HSRW Submarine Team

Design Report eISR 2022

Cygnus IV AND *Rivershark Mod III*

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ABSTRACT

Cygnus IV is a single-seated human-powered submarine designed for the 2022 edition of the biennial European International Submarine Races (eISR). The design and manufacturing included a hull, frame, propulsors, transmission system, control and control surfaces, safety system as well as ergonomics and influenced by different design aims such as innovation and biomimetic. Additionally, the submarine was trimmed and the reliability was tested.

The hull is made out of transparent PET-G panels assembled and shapes the submarine very characteristically. To reinforce the hull by resisting impacting forces to a greater extent, a supportive frame was created as a lightweight and thus innovative design part. To enable a biomimetic and sustainable propulsion, Mirage Drives, which simulate the "Aquatic Flight" of penguins, were used. To apply forces and transmit them to the Mirage Drives, a cycling pedal system was implemented. Control surfaces were designed with mechatronic automation in mind. The safety system included a safety buoy which could be released via a dead-man-switch and the convenient operation of the submarine was enabled by different ergonomic improvements.

Because of the lack of time, a previously designed and built submarine, *Rivershark Mod II*, was partially redesigned and improved to *Rivershark Mod III* for training the pilots and as a back-up plan in case *Cygnus IV* was not completed on time.

To improve the reliability of *Rivershark*, new safety mechanisms, hatch systems, and control surfaces were implemented. The safety buoy was enlarged, and the release system was improved to a dead-man-switch to meet the required standards for the race. The hatch system inside the submarine for the pilot was improved to ensure more reliable intentional opening, and to prevent accidental opening during the normal racing course. New control surfaces with a new hydrofoil-profile were adjusted to reduce drag, and stabiliser fins were applied to provide more stability.

ACKNOWLEDGMENTS

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1. INTRODUCTION

The submarine team Rhine-Waal University of Applied Sciences (HSRW) presents a new submarine *Cygnus IV* for the European International SubRaces 2022. Due to a longer covid-break, a total new team was recruited consisting of students with various scientific specialisation from mechanical engineering and mechatronics to bionics, materials, and biology.
Cygnus IV is a single-seat human-powered submarine using the unconventional propulsion system of MirageDrives to compete in speed, reliability, and manoeuvring against other submarines. *Cygnus IV* is the fourth submarine of Rhein-Waal University of Applied Sciences built in its FabLab.blue competing against the other submarines. In the past *Rivershark*, *Inia*, and *Trichitala* were built and succeeded in the international submarine races.
As sustainability and innovation become more and more crucial in the development of vehicles such as submarines, *Cygnus IV* was designed to fulfil these requirements. Therefore, the locomotion system, the production of the hull and frame, and the utilised materials were improved compared to conventional and previous submarines.
Due to the severe problems with propellers such as disturbance of underwater animals and high potentially damage to itself and the marine vegetation, an innovative propulsion system was chosen. Abstracted from the locomotion of penguins MirageDrives simulate the "Aquatic Flight" which creates thrust by lift. Furthermore, to improve the propulsion system compared to the former submarine like *Rivershark Mod II* (*Rivershark II*) a larger oscillatory radius of the MirageDrives was used and two additional MirageDrives were attached.
To reduce the material utilisation of the hull, a supporting frame was designed consisting of aluminium poles to withstand the impact of forces. The hull was designed as a thin layer of PET-G and produced as many panels, which are individually vacuum formed and screwed together. The usage of moulds of the segments for the vacuum forming enables to easily produce more hulls or panels in case of damage in the future.
Due to the limited amount of time for designing, manufacturing, and testing of *Cygnus IV* as well as an increased effort for training the untrained team members, learning how to handle and trim a submarine as well as training the pilots on its control was conducted with the previously built submarine *Rivershark II* so that the gained skills only needed to be transferred to *Cygnus*. *Rivershark II* always showed great reliability in the past. However, additional improvements of *Rivershark II* were planned and added to prepare it not only as a submarine for training but also as an optional back up plan, now called *Rivershark Mod III*.
Hence, the submarine team of HSRW presents two design reports. In the first part of this document, the design, manufacturing, and testing of *Cygnus IV* in preparation for the races is described. Additionally, the improvements, manufacturing and testing of the new parts of *Rivershark III* are further explained.

2. DESIGN PHILOSOPHY AND DESIGN AIMS

For the design of *Cygnus IV* several aims were formulated which framed the project. The aims were influenced by former experiences made with the other submarines.
Sustainability was stated as the leading ambition for the design. Therefore, it was tried to plan and

manufacture the hull, the fins, the propulsion, the control surfaces, and controls to be as energy efficient, material saving, recyclable, and reusable as possible.
Furthermore, the design philosophy of sustainability included producing as many parts as possible locally and without purchasing new machines. This reduces outsourcing as much as possible.
Additionally, innovation and biomimetic application were stated as important for the design as they play a huge role in the races. The scientific specialisation of some team members in biomimetics further benefits the approach of a biomimetic design.
As announced in the last report of *Rivershark Mod II* as a future development the aim for *Cygnus IV* is to reach 4 kn in the races. In addition, the improvement of visibility and field of view in the submarine as well as semi-autonomous control systems were planned as a future development and are also considered for *Cygnus IV* (HSRW submarine team, 2018).
Moreover, the planned design was influenced by the design aim of modularity and ability to disassemble in order to decrease the cost and effort for transportation and to simplify making changes for future developments.

3. Hull and Frame

As sustainability, better visibility, and field of view in the submarine are stated as aims for the design, the concept of the main hull was divided into a hull and a frame. These facilitate the realisation of the team's design aims while providing enough stability to withstand the occurring stresses caused by impact and transportation, as well as to support the weight of the submarine while on dry land.

3.1 The Hull

This chapter deals with the hull, which unlike the team's previous submarines is designed to be completely transparent. First, the regulatory constraints and goals are discussed, which are then outlined in the design chapter. Furthermore, in the following chapters the material selection, as well as the manufacturing process of the final hull are described.

3.1.1 Constraints and Aims

For the design of the submarine hull, some regulatory constraints must be considered in the subsequent design phase. The pilot must be fully enclosed in the hull, with a maximal width of 1.5 m and length of 5.5 m. For safety reasons, it is also necessary that the pilot's face and head are clearly visible to support the pilot while being inside the submarine.
Furthermore, it has proven to be important, though not mandatory, to ensure that the pilot has sufficient forward and sideways visibility during the racing to follow the racing course and estimate direction and speed of the submarine.

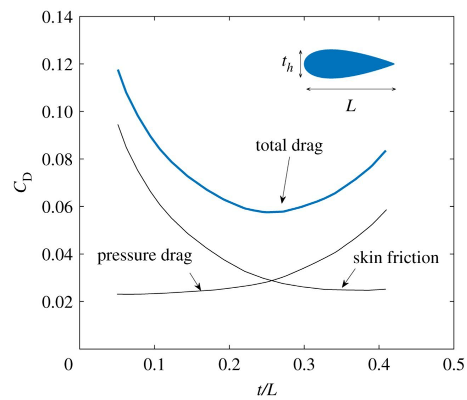


Figure 1: **Contribution of pressure drag and skin friction to the total drag.** The C_D data were obtained by dividing drag-per-unit-length data by $1/2\rho U^2 t_h$ (Godoy-Diana and Thiria, 2018).

For better performance during the races and for
energy efficiency, the submarine should be optimised to reduce drag. As the hull is the primary contributor to drag on the submarine, it is critical that the design and manufacturing of the hull take this optimisation into account. The preferred hydrodynamic shape must balance skin friction and pressure drag while maintaining a favourable fineness ratio as shown in Figure 1 (Godoy-Diana and Thiria, 2018). Reducing surface area to minimise friction goes hand in hand with a desired low volume, which decreases weight and increases the manoeuvrability of the submarine, keeping a good ratio between volume and surface area. The shape and minimum volume of the submarine is mostly determined by the size of the pilot and the propulsion mechanisms.
As modularity and the ability to disassemble were formulated as design aims the hull was designed to be produced as several panels which could be screwed together. The usage of moulds of the panels for the vacuum forming enables easy production of new hulls in the event of major damage.

3.1.2 Design

The design of the hull was carried out using the Computer Aided Design (CAD) software SolidWorks (Student edition Version 2021, Dassault Systèmes, France). All constraints mentioned in the previous chapter must be met in the final design. The width of the submarine must ensure 45 cm for the shoulders of the pilot and the height must grant 70.5 cm clearance, 36 cm for bicycle pedals, 26.5 cm for a shoe size 42 and 7.5 cm extra clearance for pedalling. To reduce the total volume, the main cavity was determined by elliptical shapes. In order to fit the pilot into the submarine, the distance between the critical point at the shoulders and the highest point where the cycling motion occurs was set to be 140 cm. Further ellipses, for example for the pilot's head and the safety buoy were sketched and afterwards connected with bent splines to reduce skin drag (Dean and Bhushan, 2010). By meeting all constraints, a reasonable ratio of the maximum height of the submarine to the total length should be selected in order to obtain a streamlined body by reducing the pressure drag. This ratio is also known as the fineness ratio. With a height of 70 cm and a length of 315 cm, *Cygnus* main body reaches a ration t_h/L of 0.22 (Figure 1). Deviating from the optimal streamlined shape that Godoy-Diana and Thiria (2018) used, the highest point was moved back to the pedalling area, to reduce the volume of the submarine.
The nose and tail of the submarine were designed to reduce the total resistance of the submarine as demonstrated by Moonesun et al. (2015) (Figure 2). Figure 3 shows the final design. The splines which connect all the ellipses were used as guidelines for lofting the submarine to its final shape. The hull was designed to consist of multiple pieces, so that in case of damage single pieces can be replaced. It contains two hatches on top of the submarine. One of them is located at the front to facilitate the

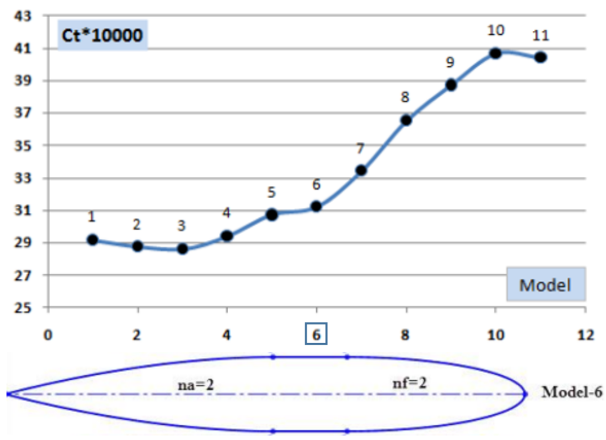


Figure 2: **Total resistance coefficient for multiple Models (based on wetted surface area).** Model six was chosen as design basis. Modified after Moonesun et al. (2015)

pilot's access, while the second is located at the rear to perform any maintenance work regarding the transmission and controls. It is important for the front hatch to allow the pilot to enter and exit the submarine easily even in emergency situations. The size of the front hatch has a width of 60 cm and length of 90 cm. For the rear hatch, single plates can be taken off since the hull is made of individual parts. According to the rules of the race, there must also be a drain hatch in the hull of the submarine, which can be achieved by loosening a single or multiple hull parts. The outriggers are less restricted and can be designed close to the optimal streamlined body with the least resistance at a fineness ratio around 4.5 (Hoerner, 1965).

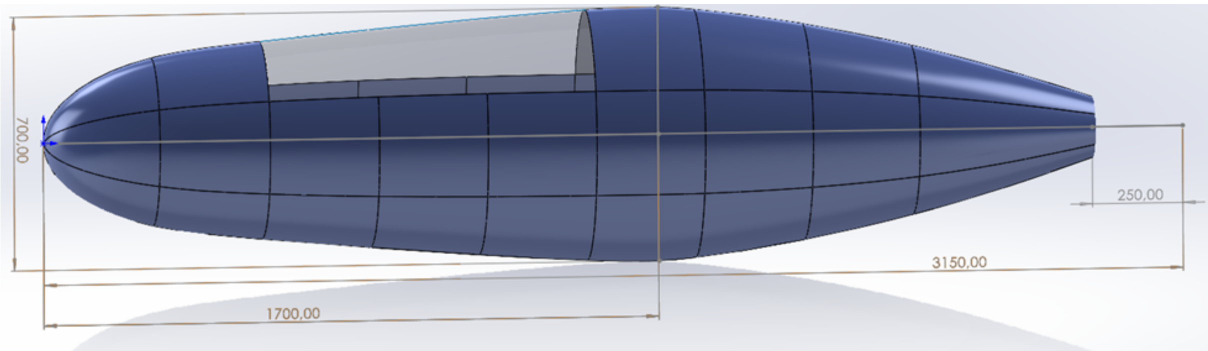


Figure 3: **Design of the Hull.** The hull consists of even parts and a big hatch for the pilot. The safety-buoy at the end of the submarine is not included in the hull design.

3.1.3 Material

For the desired transparent hull and to obtain a more sustainable submarine, a recyclable polymer was selected that can be thermoplastically deformed, has a high impact toughness and high breaking strength. The material chosen is Polyethylene Terephthalate-Glycol (PET-G) (PET-G klar, S-Polytech, Germany), which is also used for recycled bottles and provides a lightweight and comparatively inexpensive material for the hull. After calculating the amount of PET-G needed using the final design, the material was ordered and picked up from a local company near the university. The material is available in 2000 mm x 1000 mm sheets and therefore ideal for the vacuum forming process, which was therefore chosen as the main manufacturing process. During the first vacuum forming tests with the ordered PET-G, a sheet thickness of 3 mm turned out to be sufficient for this application. The disadvantage of the material is its lack of UV resistance and suitability for outdoor applications.

3.1.4 Manufacturing

The hull, which is made from PET-G, is manufactured using vacuum forming. Before the actual forming process of the PET-G sheets can begin, positive moulds for the hull have to be constructed first. In previous test phases the PET-G exhibited wrinkles at a high degree of deep-drawing, leading to the conclusion that the hull needs to be divided in smaller sections, each with a lower degree of deformation. To ensure a good connection between the individual hull sections, an overlap of

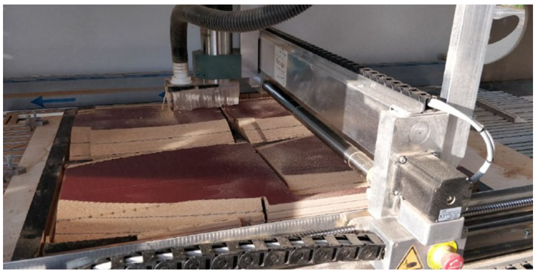


Figure 4: **Manufacturing the moulds.** All mould were manufactured in the CNC

4 cm was provided using the software Autodesk Fusion 360 (Education licence Version 2022, Autodesk GmbH, Germany). As a material for the moulds, assorted LDF and MDF boards were selected that can resist the vacuum forming temperature of about 130 °C.
In addition, the material was already available in the university lab and therefore did not need to be ordered. The moulds were made with a KinectiC-NC (High-Z S-1400/T 1400x800 mm, CNC-STEP GmbH & Co. KG, Germany) using a generated g-code in Fusion with reasonable settings. A down cut bit was used for a better surface finish of the moulds (Figure 4). After cutting, the moulds were sanded to get a smoother surface at the end. Since the right and left sides of the hull are symmetrical, most of the moulds could be used twice for the vacuum forming process. The exception to this symmetry is the area around the front hatch, where the overlap of the panels had to be arranged differently. After vacuum forming (Figure 5) each panel needed to be cut out and screwed together with the adjacent panels (Figure 6).

Figure 5: **Positive moulds and vacuum formed PET-G parts .** Each hull section was formed by a different mould.

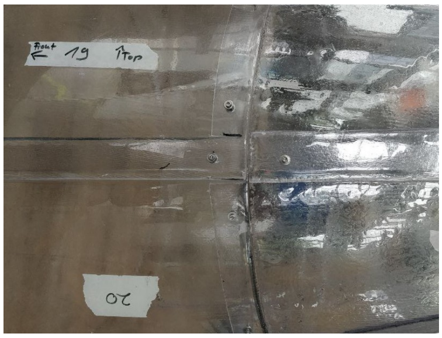


Figure 6: **Hull assembly** Multiple hull pieces are joint to form a single surface.

3.2 The Frame

Due to the formulated design aims, a frame had to be designed and manufactured to support the hull.

3.2.1 Constraints and Aims

The defined design philosophy and some regulatory constraints have been considered during the design of the frame.
The frame has to provide structure and hold the hull in place while bearing continuous forces exerted by the pilot, propulsion system and drag in water as well as possible impacts on land and underwater (e.g. bumping into the ground). It also must support the weight of the submarine while not in the water. The geometric constraints were set by the form of the submarine, as well as the positioning of the outriggers, control surfaces, and hatch.
A lightweight design had to be planned which could withstand the impacting forces and occurring stresses while using minimal amount of material.
A material had to be chosen that had low to moderate brittleness, high toughness, and high tensile strength. Additionally, high strength to weight ratio and a resistance to oxidation due to the marine environment should be properties of the material.
Propulsion system, control surfaces, control system, and transmission had to be able to be attached to the frame. Furthermore, the hatches and the entrance and exit of the pilot should not be blocked by the frame.

3.2.2 Design of the Frame

The final design is a lightweight wireframe which is made of multiple pieces to support the hull and internal components (see Figure 7).

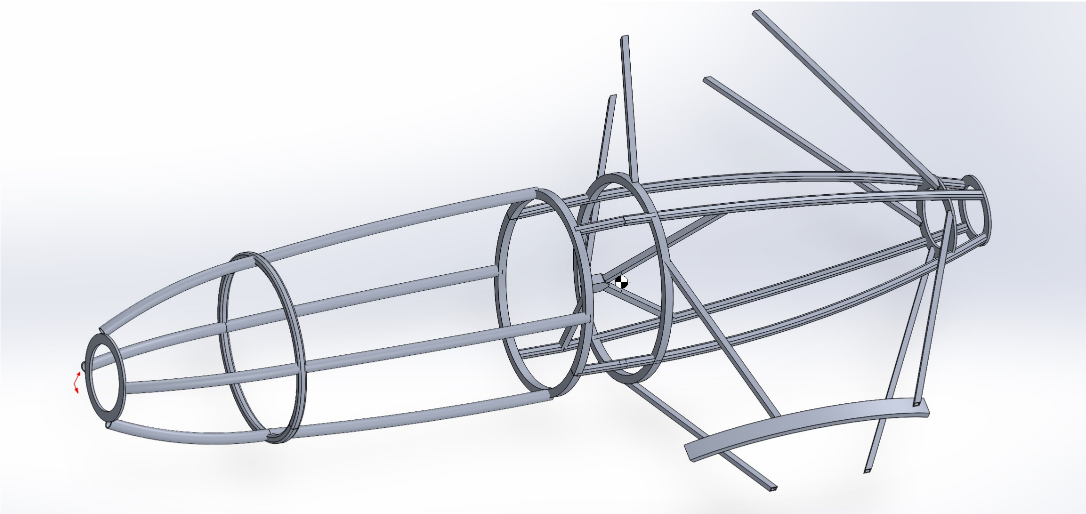


Figure 7: **Design of the Frame.** Frame is consisting of five ellipses connected with several straight tubes. In the back the tubes are connected to the outriggers.

Aluminium was chosen as material for all tubes due to its high strength to weight ratio and resistance to oxidation in marine environments. Depending on the needed support as well as the attachments to the tube a round or square form was chosen.

The elliptical rings are formed of an ellipse to match the hull as closely as possible and provide maximum support area. The rings are made by bending square aluminium pipes in some cases and cut plates in other cases. The cut plates are used whenever the bending radius is below the minimum possible bending radius of the aluminium pipe being used (Alubend, 2019). For 25 mm square aluminium pipe, the minimum bending radius (inner) is 15 cm.

There are five rings in total to provide support in case of impact of forces.

The first ring (plate) in the front of the frame is taking impact coming from the front and keeps the longitudinal beams in place. The second and third ring provide support in case of forces during hatch opening and during entering and exiting of the submarine by the pilot. The fourth ring supports the outriggers. The fifth ring (plate) is the mounting point for the elevators of the submarine and keeps the longitudinal ring in the back in place.

The longitudinal beams in the front of the frame connecting the first three elliptical rings are arranged in an "X" layout to enable entering the submarine from the top and better visibility of the floor for the pilot while improving the impact tolerance and reduce peeks of stress. These beams are round pipes to improve impact tolerance and reduce stress concentration. The square side length of the pipes is 25 mm and the wall thickness is 3 mm.

The longitudinal beams in the back of the frame connecting the last three elliptical rings are arranged in an "+" layout to enable an improved and facilitated attachment of the propulsion system and the drivetrain. Additionally, they are oriented along the forces exerted by the control surfaces and provide support points for the driveshaft. Square pipes were used as they provide easier drilling for mounting. The square side length of the pipes is 25 mm and the wall thickness is 3 mm. (Beer et al., 2015)

Between the third and fourth ring the pedal mount was design in a "K" form.
The beams are angled to take more of the lateral forces as compressing stresses rather than shear stress. The vertical beams take forces in the vertical direction and the angled beams take forces in the axis of the submarine. In the centre of the "K" a cube with the dimensions of 20x10x5,cm of massive aluminium where the beams are welded to is placed to attach the drivetrain to it.
The outriggers are attached to the main hull using four beams each. The beams are set up with angles both in the horizontal and vertical plane. The angled setup in the vertical plane provides good strength to support the weight of the outrigger. The angled setup in the horizontal plane provides good strength against impacts (head on impacts of the outrigger with wall/ slalom markers). It also provides good support to transfer the thrust made by the propulsion system. The maximum possible angle that can be reached without colliding with the mirage fins is the limiting factor in the horizontal plane. In the vertical plane, angle has been chosen such that there are no forces pulling outwards on the aluminium sheet of the keel away from the foam. The square side length of the pipes is 20 mm and the wall thickness is 3 mm.

3.2.3 Manufacturing of the Frame

The longitudinal beams and rings are manufactured using a manual pipe rolling machine (see Figure 8).

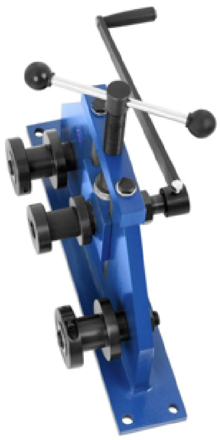


Figure 8: **Utilised Rolling Machine.** A manual rolling machine (MSW-TRM-100 Nr. EX10061177, MSW Motion Control GmbH, Germany) was used to enable bending of the needed elliptical squared pipe rings.

Due to the difficulty of making ellipses on a pipe rolling machine, the longitudinal beams are in the form of large circular arcs which do not deviate more than 5 mm from the chosen form of the submarine. The joints are welded by means of MIG welding. MIG welding is required because the walls of the aluminium pipes are relatively thin. The aluminium pipes are filled with quartz sand before rolling to prevent buckling.
The plates are hydrocut.

4. Propulsors

In the following section the chosen propulsors for *Cygnus IV* are described. The reason for the design, the design itself, and the manufacturing methods are explained in details.

4.1 Choice of Propulsion Method

Conventionally, the forward motion of submarines is induced by a propeller. Here, blades are arranged around a centre point in a helical structure and, when rotated, generate thrust. However, their use might cause problems. A big issue is the emission of noise acting as a sound pollutant as it can have a significant impact on marine animals (Nowacek et al., 2007; Merz et al., 2009; Özden et al., 2016). Additionally, the rotation of the propeller can yield such high velocities meaning low pressures according to Bernoulli's principle, that cavitation occurs damaging and potentially destroying the propeller. Furthermore, if fishing gear, marine vegetation or plastic debris are caught by the propeller, it can tie around the rotary shaft and eventually block or break its movement (Clark and Bemis, 1979; Hong et al., 2017).

Therefore, it appears to be plausible to search for a different concept of propulsion. A promising approach is biomimetics or bio-inspiration where it is assumed that nature has developed optimal designs over the span of its evolution. These principles can then be adopted to create close-to-optimal designs for technical applications (Nachtigall et al., 2002). Regarding propulsion systems and underwater motion, the shape of the fins or wings, their motion and the working principle of marine animals can therefore be used as model organisms.

Most fishes generate thrust by undulating and/or oscillating the body and caudal fin, the so body-caudal fin (BCF) movements. Instead of the body, fish can also use undulations or oscillations of the median and/or paired fins (MPF) for locomotion. This is however only employed by a smaller percentage of marine animals as the only propulsive system and occurs more frequently in addition to BCF locomotion as an auxiliary propulsor to imply manoeuvrability and stability (Sfakiotakis et al., 1999).

Thrust generated by undulations is mainly achieved by the added mass method. Here, each segment of the moving structure, i.e. the fins or the body, generates a force vector acting upon the fluid showing a lateral and a thrust component. Adding up all vectors of the segments over the body, the lateral forces ideally cancel out and only leave the thrust component. However, the existence of the lateral forces implies an inefficiency due to losses (Sfakiotakis et al., 1999) and thus do not appear to be a reasonably propulsive system. Additionally, applying undulations of the body to the submarine hull appears to be difficult to implement and impractical for the pilot.

As stated above, propulsion can also be achieved with oscillations of pectoral appendages by either drag or on lift. The former method is used in MPF locomotion of labriform fishes (e.g. Blake and Blake, 1979) but also by some insects (e.g. Nachtigall, 1974; Ngo and Mchenry, 2014), sometimes referred to as rowing. This motion is divided into two phases, the power stroke and the recovery stroke. During the power stroke, the appendage is moved to the posterior end of the body generating comparably high thrust typically induced by a maximum wetted area. The recovery stroke is an anterior-directed movement to bring the appendage back to the initial position of the power stroke. No thrust is generated in this phase. Hence, during rowing, the animal is constantly accelerated and decelerated (Nachtigall, 1974; Sfakiotakis et al., 1999; Ngo and Mchenry, 2014) yielding an erratic movement. This however is not desired for a submarine. The inconsistent motion in the water makes the control of the submarine unnecessary difficult.

In contrast to the drag-based propulsion method, the lift-based method generates thrust at almost every instant. This type of propulsion occurs when oscillating either the caudal fin, like thunniform fishes (Sfakiotakis et al., 1999), or paired pectoral appendages. The latter includes for example some labriform fishes (Sfakiotakis et al., 1999; Walker and Westneat, 1997), but also marine mammals (Feldkamp, 1987) and other aquatic animals like sea turtles (Walker, 1971) and penguins (see Figure 9, Clark and Bemis, 1979).

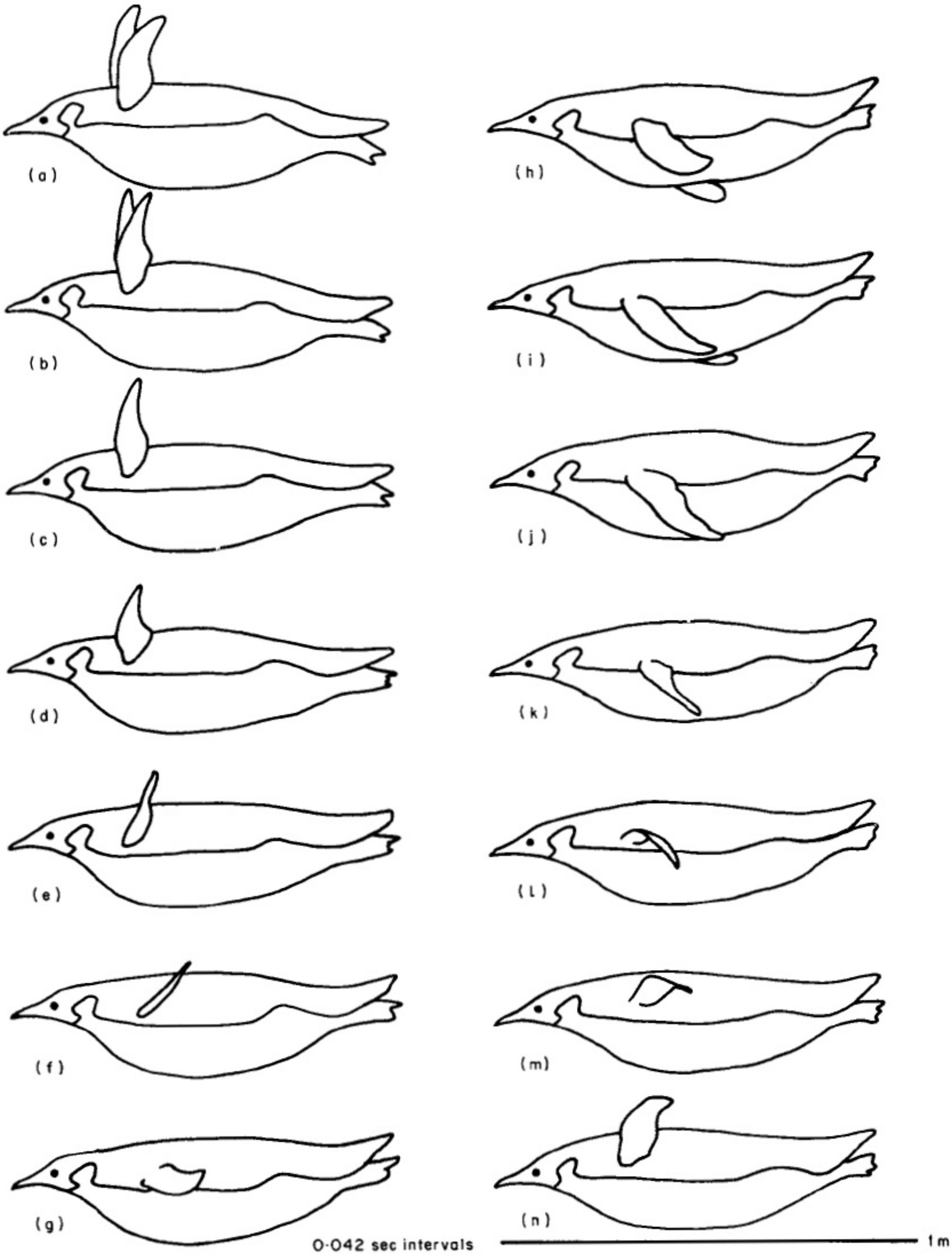


Figure 9: **Wingbeat Cycle of a Penguin.** The wing shows angles of attack and cavities due to wing bending. Modified from (Clark and Bemis, 1979)

For generating thrust by lift, their appendages function as hydrofoils and are moved in a plane perpendicular to the longitudinal axis of the body oscillating in a pitching-heaving motion (see Figure 9 and 10). This locomotion is often called "Aquatic Flight" as it is very similar to flight of birds but with almost symmetrical up- and downstrokes (Clark and Bemis, 1979). In contrast to flying birds, for aquatic birds like penguins, the effect of gravity is not as critical but rather the water resistance. Hence, the main muscle of penguins for moving the wing up, the supracoracoideus, shows a relative high mass enabling almost symmetrical wing movements (Kovacs and Meyers, 2000). Therefore, both phases, the up- and downstroke, of the aquatic flight are approximately of equal length and also generate about the same propulsive force with alternating positive and negative vertical components (Dickinson, 1996). This propulsive method therefore only has a short duration of not generating thrust during the turnover of the oscillatory motion and thus appears to be a very promising propulsive method.

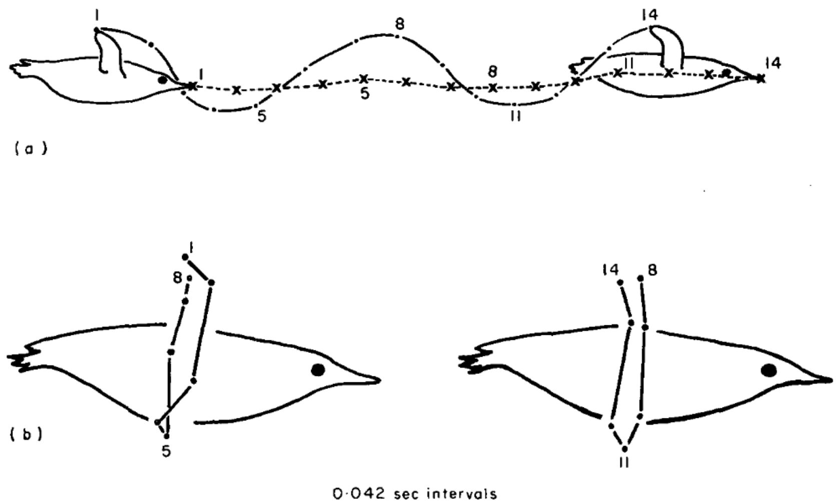


Figure 10: **Wing Tip and Bill Movement over the Wingbeat Cycle of a Penguin.** (a) Movement of the wing tip (solid line) and bill (dashed line) over time by the according frame number; (b) Movement of the wing tip relative to the penguin's body. Modified from (Clark and Bemis, 1979)

4.2 Method of Choice: Aquatic Flight

The most important component of aquatic flight is the wing and its movements. In principle this resembles a hydrofoil that oscillates with varying angle of attacks. During forward locomotion, the surrounding fluid, i.e. water, flows over the surface of the hydrofoil resulting in a separated flow with two different velocities. Based on Bernoulli's principle stating that the velocity corresponds negatively with pressure, the side with a higher flow velocity shows a decreased pressure. The pressure difference yields a suction towards the site with the lower pressure (Dickinson, 1996).

The fluid flow and the wake can be explained by the steady-state theory of lift (see Figure 11). Due to the angle of attack, the forward and rear stagnation points are located asymmetrically. The velocity is higher on one side. When the theoretical background symmetrical velocity field is subtracted from the present one, a net circulation around the hydrofoil is obtained, that circulates from the leading over the surface with the higher pressure around the tailing edge over the surface with the lower pressure back to the leading edge. The resulting circulation is called the bound vortex (Dickinson, 1996).

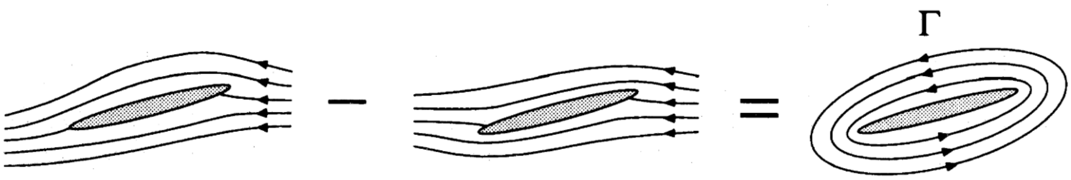


Figure 11: **Steady-state Theory of Lift.** A flow over a hydrofoil with an angle of attack shows an asymmetrical velocity field (left). If the theoretical background symmetrical field (middle) is subtracted, a net circulation is obtained (right) that induces the differences in velocities on both sides of the hydrofoil. The velocity on the upper side is higher than on the lower. Modified from (Dickinson, 1996).

Behind the hydrofoil at the tailing edge, the two streams with different velocities meet resulting in a vortex in the wake, called the starting vortex, with an equal but opposite strength. Simultaneously, both streams meet at the tip and, if the wing is simplified to a free-flowing hydrofoil, also at the base of the wing. The vortices here are called tip vortices and connect the bound and starting vortex in the third dimension forming a closed loop (see Figure 12). An upward force acting upon the hydrofoil is generated by the wake momentum (Dickinson, 1996).

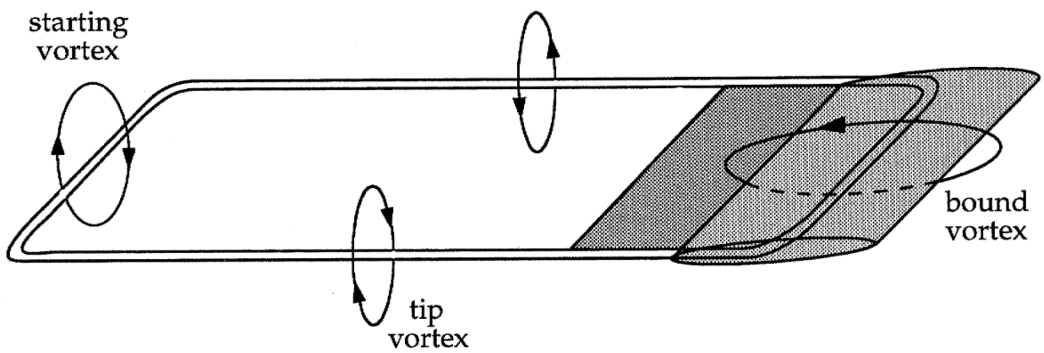


Figure 12: **Lift by Induced Vortices.** Lift is generated by the wake momentum. The starting vortex, the tip vortices and the bound vortex build a closed loop with circulation of zero in total. Modified from (Dickinson, 1996).

However, the animals using aquatic flight, e.g. penguins or labriform fishes, flap or oscillate their wings up and down. Hence, this form of locomotion is not steady-state completely but only includes parts of it. Therefore, the flow does not necessarily need to show a closed loop but can consist of multiple single vortices in a pattern. Depending on the amplitude and the frequency, i.e. different gaits of the animals, the wake can appear differently. Additionally, cavities due to wing bending can occur and change wake characteristics (see Figure 10 and 9). The paired fins or wings move symmetrical to the sagittal plane to prevent a roll movement of the body around the longitudinal axis (Clark and Bemis, 1979; Dickinson, 1996).

4.3 Previous Design

To include the biomimetic type of propulsion, the previous design, *Rivershark* is propelled by the help of MirageDrive fins (see Figure 13) designed and built by Hobie Cat Co. (Oceanside, USA) and developed further by the people working on *Rivershark* in the previous years. The MirageDrive system transformed pedalling motion of the rider into transverse sweeping at the point of attachment of the submarine. It has two input links at either side of the MirageDrive that move in opposite directions. This allowed a biomimetic bird flight-like motion, called "Aquatic Flight", for the submarine. The system and design of the propulsion of *Rivershark* included a total rotary oscillation of 196 °. A lift to propel the submarine is only produced after a period of drag at the initial few degrees after the turnover of fins.

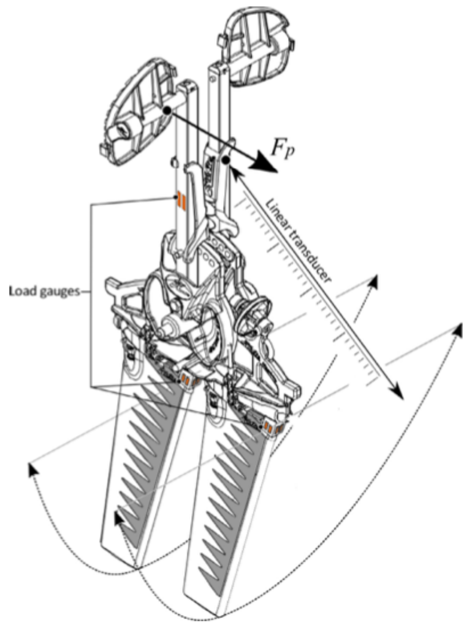


Figure 13: **Hobie MirageDrive.** Modified from (Yan et al., 2016)

With the MirageDrive, the following advantages were implemented:

1. The design was biomimetic and had all the advantages of the biomimetic design (see subsection 4.2).

2. The system was able to achieve top speed of 1.49 knots.

3. The propulsion system consumes relatively lesser space and allows the engineers for room to maintain the submarine's buoyancy.

4. Easy replacement of the fins was possible in times of assembly, disassembly and damage to fins.

However, there are also some drawbacks to the MirageDrive:

1. It is well known that although pedalling is a continuous motion of the lower body, at lower speeds it does have a 'dead point' at the extreme top and bottom of the pedalling movement due to one leg being fully extended and the other vertically above the mechanism. This effect is even more severe underwater due to the inertia opposing the motion of the crank. Coupling the oscillations of the MirageDrive fins with the crank of *Rivershark*, also showed dead points in its mechanism which made it harder for the pilot to continue rhythmic movements underwater.

2. Although the presence of just two pairs of fins allowed the pilot of the submarine to reach a decent speed, it was experienced by the pilot that the pedalling motion became saturated and the mechanism had reached its maximum output when the pilot could exert more energy.

3. The turnover of the fins at the extremes is around 40° long, which gives the pilot about 140° to exert power. Although this allowed the generation of thrust, the pilot could produce a forward

motion for the submarine only in the 140°, out of which the initial region of drag for developing a thrust generating flow took up some degrees. Hence, the room for actual propulsion at maximum output of the MirageDrive system was even less.

4.4 Propulsion in *Cygnus*

Although the basic idea of *Cygnus* had evolved over the years by previous teams, the actual transmission system and the propulsion system were not yet completed. This led to numerous modifications of the final transmission design and henceforth the propulsion system of the *Cygnus IV*.

The concept idea of the *Cygnus* propulsion system is based on the idea of having fours fin pairs on the submarine outriggers such that they would follow a similar motion pattern as followed by Hobie fins as used in *Rivershark* in the previous years and provide more thrust and better control under smoother flow to the submarine. Hence, instead of two fin pairs going through a rotation, it was envisioned that four fins would have similar oscillations to multiply the thrust (envisioned to be over 4 kn, as formulated in the design aims, see section 2).

Apart from this, for *Cygnus* it was also tried to increase the angle of rotation of the fins above the current angle of rotation to provide a higher range wherein thrust would be provided to the submarine.

The idea was to have the fin pair at the front side of the outriggers out of phase with respect to the rear outriggers, so the submarine is able to produce continuous thrust throughout the oscillations of the fins as on both the outriggers, one fin pair would provide thrust while the other is at the turnover point.

Along with a completely new design for the submarine, *Cygnus IV* also has four pairs of fins, two pairs on either side of the main hull of the submarine and each pair attached at the extreme ends of the outriggers. The design attempts to cover up the shortcomings of *Rivershark* and improve upon the ideas of its own predecessors. It still allows for a biomimetic penguin, bird like propulsion, only oriented differently on the body of the submarine.

4.5 Features of *Cygnus*' Propulsion System

The presence of outriggers and the presence of the fins at the extremes of the outriggers allows the fins to have a greater degree of rotation, they still do not cross the 360° mark and complete full rotations, however the fins go through an angle of 310° from one extreme to the other. Even considering a turnover angle of 40°, the fins have a propulsion angle of around 270° that would provide the submarine with about twice the thrust from each pair of fins as compared to the older submarine.

Unlike *Rivershark*, the pair of fins attached to shafts themselves are not counter rotating, rather the pairs on opposite sides of the submarine are counter rotating. The fins are attached on opposite ends of a counter-rotating pair of fins allowing division of thrust into two fin pairs, moderately loaded instead of one with a higher load. This allows a higher lifetime of fins and higher efficiency to both the pilot and the submarine. This also allows biomimetic propulsion in the submarine. However, a major drawback of counter rotating fins is that they provide instability to the fact that they are considered to be rather unsteady configuration (Grassi et al., 2010). Nevertheless, the angular velocity of the fins is not enough to cause any major disturbance to the movement of the submarine.

As mentioned before, fins have a turnover angle of 40°, wherein the fin pairs do not provide any thrust to the submarine. To counter this problem, the fin pair on each outrigger are 90° out of phase. So at every given point in time, the submarine is producing thrust. This means that when the rear pair of fins is at the turnover point, the front side is producing maximum torque and vice versa. Moreover,it enables the pilot to continue a more rhythmic motion and not lose energy at the dead points at the hands of the mechanical systems there is a continuous inertia that helps motions the submarine. Although the fins being out of phase creates a certain pitch in the submarine due to the production of thrust at the bow and the stern alternatively, they are theoretically cancelled out by each other when considering the overall motion of the submarine.

4.6 Final Propulsion System

Since the idea for *Cygnus IV* is a total revamp of the transmission system that was initially taken from Hobie, there had to be major changes made to the fastening system for the fins to its shaft. In fact fins are the only parts that have been taken from the old Hobie system since they meet the required material strength. Additionally, their shape efficiency is higher than systems that could be made at present with the local manufacturing options. The new fin attachment system takes up the basic attachment idea from Hobie. However, it adapts the fins to form a more secure design according to the requirement of transmission system.

The new propulsion system attempts to improve the pilot's efficiency and to increase the power output for the submarine to achieve more speed. Although the idea of *Cygnus IV* has been in progress for around 4-5 years, the transmission and the propulsion system have never actually been designed or completed. Over time, it has developed into a new and innovative approach to a propulsion system and seems plausible even for the future submarines.

5. Transmission System

5.1 Power Conversion from Pilot

The team's previous submarine, *Rivershark*, used a stepper motion from the pilot to produce the power for the propulsion. It can be found, however, that a rotary motion like that of a bicycle can produce a similar amount of power while tiring the pilot much more slowly. However, this poses a new challenge in that the MirageDrives need an oscillatory input rather than the continuous output from the pedals. As such, the primary goal of the transmission is to convert the continuous rotation of the pedals into an oscillatory rotation while still maintaining an angle of rotation between 300 and 360°. The reason for this is further explained in section 4 of the report.

5.2 Choice of Conversion Mechanism

In order to achieve the conversion of continuous pedal motion into rotational oscillation, a mechanism had to be chosen. Several options were considered, as shown here:

5.2.1 "Half Bevel" Gearbox

This mechanism (see Figure 14) consists of two bevel gears on the input axle and one larger bevel gear on the output axle. Each smaller bevel gear has teeth on only 180° so that they mesh alternatively with the larger gear to produce an oscillation. The output oscillation is fixed at 180°, and it can be increased to 340° by using another pair of gears. This mechanism is very space efficient, but carries a high risk due to the teeth having to constantly re-mesh.

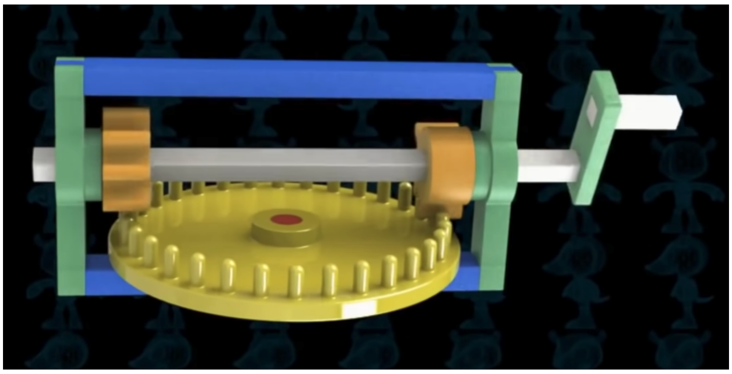


Figure 14: Concept drawing for a half bevel system. (Franco Fonnese, 2018)

5.2.2 Camshaft with Rack and Pinion

This system (see Figure 15) works with a camshaft which drives a rack and pinion along a linear rail. This converts the continuous rotation into a linear oscillation, and then into a rotational oscillation. While it functions in theory, the practical construction of this system would be difficult, as all the parts would need to be in near-perfect alignment or the linear bearings could seize, or the teeth could come un-meshed.

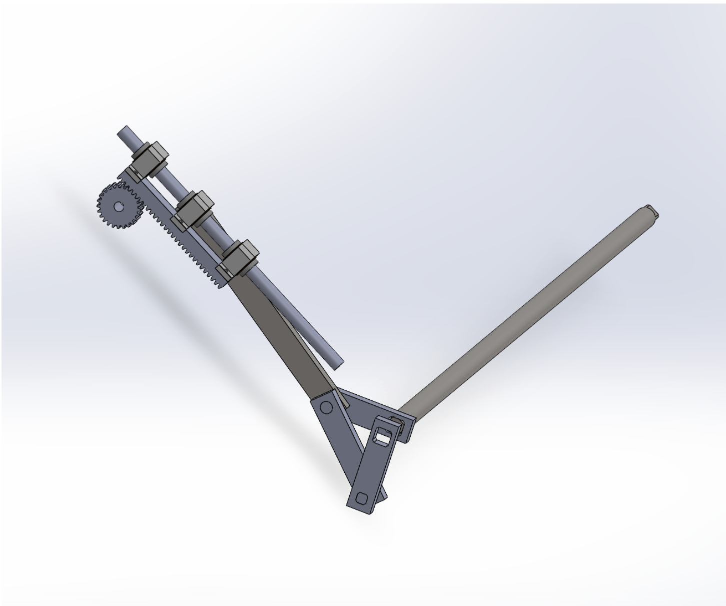


Figure 15: Early prototype CAD model

5.2.3 Crank Rocker

A crank rocker (see Figure 16) is a form of four-bar linkage in which one crank is much smaller than the other. When the smaller crank is rotated continuously, it creates an oscillatory motion in the other. This yields an oscillatory rotation at the rocker, which is located at the base of the longer crank.

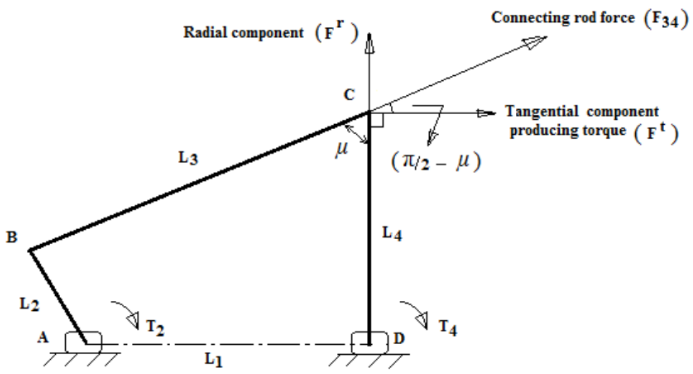


Figure 16: Simplified crank rocker system (Mohammed et al., 2006)

5.2.4 Coaxial Cylinders with Path Cutout

This mechanism (see Figure 17) functions with two coaxial cylinders. The inner cylinder has a continuous slot cut in a sine wave pattern, while the outer slot has a single slot which is only the portion of a sine wave between zero an π. These slots are then connected via a pin, such that a continuous rotation of the inner cylinder produces an oscillatory rotation of the outer cylinder.

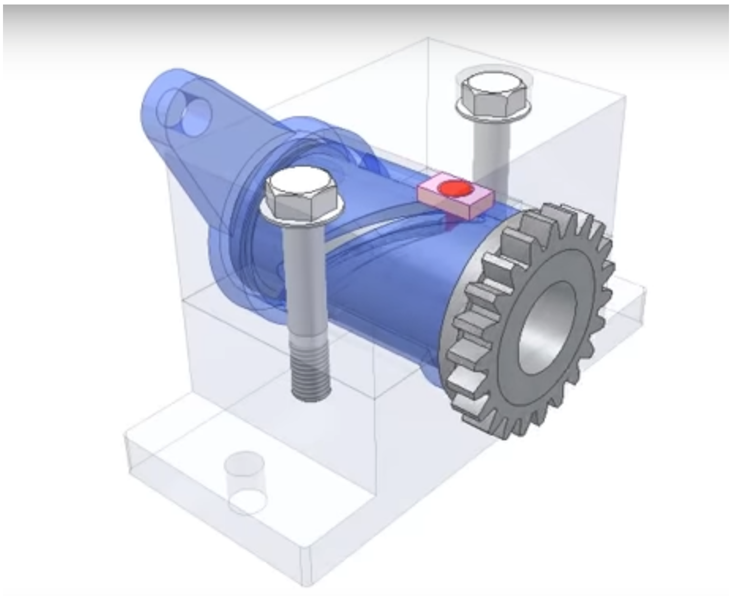


Figure 17: Concept model for a coaxial cylinder mechanism (Thang010146, 2019)

5.2.5 Assessment Matrix

These systems were compared using the assessment matrix shown in Table 1.
Based on this matrix, it can clearly be seen that the crank rocker system is the best choice. This is especially true when considering the time restraints and nature of the competition, which give reliability and ease of manufacturing higher weight in the consideration.

Table 1: **Assessment matrix.** *Weight, volume, and cost are scored inversely, where a low score indicates a high value
**EoM: Ease of Manufacturing

Mechanism	Weight*	Volume*	Cost*	Reliability	Efficiency	EOM**	Total
Half Bevel	1	4	1	1	3	3	13
Camshaft with Rack	2	2	2	1	2	3	12
Crank Rocker	3	1	4	4	4	3	19
Coaxial Cylinders	4	4	2	3	2	1	15

5.3 Final Design

Once the mechanism for the conversion of continuous to oscillatory rotation was chosen, the rest of the transmission was designed around it. The system begins with the pedals, which are standard bicycle pedals. From there, a sprocket and chain transfers the rotation to a primary drive shaft, which runs all the way in between the outriggers. The rest of the transmission is contained in the outriggers (Figure 18). The drive shaft turns a crankshaft system, which in turn drives the crank rocker. The rocker is connected to a set of sprockets and pulleys which imitate a bevel gearbox, turning the rotation 90° and increasing the angle of rotation. A second set of sprockets increases the angle further to a total of 315°, before the power is finally transmitted to the mirage fins. All of these systems are supported by a twin-keel structure which gives both buoyancy and stability. The following figures and descriptions show each of the key mechanisms in greater detail.

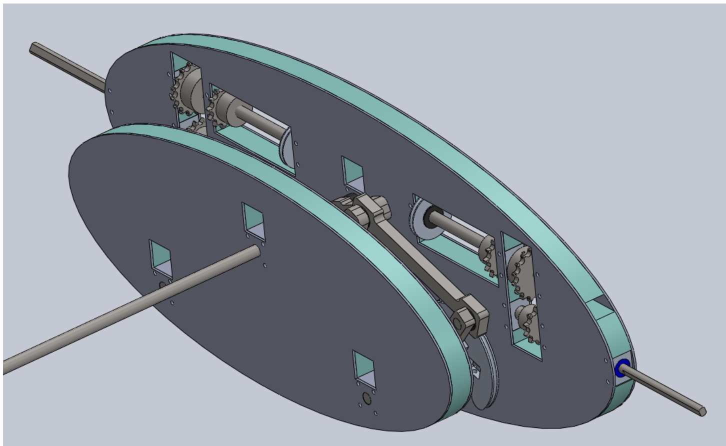


Figure 18: CAD model of the full transmission system in the outrigger. The MirageDrive fins will be attached in pairs to the protruding shafts in the top left and bottom right corner.

The crankshaft system (Figure 19) is designed to serve as the first part of the crank rocker system as well as to keep the front and back sets of mirage fins 90° out of phase in their oscillation. The rotational forces on the joints under maximum expected loading were calculated to be too high to comfortably connect them using keys. Instead, tapered square shafts were used for all non-welded connections. By then attaching the arms of the crank rocker 90° apart from each other, the motions of the mirage fins are controlled such that the power output is more continuous. This effect is described in greater detail in the propulsion section of the report.

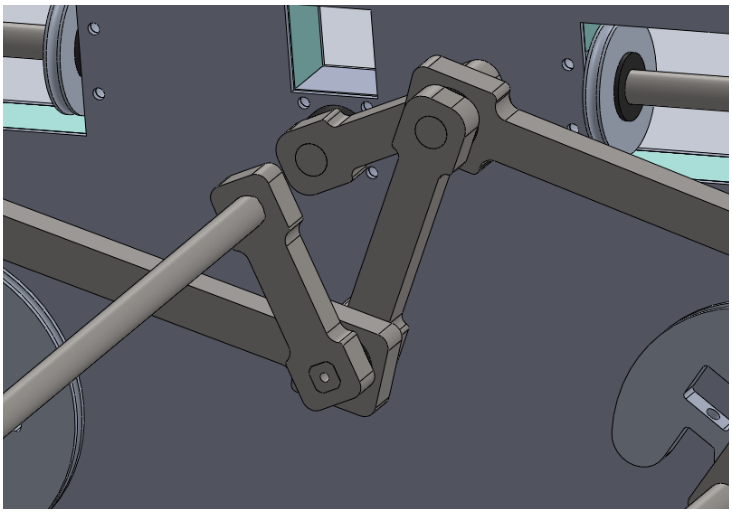


Figure 19: CAD model of the crankshaft system

The crank rocker mechanism itself (Figure 20) is the heart of the transmission system. There are several key factors which had to be taken into account. Most critically, the angle between the piston arm and the rocker arm could not be smaller than about 40°, or the system would seize. This leaves a maximum angle of rotation of 100° for the rocker. This was further reduced to 85°, as the sine of the angle between the arms also dictates the amount of force which is actually converted to rotation. The rocker must also be sufficiently large to create a high gear ratio with the associated sprocket due to the relatively small angle of travel of the rocker.

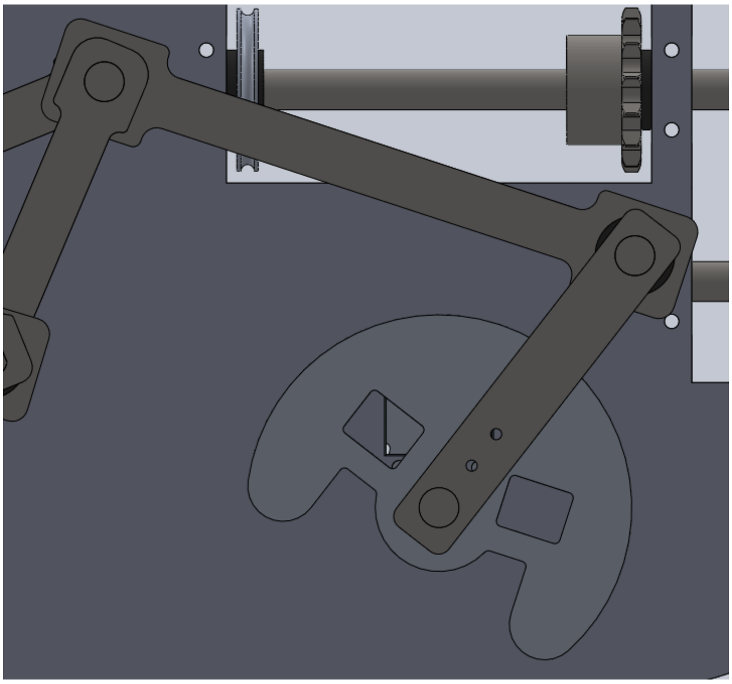
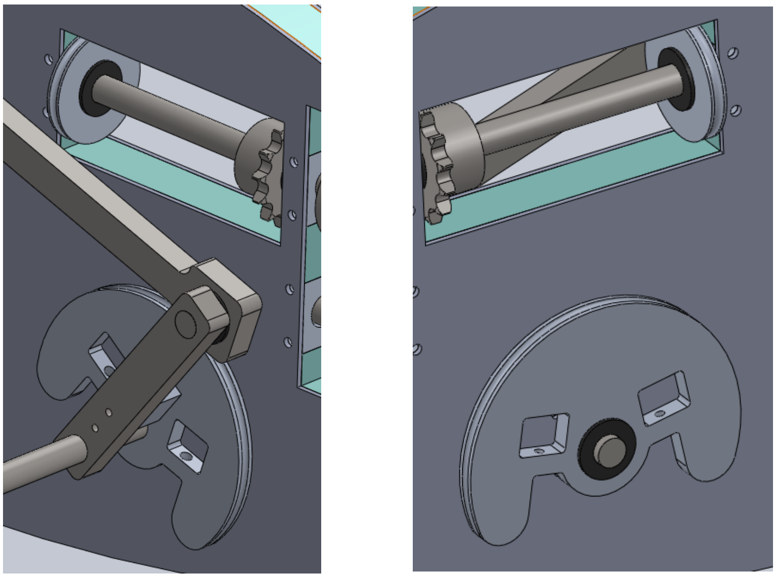


Figure 20: CAD model of the crank rocker

The sprocket and pulley system (Figure 21) is adapted from the original MirageDrive, and is intended to approximate a bevel gear while requiring less precision in its construction and without the risk of skipping teeth under high loads. A section of chain is placed on the sprocket, and is connected at the ends via swages to a wire. This wire then connects to the drive rocker, as well as the driven rocker on the opposite side. These rockers also serve as tensioners, as the cables are connected via threaded swages which can be manually adjusted.



(a) From the inside face of the outrigger (b) From the outside face of the outrigger

Figure 21: CAD models of the pulley system, chain and wires not shown

The twin keels serve three purposes. First, the foam centres provide enough buoyancy to make the outriggers close to neutrally buoyant, which makes trimming much easier. Second, the lightweight nature of the keels helps to offset the amount of steel and aluminium required for the transmission. A fully metal support structure would have made the outriggers far too heavy. Finally, the sandwich structure of the keels allows parts to be embedded (Figure 22) so that the shafts can run internally, which in turn makes the "bevel gear" system far easier to support.

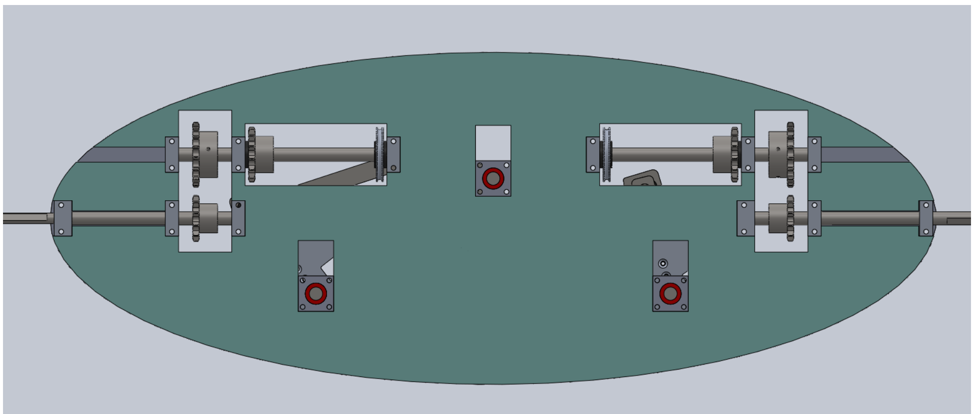


Figure 22: Bearing blocks embedded in the keel

5.4 Materials

The majority of the transmission system is made from aluminium and steel. Aluminium is used as much as possible, but many of the structural elements must be made from steel in order to prevent bending. Rather than using stainless steel, which is generally not as strong as mild steel while being significantly harder to machine, it was decided to use mild steel and treat it with a bluing agent. The bluing liquid

rapidly anodises the outer layer of the steel, which protects against corrosion. If the steel is first sanded to approximately 400 grit, then blued, oiled, and painted, there is minimal risk of corrosion compared to untreated steel. This was tested empirically using scraps of the same steel from which the parts were made (see section 10).
All the spacers and bushings in the transmission were made from igus plastic (iglidur®X round bar, igus®GmbH, Cologne, Germany). It has high wear resistance, low friction coefficient with both aluminium and steel, and is designed specifically for underwater application. These properties make it perfect for this application.
The keels are made from 30 mm sheets of rigid, lightweight foam, which are epoxied between two 3 mm aluminium plates to create a sandwich structure. This provides a good structural integrity while keeping weight low and providing high positive buoyancy.

6. Trim, Hydrostatic and Stability

The hull in *Cygnus* is made out of PET-G which is nearly neutrally buoyant by itself. The hull material is also one of the reasons that the submarine is higher in volume with respect to the submarines that the team had in the previous years yet has a lower theoretical weight, in fact almost half of the weight of a previous submarine, *Rivershark*. The hull for both the outriggers are made out of PET-G as well allowing more capacity to add foam and hence more buoyancy in the submarine. Some general parameters about *Cygnus* based on the SolidWorks model are displayed in Table 2.

Table 2: **General Information about the Submarine.**

Cygnus:			
Dry weight	65 kgs (approx)	Length	2.90 m
Volume	44348.97 cm^3	Maximum Surface area	139746.80 cm^2

The frame (Figure 23) however is made out of Aluminium and occupies 27870.23 cubic centimetres and weighs around 0.4 of the total estimated weight. The *Cygnus* frame is distributed all over the body with thicker rings and differently shaped rods at the back of the submarine to support the transmission system and the outriggers for the transmission system.

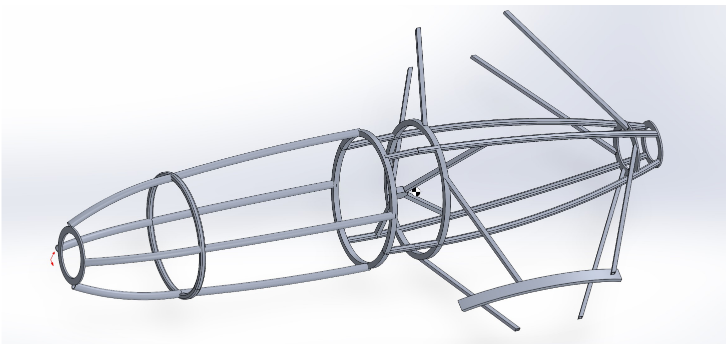


Figure 23: **Model of *Cygnus* focusing on the weight distribution of the frame.**

6.1 Centre of Mass

The estimated centre of mass of Cygnus is shown in Figure 24. The side view of the model indicates that the centre of mass is beyond the front sprocket of Cygnus pedal system. Furthermore, it is located in the longitudinal plane due to the symmetry of the submarine.

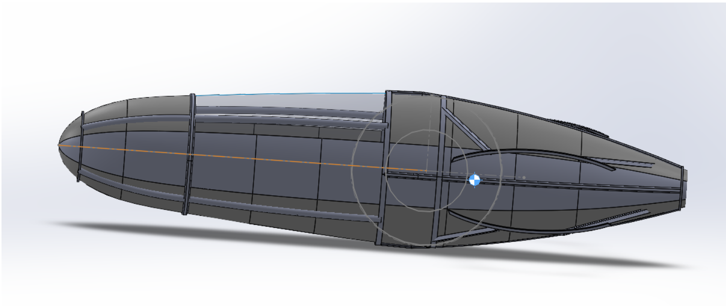


Figure 24: **Centre of mass of *Cygnus*.** Side view of the SolidWorks model of the frame and hull.

In Table 3, the principal axes of inertia (Ix, Iy, Iz) and principal moments of inertia (Px, Py, Pz) are shown, taken at the centre of mass.

Ix = (0.00,0.01, 1.00)	Px = 79802171.02
Iy = (1.00,0.00, 0.00)	Py = 117937127.52
Iz = (0.00,1.00, -0.01)	Pz = 188048841.09

Table 3: **Principal axes of inertia and principal moments of inertia around the x-, y- and z-axis.** Values have the unit of gcm^2.

The moments of inertia taken at the centre of mass and aligned with the output coordinate system are shown in Table 4.

Lxx = 117937237.44	Lxy = 95330.08	Lxz = 25838.64
Lyx = 95330.08	Lyy = 188036098.18	Lyz = 1168447.61
Lzx = 25838.64	Lzy = 1168447.61	Lzz = 79814804.0

Table 4: **Moments of inertia taken at the centre of mass and aligned with the output coordinate system.** Values have the unit of g/cm^2.

In Table 5, the moments of inertia taken at the output coordinate system are shown.

Ixx = 117937254.65	Ixy = -67703.08	Ixz = 43707.91
Iyx = -67703.08	Iyy = 1751295851.26	Iyz = 1168445.75
Izx = 43707.91	Izy = 1168445.75	Izz = 1643074573.90

Table 5: **Moments of inertia taken at the output coordinate system.** Values have the unit of g/cm^2.

6.2 Trim and Ballast Plan

The trim and ballast plan for *Cygnus* is not very different from that in *Rivershark*. The submarine is to be brought down to race depth and the pilot and the submarine are to be made neutrally buoyant separately, however one issue here is that the *Cygnus* unlike *Rivershark* has three separate hulls (one main Hull and

two hulls for the outriggers). The submarine hulls are made buoyant by adding styrofoam in the empty pockets of the submarine and allowing the submarine to get buoyant over time.
These hulls are connected by aluminium rods that are a part of the frame of *Cygnus*. To avoid stresses in the frame and cause fractures at any point in the submarine, the outrigger hulls and the main hull are made buoyant separately, and a balance needs to be maintained between the three hulls, so the centre of buoyancy is maintained at the centre of the main hull even without the pilot.
The main hull is designed to have pockets for blocks of styrofoam but additionally has an inbuilt styrofoam keel already. It does not add any stability to the submarine but serves the only purpose of buoyancy. It is placed behind the pedals running along the vertical axis to the back of the submarine. To protect it from damage, the keel is designed to be a sandwich structure out of two outer PET-G sheets with a thickness of 3 mm and an inner styrofoam sheet with 30 mm thickness.
After the submarine is made buoyant completely, the buoyant pilot is allowed to enter the submarine such that the whole system is buoyant overall.

7. Control Surfaces and Controls

Controlling the direction of propulsion and manoeuvring while providing enough stability of the boat is a crucial task. Therefore, two rotational degrees of freedom (elevator and yaw movement) have to be controlled with control surfaces and by equating the centre of buoyancy as well as the centre of gravity while the last rotational degree of freedom (roll movement) as to be blocked as good as possible with stabiliser fins and outriggers as shown in (Figure 25).

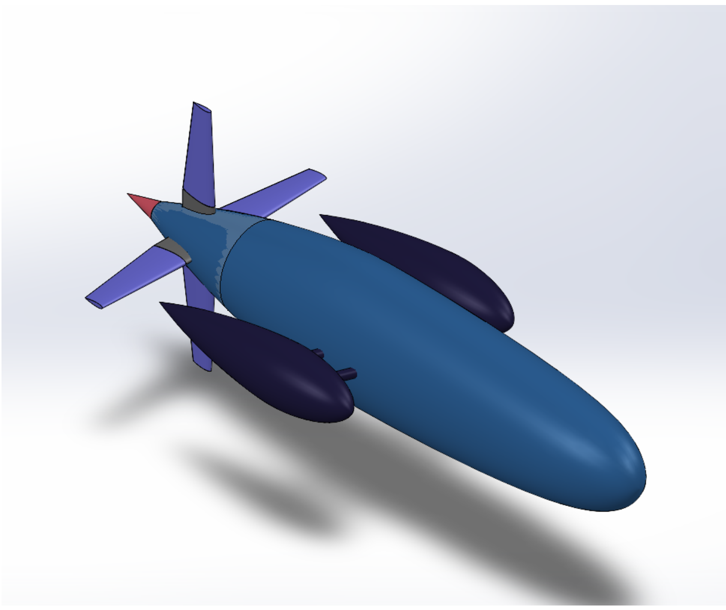


Figure 25: ***Cygnus IV* in modelling phase.** Cross plane rudders are attached at the end.

7.1 Design of Control Surfaces

To design the control surfaces for *Cygnus IV* while considering the design philosophy the task was divided into three sub-tasks.

1. Choosing the right mechanism and designing the CAD model.

2. The electrical circuit defined with a proper Code (Arduino).

3. Sealing the components underwater.

Considering the design philosophy a simple, easy attachable, and efficient way to transmit a movement of the hand or an electrical signal to a movement of the rudders and elevators with minimal reaction time had to be designed.

7.1.1 Mechanism and Computer Aided Design Model

For simplicity a cross plane rudders' configuration for manoeuvring was chosen. A cross plane rudders' configuration consists of two rudders on the y-axis to enable the boat to manoeuvre on the yaw rotation (α) with two elevators (fins) to control the motion of up and down (pitch rotation, β). The configuration of the rudders is shown in Figure 26.

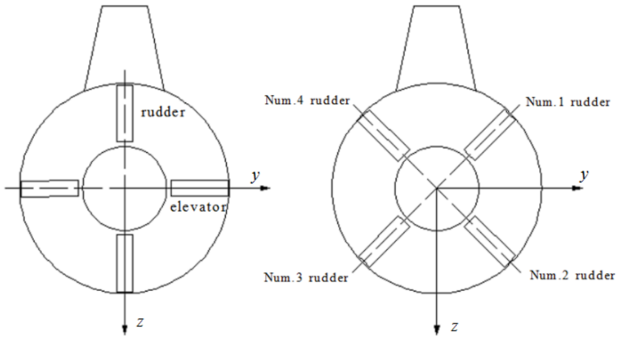


Figure 26: **Cross plane rudders to X-Plane.** For the rudders Cross plane is used on *Cygnus IV*.

7.1.2 Calculations for the Control Surfaces

A rudder controls the yaw and two fins running along a perpendicular surface to the rudder controlling the pitch of the vessel. The lift force acting per fin and torque acting on rudder with dimensions displayed in Figure 27, are calculated as below.
The torque C is calculated with

$$C = S \times [(0.4 \times Lg) - Lc] \times V^2 \times K, \quad (1)$$

where,
S is the surface are of the rudder in m^2, Lg the width of the rudders in m, Lc the compensation width in m, V the velocity of sub in kn and K the coefficient as a function of total rudder angle, that is 15.89 for a port to starboard angle of 70°, 17.80 for 80° and 19.52 for 90° (Lecomble & Schmitt, nown). The assumptions for the rudder dimensions for these calculations were a height of $H = 0.5\,m$, a length of $Lg = 0.3\,m$, a compensation width of $Lc = 0.1\,m$, a port to starboard

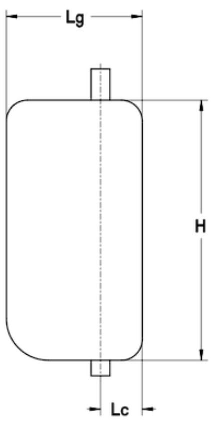


Figure 27: **Equation parameters for the rudders.** Modified from Lecomble & Schmitt (nown).

angle of 70° with $K = 15.89$ giving a surface are of

$$S = H \times Lg = 0.5m \times 0.3m = 0.15m^2. \tag{2}$$

This results in

$$C = 0.15\,m^2 \times [(0.4 \times 0.3\,m) - 0.1\,m] \times (5\,kn)^2 \times 15.89 = 1.19\,kpm = 11.6\,Nm \tag{3}$$

as the torque on the here designed rudders (Lecomble & Schmitt, nown).
For the fins, the lift force FL is calculated with

$$FL = 0.5 \times CL \times \rho w \times V^2 \times A, \tag{4}$$

where CL is the lift coefficient, ρw the density of water in $kg \times m^{-3}$ and A the area of the fin in m^2. The fins' profile is a symmetric NACA 0021 profile with a height of $H = 0.5\,m$ and a length of $Lg = 0.3\,m$. The angle of attack is defined to be 23° resulting in a lift coefficient of about $CL = 1.5$ (see Figure 28, Hansen et al., 2014). Hence, the lift force has a value of

$$FL = 0.5 \times 1.5 \times 1000\,kgm^{-3} \times 2.57^2\,m^2s^{-2} \times 0.15\,m^2 = 743\,N. \tag{5}$$

With two fins, the total lift force is $2 \times 743\,N = 1486\,N$. The torque per fin is the lift force times the leaver arm length and thus results in a value of $743Nx0.5m = 371Nm$.

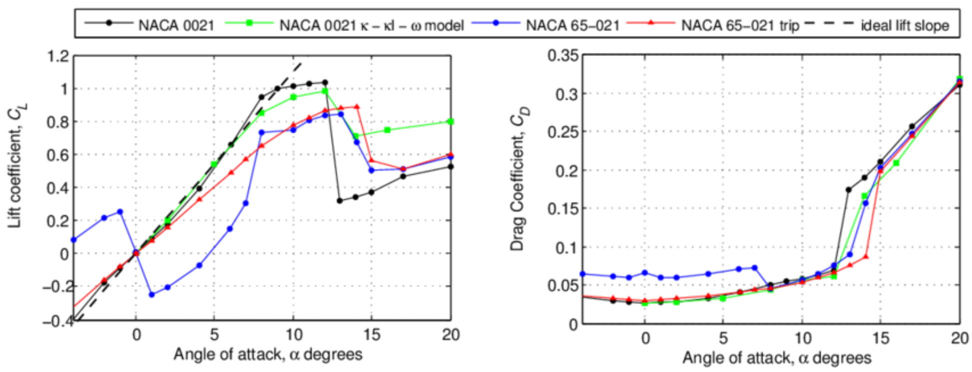


Figure 28: **lift Coefficient values compared to angle of attack.** Modified from Hansen et al. (2014).

7.1.3 Control Mechanism: Slider Crank

To control the motion of the rudders and elevators, a crank slider mechanism was considered. It enables to convert the linear motion exerted by the linear actuators into half circular motion, as the stork of the linear actuators is 100 mm, it was divided into to sections, the first section is between 0-50 mm which controls the degree of tilting the rudders left and the elevators down, the second section is between 50-100 mm which controls the degree of tilting the rudders right and the elevators up as shown in Figure 29.

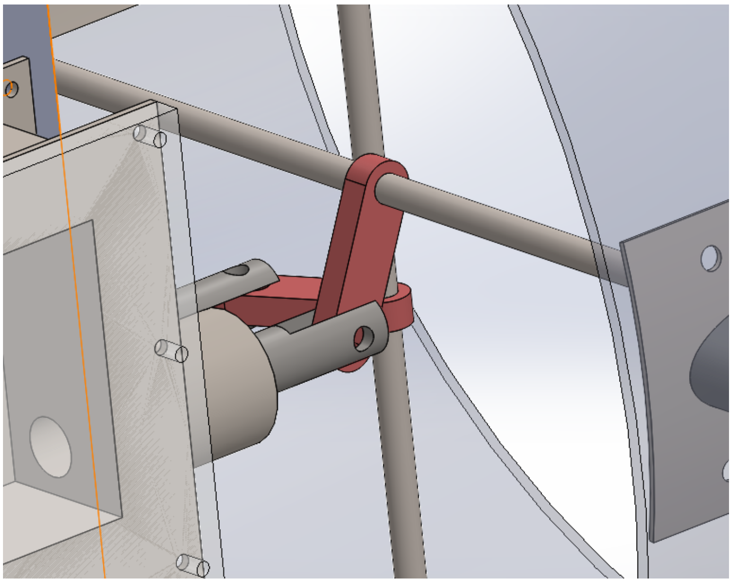


Figure 29: **Simple crank slider mechanism.** An aluminium link is attached between the linear actuator and the elevator shaft.

7.1.4 Electrical Circuit and Components

Controlling the rudders and elevators in a very precise way is important. Therefore, a electronic system that runs on batteries underwater was chosen with the following components

1. Linear actuators
2. Motor Drivers (BTS 7960)
3. Arduino Nano (Arduino ®)
4. Lithium-Polymer batteries
5. Joy sticks

Linear actuators

To insure a sufficient amount of force, it was decided to use linear actuators as motors (Figure 30) that produces maximum force rating of torque of 800 Nm to power the mechanism, which is more than the torque needed to manoeuvre the rudders and to have a lift force.

Figure 30: **Servo city Linear actuator 150 N 50 mm Stroke** (ServoCity.com ®, Winfield, Kansas)

Motor Drivers (BTS 7960)

As it was chosen to work with linear actuator with no self potentiometer to control, it was necessary to use a motor driver to facilitate the controlling part, choosing BTS 7960 (see Figure 31, Arduino ®) was important as it is the most available motor

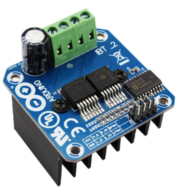


Figure 31: **BTS 7960 board compatible with Arduino.**

driver that can hold the maximum current from the linear actuator which is 15 $\frac{A}{s}$. BTS 7960 can take up to 43 $\frac{A}{s}$ of current which is sufficient for the motor.

Arduino Nano

The Arduino (see Figure 32) collects all data given from the joystick as inputs and gives the feedback to the motor drivers. The Arduino is powered by 12 V from the LI-PO battery and running with a code designed specially for the circuit.

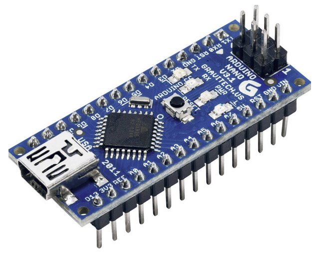


Figure 32: **Arduino Nano used for the electronic circuit**

Lithium Polymer Batteries

Powering the whole circuit underwater needs a powerful water-resistant battery and lid acid batteries cannot be used. Hence, it was chosen to work with Lithium polymer (see Figure 33) batteries as they offer several performance enhancements compared to Li-ions, including higher energy density and lighter-weight batteries, we are using two LI-PO batteries 12 V 5200 mAh while charging two more to use as a spare in case the used two are empty.

Battery Life calculations:

(battery capacity / current drain) x FOS = battery life.

(2 x 5200 mAh / 2 x 300 mA) x 0.7 = 12 hr of continuous power for two linear actuators.

Figure 33: **12V 5200 mAh LI-PO battery.**

Joy Sticks

To send feedback to the rudders and elevators it needed a precise input to send to the Arduino, to do so, the team has to use two joysticks, first one to control rudders and the other for elevators.

The joystick consists of two quick release push buttons connected to analogue pins (PWM pins) on the Arduino to measure the push timing.

The joystick is made of a plastic sealed box mounted on a 3d handle part to be hold firmly in the pilot hands as shown in Figure 34.

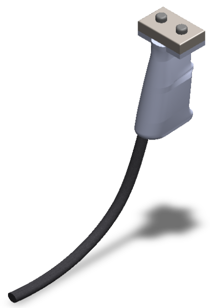


Figure 34: **Sealed box mounted on 3D printed grip**

7.1.5 Sealing the components

To ensure a working and secured electronic circuit underwater, every component have to sealed completely from water.

Therefore, water glands (Figure 35) were used to seal boxes of aluminium which hold the components.

Figure 35: **Underwater aluminium cable gland M9**

Linear Actuators

A fit aluminium box that hold the whole linear actuator sealed by gasket with acrylic shield on top has been designed. As shown in Figure 36 the electrical box.

Electrical box

An aluminium box (see Figure 37) that has two motor drivers with the Arduino Nano has been designed and manufactured. The whole box was filled with epoxy to save the circuits in case of any leaks.

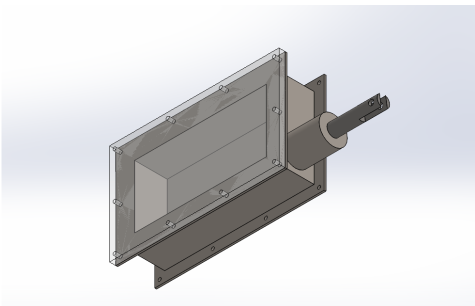


Figure 36: **Linear actuator sealing box**

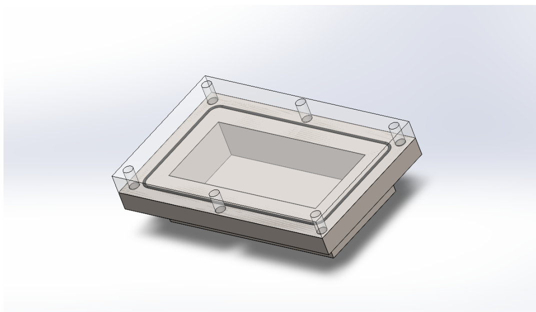


Figure 37: **Sealed box holds two motor drivers and Arduino Nano**

Battery Box

To seal the batteries the way of sealing with o-rings has been used. An acrylic tube with two end caps fitted in with double o-rings have been used (see Figure 38) instead of one to be more safe if any of the o-rings cut while being inserted in the tube.

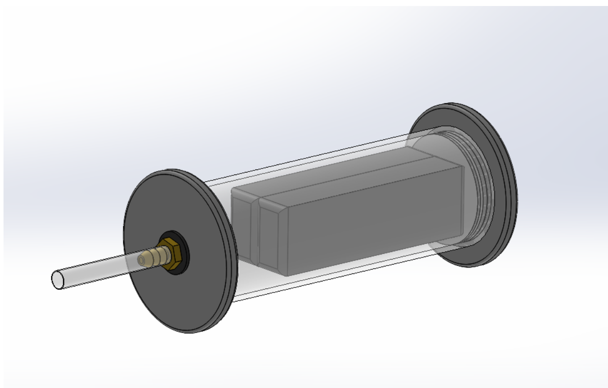


Figure 38: **Battery Box that fits two LI-PO batteries inside**

8. Ergonomics and Pilot Biomechanics

The ergonomics of a human-powered submarine encompass the question of how a human pilot will fit, control, and move within the vessel underwater. In this sense, interactions between the body and the mechanical parts of the submarine are considered: the joystick, pedals, and shoulder-pads are all valid candidates for discussion.

Consider Figure 39 below. The initial plan was to design ergonomically “correct”, lightweight, and efficient components that would allow the pilot to pedal, control, and get into and out of the submarine as comfortably as possible. This would involve, for example, modelling joysticks that fit to the thicker gloved hand of the pilot, stomach padding that would allow the pilot to spread the weight of their stomach over a larger area than the scuba tank anchored to the centre of the hull. Furthermore, a “handle” was proposed as a way to keep the position of the pilot rigid while they were pedalling; one arm would control the submarine while the other is stiffly extended forwards to grab the handle and keep the torso in place.

The necessity for stomach padding was made null in the face of the notion that both the pilot and submarine would be neutrally buoyant underwater. To that end, it is far more likely for the pilot to float upwards and hit the ceiling of the hull rather than be pushed down onto the tank as is the case on land. Furthermore, the pilot is already encased in 14 mm of neoprene, which also serves to act as passive padding.

Creating an “ergonomically correct” joystick is negligible in its actual effectiveness in controlling the submarine. Size does matter in the context of being big enough to grip but small enough to wrap a gloved hand around. Creating a “casing” with spaced grooves for a proper (and more elegant) grip around the basic stick is, while feasible in theory, unnecessary in the context of a fixed deadline.

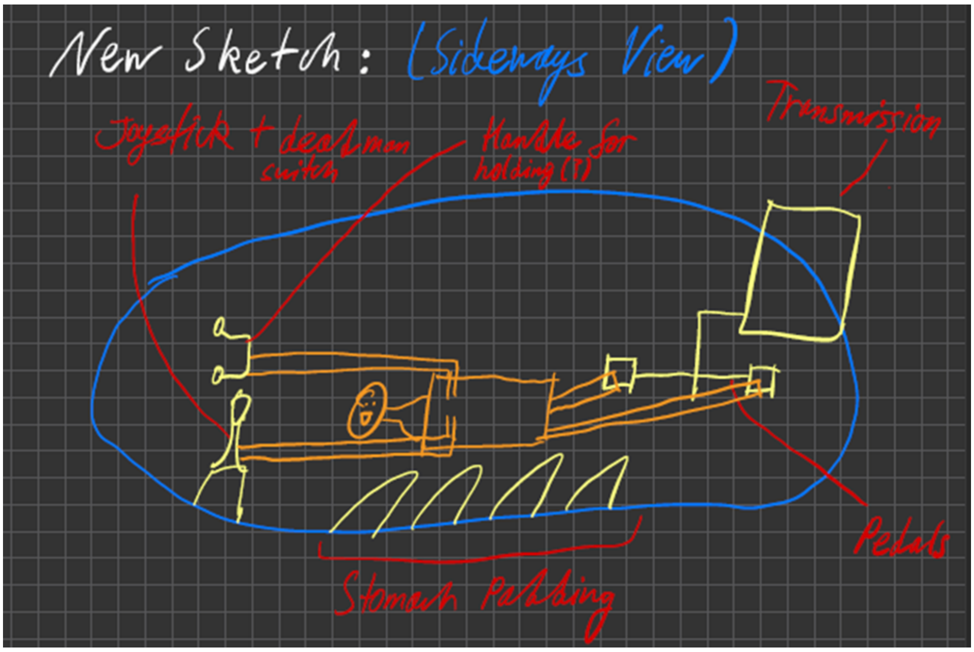


Figure 39: **An initial sketch of ideas relevant to the ergonomics subsection of the submarine.**

The ideation process behind the pedals follows a similar trajectory to that of the shoulder-pads. Initially, a complicated “handmade” solution is theorised which, as it later becomes clear, can be solved by repurposing an existing mechanism / item(s) readily available from third party retailers.

To adjust cycling to underwater several changes had to be considered. The reasons for this are twofold: first, the pilot is pedalling on their stomach horizontally as opposed to sitting upright in a bike saddle and exerting force downwards. This pealing position, combined with the neutral buoyancy of the submarine and the pilot, result in missing counter-forces (on land gravity) which generally enables a cyclist to push on the pedals continuously while remaining in their seat. The former point is a fluid-dynamics relevant choice that can not be avoided within the natural constraints of this project: making a submarine around an upright-sitting pilot that is efficient in its movement through water would require a total design overhaul as well as a much larger hull. The second point, however, can be addressed on two fronts: one of these is the pedalling setup, and the other is the shoulder straps. Both of these serve to keep the pilot "in place" and translate their naturally imperfect horizontal pedalling motion as efficiently as possible into the MirageDrives.

When the pilot exerts force upon the pedals they rotate. Keeping in mind the two aforementioned points above, it becomes necessary to secure the feet of the pilot to the pedals. This is to compensate the innate imperfection of the pedalling motion of the pilot. Concretely, during a rotation, a pilot may begin to pull away (or push) one of their legs at a point where it mechanically does not make sense to pull away yet with respect to the transmission and the position of the pilot's legs. Said otherwise, it is difficult to learn, much less consciously and continuously keep in mind the perfectly efficient pedalling movement of the submarine transmission. It is not erroneous to assume that most pilots simply pedal in the same unconscious motion as on their normal bicycles. Keeping the feet securely in place with the pedals serves to compensate some of this innate inefficiency.

Traditionally, click-shoes are used in professional cycling to maximise the effort exerted by the cyclist. These shoes have a mechanism on the underside towards the front of the sole that is specially designed for inserting or "clicking in" to a specific make of pedals. As the cyclist moves his feet, the shoes and the pedals remain joined, thus resulting in higher efficiency each rotation. However, at the time, the team members were not aware of the concept of a click-shoe. As such, a "proto-click-shoe" (PCS) was devised to meet the need of securing the pilot's feet (see Figure 40).

The PCS is not a shoe per se; rather, it is a "platform" that attaches to the pedals to which the feet are secured. The platform consists of a bottom plate that is welded onto the pedal and a back-plate to hug the heel. Both plates have regularly spaced holes around the edges through which straps (for example nylon webbing) are pulled through. Each strap has a quick-release buckle (see Figure 41) attached to it which allows for easy adjustability and quick disconnection. This whole construct then clips on to the pedal, and so fulfils the same function as a click-shoe.

Ultimately, click shoes with the appropriate pedal were used in place of the PCS due to ease of use and feasibility compared to manufacturing this construct from the ground up.

There are two possible approaches to how to keep the torso of the pilot in place. The first is to create a structure like the handle in Figure 39 against which the pilot can hold themselves rigid with their arm. This was deemed to be a poor solution as the pilot would quickly tire from the added force necessary to keep their arm extended as they pushed against the pedals. Furthermore, it would make steering the submarine more difficult due to both arms being occupied. On top of that, if the handle is somewhere on the side of the hull, rather than in the centre, then the pilot will drift to the side where they are not supporting themselves with each push against the pedals.

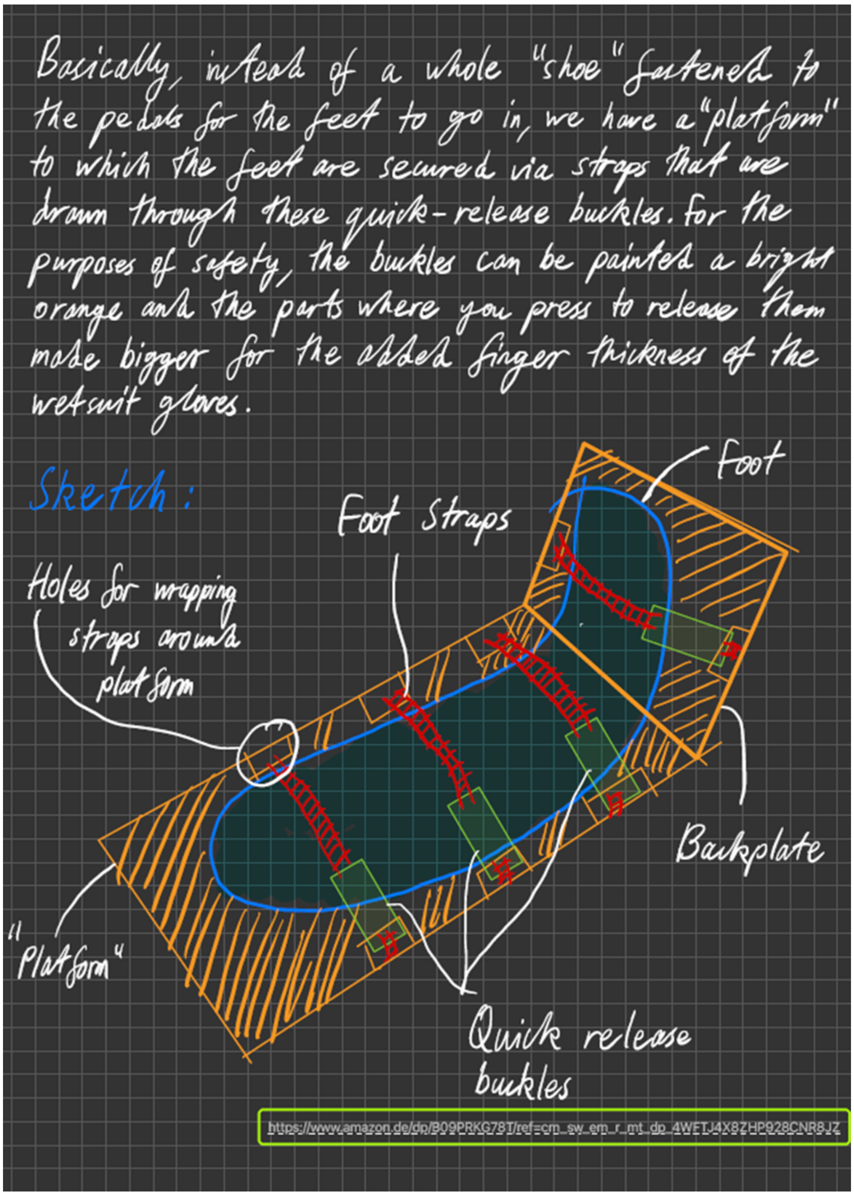


Figure 40: **A sketch of the proposed proto-click-shoe made for an upcoming team presentation.**

As such, shoulder pads were opted for instead. This restricts the movements of the shoulders but gives the pilot something to firmly push their weight into as they pedal. Ideally, the shoulder pads should fit all pilots uniformly with respect to their dimensions (while they are in their wetsuits and shorties). Furthermore, they should allow the arms to move around as much as possible below the shoulders to facilitate steering. Their specific positioning with respect to the frame should also be adjustable to accommodate the different sizes of the pilots. Attaching the shoulder pads to the frame rather than to the hull was done for aesthetic and practical reasons, albeit with the added risk of excessive force translating into high torque on the pipe, which could lead to deformation or failure.

In Figure 42, the shoulder pad is screwed into the triangular profile (orange part). This profile then has a sliding part that envelops the blue component from the side. The two are connected by inserting a solid cylinder through their holes; adjustments necessary to accommodate the varying heights of the pilot can be done by sliding the orange component along the blue one and inserting the cylinder where comfortable. The blue component is rigidly mounted to the front-most circular section of the hull (purple circle). The shoulder pad itself would be made from plastic with the help of a negative mould that can be produced by a CNC machine. This idea, however, was not implemented.

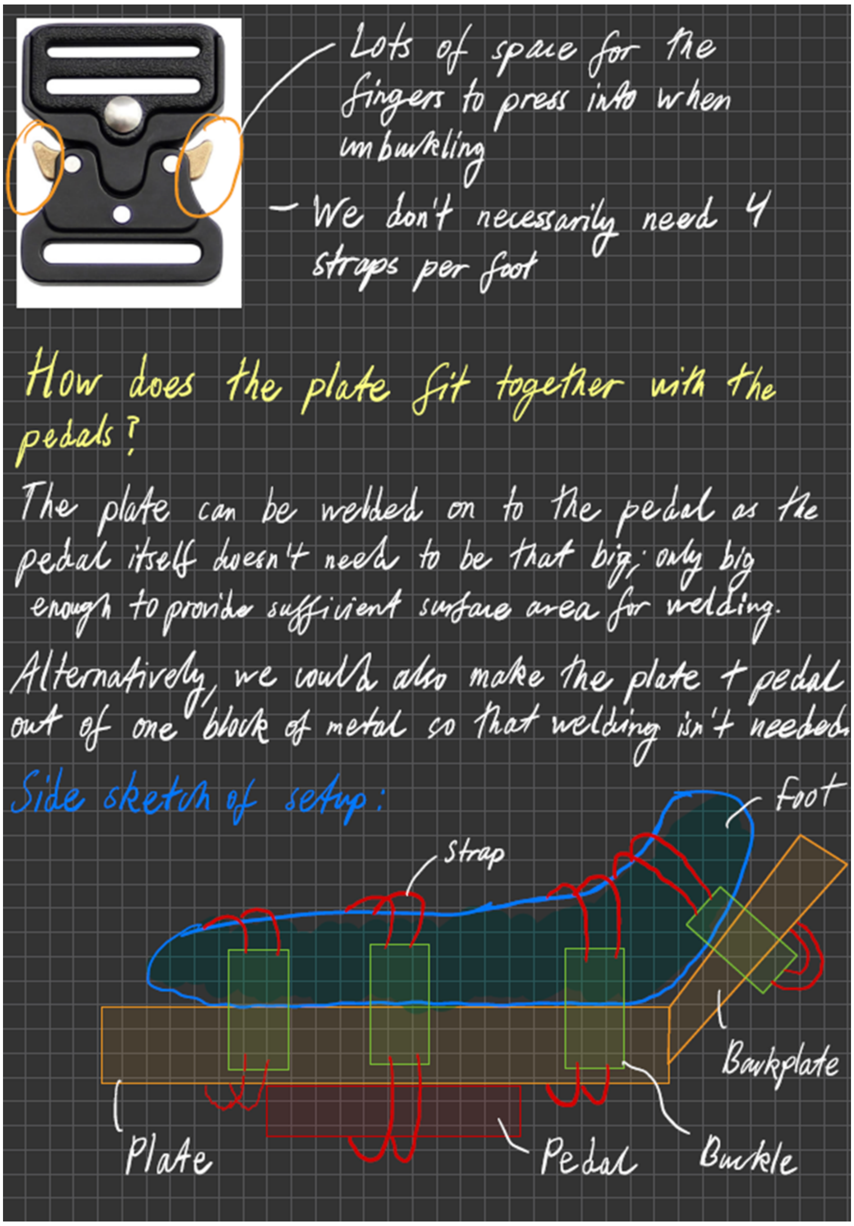


Figure 41: **Sketch of a proposed proto-click-shoe.**

As is the case for the pedals and click shoes, the final result proved to be far more feasible and simple than the proposed ideations. Two straps of vertical harness webbings were mounted to the frame at the top and bottom with a distance of about 30 cm resulting in two straps running over the shoulders of the pilot. The lengths of the straps are adjustable with the help of tri-glides and release buckles. Once inside, the pilot pushes against these shoulder straps in the same way that they would against typical shoulder pads. If, for either comfort or durability reasons the need for a secondary (or tertiary, etc.) set of straps on each shoulder arises, this can be done by duplicating the same design as for the original strap set. The notes on high torque still apply, albeit being somewhat negated by adding in extra straps to spread out the force.

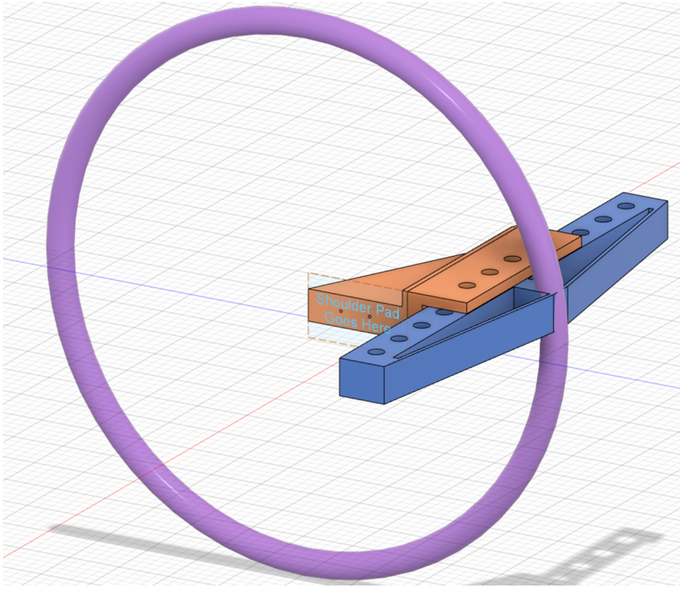


Figure 42: **Ideation of the shoulder pad setup.** Note that the pad itself is not included, rather only a proposition of how it could attach to the frame.

9. Safety and Design for Recovery

In the following section the design for recovery to ensure the safety of the pilot is described. A safety buoy is used to enable the pilot to contact persons outside the submarine about his/her location.

9.1 Safety Bouy

The safety buoy was located at the stern of the submarine as a tail cone with a length of 20 cm and was built of styrofoam. The volume of the safety buoy V and the negative buoyancy $\sum F = 12.5\,N$ were calculated with Equation 6 and 7.

$$V = \frac{1}{3} \cdot \pi \cdot r^2 \cdot h \tag{6}$$

$$\sum F = F_L - F_G = V \cdot \rho_{foam} \cdot g - V \cdot \rho_{water} \cdot g \tag{7}$$

With a radius of $r = 7.9\,cm$ and a height of $h = 25\,cm$, a volume of $1.96\,l$ was calculated. The resulting force calculated with the density of the foam $\phi_{foam} 0.35\,\frac{kg}{L}$ and the water $\phi_{water} 1\,\frac{kg}{L}$, and a gravitational constant of $g = 9,81\,\frac{m}{s^2}$, a positive buoyancy of $-\sum F = 12.5\,N$ was calculated.
The safety buoy is held in place with a layer of PET-G witch can be put together with the rest of the hull without being fixated to the hull. A safety buoy red line (Dyneema rope with 3 mm thickness, Kanirope ®GmbH, Dortmund, Germany) on a reel (SUBGN002 - Reel Stella 120 SS - Trigger, Gibielle de Beretta, Vignate, Italy) is fixating the buoy.

9.2 Release system

To hold it in place during normal operations, the attached red rope holds the buoy at the stern. While operating the submarine, the pilot uses a repurposed bike break as a dead-man-switch which to stop the rope from unreeling from the reel. The reel mechanism was changed by placing the spring on the other side of the release mechanism. By this, the default setting is a fixed reel instead of the unreeling ability. Hence, by releasing the dead-man-switch the reel no longer fixates the red rope which will then (still attached to the buoy) release the buoy due to its buoyancy.

10. Trial and Testing

Tests were performed on various components and assemblies to verify their proper function and determine whether changes to the existing design were needed. The frame was subject to finite element analysis to ensure its structural integrity under the expected structural and active loads of the pilot during pedalling. It was planned to thoroughly test the safety buoy system and hatch release mechanism to ensure the safety of the pilot. Fluid tunnel tests of the scale model were planned to decrease the amount of hydrodynamic drag. It was also planned to test the complete submarine by immersing it in a pool with a simulated current to do complete analysis of the drag at the relevant Reynold's numbers. Tests would also have been done with the submarine in the water to ensure that the amount of control authority at different speeds is sufficient.

10.1 Hull

The hull was constructed by assembling individual vacuum formed pieces of PET-G together into the final design. The design itself was tested by initially making a scaled down 3D printed model (see Figure 43).

The fit was observed, and minor changes were made to the interface between various pieces.

Figure 43: **3d printed scale model of the hull**

10.2 Vacuum Forming

The initial plan was to make moulds out of foam and use them for vacuum forming. This was first opted for as foam was very easy to prepare and CNC.
However, this production method was rejected as it was found that the PET-G sticks to the foam (see Figure 44) and therefore renders the parts unusable.

Figure 44: **Vacuum forming test piece**

10.3 Pipe rolling test

Tests were done to check whether the pipe roller is able to bend the required pipe to the expected radii of curvature (see Figure 45).
The properties of the machine were characterised. The amount of spring-back after rolling was measured.
The impact of rolling on the pipe, both in terms of geometry and surface finish, were noted.
Plans were made for the frame building based on the knowledge acquired.

Figure 45: **Test of Bending Pipes for the Hull**

10.4 Steel bluing test

It was decided to use either a paint layer or bluing to protect mild steel from corrosion in an aquatic environment.
The tests were done by comparing three different pieces of steel, one of which was blued and the other was blued and oiled. The last piece was kept as such to use as a control piece.
The samples were left in chlorinated water for two days.

Figure 46: **Bluing test**

Based on these trials (see Figure 46)it was determined that the bluing technique was effective at protecting mild steel.

10.5 Mirage fin adapter

The adapter designed to attach the mirage fin was tested by making a 3d print of the same (see Figure 47and checking its fit.

Figure 47: **Mirage fin adapter**

10.6 Hull assembly test

The manufactured pieces from PET-G were attached together by using bolts (see Figure 48). The resulting surface finish and attachment points were observed. It was decided to do a partial redesign of the hull to get a smoother and continuous surface.

Figure 48: **Hull assembly test**

10.7 Wet Test

After finishing the manufacturing of all components and assembling them for a complete submarine, the functionality must be tested. As these steps have not yet been done, only a plan exists that has not yet been executed.

Firstly, it is necessary to test whether the safety buoy is reliable by releasing the dead man handle at least seven tests with resets in-between. Additionally, the hatch opening must be tested to investigate whether it opens any time when desired. After the safety features, the transmission and control will be tested.

By successfully testing the above-mentioned aspects, the functionality of the submarine appears to be implied. Hence, the submarine works but further improvements can occur by testing the efficiency and ergonomics, for example.

11. Maintenance and Repair

Cygnus was designed specifically for ease of repair. By dividing the hull into panels and connecting the panels with bolts, each panel can be individually removed. This means that rather than having to design access hatches which are cut out from the main hull, the hull is instead made up entirely of access hatches. This grants easy access to all the internal components for repair and maintenance. This also means that if any panel becomes damaged, it can be easily replaced without having to take the submarine out of the water, as opposed to a traditional fibreglass hull which must be patched on dry land. Using PET-G also provides the benefit of higher toughness and flexibility. If the submarine crashes into the bottom of the pool, the hull can flex to absorb the impact far better than a brittle fibreglass hull.

The transmission system was also designed with maintenance in mind. All the bearing housings embedded within the keels are able to be removed so that the bearings can be easily replaced. The systems are also designed in such a way that it can be fully disassembled. As such, any part that breaks can be replaced so long as spares are available. This is especially important for any spacers or bushings which will face high wear, as they will need to be replaced with some regularity.

The control surfaces are designed to withstand small impacts, but in the event that they break on contact with the ground or with a wall, they are designed to be easily replaced. The connection between the fins themselves and the shaft is done with pins so that the fin can be removed and replaced in the event that it cracks or fully breaks.

12. General Arrangement

The sturdy aluminium frame of the submarine is the reference around which the other parts are positioned. It acts as an anchor for the transmission system, hull, and control surfaces. The frame by itself is around 2.9 m long and has the maximum width of 56.3 cm and 72.5 cm around the knees of the pilot. The pilot must lie down on their front in order to propel the submarine. The position of the pilot is such that their feet come almost to two-thirds of the submarine's length, this pushes the position of the pilot to the front of the submarine's frame.

The frame, although being a single piece welded together, can be separated into three parts on the basis of its function, namely, the main hull, including the pipe bends and the rings. On the top and bottom in Figure 49, the frame shows a bar that will run along the upper side of the main outrigger keel. They are connected to the main frame via four angled rods per outrigger. The main hull will is covered with PET-G.

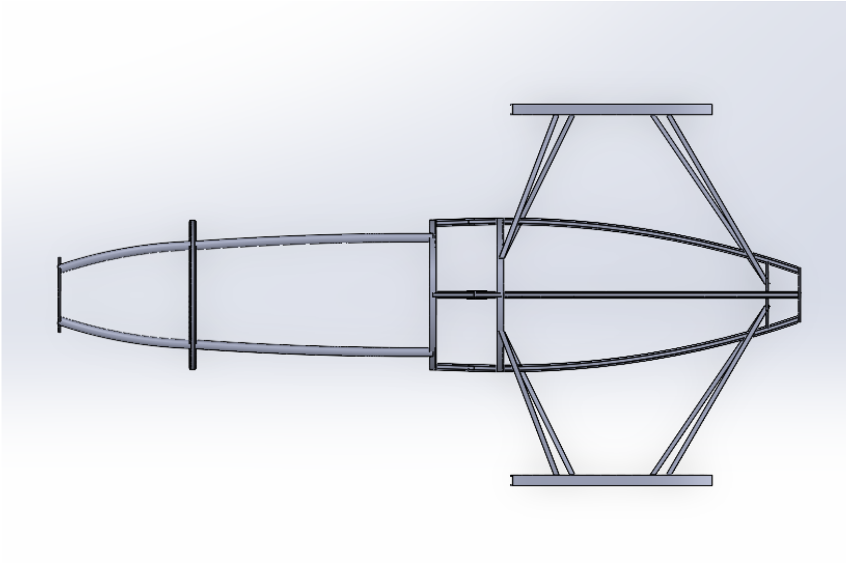


Figure 49: **Frame breakdown on the basis of functionality**

As the pilot pedals within the submarine, the thick steel shaft attached to the rear sprocket of the pedal system transfers the torque to the outriggers.

12.0.1 Outriggers

The two aluminium-styrofoam sandwich keels make up the heart of the outriggers. They convert the rotational motion of the shaft into an approximately 330 degree to and fro fin-like motion that propels the submarine forward. The propellers are attached to the extreme ends of the shafts that extend to the top and bottom of the outrigger keel as shown in Figure 50.

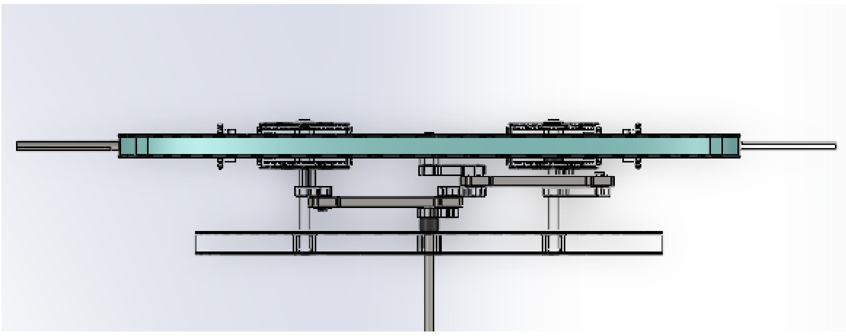


Figure 50: **Outriggers top view connected to the main frame through the shaft (displayed in the bottom).**

The keel of the outriggers is the defining factor for the outrigger hull along with their allowable distance from the main hull. The outriggers are approximately 1 m long, 20 cm wide, and 40 cm in height in total including the PET-G hull.

12.0.2 Stern

The pilot controls the submarine using joysticks placed under their head. The joysticks are connected to the control surfaces at the rear using Bowden cables, making it not only an efficient but reliable to control the submarine. The control surfaces are placed at the extreme end of the submarine. Beyond the

control surfaces is the safety buoy; it is placed here so that it is not entangled by the pilot's legs or the moving parts of the transmission.
The safety buoy is connected via a nylon cord to a reel mechanism. This reel is in turn connected via a Bowden cable to a brake on one of the joysticks. As long as the brake is held down, the reel is locked and the buoy is held in place. As soon as the brake is released by the pilot, the buoy is released and floats to the surface. This way the pilot can signal to the support divers in the case of an emergency or if they somehow fall unconscious. Both the main 10L tank and the secondary 3L pony tank are located near the pilot's abdomen so that they can be easily accessed in the case of an emergency.

13. Future Development

In the future, there are several things that the HSRW submarine team would like to improve on *Cygnus IV*. One of these would be the application of Computational Fluid Dynamics (CFD) with respect to the design of the hull. Combining CFD with iterative CAD modelling would allow the team to be aware of and quickly iron out any large problematic points in the hull design.
In the context of efficiency, a transmission system with no deadpoints is ideal. Reducing the weight and volume of the submarine with different, lighter materials would move the team towards this goal as well. For instance, using aluminium everywhere within the design rather than a combination of it and stainless steel can considerably reduce the weight while also making the manufacturing process more "homogenous". Welding aluminium or manufacturing all our own bearings / rods / chain / etc., however, requires significantly more time than compromising in the face of a set deadline. Additionally, a new design have to be implemented eventually due to other material properties.
Quality-of-life-wise, a "fully electronic" (mechatronics) control system could allow for better fine-tuning of the steering of the submarine. This necessitates waterproofing the electronics of the submarine, which makes maintenance more difficult. Furthermore, significant space would have to be allocated for the waterproofed elements as well as the batteries, motors, and cabling required to put this into practice. There is a "purely mechanical" system as backup, though, were the electronics to fail.
The design aim of biomimetic has only been considered in the propulsors. For the future development more biomimetic application have to be considered. In case of the stabiliser fins and the control surfaces this application can bring the benefits of drag reduction and, therefore, higher velocities of the submarine underwater.

14. Summary and Conclusion

Compared to previous HSRW submarines, *Cygnus IV* is a modern, highly innovative and sustainable submarine. The transparent hull made out of recycled PET-G panels in combination with a supporting frame make it not only attractive in design, with its modern look and great internal visibility, but also sustainable. Additionally, four pairs of MirageDrive fins as well as outriggers have never been used in any known human-powered submarines. The transmission system also allows for a rotary motion with a range increased by about the factor of 1.61. Hence, new technologies and innovation were implemented in the design of submarine.
However, due to time pressure, not all the desired features of *Cygnus IV* could be implemented. For

example, the frame itself could have been planned with 3D-bending instead of only 2D-bending to give more control over the form. Additionally, not every designed part has yet been manufactured. Hence, it will show in the future whether *Cygnus IV* will be ready for the European International SubRaces 2022. So far, *Cygnus IV* has not been tested underwater, as the manufacturing has not been completed. Hence, neither the total design, including the frame, outriggers, transmission and propulsion, could have been tested, nor the performance underwater, e.g. speed, control, handling and manoeuvrability.
Nevertheless, the team is highly motivated to continue working and finish these remaining tasks. University restrictions due to the Covid-19 pandemic lasted for a long time, forcing the team to start very late in the year. Most of the students from previous teams had also graduated over the 2 years of shutdown, so much of the prior knowledge was lost. Despite these hurdles, the team was still able to come together and make a remarkable amount of progress towards a new, innovative submarine, and is eager to participate in the races.
For the future, the design can be further developed. Improvements to the submarine design can not only yield a better performance but also increased efficiency and sustainability.

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16. APPENDIX

TABLE OF CONTENTS

A. Rivershark Modification III

As back up *Rivershark Mod II* was modified to *Rivershark Mod III* and tested due to lack of time and the great reliability of *Rivershark* in the former races. The pilots were trimmed and trained in *Rivershark* Mod III for the races. Original *Rivershark* was introduced first in the subraces of 2013 and was modified several times so far while the basic propulsion system of MirageDrives and the hull stayed the same. *Rivershark* competed the last time in 2018 achieving the best biomimetic and the best female pilot award. Several improvements were planned and done on *Rivershark Mod II*. Due to several other projects only the hull, the propulsion system, the drivetrain, and the transmission were left of the *Rivershark Mod II*. Therefore, different changed have been planned and executed.

Firstly, the attachment of the foam to get the method of getting *Rivershark* neutrally buoyant has been improved.

Due to problems with stabilisation and reaction time of the control surfaces in the past, stabiliser fins and a new system for the control surfaces has been manufactured.

As a consequence of the failure of the opening system of the hatch from the inside of the submarine in the past, the system of opening the hatch was improved.

During the modification of *Rivershark* the pedal stepping was changed to a cycling system due to the higher efficiency of a cycling system. Even though this is the case for cycling on land with a bicycle the efficiency is not adaptable to *Rivershark* to the lack of space for the pedalling motion which need about a diameter of 70 cm. Therefore, the cycling system has been changed to a stepping system again.

B. Design Philosophy and Design Aims

As Rivershark Mod III functions as a back-up plan, the main design aim is to address and fix the issues which occurred during the last races and training with *Rivershark Mod II*, to increase reliability as well as to realise changes and improvement as cheap and fast as a possible.

This design philosophy includes to try to use every material and manufactured part of *Rivershark Mod II* for *Rivershark Mod III* and do minimal changes.

C. Hull

*Rivershark*s hull was constructed of fibreglass, using a positive foam mould. The form is based on space requirements of the driving mechanism and pilot position, while aiming for the most streamline shape possible. The primary forces acting on the moving submarine are skin friction and pressure drag. To minimise these drag forces, the hull of the submarine can be described with the finess ratio. In this ratio, the streamline characteristics are defined as maximum length (3.4 m) divided by maximum diameter (0.7 m). *Rivershark* has a finess ratio of 4.85. The hull contains two main hatches at the top. One in the front, for entry and exit of the pilot, and one in the back to access the pilot's feet and the propulsion mechanism. Underneath the pilots' chest a repurposed BCD tank strap was attached to the hull to hold the scuba tank. Additional rails have been fibreglassed along the ventral inside the hull. Those rails were used to attach and move mechanisms and instruments inside the submarine and adjust weight distribution. The centre of gravity of the submerged submarine was moved to the bottom and centre of the submarine

using foam at the top, increasing stability while driving. The buoyancy therefore had to be distributed uniformly.
In the front, the pilot hast three windows, one on the ventral and two on both the lateral sides. In the previous design, these windows were made out of plexiglass and attached to the hull by silicone. However, plexiglass is a brittle material and hence, the windows showed cracks after few practice sessions with occasional crashes. Therefore, the windows were replaced with PET-G that was cut into shape with a 2 cm overlay and heated up with a heat gun so that the sheet of plexiglass fit perfectly in the window hole. The window panels were also attached by silicone.

D. PROPULSORS

D.1 CONCEPTUAL DESIGN OF THE PROPULSION IN *Rivershark*

In order to select a concept for the propulsors of *Rivershark*, propellers were evaluated against a biomimetic design. Due to the reasons of a reduced impact on nature, noise reduction and a longer runtime (see subsection 4.1), a biomimetic propulsion was selected. For an efficient and non-erratic but smooth locomotion, "Aquatic Flight" was chosen (see subsection 4.1). Here, the pectoral appendices are moved in a dorsal-ventral trajectory yielding two phases, the up- and downstroke, with an approximate equal length that generate a similar amount of propulsive force. Please also refer to subsection 4.1 and 4.2 for further details on the biomimetic propulsive principle.
To imply this concept in the submarine *Rivershark*, the MirageDrive of by Hobie Cat Co. (Oceanside, USA) has been in use since the first *Rivershark* introduction in 2013. However, over time, several changes have been made that have made the transmission and propulsion system in *Rivershark* a work of many generations of students over the years. It uses two fin pairs that protrude from the dorsal and the ventral side of the submarine positioned symmetrically in the mid-sagittal plane.
Similar to the flight pattern in birds and some flightless birds like penguins, the fin pair go to an angle of around 196 degrees. The two fin pairs at the top of *Rivershark* provide a more continuous propulsion to the submarine as they cancel out the pitch moment caused by the propulsion (upward lift in birds). However, have a turnover point of 20° at each extreme of the „flapping motion“ which is expected from the biomimetic propulsion system as it does not go all the way to 360°. Nevertheless, the percentage of the turnover in comparison to the whole cycle is minimised.

Table A: ***Rivershark* propulsion system over the years.** Modified from HSRW submarine team (2018).

Year	Innovation
2013	Tuna-inspired crescent shaped fins instead of flexible fins.
2017	Twin MirageDrive propulsion system
2018	Improved power transmission and propulsion system
2019	Cycling motion instead of stepper motion for energy production in the fins
2022	Improved and more balanced transmission system

D.2 WORKING OF PROPULSION SYSTEM

The MirageDrive as shown in the figure below is a human-powered propulsion system that transforms the pedalling motion of a driver into transverse sweeping motion of two underwater foils. The Hobie MirageDrive system has two input links moving in counter-rotating directions. The input links drive with a single connecting link, forming a four bar linkage allowing mimicry of a full MirageDrive cycle (see Figure A). At the end of the „flapping motion", the fins have a turnover area of maximum 40°, which allows the fins to produce thrust in both clockwise and counterclockwise directions. The fins have a hydrofoil shaped profile and function based on the principles of drag and lift. Lift is produced after a certain region of drag in the motion of the fins. During this region of drag, the fins are not able to propel the submarine, rather it counteracts the force the water applies on the submarine pushing it astern. With the faster angular velocity, the mirage fins are able to produce greater thrust.

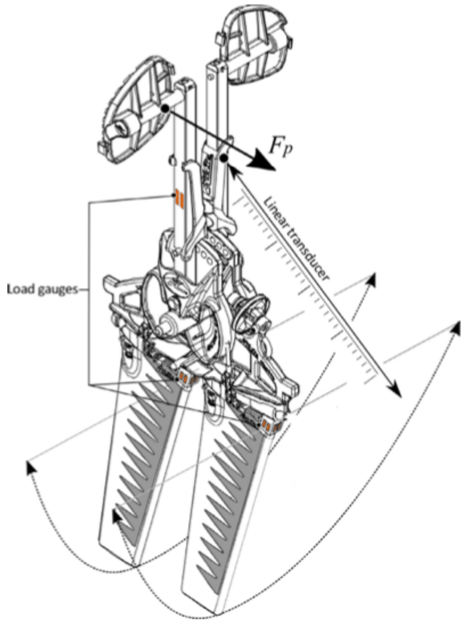

Figure A: **Hobie MirageDrive.** Modified from (Yan et al., 2016)

If the velocity of the submarine is 3 kn is assumed and a flap frequency of 1 Hz, the steady component of thrust should theoretically produce 51 N. The total thrust of the submarine is assumed to be 120 N, which includes the lift generated off lift due to vortices in the front direction (HSRW submarine team, 2018).

D.3 Parameters to Optimise

The propulsion system in *Rivershark Mod III* was last used in 2018. Due to the lack of maintenance certain parts have corroded and had to be replaced. Hence, the first and foremost goal of the parameters of optimisation in the propulsion system was the replacement of these oxidised parts.
In the previous years when *Rivershark* was used, it was noticed that the propulsion system was relatively reliable and in an attempt to keep the submarine reliable under the pressure of time, the propulsion system has not been changed extensively.

E. Transmission System

The transmission system of *Rivershark Mod II* has not been modified from its previous iteration. As seen in Figure B, it functions as a system of paired MirageDrives which are driven by a pair of pedals and connected via a sliding block. This creates a yoke system by which both MirageDrives can be simultaneously driven.

An attempt was made to convert the transmission of *Rivershark* into a pedal-driven system in order to get empirical data on the efficiency of a cycling motion vs a stepping motion. It was found, however, that there is insufficient space in the hull of *Rivershark* to fit a system of sufficiently large diameter.

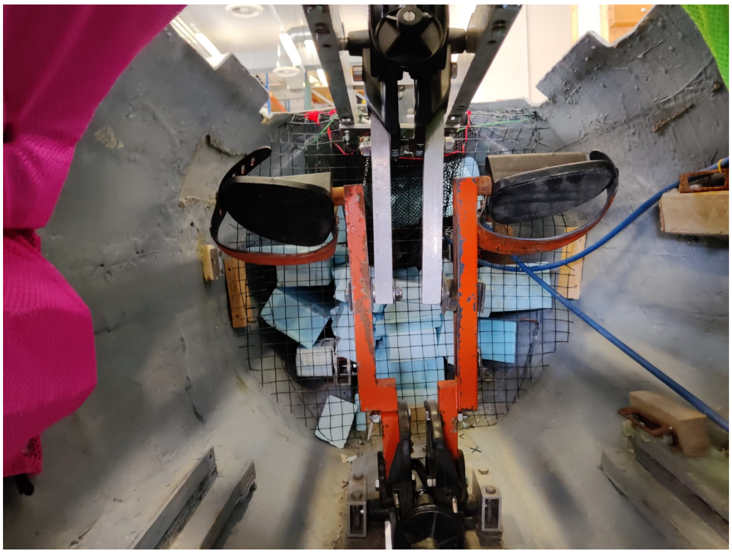

Figure B: ***Rivershark* Transmission System.**

F. Trim, Hydrostatic and Stability

Some vital information for calculation of the hydrostatics are shown in Table B.

Table B: **General Information of Rivershark Mod III.** Modified from HSRW submarine team (2018).

Rivershark:			
Dry weight	114 kg	Submerged weight	714 kg
Volume	0.8 m^3	Maximum Surface area	11.9 m^2
Length	3.4 m	Total Diameter	0.7 m

Since the hull is made of quite homogeneous mixture of cork and fibreglass, the weight of the submarine is similar to the visual symmetry of the submarine. It is symmetrical about both the axes. The centre of lateral resistance lies on the middle plane along the vertical axis. Using SolidWorks, it is estimated that the centre of lateral Resistance is estimated around 45 to 50 % of the length after the bow. Due to the submarine transmission and propulsion lying around the middle of the sub, which also happens to be the centre of lateral resistance, the majority of the mass in the empty submarine lies at the centre. To counteract certain offsets when in motion, the hull is fitted with styrofoam. This styrofoam also makes the characteristically negatively buoyant submarine neutrally buoyant when it is in motion. The distribution of Styrofoam ensures that the submarine is neutrally buoyant at race depth.
Results on the fluid dynamic simulations, regarding the cut plot velocity and pressure and a surface plot pressure, are seen in Figure C, D and E.

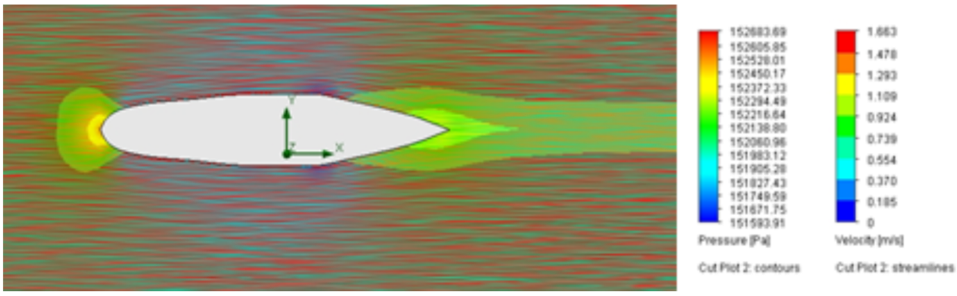

Figure C: **Cut Plot Velocity Pressure .** Modified from HSRW submarine team (2018)

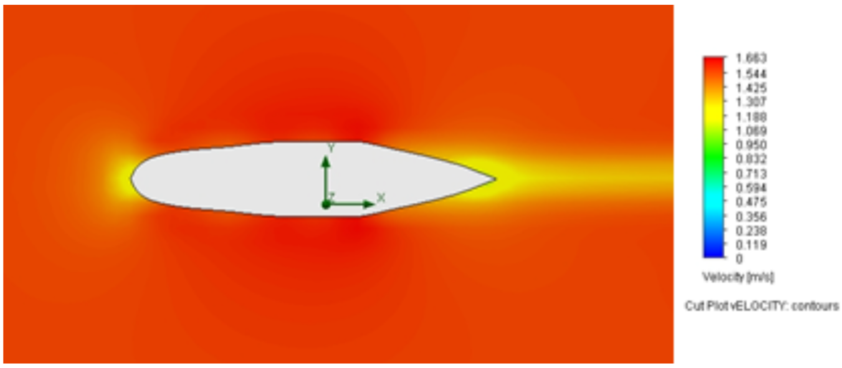

Figure D: **Cut Plot Velocity .** Modified from HSRW submarine team (2018)

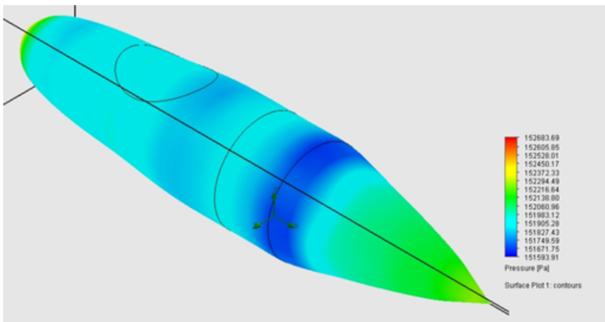

Figure E: **Surface Plot Pressure .** Modified from HSRW submarine team (2018)

After trials, it was found that the Styrofoam best needed to be around the centre of the hull and the extreme front and the rear of the submarine to ensure it is neutrally buoyant throughout the race period.
Stability in the submarine is achieved by first achieving neutral buoyancy in the submarine at the depth for the race using styrofoam and then the same for the pilot at that depth and then putting the pilot in the submarine and checking for buoyancy.
The centre of gravity buoyancy and gravity coordinates are displayed in Table C and D.

Table C: **Coordinates of the Centre of Buoyancy.**

Ix	(1.00, 0.00, 0.00)	Px	39
Iy	(0.00, 0.71, -0.71)	Py	430
Iz	(0.00, 0.71, 0.71)	Pz	430

Table D: **Coordinates of the Centre of Gravity.**

Ix	(1.00, 0.00, 0.00)	Px	13.6
Iy	(0.00, 0.22, -0.98)	Py	115.9
Iz	(0.00, 0.22, 0.98)	Pz	115.9

G. Control Surfaces

New control surfaces were implemented into *Rivershark*. The previously installed flat plate control surfaces were replaced with hydrofoil sections. The area of the control surfaces was enlarged to improve control authority. The control surfaces were mounted farther away from the hull to ensure that the control surfaces are not in the fluid shadow of the hull.
The hydrofoils were manufactured using MDF wood and the CNC. One hydrofoil was split along the symmetry plane. The resulting shapes were sanded, smoothened with wood filler ("Holz Schnellspachtel", Molto, Köln, Germany) and sanded again.
The wooden halves were glued to a 4 mm aluminium plate that was cut to the shape (see Figure F). Here, epoxy was used. To attach the rudders to the turning shaft, that controls the angle of attack, a groove with 20 mm width and a length of 50 mm was cut axially starting at the base at about one third of the radial length. The groove ended with the aluminium plate such that the turning shaft could be inserted into the groove and attached with bolts.

Figure F: **Arrangement of the Rudders.** The two wooden halves of the rudders show an aluminium plate between them for additional stability during usage.

To restrict the water uptake in the case of being submerged, the wooden parts were lacquered with „Bondex Bootslack farblos“ (Bondex, Bochum, Germany).
Apart from the control surfaces which control the pitch and yaw movements, stabilizer fins were built to restrict unwanted motions in other directions than forward, pitch or yaw. The stabilizer fins were attached on the ventral, dorsal and both lateral sides of the hull at about the middle, between the rear and front hatch. They consist basically of the same wooden halves as the control surfaces but were attached differently as they do not require a turning radius. Here, two grooves were cut into the flat surface of the wooden parts (see Figure G) resulting in two long axial holes with a distance of 60 mm and a diameter of 10 mm. After gluing both wooden parts together with epoxy, the part was slid on two long M8 threaded rods that fit into the cut grooves or holes. The rods were welded on a bent steel plate with a thickness of 3 mm. To secure the fins in place, opposite of the steel plate, a securing nut was used after the rod was cut at the needed length. Finally, the stabilizer fins were also lacquered with „Bondex Bootslack farblos“ to prevent water uptake.

(a) Separated wooden Halves.

(b) Wooden halves placed on top of each other.

Figure G: The two wooden halves (a) of the stabiliser fins show two parallel grooves on the symmetry plane. In (b) both fins are placed on top of each other

H. CONTROLS

The transmission of the movement of the hands to the movement of the control surfaces has not been changed. The current setup involves Bowden cables attached to joysticks that can control the pitch and yaw of the submarine.
However, the control body for determining the depth and diving time has been changed from the former tablet to an Aladin Pro (Johnson Outdoors, US-WI) fixated to the hull.

I. ERGONOMICS AND PILOT BIOMECHANICS

The main change to the ergonomics of *Rivershark Mod III* was to replace the existing shoulder pads with the shoulder straps as described in the *Cygnus IV* report. However, instead of securing the straps to the frame, they were welded to a plate that was screwed into the hull. Using this form of shoulder straps is a useful trial run before fully committing to the concept on *Cygnus IV*: potential kinks can be discovered and ironed out, which enables a better decision on whether actual shoulder "pads" are worthwhile.
Click shoes were not used as an existing strap-and-shoe mechanism was already in place on the pedals.

J. SAFETY AND DESIGN FOR RECOVERY

By replacing the old control surfaces with an improved design, the previously used version of the safety buoy became impractical. The safety buoy was located at the caudal end of the submarine and could now come in contact with the fins, when ascending. To ensure flawless functionality a new safety buoy was installed beneath an opening in the dorsal back hatch, utilising the space between propulsion and controls. A painted stack of extruded polystyrene foam, internally connected by cave line and double-sided sticky tape, in a cylindrical shape with a volume of about 1 l (d = 7.2 cm, h = 25 cm) replaces the old safety buoy. It will ascend to the surface attached to a yellow rope from a reel (SUBGN002 - Reel Stella 120 SS - Trigger, Gibielle de Beretta, Vignate, Italy) below the buoy. The new safety buoy is located inside a tube, behind the propulsion mechanisms, which will act as guidance until the buoy has completely emerged from the vessel in case of an emergency. To hold it in place during normal operations, the attached rope (Dyneema rope with 3 mm thickness, Kanirope ®GmbH, Dortmund, Germany) will hold the buoy at the bottom of the tube. While operating the submarine, the pilot uses a repurposed bike break as a dead-man-switch which to stop the rope from unreeling.

K. Trial and Testing

Due to the increasing reliability and importance of testing and accustoming the pilot for the pilot's safety, several test dives were performed with *Rivershark Mod III*.
The tests included to test the functionality of the safety buoy system to ensure the safety of the pilot. Furthermore, the functionality of the controls and the diving computer were tested underwater. Additionally, tests for the buoyancy were preformed. This included to ensure the submarine to be neutrally buoyant as well as a trimming to adjust the centre of buoyancy and the centre of gravity.
As the hull, the propulsion system, and the transition were hardly changed and showed structural integrity in the past, no further tests for these arts of *Rivershark Mod III* have been performed.

L. Maintenance and Repair

Rivershark has two major access points through which upgrades and maintenance can be done. This includes long-term maintenance such as replacing rusted screws, patching cracks, and repainting steel components where the paint has chipped or rubbed off, as well as more short-term fixes while at the race. These short term fixes include replacing worn sliders in the transmission, adjusting the shoulder straps for the pilot, and replacing any components which are broken while running the submarine.

M. General Arrangement

The submarine consists of the same foam and fibreglass hull as previously. The front windows are still there for the pilot to see through, but they have been re-made from PET-G. There is one air bottle in the centre of the hull below the stomach of the pilot. Both MirageDrives are controlled by the same transmission mechanism. The drives are mounted to a frame that is secured to the hull. The new safety buoy was placed behind the upper MirageDrives without getting in the way of the motion of the fins. The four stabiliser fins are placed between the MirageDrives and the hatch in an "+" formation. The new arrangement is shown in Figure H.

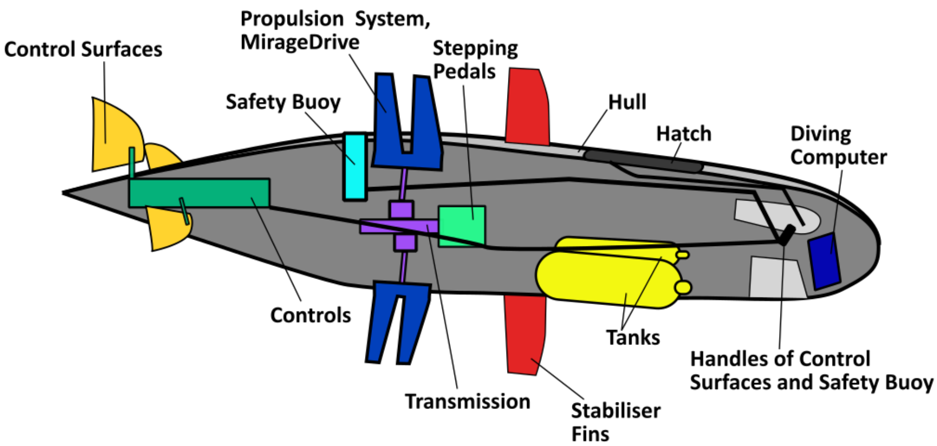

Figure H: **General Arrangement of *Rivershark Mod III*.** Layout of *Rivershark* Mod III with the position new safety buoy and stabiliser fins.

N. Future Development

As future development of *Rivershark Mod II Cygnus IV* was designed and manufactured. Moreover, the old submarine *Rivershark* has an outdated design not complying the formulated design aims any more for example a bigger sustainability.
As the redesign and implementation of *Rivershark* within this year's competition was only a compromise in the face of a deadline, there are no foreseeable future development plans for this submarine. After the competition this submarine will be retired in the university's lab, and used only for training new divers and pilots.

O. Summary and Conclusion

Rivershark Mod III was designed for testing and trimming underwater due to limited amount of time for *Cygnus IV*. In previous races, the propulsion system, the transmission, and the hull have proven to be reliable and were not changed. Due to problems with stability, reaction time of the control surfaces, the drivetrain, the opening mechanism of the hatch, and the size of the safety buoy as well as the mechanism of the safety buoy in the past, several improvements have been considered and done.
Stabiliser fins with a cross plane configuration have been attached. The reaction time of the control surfaces have been minimised as well as new control surfaces have been implemented. The drivetrain was changed from a cycling pedals to steppers due to lack of space for a cycling motion. The hatch was changed to be easily operable for the pilot in the submarine underwater. A new safety buoy was designed that conformed to the rules of the race and a mechanism was created to release the buoy via a dead man switch.
The reliability of the implemented improvements of *Rivershark Mod III* were tested underwater afterwards.

P. References

For the references, please refer to section 15.