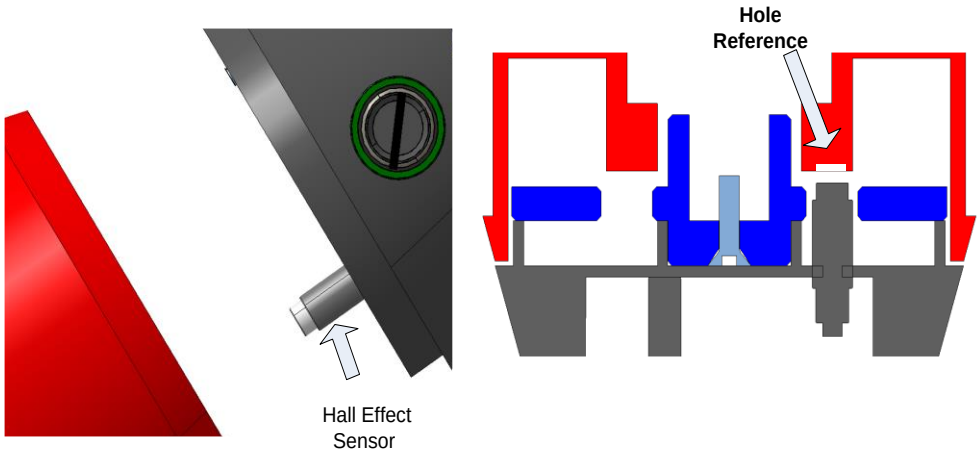


Figure 34- Hall effect sensor position

The design of the circuits and electrical boards are done in specifically designed software. We then ship the drawing to a company that fabricates the board with the electrical circuit wanted. The image below displays the electrical board that will be used in OMER 9.

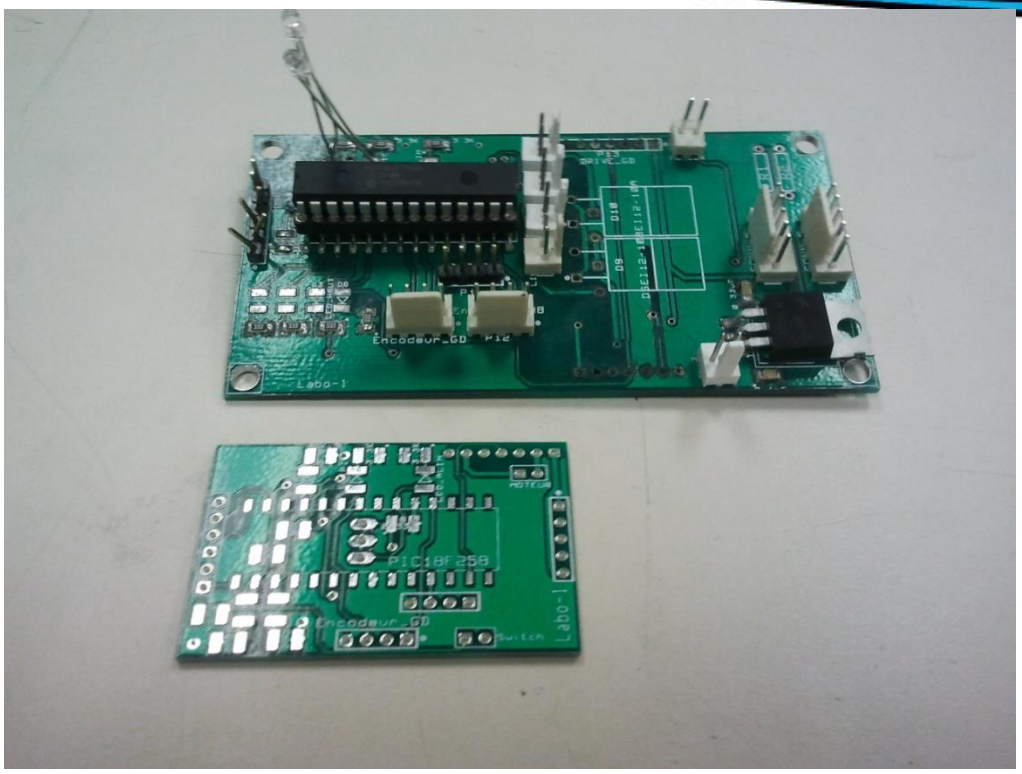


Figure 35- Direction PCB for OMER 7 (on top) and variable pitch PCB for OMER 9(on bottom)

7.7 PILOT BIOMECHANICS

7.7.1 Power available

This parameter is very important for all the calculus on the propulsion. We can add that all the measurements were taken in ideal conditions and on dry earth, and not into water. Thus, a good pilot is able to reach 1.2 HP. But several problems are encounter in the submarine:

- Friction with water when pedaling
- Difficulty to breath in water
- Loss of corporeal heat
- Nervousness because of the event and the restrained space.

With all this factors, and after running some tests in our basin, we can see that the power a good pilot can deliver is more about 1 HP. When a second pilot is added, the power they can deliver together when synchronized is about 1.5 HP

Figure 36: Our former main pilot David Barry (on the right) at ISR 11

7.7.2 Breathing resistance

On earth, we breathe without thinking about it, and without making any effort. However, we have limits about the pressure when we breathe in and out. Actually, we can blow out 2 psi maximum and breathe in -1.5 psi. Then, when the pilot is under water with pressure applied on his chest, it becomes important to help him breathing. Two simple solutions can solve this problem:

7.7.2.1 Choice of the reducing valve

The first solution is within the choice of the second stage of the pressure reducing valve. That component, which will be in the pilot mouth, has a big influence. First of all, there should need a maximum of 0.15 psi to activate itself in free air. Above that pressure, the effort asked to breathe is too important and case of stunning can appear.

7.7.2.2 Air consumption according to the pilots position

According to a study run by doctor M.L. Nuckols, the position of the pilots has a non-negligible influence on the air consumption. His conclusions shows that it is easier to pedal while lying on the back, in terms of power. However, the air consumption is bigger, breathing is harder and this position non-natural for a diver. That study confirmed our choice made several years ago to let our pilot pedaling face down, which is also much better for looking at the outside of the submarine.

8 TRIM, HYDROSTATICS & STABILITY

8.1 WEIGHT ESTIMATIONS & VOLUME CALCULATIONS

The estimation of the mass of the different parts of the submarine is important to calculate the center of gravity, the buoyancy center, and the gravity and buoyancy forces.

A first estimation of the mass will be made from models realized in CATIA and the exact mass will be measured both machined parts. The volumes of the different parts of Omer 9 are also estimated from models realized with CATIA. The actual volumes are then calculated from different masses and densities of different elements.

$$m = \rho . V$$

With m, the mass in kg, ρ, the density in kg/m^3 and V, the volume en m^3

8.2 CENTRE OF GRAVITY

The center of gravity of the submarine is determined theoretically from the weights and centers of gravity of the different elements present in the submarine. Note that to a system composed of n sub-assembly, the center of gravity is calculated as follows:

$$\overrightarrow{OG} = \frac{1}{p} \sum_{1}^{n} p_i . \overrightarrow{OG_i}$$

With:

$$p_i = m_i . g = \rho_{subset} . V_i . g$$

$$p = \sum_{1}^{n} p_i$$

In the formula above, point O represents the point at the top of the nose sub. Force p is the total weight of the submarine while pi force represents the weights of the different subsets of the submarine. The G point characterizes what we want, that is the center of gravity of the submarine while Gi points characterize the centers of gravity of the different subsets.

Table 5 : Weight and center of gravity of the subsets of Omer9 on the longitudinal (x) and vertical (y) axis

Subset	OGi on x (m)	OGi on y (m)	Weigth (kg)	Gravity force (N)
Propulsion support	2,032	0	2,241	-21.98
Propulsion	2,445	0	7,1319447	-69.96
Tail cone	4,075	0	3,1	-30.41
Fins	3.825	0	3	-30
Flap	3.950	0	1	-10
Hull	2,035	0	32,763234	-321.41

Direction	3,825	0	0,972	-9.53
Scuba tank	2,125	-0.324	28	-274.7
Propulsion's insert	2,032	0	7,3891494	-72.49
Protection axis	3,056	0	1,35	-13.24

With the above data, we can calculate the position of the center of gravity on the longitudinal axis of the submarine. It is located at 2.214 m from the nose of the submarine. Remember that the total size of the submarine is 4.25 m, it means that the center of gravity is located at 52% of the length of the submarine.

Scuba tanks are the only components of the submarine which will affect the position of center of gravity on the vertical axis. Indeed, all the others systems of the submarine are distributed symmetrically. Using the formula seen above, we can determine the position of the center of gravity along the y axis.

$$\overrightarrow{OG}_y = \frac{p_{scuba\ tank}}{p} \overrightarrow{OG_{y_tank}}$$

The center of gravity is located at x=2.214m and y=-0.11m considering the point with the coordinate (0,0) is the nose of the submarine.

The center of gravity of the submarine will encounter some changes when we will perform the balance of the submarine. Indeed, the fact of adding the foam and weights will change the location of the center of gravity. We will give new localizations progressively.

8.3 CENTRE OF BUOYANCY

To determine the center of buoyancy, we need to calculate the buoyancy generated by the different subsets of the submarine. The calculus of the buoyancy is based on the Archimedes' principle described below:

$$F_B = \rho_{water} . V_{subset} . g$$

In this formula, V represents the displaced volume of the subset considerate. In our case, the submarine and all the subset are totally immerged in the water so the volume V is the complete volume of the subset. We can also write the buoyancy formula as follows:

$$F_{B=} = \rho_{water} . \frac{m_{subset}}{\rho_{subset}} . g$$

Tableau 1 : Density and center of buoyancy of the subsets of Omer9 on the longitudinal (x) and vertical (y) axis

Subset	OGi sur x (m)	OGi sur y (m)	Density (kg/m3)	Bouyancy force (N)
Propulsion support	2,032	0	2700	8.14
Propulsion	2,445	0	2700	25.91

Tail cone	4,075	0	2700	11.26
Fins	3.825	0	1500	19.62
Flap	3.950	0	1500	6.54
Hull	2,035	0	/	223.2
Direction	3,825	0	2700	3.53
Scuba tank	2,125	-0.324	7800	34.77
Propulsion's insert	2,032	0	2700	26.85
Protection axis	3,056	0	2700	4.91

In the same way in order to determine the center of gravity, we will use the following formula:

$$\overrightarrow{OB} = \frac{1}{F_B} \sum_{1}^{n} F_{Bi} . \overrightarrow{OB_i}$$

B is here the center of buoyancy, which is, after calculation, at a distance of 2.18 m from the nose of the submarine on the longitudinal axis. It means it's located at 51.3% of the total length of the submarine, slightly before the location of the center of gravity.

The center of buoyancy is located at x=2.18m and y=-0.033 m considering the point with the coordinate (0,0) is the nose of the submarine.

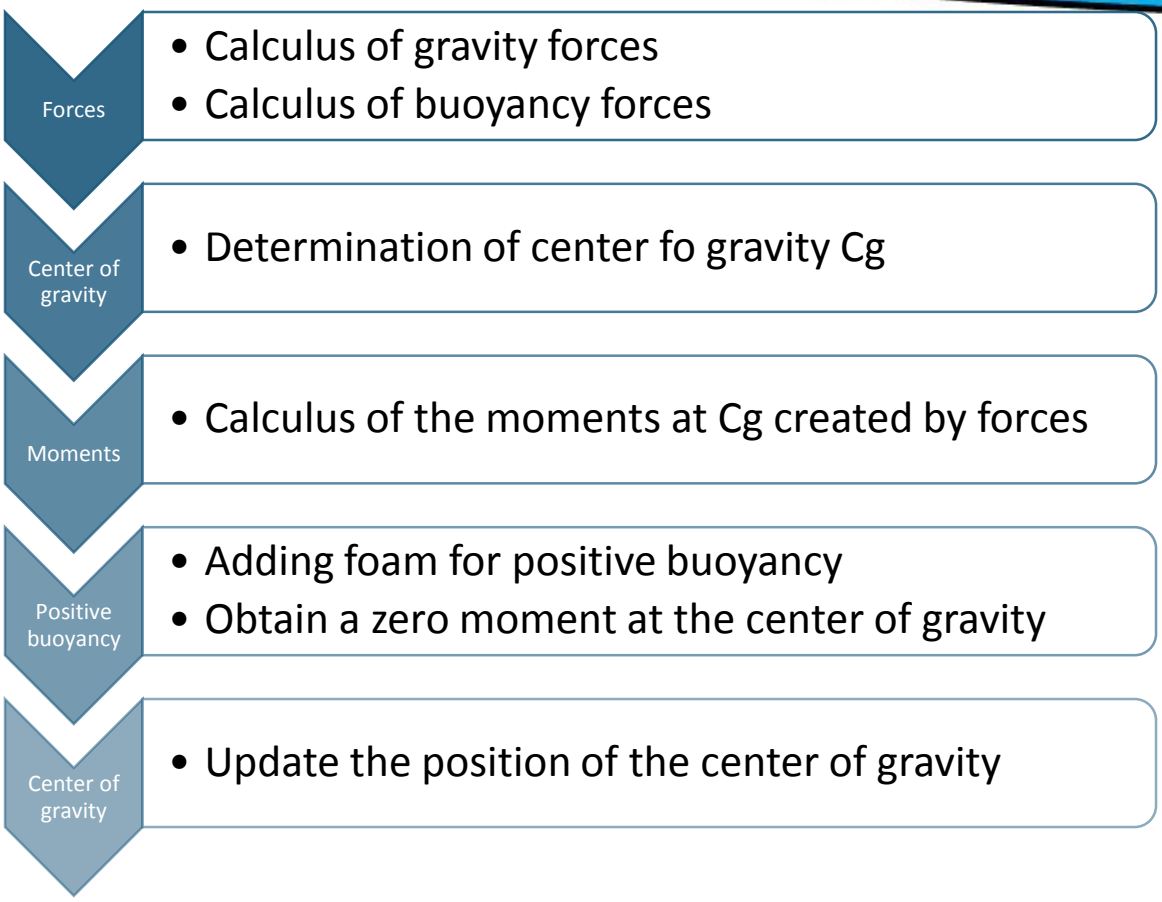
8.4 CENTRE OF LATERAL RESISTANCE

The center of resistance (CLR) can be defined as that point on the hull through which a single force acting would produce the same effect on the hull as all the water forces. The hydrodynamic CLR position is not constant and varies with respect to inclination angles. (Methods to determine the hydrodynamic CLR and directional stability of yachforms, C.H.K. Williamsin, University of Southampton, July 1978)

Calculating the dynamic CLR is difficult because it requires a lot of computing hydrodynamic calculation and its position will change with several parameters as we have seen previously. However, we can estimate the location of the static CLR, it will be located near the center of gravity of the fins of the submarine.

8.5 TRIM AND COMPENSATION BALLAST/BUOYANCY

In this section, we'll see the method we used to calculate the weight of foam we need to put in our hull to have a neutral buoyancy. The diagram below describes the different steps of the compensation buoyancy study. Each step will be explained in details to understand our choices.



First, we need to calculate all the static forces applied on the submarine. We can discern two types of forces: gravity forces and buoyancy forces. The submarine is divided into several subsets as we saw in the previous sections. So we calculate the resultant force of all the subsets with the formula presented bellow which combine gravity and buoyancy forces:

$$F_{subset} = \frac{\rho_{subset} - \rho_{water}}{\rho_{water}} . m . g$$

The resultant forces are summarized in the table below.

Table 5: Resultant forces of the different subsets of the submarine

Subset	**Resultant force (N)**
Propulsion support	-13.84
Propulsion	-44.05
Tail cone	-19.15
Fins	-10.38
Flap	-3.46

Hull	-98.2
Direction	-6.01
Scuba tank	-239.91
Propulsion's insert	-45.64
Protection axis	-8.34

The sum of forces gives us -475.15 N to compensate with foam to obtain a neutral buoyancy.

Secondly, we have to determine the center of gravity and the center of buoyancy of the submarine. Those two steps are described respectively in the sections 8.2 and 8.3.

After the determination of the gravity center (Cg), we'll calculate the moment created by the resultant force of the different subsets at the point Cg. For the buoyancy compensation, we want a neutral buoyancy but we also want a good stability of the submarine. That means a zero moment at the center of gravity. This is equivalent to change the position of the center of buoyancy to make it exactly coincides with the center of gravity on the longitudinal axis.

$$M_{subset_Cg} = (Cg_{subset} - Cg_{submarine}).F_{subset}$$

With Cg_subset represents the emplacement of the center of gravity of the subset studied.

Before we start placing the foam, we have a resultant of moment equal to -12.7 N.m.

To calculate the volume of foam we need to compensate the resultant force, we used the formula follows:

$$V_{foam} = \frac{475.15}{g.(\rho_{warer} - \rho_{foam})}$$

Avec ρ_{foam} = 140 kg/m^3, on obtient :

$$V_{foam} = 0.0563\ m^3$$

Which is equivalent to 7.88kg of foam. We want a positive buoyancy because it's easier to add weight in the submarine than add foam, so we will use a security factor of 1.2 to increase the weight of foam we'll place in the submarine.

$$m_{foam} = 1.2 * \rho_{foam} * V_{foam} = 9.46\ kg$$

To determine the possible positions of the foam in the submarine, we use the CATIA model to estimate where will be the elements which constraint us.

Each time that we add a volume of foam, we update the calculation of the center of gravity, the resultant force and the resultant moment until we have a resultant force positive. After adding the foam in the hull of the submarine, we have to add weight at the front of the

submarine to adjust the resultant moment to have a good stability. Theoretically, we need to add 7.35 kg of weight but we will find the good balance and position of the weight when we will do some underwater buoyancy tests.

The values of resultant force and resultant moment at the different steps of the buoyancy study are summarized in the following table.

Table 6: Resultant forces, moments and center of gravity following the steps of balancing the submarine

	Resultant force	**Resultant moment at Cg**	**Gravity center (x)**
Submarine without foam	-475.15 N	-12.7 N.m	2.214
Submarine with foam	189 N	-131.1 N.m	2.192
Submarine with foam and weight	11.2 N	-3.1 N.m	2.084

Now, we have theoretically a good balance of Omer9. To confirm all the calculation made above, we have to test our submarine in a swimming pool.

8.6 STABILITY WITH AND WITHOUT PILOTS

We previously calculated the position of the centers of gravity and buoyancy. We found that the positions x were very close but the vertical positions were different. The center of gravity will be located below the center of buoyancy, which will give a better stability to the submarine.

We consider the pilots as neutral buoyancy bodies, so they will have no impact on the stability of the submarine.

The change of volume in the scuba tanks will have some influence on the stability of the submarine. Indeed, when the cylinders will start to empty, they will lighten and this will change the position of the center of gravity. The submarine will be less stable progressively during the race.

9 CONTROL SYSTEMS

9.1 PITCH & DEPTH CONTROL

As for most submarine, all the control are managed by fins. Most submarine or plane have those fins at the back of the profile. In our case, those fins are located just before the propeller at the very end of the submarine. On previous submarine generation, fins were used for control and stabilizations were used for stability, the fins were generally located at the end of the submarine, when the stabilization where close to the center points. Stabilization, are normally fixed surfaces that have stabilize the submarine by having an angle between then and the fluid only then the submarine in not straight. Directional fins are mobile and can turn to generate lift on either direction to change the submarine trajectory. On different submarine, the mean to change angle of those fins were ether mechanical or electrical. The mechanical system were using cable and pulley, when the electrical systems were using DC motor. The OMER9 direction is electrical and using 1 servomotor for each fins, this will allow an easier control, easier replacement, and the possibility to move each fin individually compared to previous system when the up and down fins and port and starboard were mechanically linked and had to move together. This increased adjustability will, for example allow to create some torque using the 4 fins to counter the propeller torque which is way greater in the few first meter of the race.

9.2 CHOOSING THE TYPE OF STEERING.

For the direction of our submarine OMER 9 we chose to design an electrical direction to have a better control of the fins' position, in order to reduce the drag generated by the trajectory corrections. The design of such a direction involves three distinct parts

- a ''Joystick''
- a ''Brain''
- ''Actuators''

For reasons of efficiencies and robustness, each of these parts must be independent and easily replaceable in case of damages or mal-functioning.

9.3 DESCRIPTION OF THE STEERING VARIOUS COMPONENTS

9.3.1 Joystick

The joystick is a key element of the steering system because it is through him that the driver will control the submarine orientation. It must be ergonomic and should have a short response time to give the driver a feeling of physical connection between the handle and the movement of the submarine.

The main challenge is to convey the handle position information with precision in a sealed system. For this it is best to have a system where there the electronic part is not directly linked to the movable part of the handle, so without contact and wires. For this we decided to use a magnetic sensor to receive the data, and a magnet to transmit them.

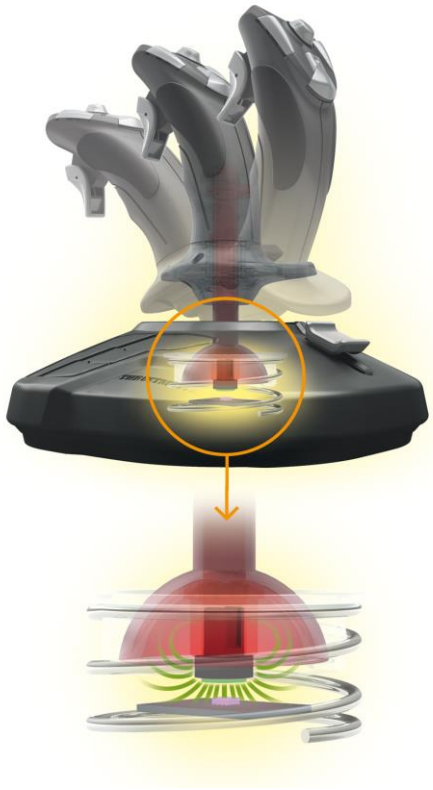


Figure 37: High resolution 3D magnetic sensor with Hall Effect

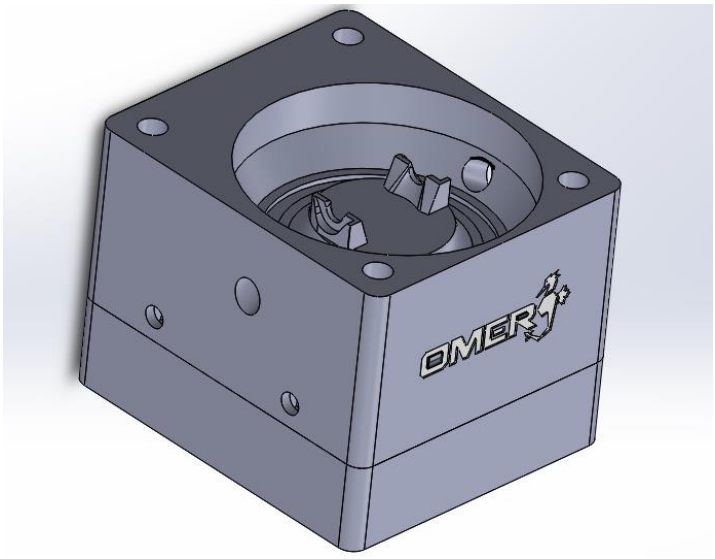


Figure 38: Joystick designed on SOLIDWORKS software

To ensure the water tightness of the electronic part, we sealed it in resin so that nothing can reach it except the magnetic field of the magnet sleeve.

In order to make the joystick the most ergonomic and smallest possible we chose to design it ourselves and use the technique of 3D-printing so that meets all our requirements.

9.3.2 The brain

To treat information from the joystick and transmit it to the actuators, we chose to use a microcontroller ATMEGA which is a component widely used in industry for simple applications such as actuators control and signal processing. With that in hand, we designed a printed-circuit in order to integrate all the necessary components to be able to change the settings if necessary and recharge the batteries from the circuit and those from the actuators.

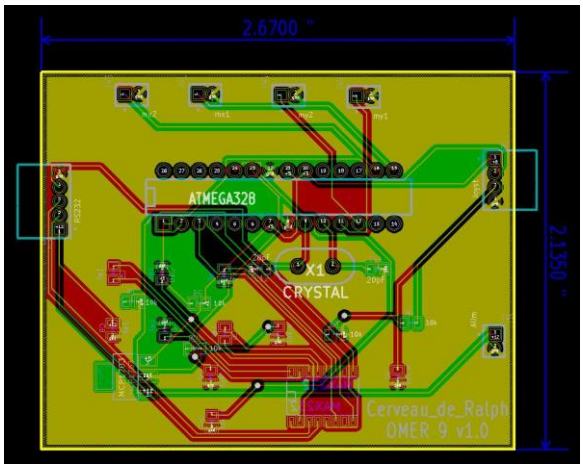


Figure 39: Brain PCB

Since everything must be done in the water, all the cases are sealed permanently. However, we can communicate with the brain through waterproof connectors, a courtesy of Subconn©.

9.3.3 The actuators

In order to get a better robustness and a reduced footprint, we chose to have cases for each independent actuators. So each fin has a motor that will be assigned to itself. The torque needed was calculated as follows:

Lift L:

Water density [ρ] = 1000 kg/m^3

Max speed of the submarine [v] = 6 Knots = 3.08 m/s

Max lift coefficient (18°) [C_L] = 1.37

Flap area [A] = 0.01986 m^2

$L = \frac{1}{2}*\rho*v^2*C_L*A = \frac{1}{2}*1000*(3.08)^2*1.40*0.01986 = 129.41$ Newton

Torque T:

Pitch angle [α] = 18°

Quarter-chord distance [R] = 0.25*Flap length

Lift [L] = 129.41 N

T = sin (90° - α)*R*L = sin (90° - 18°)*R*129.41 = 4.2395 Nm

We therefore chose an engine capable of countering this torque. Servomotors Hitec RCD HS-M7990TH with a torque of 611oz.in (4.31Nm).

Figure 40: Servomotor HITEC

9.4 CONTROL SURFACES

On past submarine, combining control surfaces and stabilization surfaces was attempted few time. In theory, using straight fins with flap should give both stability and control to only one fins. This is what is attempted with OMER9 direction. 4 fins located at the very end of the submarine have a front part which is fixed and a back part which can be control in angle using servomotor. The axes of the moving part is located a 42% of the cord of the fin, this value was obtain during an optimization calculation made on Xfoil.

The fin geometry is similar to the one present in our previous submarine. The method of drawing is the same that is to say that fins are formed from NACA-0009 profiles drawn on different levels. The leading edge is shaped like an ellipse and the trailing edge like a straight line.

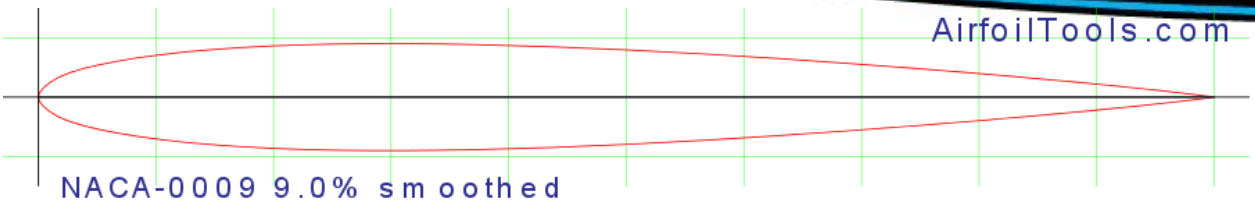


Figure 41: NACA 0009 profiles

The principle used is to have a fixed fin with a flap moving because of a servomotor rotation, controlled by the joystick. The ‘’flap configuration’’ allows a better stability by the presence of the fixed fin. Figure 39 shows the drawing made and figure 30 the assembly with the motor case, the insert and the fin.

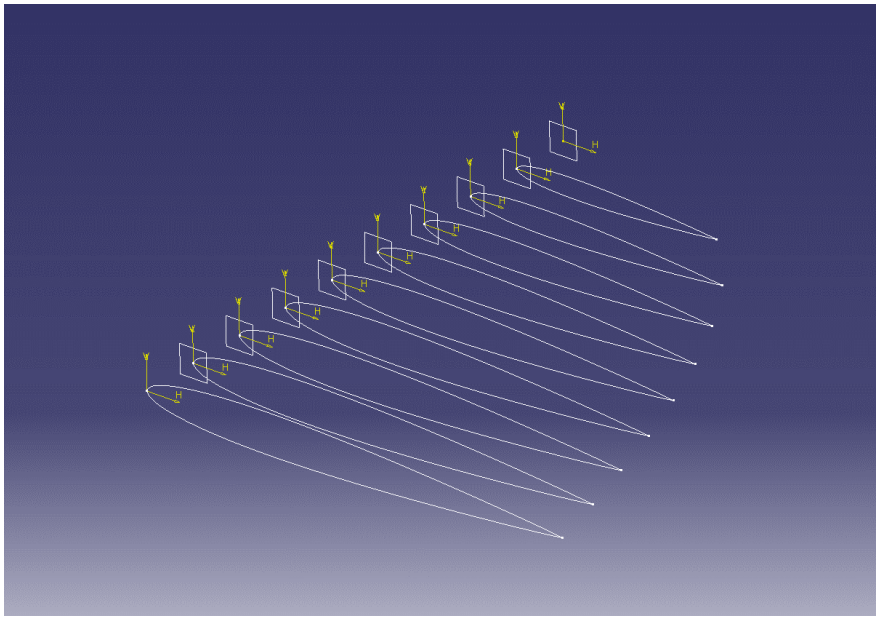


Figure 42: Drawing of a fin

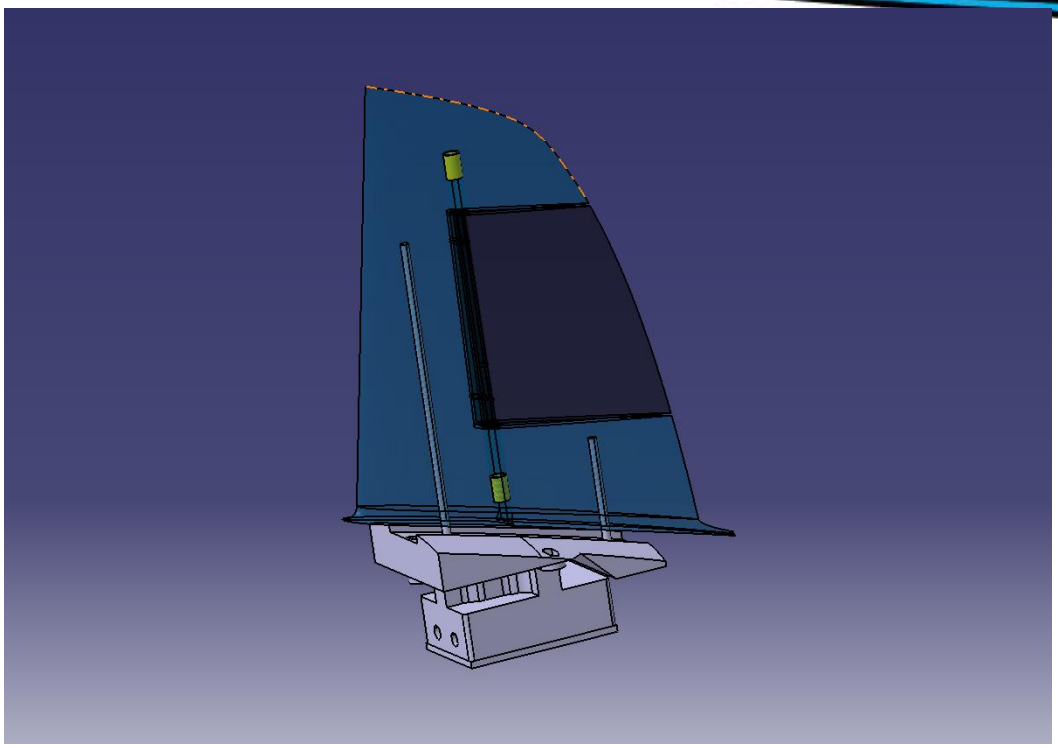


Figure 43: Steering system assembly

An in house code is used to create the geometry of the fin with flap after rotation of the flap. This code allow us to modify the position of the axis of rotation of the flap. The output of this code give us a data file with the position of the points of the fin and flap after rotation as we can see with the figure below.

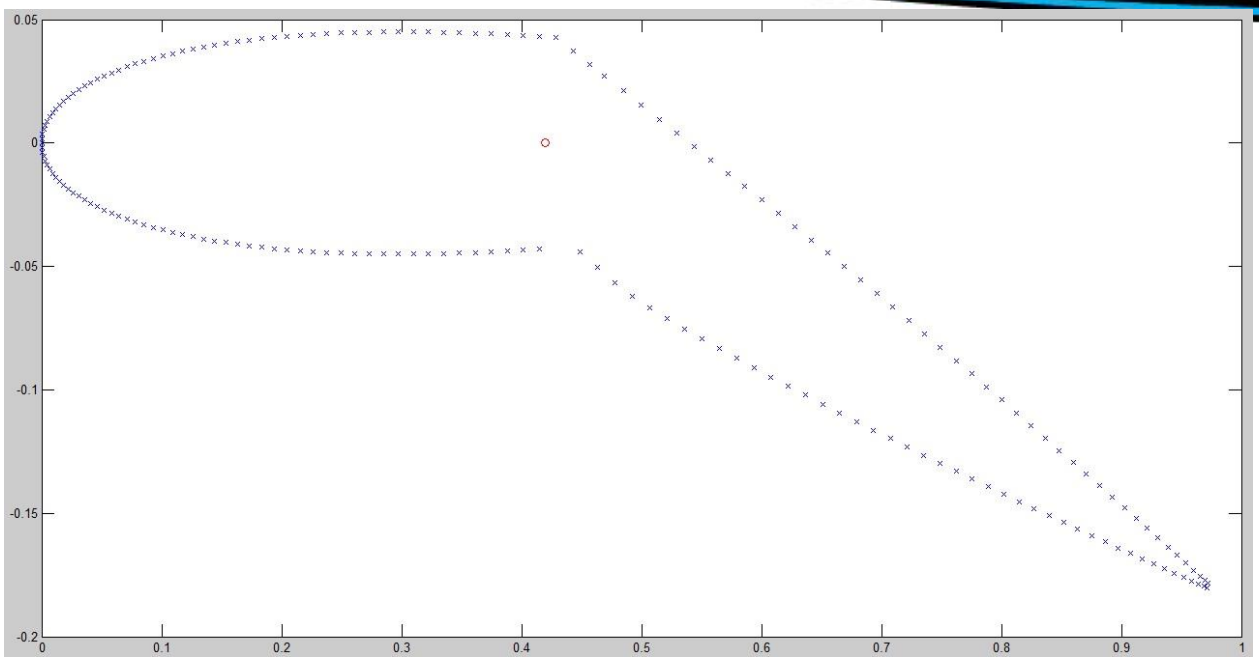


Figure 44 Fin and flap after rotation

An optimization loop is created to find the best position of the rotation axis. This loop is built in the following way:

In-house code
- Choice of the position of the flap axis
- Creation of flap geometry with 18° rotation

XFoil
- Drag and lift determination
- Transition laminar/turbulent determination

MOGA
- Multi Objectives Genetic Algorithm
- Find the best location for the flap axis

We simulate the hydrodynamic comportment of the fin with flap for different positions of the flap axis between 25% and 90% of the chord length and we obtain the following result. This figure represents the lift coefficient versus the position of the flap axis. 42% of the chord length is the best position for the flap axis considering a submarine velocity of 8 knots.

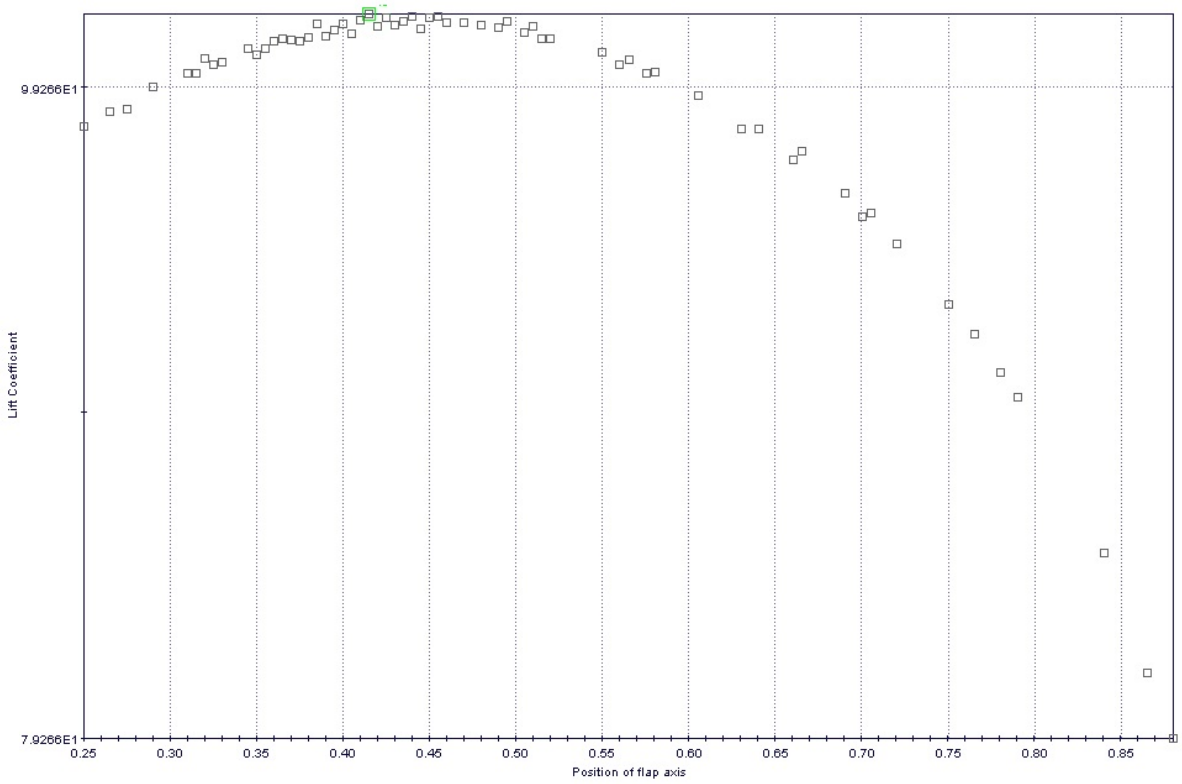


Figure 45 Lift coefficient versus position of the flap rotation center

We also make an optimization loop to find the best angle of rotation of the flap. We have two solutions depending of the optimization objectives we choose. The first objective we set up is the maximization of CL/CD (lift coefficient divide by drag coefficient) which means the best compromise between the force developed by the flap and the drag force created by it. The second objective is just the maximization of the lift coefficient to have the biggest force of thrust created by the flap.

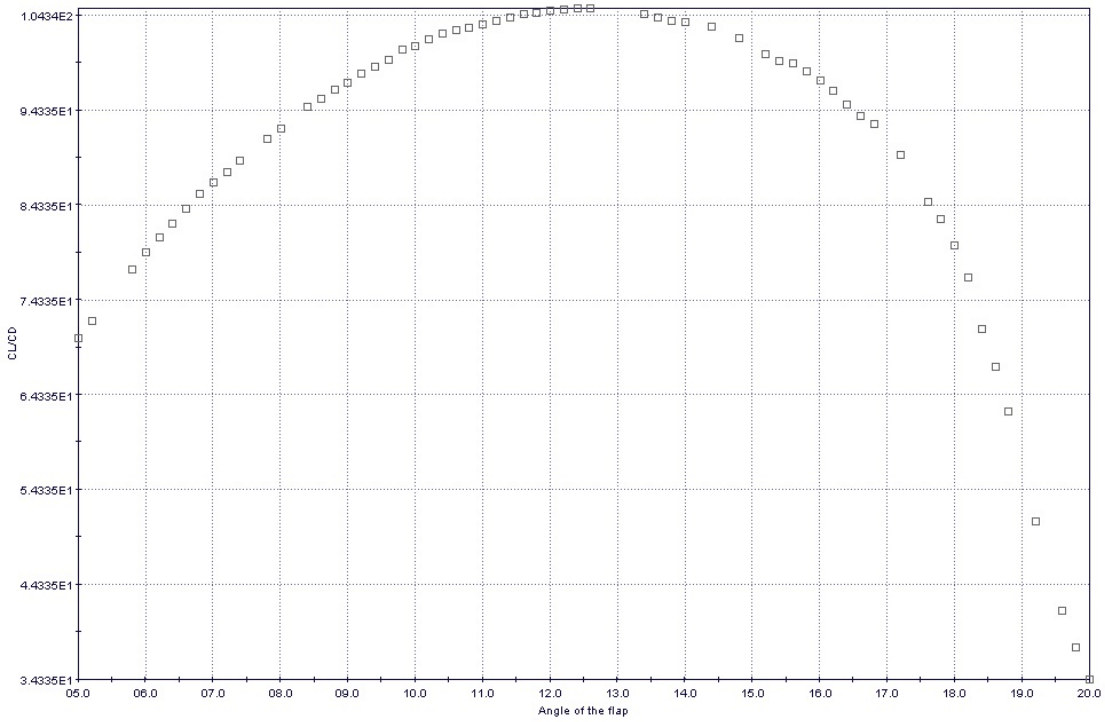


Figure 46 First objective: CL/CD versus the angle of rotation of the flap

The best angle of rotation of the flap for this objective is around 13°.

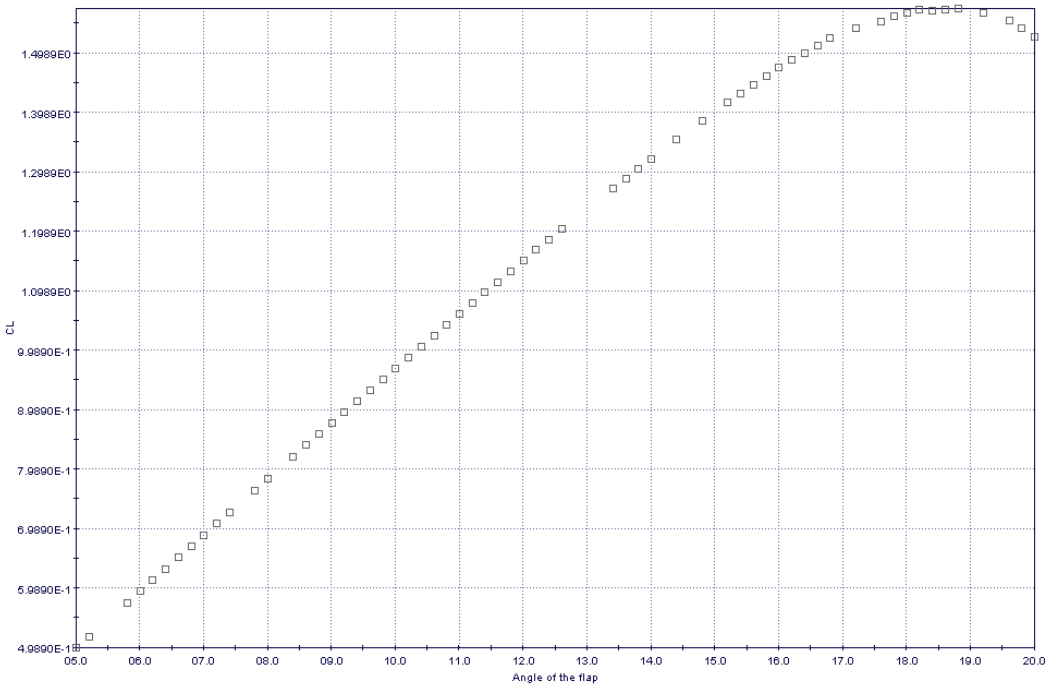


Figure 47 Second objective: Lift coefficient versus the angle of rotation of the flap

We decided to follow this objective and the angle of rotation of the flap which give us the best lift coefficient is close to 18°.

9.5 BRAKING/REVERSE THRUST

To slow down the submarine, a reverse thrust system is used. The easiest way to reverse the thrust is simply for the pilots to pedal backward. This create a lot of drag that will slow the submarine down until a full stop. Since the propeller blade are not designed to go backward, the huge drag created, force a lot of torque that is in the opposite direction of the torque created by normal thrust. Since foam and lead is installed in the submarine to counter “normal” torque, this reverse torque forces the submarine to roll a lot, almost until going upside down.

10 STRUCTURES

10.1 MATERIALS

10.1.1 Fibers choice

The choice of the fiber to be used was one of the first steps in designing the hull. In fact, the fiber properties have greatly influenced it. Several options were considered, such as carbon fiber, fiber glass, INEGRA (polyester carbon) and the basalt fiber. Each type of fiber has its advantage and disadvantage. Carbon has the advantage of being extremely durable while being relatively light, but at a high price. Fiberglass is weaker, but much cheaper. INEGRA for its part has a good impact resistance while having some of the properties of the carbon fiber. Finally, basalt has a strength between glass and carbon fiber, for a near fiber glass price. However, the availability of this fiber is rare and the weaving choice is more limited. For economic reasons, the basalt fiber was the chosen solution. Actually, it has a good ratio price/strength. However, the only weaving available that met our needs is the TX-10-P from the JB Martin Company. Complete specifications are listed in Appendix. This fiber being relatively lightweight (340 g/m^2) and thin (0.25mm per layer), we planned to use several layer in order to ensure a good mechanical strength. To confirm these results and the compatibility fiber/resin/release agent, several tests plates were made. Therefore, some with foam, some with only fiber were made to represent different parts of the submarine.

Figure 48: Basalt fiber

10.1.2 Resin choice

The choice of the resin to be used has for first condition the compatibility with the fiber used. According to the technical specifications of the basalt and glass fiber, epoxy or polyester resins are consistent. The first resin chosen was an epoxy resin DER331, a courtesy of CFP Desmoulins. Several plates were made to ensure the compatibility of the resin and fiber, and we observed that the resin too old, crystallized and thus unusable. Because of that, a new epoxy resin was purchased, a Mia epoxy used for boats, so perfect for prolonged contact with water. Test plates were performed to confirm once more the gel time and the compatibility of the resin with the different fibers. No problem being noticed, and the gel time being slightly higher than the specifications, which allowed us to infuse large parts.

10.1.3 Layer number and orientation

To ensure a good safety factor, we decided that 3 half hulls should be manufactured in case one of the two first would be defective. The basalt roller we purchased being a 100m long, 33m of fiber was provided for each half-hull. The length of the hull being close to 4.5m, 6 layers of basalt were available, providing an extra for future wet layups. That decided, we made test plates of 6 layers and ran some tests once made. The tensile test was prima facie sufficient, but the low thickness of the laminate engendered a significant bending. Thus, another test plate with an additional fiber glass layer 0-90 added in the middle of the layer was made. This addition of fiberglass greatly enhanced the flexural strength of the laminate. We decided so that the final laminate would be a 7 layers laminate in the following order (from the outside of the hull):

- 2 layers of basalt fiber
- 1 layer of fiberglass
- 2 layers of basalt
- 1 layer of Foam where needed
- 2 layers of basalt

The hull shape also increase the resistance of the laminate and the final state, with all the Foam reinforcement, the hull will not allow any deformation.

10.2 CONSTRUCTION OF THE HULL

10.2.1 Mold

Since the submarine is symmetrical on is axis, the top and bottom part have the same outer shape. This symmetry will help during the fabrication process by allowing to use the same mold on the 2 half of the hull.

Using the surface outer shell of the sub, we designed the mold. inserting reference point, flange to facilitate demolding, and assembly, etc. we had 2 option of material for the mold, the first one, more traditional and usual is to have a half submarine male shape milled that would be used to general a female mold in gel coat and fiberglass, this technique allow to reuse the fiberglass mold few time will minimal degradation. The second option is to make a half submarine female shape what would be directly use as the mold. This technic save time since we remove one step but the plywood mold will deform and lose is quality much faster. Since we will only need to mold 2 part from the mold, we decided to go with this faster method.

The final mold look like a big block with a female half submarine shape inside. The mold was made outside of ETS since wood is not allowed in the CNC milling we have access to. The most logical material to choose was MDF due to price and easiness to mill to a precise shape.

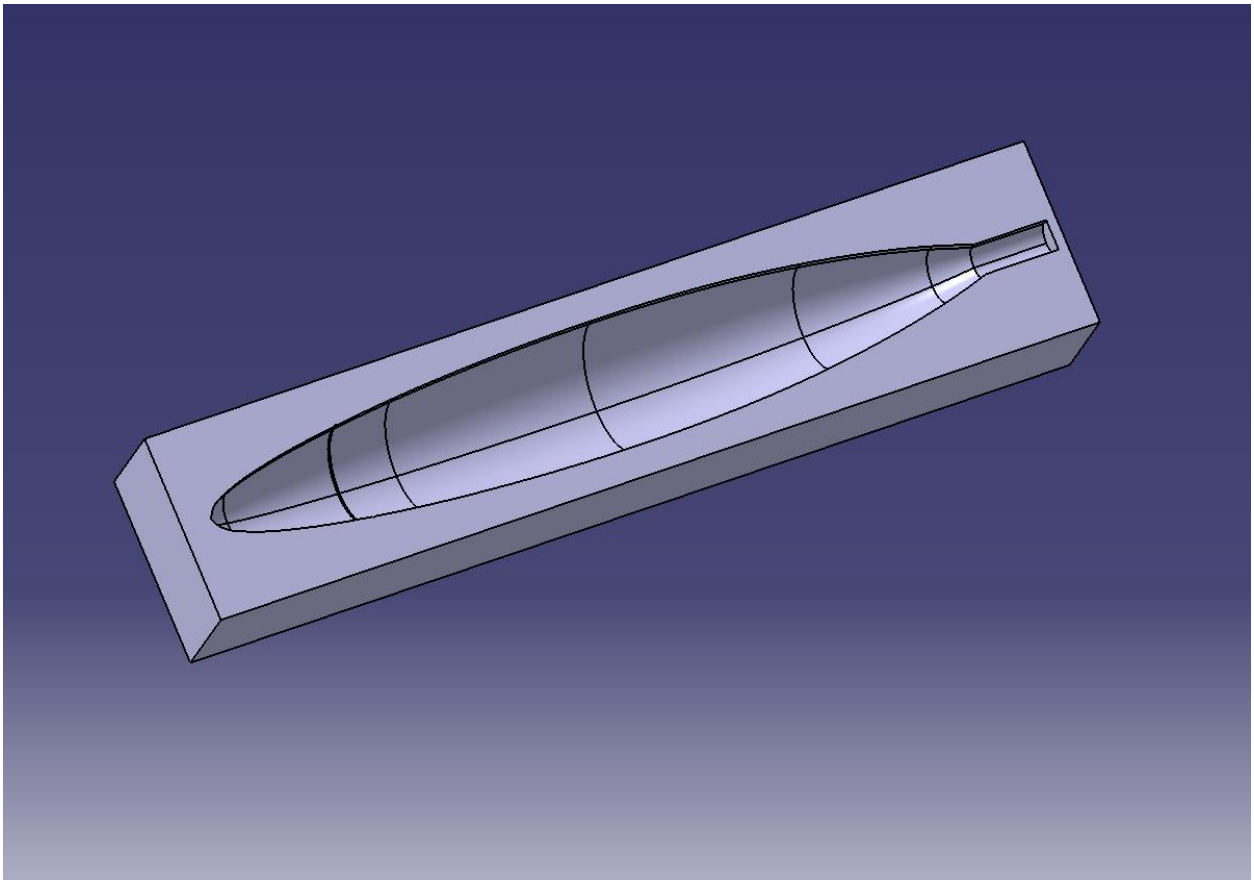


Figure 49: OMER 9 mold in CATIA V5R20

Figure 50: Mold when received from Moules SAMCO Inc

10.2.2 Preparing the mold

To ensure a good surface finish, the MDF mold was coated with Duratech to seal it and offer a hard and watertight surface to work with. The Duratech was then sanded manually until a 2000 grain. To ensure no pressure point would remove more material on a spot or another, sandpaper attached to sponges were used during the full sanding process. After sanding was done, the few polishing step were done until a mirror like finish was obtained. At this point, the mold have is final surface finish that would be used to mold the composite hull. To prepare the finish mold to composite lamination, a full preparation was done including, a mold cleaning and a mold sealing step and finishing will release agent application.

Figure 51: Preparing the mold

Figure 52: OMER 9 mold after treatment

10.2.3 Composite

The laminating process used was resin infusion which consist in placing dry fiber in the mold under a vacuum bag and then sucking the resin into the fiber using the vacuum force.

The first step of building the composite hull was to choose witch fiber and stack up to us to ensure a good rigidity. For that decision to be made easily, we made few flat test laminate with different fiber and different stack-up. The final choice was a 7 layer stack up composed of 2 layer of basalt fibers, one layer of NCF 0/90 fiberglass, 2 layer of basalt fiber, a layer of close cell core with variable thickness, and finally 2 layer of basalt fiber.

The foam is used for 2 main purpose. The first one is to add rigidity to the hull by increasing the moment of inertia, and the second one is to adjust the floatability of the sub. The position and thickness was calculated to ensure proper stability in water on all axes, partially counter the torque of the propeller while ensuring proper ergonomics for the pilots.

During the stack-up process in the mold, the fiber was place carefully to eliminate any fold. The foam was then glued to the fiber using airtak 2 adhesive which will dissolve in resin. All edge of the foam was sanded to a 45° to 55° angle to ensure no fold will be generated on the next layer of fiber. The foam was also pierced every 25mm to allow resin to pass from one side to the other. Then the 2 last layer of Basalt fiber where place in the mold, to eliminate any fold in the fabric, some part of the fiber where glued to the foam using airtak 2 adhesive.

After all fiber were positioned in the mold, a layer of peel-ply fabric and media flow were places on top of the stack-up. Three line were placed on top of the media flow, one for resin distribution and 2 for vacuum. The 2 vacuum line were placed on the two long edge of the mold on top of the flange, 2 vacuum hose were attached to every vacuum line for a total of 4.

The resin input line was placed in the center of the mold with 2 input hose, one on each extremity.

With all input and output line in place, the vacuum bag was placed on the mold and sealed using dum-dum. A vacuum pump was then hooked up to all 4 vacuum hoses and the bag was carefully and slowly pushed down onto the laminate. When the few leak were fixed, the 2 resin input hoses were placed in resin and opened, resin start to flow into the fiber laminate, after a 2 hours process, the fiber were fully impregnated, the resin input hoses were closed, and the vacuum was maintained for a 12h period to allow resin to harden. After 24h, the first half of the hull was unmolded. The same process was repeated for the second half of the hull.

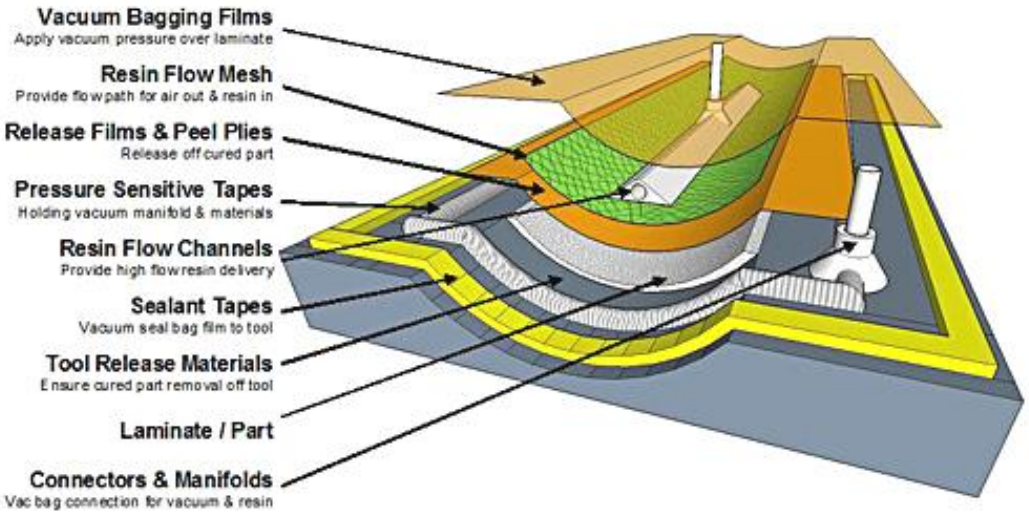


Figure 53: Technique used for the resin infusion

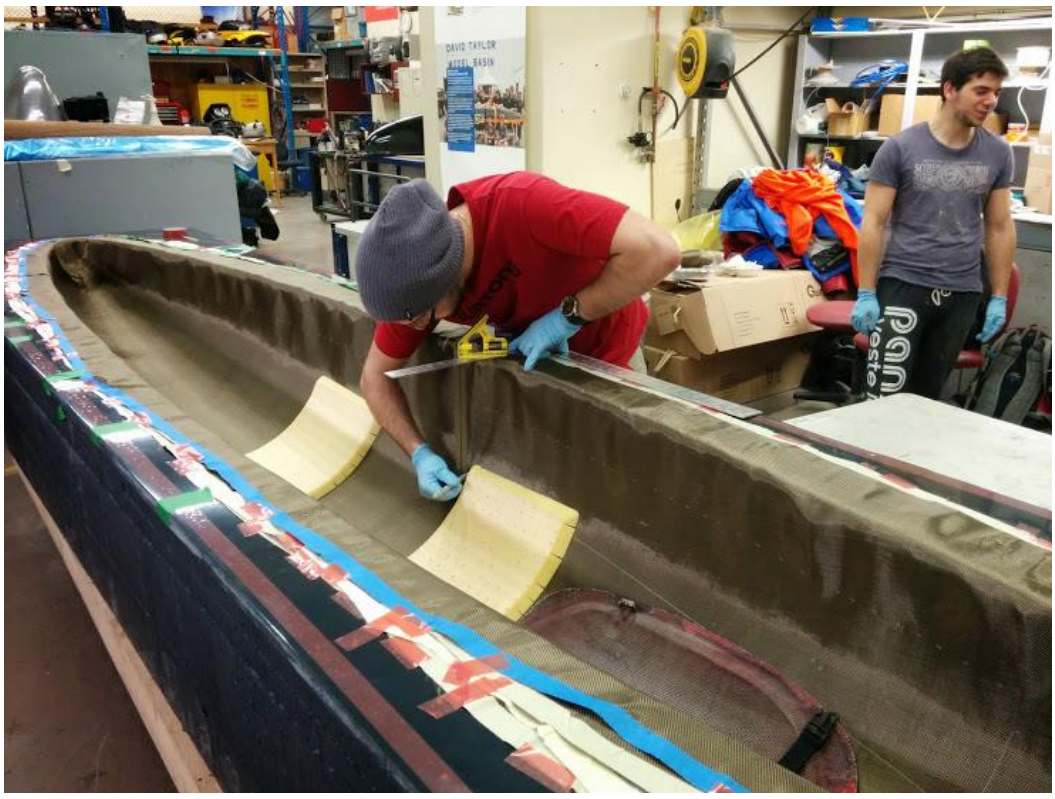


Figure 54: Placing the foam between two layers of basalt

Figure 55: Foam placed in the mold

Figure 56: Placing a superior layer of basalt

Figure 57: Adding the peel-ply and the media flow to control the resin speed

Figure 58: Bagging the part

Figure 59: part once the vacuum is created

Figure 60: Infusing the half-hull

Figure 61: Half of the hull once finished

10.2.4 Water drainage opening

The drainage hole is one of the difference source of drag that could be easily remove. Instead of using a holes at the bottom of the submarine, a trap similar to a door was cut at the lowest point of the hull. This trap could be open or close to allow fast water drainage or low drag during races. CNC milled aluminium insert were used to allow easy closure of this trap.

Figure 62: Drawing of the water drainage hole

Figure 63: Water drainage hole once cut

10.2.5 Pilot access

When cutting the door, positioning of the cut was critical, since the position of the foam was one of the main criteria regarding door positioning, therefore door cutting pattern was drawn inside the submarine using only straight line. Then at each intersection points, a really small holes was pierced. Toothpick where place in those holes from the outside, a string was tighten in between the toothpick to show the outline of the door on the outside surface. Both door were then cut using a dremel cutting tool with diamond cutting blade. Then the door tab and latched where glued in place using jig for positioning as well as the pneumatic piston assembly in the full to secure the door in place. At this point the door where fully functional

Figure 64: Submarine once the doors are cut

and in a final stage of preparation. Both door had to be cut before gluing the two half of the hull together as access to the inside of the submarine in allowed only throw those door.

10.2.6 Pilot visibility

For the window, a wood matrix was machined for thermoforming. The shape was sandblasted and painted with Duratec Primer. After that, the surface was prepared for polycarbonate thermoforming. That solution was decided because it was the same we used for OMER 8, and it has proved its efficiency over the years, giving us windows with a high impact resistance. It should be noted that the mold shape is 4 inches longer than necessary to allow a cutting area and an area with irregularities due to the suction during thermoforming.

Cutting the opening to insert the back windows was similar to the technic used for the door, vinyl stencil was glued to the hull and the opening was then cut using dremel tool with a diamond cutting disc.

For the front windows, the windows itself was trimmed to the desired shaped and place over the nose of the hull, the cutting line was traced on the hull, cut and then adjusted until a perfect fit using sandpaper. Some composite plate were separately produced to use as junction surfaces in between the hull and the windows.

Figure 65: Cutting the hull for the front window

Figure 66: Wet lay-up to create the flanges

Figure 67: Assembling the front window

Figure 68: Front window once settled

10.3 Assembly

To ensure a good male female fit between the 2 parts, calibrated wax was place on the flange of the lower half. At the junction line, twice the thickness was present which ensure a strong bond between the two half. Before gluing permanently the two half, the propulsion system was installed in the submarine to make sure all dimension were exact and that it would fit properly. All metal insert as the one for the propulsion, the end-cone or even the joystick, were incorporated in the composite afterward using a wet lay-up technique before gluing the two half together.

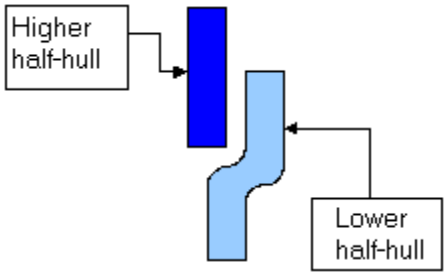


Figure 69: Principle of the hull assembly

Figure 70: Drilling the holes for rivets

Figure 71: Hull fully assembled

10.4 MANUFACTURE

Despite all the work done on the hull, several other parts have to be built. Over the years, OMER has been very proud to be able to manufacture and machine the parts composing the submarine. In fact, almost all parts of the submarine, except the hull mold and the windows, are manufactured or machined by the club's students into our school machining centre or shops. This section will present some of the work done in that area.

10.4.1 Propulsion system

10.4.1.1 Propeller

Machining the propellers is a real challenge, because it requires that the geometry is almost identical to the design, and several factor scan interfere. First, the machining programing was made so that a sweep of the geometry is done with ball nose tool. Before that sweep, a roughing is carried out with a standard drill, then the sweep is used for semi-finishing and finishing. A problem was encountered during the sweep of curves because the cubic splines were not constant, which leads the tool in the geometry close to the leading edge. This problem was solved by importing a smaller number of points by profile for the 3D drawing of the propeller. For the rest of the programming, speeds are fast enough because the material used is an aluminium 7475. The following picture shows the tool path during the semi-finishing sweep.

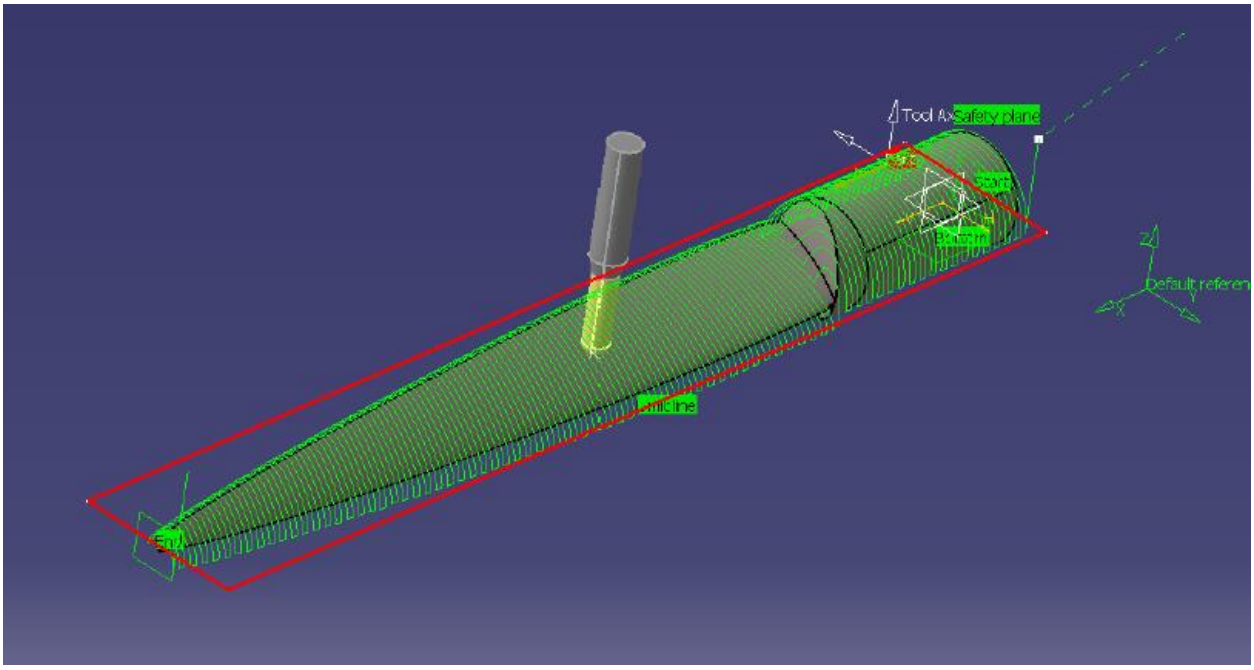


Figure 72: Tool path for semi-finishing

Machining strategy for this type of geometry is to manufacture one side in order to create a pool inside the large bare of aluminium. This pool is then filled with plasticine to allow machining on the other side of the propeller without having too much vibration (see next picture).

Figure 73: First side machining, then filled with plasticine

The machining on the second side is very well done with plasticine which exerts a good pressure to prevent vibration. When machining that side, the part positioning is done using pins whom holes were drilled and reamed in the machining of the first side. You can see in next picture the complete draft of the second side.

Figure 74: Second side machining

After milling, the propeller is put in a machining centre Mazak Integrex to turn the diameters that will be needed for coupling with the rotor mechanism. Giving the precision of the milling, the cylinder at the end of the propeller can be used as a support for the chuck. The next figure illustrates the propeller blade installed in the chuck system.

Figure 75: Turning the propeller blade

10.4.1.2 Propulsion

The rotor is a special part that requires a multi-axis machining. That is why this part was machined in a Mazak Integrex machining centre in order to be able to turn and mill in different axes. In the next figure, you can see the rotor being machined. The next one is the head cone machined in a digital milling turning machine.

Figure 76: Machining the cone

Figure 77: Machining the head cone

Most of the parts in the propulsion system are cylindrical or conical and could be machined in a CNC lathe with a milling module. Those parts are in aluminium 6061-T6. The next picture shows the machined parts for the variable pitch system. Top left are the head cones. Bottom left are

the turning plates. In the center you can see the engine supports. On top right others parts of the engine supports and bearing supports.

Figure 78: Parts machined for the variable pitch system

Figure 79: Parts composing the propulsion system

10.4.1.3 3D printing

In this section, we will present the manufacturing of the fins of the joystick because a brand new method of manufacturing was used for them. In fact, we used the 3D printing to manufacture those part, which allowed us to gain much time and weight in the submarine.

The main principle of 3D printing is to warm plastic and extrude it layer by layer in order to create a part. That technique is starting to be quite famous because of all the possibilities and the low price of such a manufacturing method. Because of that, we acquired several 3D printers in order to develop our designs. This has been one of the major improvement in our design and has really helped us. In fact, many parts such as the joystick, the fins, and several inserts were printed and used for OMER 9. The next two sections will show you some of our results in 3D-printing.

10.4.1.3.1 Fins

Deciding to 3D-print the fins and flap was a great idea for the club. In the past, manufacturing the fins was a long process because we had to create metallic molds before molding our parts, which was long and expansive. Now with 3D-printing we were able to create a fin and flap in 48 hours of process, which allowed us to have several spare fins in case one of them would break.

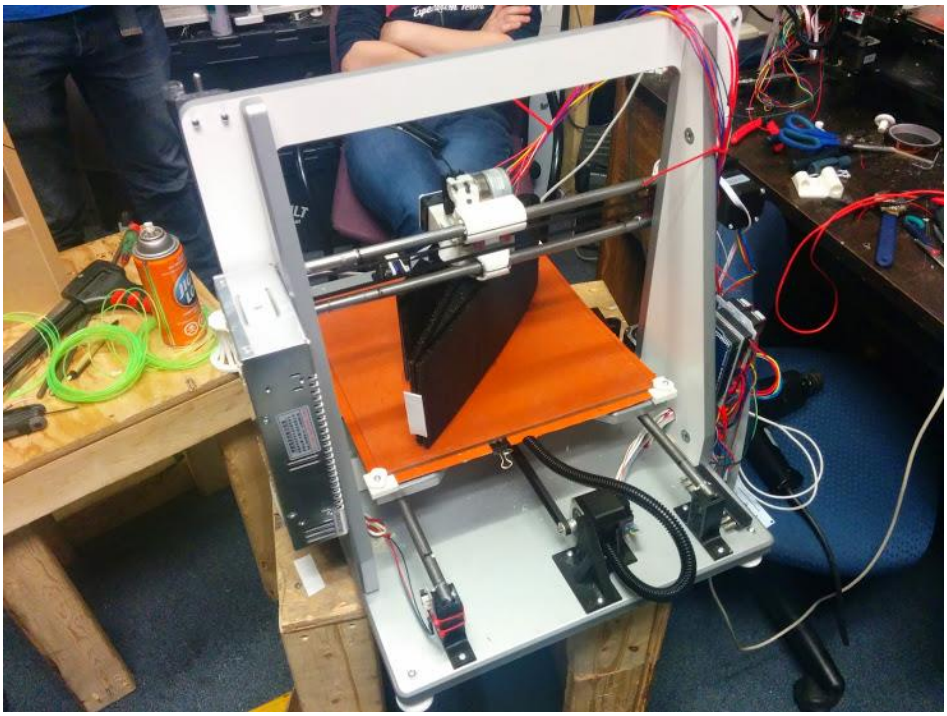


Figure 80: 3D-printing of the fins

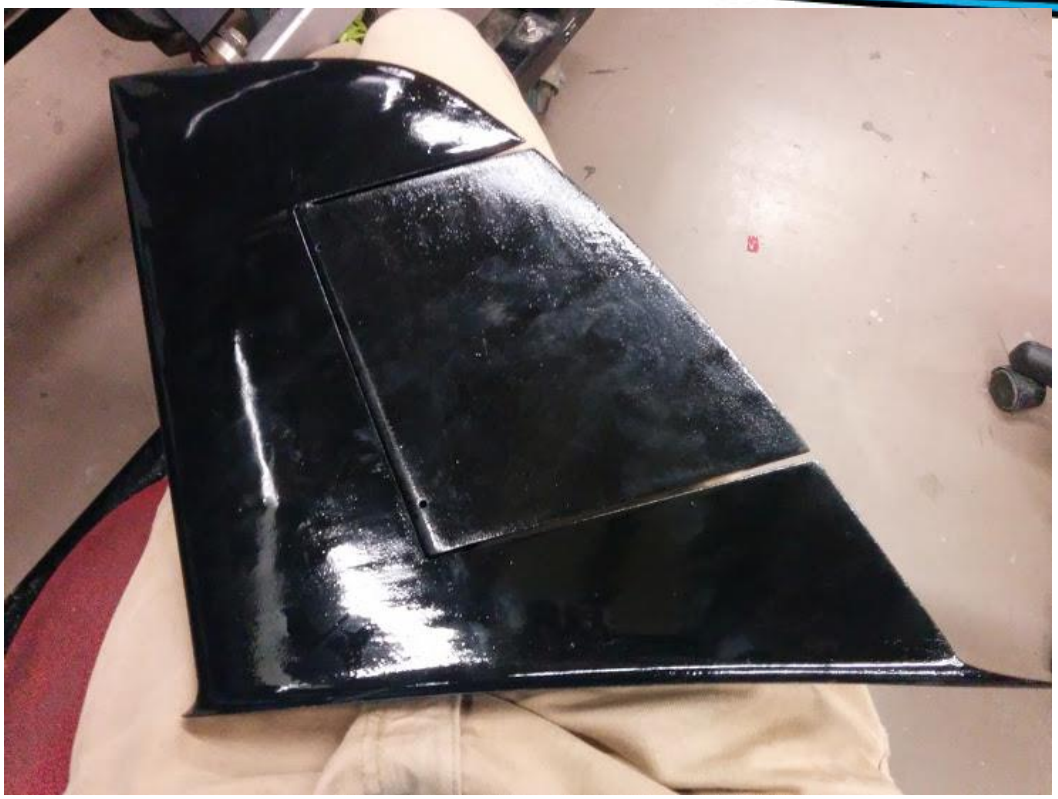


Figure 81: Fin and flap before sand blasting and painting

10.4.1.3.2 Joystick

We decided to use 3D-printing as well for the joystick because over the year that part needed constant improving, What's more, that part has always been difficult to manufacture because of all the small parts inside it. You can see in the picture below some of the prototypes made for the joystick.

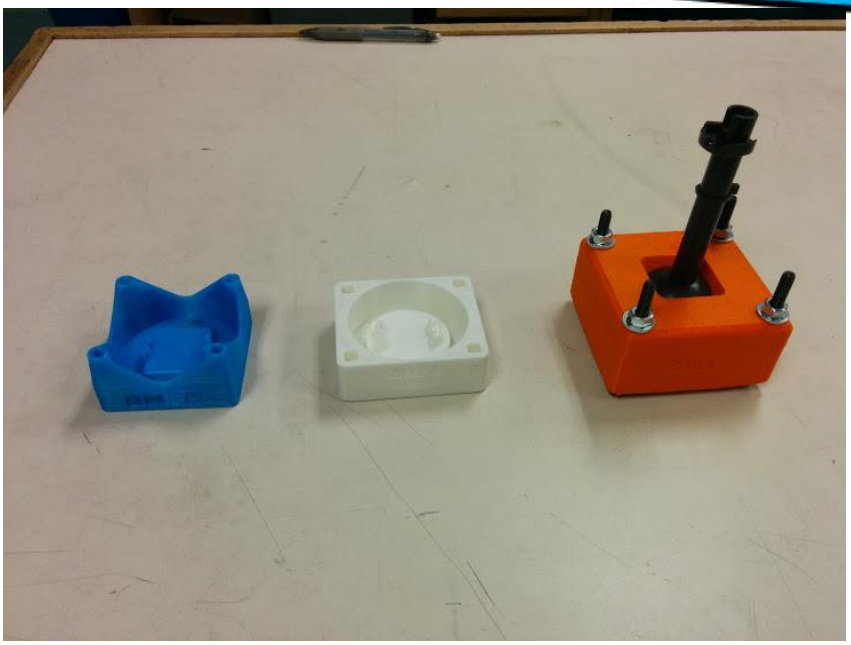


Figure 82: Several prototypes for the joystick

11 ERGONOMICS

11.1 COCKPIT

As said in the hull design section, an important parameter is the internal space constraint, which needs to be respected in order to let the pilot develop his full power. This constraint corresponds to the volume that the two pilots occupy inside the submarine. The following figure represents the position of both pilots inside the hull.

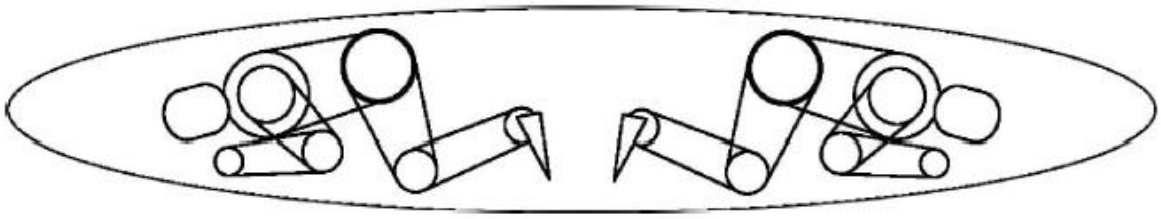


Figure 83: Position of pilots

The hull and windows were made so that the pilots could see outside and being seen by the divers around the submarine. That is needed in order to be able to communicate with them and see if they are conscious.

11.2 INSTRUMENTATION

The only instrumentation the pilots will have this year are the pressure gauge for knowing the pressure left in their diving tanks. However, some innovations such as a speed indicator connected to the speed sensors are meant to be implemented for the next competition.

11.3 DEPTH INDICATOR

Since the only goal of submarine races is to maximized speed, depth is not a relevant information to display to pilots. To allow pilots to focus on pedaling, as less information as possible is displayed. No depth indication is displayed to pilots nether recorded.

12 SAFETY AND DESIGN FOR RECOVERY

The security system of OMER 9 is the same concept of Omer 8. It's the same pneumatic system except there are components for two pilots. This system seems to be the best design the Omer team has had because there is no need to make adjustment, it rarely breaks and if there ever was a malfunctioning, like a tube breaking, then the buoy and the doors are automatically released. In conclusion, we noticed that it is the safest system we have ever had.

For the competition, a few security measures are necessary. A door opening system from the inside of the submarine, a "dead-man switch" and a buoy that will be automatically launched by the pilot in case of distress. These security measures are required for all teams participating in the races. In OMER 7, the system consisted of releasing a buoy from a door situated at the back; the concept will be reused in Omer 9, except that this door is located near the center of the submarine. The system is redundant and designed to avoid failures; the triggering mechanism of the buoy is combined with the door opening system in order to facilitate the rescue our pilot and ensure that the pilot does not get stuck in the submarine if ever there is a system failure.

12.1 SYSTEM OPERATION

Here is a brief summary of operating requirements:

Table 7: Requirements and operations of security systems

Systems	Operations	Requirements
Doors opening system	Order the doors open when the pilot inside the submarine wishes	• The driver opens the doors by pressing a button in order to coordinate efforts at the end of the race and for the security. • The lock system is operated by a system of pneumatic cylinders.
The triggering mechanism of the buoy	Order the doors open and the triggering of the buoy if the pilot loses consciousness or is in distress.	• Pilot must maintain in position at all times a button pressed. When this valve is released, the buoy and the doors of the driver are released. • In case of system failure, it must be impossible to be trapped inside the submarine.

12.1 PRESENTATION OF THE PNEUMATIC DIAGRAM

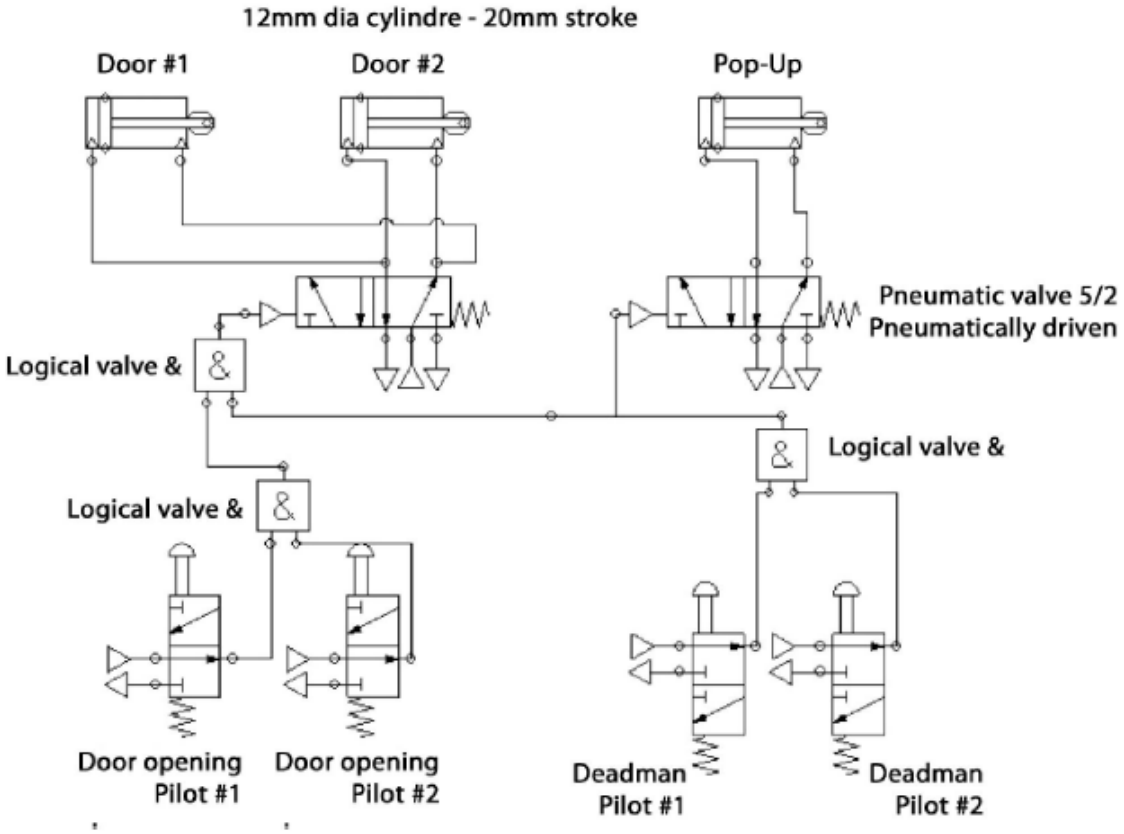


Figure 84: Pneumatic system's diagram

The schematic of the system in figure 50 shows the different components used and the connections needed in order to do the actions wanted. The two manuals valves at the right are the valves for the triggering of the safety buoy while the two valves at the left will be used for the doors opening. It can be easily seen that if one of the two security valves is released, the two doors are released and the safety buoy is launched. It is important to clarify that the ejection of the doors is done by the withdrawal of the cylinder. Moreover, if one of the air ducts is disconnected at any point in the system, the cylinders automatically release the doors of the pilots.

12.2 DESIGN OF THE DOORS OPENING SYSTEM

The mechanism used for opening doors is composed primarily of a pneumatic actuator, a linear rail and a spring. The cylinder is supplied with air by the circuit shown in figure 25 and is shown in figure 26. The linear rail serves here as a slide to facilitate the opening of the door and must be dimensioned correctly to take the moment imposed by the clasp. The spring is used to prevent a pilot to be trapped in the submarine. Thus, if a lack of air occurs, opening of the door will be done automatically. Moreover, the mechanism must be removable to allow the installation of the propulsion in the submarine.

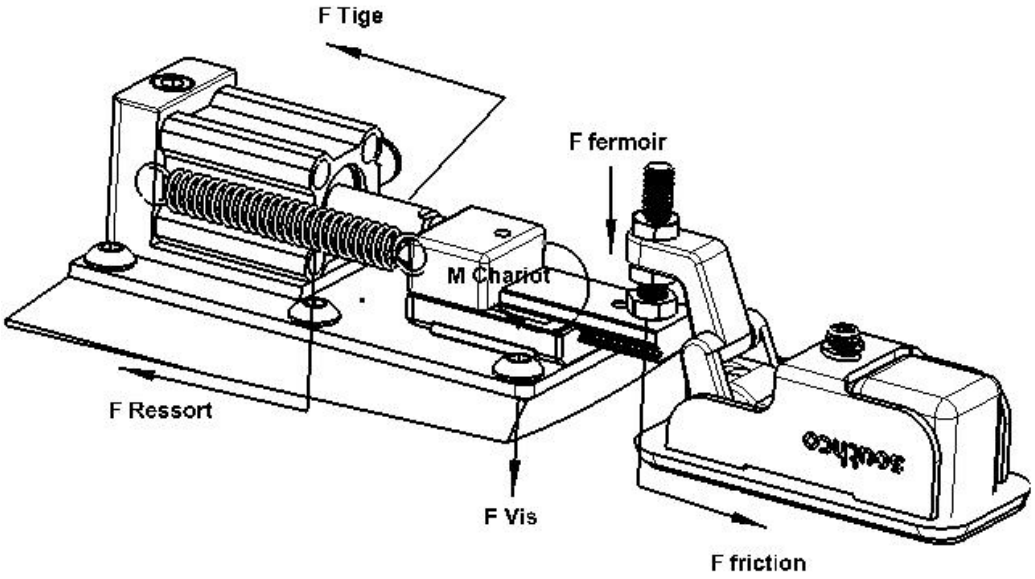


Figure 85: Closing mechanism

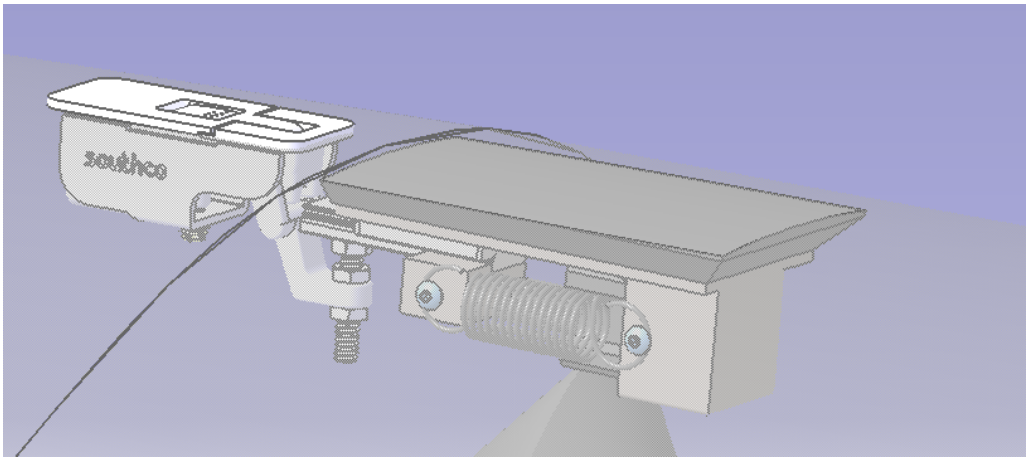


Figure 86: Modeling of closing mechanism

Table 8: Safety system detail

NO.	QTE.	NOM	DESCRIPTION
1	2	Door opening valve	**NVM230-N02-08**
2	2	Pop-up buoy switch	**Manufactured (OMER)**
3	4	Air container 13 PI^3	**Already in stock**
4	2	Dead-man switch	**Manufactured (OMER)**
5	2	Door-releasing system	**Manufactured (OMER)**
6	4	SOUTHCO Latch	**SOUTHCO**
7	**4**	5/2 pneumatic valve	**SYA5120-01T**

12.3 RECOVERY TOW POINT

The recovery tow point is linked to the pop-up buoy. The line liking the pop-up buoy to the submarine is ment to be used as a tow rope, therefore, no other recovery tow point in specifically designed for this purpose. Is case this solution is not optimal, or if the submarine have to be towed without the pop-up buoy being release for example, in a normal race without incident, a rope can be attached to the propulsion system passing throw one of the door, preferably the front one.

12.4 POST-RACE EXCESS POSITIVE BUOYANCY

After each race, assistance diver, will recover pilots and submarine, they will at first, ensure both pilots and out of the submarine, at the surface and ok, then the submarine, will be haul to the surface and floting buoy will be place inside the sub, or under it to allow positive buoyancy. During that time, pilots would had swim to the side of the basin. The submarine will then be tow out of the finish area to allow the next race to take place.

13 TRIALS AND TESTING

13.1 FIRST TEST

As soon as the submarine had a completed hull, widows for communication between pilots and outside and that air supply was installed, first in water test was performed. For those first test, the submarine was places in the in-house basin, pilot's air supply was positioned inside the submarine, but to allow for longer test, the breathing air was from bigger scuba bottle located outside of the submarine. Those test don't allow the submarine to move, since it is strapped to the basin, but allow to test ergonomic, easiness to enter en exit the submarine, coordination between both pilots and communication between pilots and assistance divers. Since the submarine is submerge by only few inches of water, those test allow for new pilots to try the submarine in safety of a controlled environment without any potential recovery situation. As much as possible of those test were performed. Is we could not work on the submarine itself, for example because we were waiting on part or because we were working on removable system (direction, variable pitch, etc.) the submarine was tested in those condition.

13.2 FULL SCALE TESTING

When the submarine was fully assembled with air supply, direction system, variable pitch and pop-up buoy, we went to the Montreal Olympic diving basin constructed for the 1976 summer Olympic to test all the submarine system. Those test were performed on June 4th and June 11th 2014. Those test allow to check compatibility from all system test previously. To ensure that the control surfaces and electrical direction system were enough for the submarine to do a slalom or U-turn, full size test were mandatory.

The test describe previously do not include diver test for pilots or assistance diver that were performed way earlier in the winter using OMER8 submarine. Those test were to ensure that everyone diving with the submarine knew the proper underwater communication specific to submarine manipulation and proper submarine manipulation as well as the OMER specific technique learned over the last 20 years.

In May 2015, our team headed to Florida for a week test in the Broward County college lake in Hollywood. Those allowed us to have full scale testing of a race in order to get our pilots and divers used to the underwater operations.

14 SUMMARY/CONCLUSION

Many efforts have been put throughout the year to get the best submarine out of the shop. The past years have been very successful with OMER 8 and we hope to reiterate that with OMER 9.

The new hull and fins, of which the hydrodynamic has been studied, the new propulsion and electrical steering system and all the safety features will for sure help the OMER team to try pushing the speed limit for a two-person submarine. All of those innovations are great additions to this submarines.

The fabrication and manufacturing methods are also not to be forgotten. A better way to mold basalt fiber has been applied for the hull, new machines have been used by OMER members to achieve the mechanical parts, and 3D-printing has become a great part of our manufacturing process. The result is a good-looking submarine that shears the water and that can resist long enough. Pushing it to its limits will be possible.

Tests in pool and lake will have been done before the competition to ensure a good team work and spirit at the competition. The real test will perhaps stay the 13th ISR!