Design of an Autonomous Robotic Fish

LSRO - Semester Project

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Abstract for the semester project MA2

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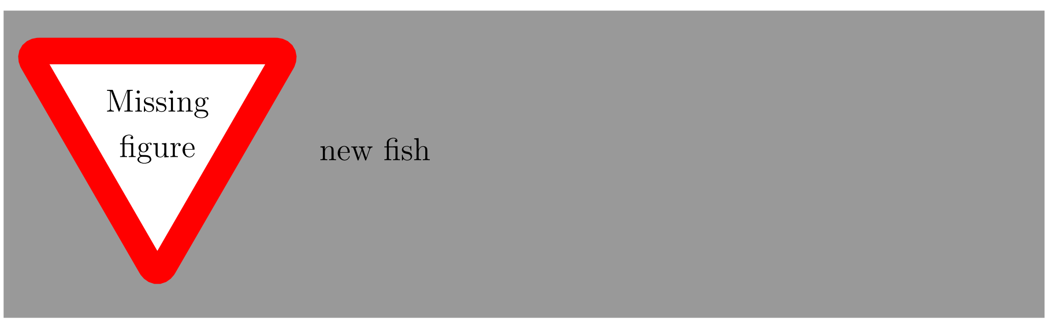
Abstract

The goal of this project was to create a robotic fish capable of moving autonomously in water. It is based on a version which didn't have the capability to move up and down, and was fixed at the bottom of a tank. With inspiration from a state-of-the-art study, we developed a system used to shift the center of mass of the fish. This movement makes it possible to orientate the fish in water.
This system, based on a tapped metal part locked in rotation on a screw. Rotating the screw effectively moves the weight front and back.

A PCB was produced, as well as mechanical parts for the moving weight mechanism. Assembling these different parts gave us the robotic fish shown in the figure below.



Testing revealed that, even though slow, the weight move as it was intended during the planning phase. Preliminary results showed a change in the center of mass' position of approximately six millimeters between the weight's front and rear position.

Contents

1 Introduction

This project was attributed to me as a semester project inside of my second semester of Master in Microengineering. It was done under the supervision of Frank Bonnet and Pr. Mondada.

The goal of this project is to enhance an existing design of a robotic fish, shown in figure 1 below. As it is, the fish produced in the LSRO laboratories[1, 3] can only move following a robot outside of the water tank. The goal of the project shown in Bonnet *et al.* is to prove the influence of one fish on the other of its group. The important characteristic of the robotic fish is that it should be similar in term of size and aspect ratio to the *Danio Rerio* zebrafish.
To increase its biomimeticity, the fish is already capable of moving its caudal fin, and has infrared LED close to the eyes. It has a base (not shown in figure 1) containing magnets which enable the fish to follow a wheeled robot placed on a plate underneath the fish tank.

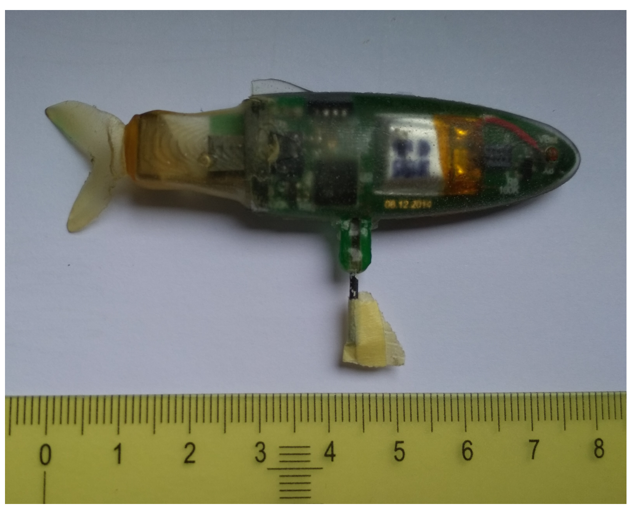


Figure 1: Existing design for the robotic fish

At the end of this project, the new robotic fish should be able to move freely inside all of the water tank. The fish can already move forward by movement of the caudal fin. It can also turn left and right by changing the amplitude of movement of the fin. For it to be able to move freely inside all the fish tank, we need to add a mechanism to enable movement up and down.

Another robotic fish designed at LSRO was already able to move as such, but with the help of pectoral fins. As a result, it wasn't as biomimetic as the previous iterations. It is shown in figure 2 without its fins, normally fixed on the white 3D printed part, and is 95 millimeter long with its caudal fin.

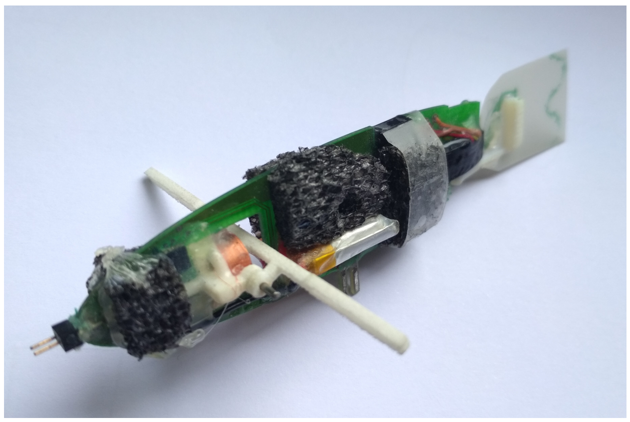


Figure 2: First solution for 3D movement

In addition to the 3D movement, the robotic fish should keep its aspect ratio, with a possibility of increasing the size by up to 30% from the fish shown in figure 1 if required. These requirements are here to keep the fish biomimetic capabilities relatively high.

The project is divided into sections as follows. First, we will need to research on the existing state of the art. This will mean looking into all solutions already on the market or in development. Understanding this will enable us to better situate the project, and gain inspiration from the existing designs.
Then we will need to get a better understanding of the physics of fish. The two main aspects are the forces involved, and the complexity of movement for the caudal fins. This will create clear constraints we will need to respect during the creation of the fish.
The third stage of the project is to brainstorm the different solutions available to enable 3D movement in the water tank. This will be based on the state of the art research done as the first task.

The final stage will be to implement the solution(s) found on the existing design, according to the constraints fixed. That includes creating a PCB and the mechanical parts needed for the system, as well as assemble everything together. In addition to these tasks, testing the fish in its environment would be essential if time allows it.

2 State of the art research

The first stage of this project was to evaluate the current state of the art on the subject of robotic fishes. The research done for this section was mainly done through academic article indexing websites, such as Google Scholar.
As not all solutions currently available are of academic purpose, some of them were found on other diverse websites. These tend to be less instructive, as most of their internal content and technologies are not revealed publicly.

Robotic fishes were developed from the 1990s, with the first being the RoboTuna series, developed at MIT by Barrett *et al.*[4]. The goal of their creation was to study hydrodynamics, energy efficiency of fishes, as well as control algorithms for fin movements. The creation of this fish engaged a large outburst of research on fish hydrodynamics, which lead to a creation of different robotic fishes.

Following this one, many other were developed, mainly in the United States, China and Japan. We will classify the different robots using several characteristics. The main points of interests are as follows.
First, the goal of the creation of the robotic fish varies a lot. While for some of them, the purpose of the robot is academic, more and more robots are developed for commercial purposes. The academic robots are often concentrated on one specific point of study (caudal fin movement, outer skin for drag measurements, etc), while the commercial ones can include other components like an HD camera or LED lighting and are used mostly for entertainment purposes.
The second main point of study is the means of propelling. The solutions studied change depending on the size of the robotic fish, and on its speed requirements (if present). Some of them use proved technologies, most of the time electric motors, but some try to implement new solutions, with for

example Electro-Active Polymers.
In addition to these two main points, many smaller characteristics define the different fishes. For example, these can be points such as autonomy, biomimetic capabilities, or networking between them to create a fish school.

The first robot studied is the *Jessiko* fish, from the French company RobotSwim[5], commercialized in 2009.
It is a fish used as ornament, sold as a package of service, including a show with coordinated fishes. RobotSwim also sells a "Research Pack", containing four fishes, some fish attractors (light beacon) and software support. This package is aimed at researcher on biomimeticity, collaborative tasking of underwater vehicles, or 3D control algorithm development[5].
The fish in itself is approximately 22cm, and uses electric drives to power its caudal and front fins. The caudal fin enables movement forward and left and right turns, while the front one regulates the up/down movement, and can also be used to escape deadlock positions.
As shown in figure 3, it is bright and colorful (with RGB LEDs), appropriate for its entertainment uses, and has schooling capabilities with a proprietary software named *JessikoCommand*[5].
In term of maneuverability and size, it is one of the closest available on the market. However, its front pectoral fins make it unsuitable for our the applications of LSRO, as they are too visually different from the *Danio Rerio* zebrafish studied at LSRO.

Next we have the fish *BIKI*, created by Chinese company Robosea. It was funded using the crowdfunding platform *KickStarter*[6], collecting more than five times its original objective.
The main selling point of this robot is its integrated 4K camera. Indeed, the goal of the robot is to film underwater movies, and potentially explore the water's depth. From their *Kickstarter* campaign page, its application are in swimming pools to capture "the most beautiful moments in your life"[6], or as a scuba diving companion to record adventures in the depth.
Once again, the precise integrated components are unknown as the robot is sold publicly. The most probable option is the use of an electric motor to power its caudal fin, and moving weights inside to balance the robot and enable it to go up and down. In opposition to robots propelled using a rotor, the use of a caudal fin makes it safe to use in swimming pools next to children.

BIKI also has obstacle avoidance capabilities, enabled by infrared captors. It is also equipped with powerful lights for film in the depth. The fish is controlled wirelessly via a smartphone application, and can be send on predefined routes.
As we can see in figure 4, the robot has an aspect ratio very different from the zebrafishes.

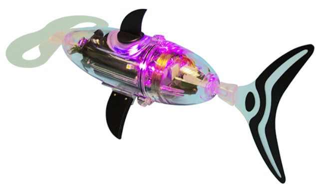


Figure 3: Jessiko, from Robotswim [5]

Figure 4: Biki, from Robosea [6]

Shifting to an academic scene, the *MT1*, developed at the University of Essex by Liu *et al.*[7], is a 50 centimeter robot capable of imitating fish tail movement thanks to its 4-joints tail. All of these joints are driven by electrical motors. In addition to that, it has pectoral fins that can orientate the fish up and down.
The goal of the study is to develop drive equations for the C-bend of the fish's tail, imitating carangiform fishes. Having an articulated caudal fin makes the fish more prone to approximate correctly the swimming motion of a real fish. This actuated tail can be seen on figure 5.
The robot's joints can be approximated to dampers, apart from the first one that is actuated. The interaction of the water with the fin creates its movement. In the fish presented in Bonnet *et al.*[1], a similar behavior exists from the fact that the fin is flexible. When exposed to the water, it will deform to create the same kind of movement observed in Liu *et al.*.

A similar fish is developed at the Chinese Academy of Sciences of Beijing by Yu *et al.*[8]. It is described as a fish "with flexible posterior body and an oscillating foil as a posterior"[8]. The first difference is the lack of pectoral fin, or any other system to regulate the depth of the fish. Thus this fish is limited to planar movement, and moves across the bottom of the water tank. The second difference comes from the actuation method. Here, all of the

joints are actuated. The joints have an increasing movement along the length of the fin, and each have a phase shift in comparison to the first joint.
However, this system is too bulky to be implemented in our robotic fish. Indeed, this robot is 40 centimeter long, and most of the space is taken by the articulated fin.

The next one is developed at the University of New Mexico by Mojarrad *et al.*[9]. It showcases a different method to drive the caudal fin. Indeed, it uses electro-active polymers, more precisely polyelectrolyte Ion-Exchange Membrane Metal Composites (IEMMC) as a propulsion fin. These kind of polymers bend when exposed to electric fields, with the potential to create an oscillating motion, perfect for an application to a robotic fish fin. However, their oscillating frequencies are limited by the material properties. A model of the oscillating membrane is shown in figure 6.
With a driving voltage of 2.5V, they achieved a movement amplitude of 10 millimeter Their research was more focused on the actuator than on the robotic fish. Indeed, the "fish" in itself is a Styrofoam boat to which the actuated fin and its driving circuit is attached.

Figure 5: Essex MT1 [7]

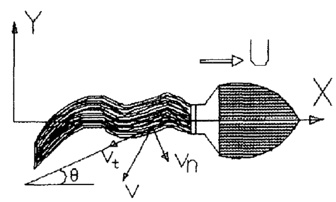


Figure 6: Model for the EAP actuator [9]

Similarly, another fish was developed at the Michigan State University by Chen *et al.* using an Ionic Polymer-Metal Composite (IPMC) caudal fin[10]. Here, the goal of the research is to understand the actuator mechanism better. They also discussed the interesting possibility to use these membranes as "flow sensors for robotic fish control"[10].
In this case, the body of the fish was molded, and a passive fin was fixed at the end of the EAP membrane. The model can be seen in figure 7. In addition to that, they tested the fish's speed with or without the passive fin, and with different fin size.

Using a piezoelectric membrane, Heo *et al.* at Konkuk University (Korea) managed to obtain enough amplitude to drive a 27 centimeter long fish[11]. The membrane is made of layered glass/epoxy, carbon/epoxy and PZT ceramics. The decoupling mechanism used to increase the amplitude of the piezoelectric membrane movement is shwon in figure 8. It is made of a rack-and-pinion transforming the deformation of the membrane in a rotation movement. This rotation movement corresponds to the movement of the caudal fin.
Another part of their research was to study the fin's dimensioning. They measured the real thickness of a mackerel, and used two different kinds of fin for their experiment: one with a constant thickness and one with a thickness corresponding to what is found on the mackerel. For the constant thickness one, they tried three different sizes. Overall, the variable thickness fin produced the best results.

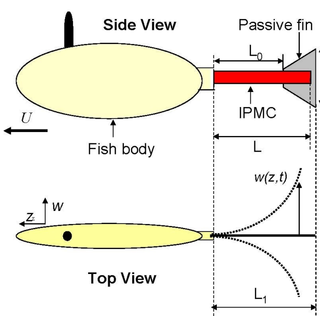


Figure 7: Model of fish developed by Chen *et al.* [10]

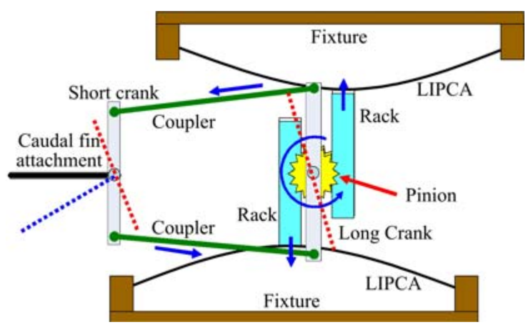


Figure 8: Piezoelectric motion mechanism of Heo *et al.* [11]

Berlinger *et al.*, at the Cambridge University also developed a model of robotic fish[12]. The goal of their project was to develop a miniature low-cost underwater robot with a high maneuverability. Their solution uses magnet-in-coil actuators. These are cheap, and very easy to manufacture. The resulting fish has four fins (caudal, dorsal and two pectoral), for 10cm of length. It is shown in figure 9.
Their objective in term of price was to develop the fish for a production cost of less than 100$, which they managed to achieve. This solution shows the strength of the magnet-in-coil technology when the objective pursed allows

it. Indeed, the movement amplitude is not very high, and it has a current drain when needed to hold a fin into a certain position.

The same concept comes back inside another project by Clark *et al.*[13]. In this striped version, a caudal fin is actuated by a unique magnet-in-coil actuator, resulting in a very cheap fish.
While the fish in itself is very simple, they used evolutionary algorithms to decide its shape and parameters. The parameters evolved are the frequency and pulse-width-ratio of the fin movement, length and height of the fin, and spring constant applied to return it to its centered position. They used 25 parallel evolutions, based on a population of 64 individuals on 100 generations, with a fitness function based on the fish's speed. The speed obtained through this evolution is shown in figure 10 on 50 generations.

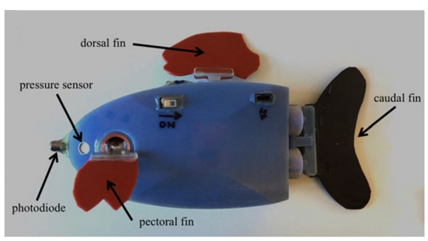


Figure 9: Low-cost solution by Clark *et al.* [12]

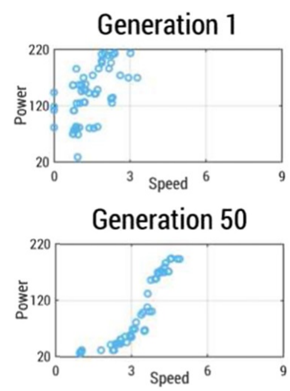


Figure 10: Evolution of the fish speed on 50 generations [13]

Recently, Chen *et al.* developed a robotic fish based on a "novel magnetic actuator system"[14]. Their system is composed of a solenoid in between two magnets. Applying voltage to the solenoid "pulls" it on one magnet or another, resulting in an oscillating motion. In addition to that, they researched a driving voltage more efficient than the classic sinusoidal function. They named it MAPWM, for "magnetically actuated pulse width modulation" function, proved in the article more efficient and enabling the fish to go to faster speeds.
The fish is 69 millimeters long, but most of the space inside is taken by their driving system. It has no other actuator than the one described above (and

shown below in figure 11), resulting in only 2D motion.

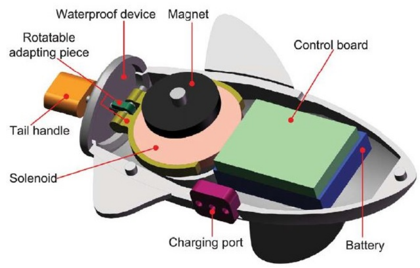


Figure 11: Novel actuation mechanism of Chen *et al.* [14]

Below in table 1, you can find a summary of the different robotic fishes studied until now. We can see there that not even half of the studied robots have 3D movement capabilities.

Name, source	**Actuation method**	**3D movement method**	**Goal**	**Misc**
LSRO lure [1]	Stepper motor	n.a.	Biomimetism to study fish swarm comportment	Robotic fish to improve
Jessiko [5]	Electric motor	Moving front fin and change of internal volume	Commercial application, ornemental expositions, also available as a reseach package	LEDs and swarm capabilities
BIKI [6]	Electric motor	Weight repartition inside the fish	Commercial application, shoot underwater movies	Floodlights and 4k camera
MT1 [7]	Electric motor	Paired pectoral fins	Study of fish tail bending inside a body of water	One actuated joint, 3 non-actuated (water pushes the fin and creates its shape)
n.a. [8]	Electric motor	n.a.	Study of fish tail bending and control algorithm, answer Gray's paradox (fish doesn't have enough power to propel itself)	Four actuated joints, PTP (point-to-point) control algorithm
n.a. [9]	Electroactive Polymer	n.a.	Investigate applications of EAP as artificial muscles	Polyelectrolyte Ion-Exchange Membrane Metal Composites
n.a. [10]	Electroactive Polymer	n.a.	Predict movement based on amplitude and frequency of fin movement	
n.a. [11]	Piezocomposite	n.a.	Prove viability of piezo and test different fin thicknesses	Piezoceramic actuator amplified via rack-and-pinion system
n.a. [12]	Magnet-in-coil	Pectoral and dorsal fins	Create a low-cost robotic fish (¡100$), capable of autonomous 3D movement	
n.a. [13]	Magnet-in-coil	n.a.	Test caudal fin length, height and flexibility	With evolutionnary algorithms: five parameters (frequency, PWR, length, height, flexibility) on 100 generations
n.a. [14]	Solenoid and magnet	n.a.	Test a "novel actuation system" consisting of a solenoid with a magnet in it, and a decupling mecanism	

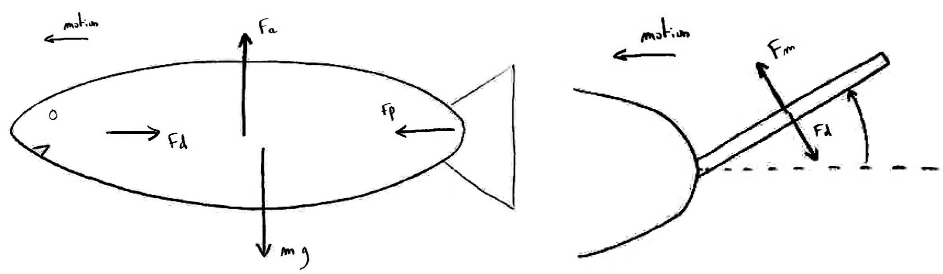
Table 1: Summary table for the state of the art

Overall, all of these solution uses different actuators, and represent a large range of size, from 60 millimeters to half a meter. In addition to that, they use different methods for 3D maneuverability.
The main actuators we can think about using for our project are as follows. The magnet-in-coil is the cheaper and easier to create, but has low controllability. The electro-active polymers is a novel solution, but would require a lot of adaptation from the existing robotic fish. The piezoelectric membrane mechanism is not adapted for our project as it needs a bulky mechanism to amplify its movement. The electric drive or servomotor is very versatile and adaptable, and for this reason we will stay with this solution for the improved design.
In the different solutions presented for 3D maneuverability, the best adapted for this project is the moving internal weight. Indeed, the final robotic fish needs to be biomimetic, and the zebrafish doesn't have large pectoral fins. As such, adding a moving fin at the front would be noxious for its adaptation to the environment. However, it will also be a challenge to fit a moving weight inside a small body as the one previously developed in Bonnet *et al.*[1].

3 Physics

To be able to create a viable system, we first need to consider all the forces applied on the fish, both from a static and from a dynamic point of view.
From a static point of view, these are the Archimedes force, and the gravity. When the driving actuator is activated, the fish enter a moving state, hence drag forces appears.

These forces are shown in figure 12. The first picture shows the fish from the side. F_d is the drag on the fish body, F_a is the Archimedes force, F_f is the force produced by the fin, and mg is the gravity. On the second picture, seen from above, F_m is the force produced by the motor to counter the drag on the fin F_d.



(a) From the side (b) From the top

Figure 12: Representation of the forces applied on the fish.

3.1 Drag force

The drag force formula is calculated with:

$$F_{drag} = \frac{1}{2}\, C_D\, \rho_{water}\, U^2\, S \tag{1}$$

With C_D drag coefficient [-] (obtained experimentally or from tables), $\rho_{water} = 1000$ water density [kg/m^3], U speed [m/s] and S exposed surface [m^2].

For our fish, we can take the coefficient C_D from the book *Engineering Fluid Mechanics*[15]. From the table of page 367, and for a "streamlined" body, we get $C_D = 0.2$.
We can now apply equation 1 to obtain the drag force. For a first estimation, we can take a fish of dimension 20% superior to the previous design. This gives us a fish 78mm long, 20mm high and 12mm thick. We can take a speed of 20 centimeter per second, corresponding to between 2 and 3 fish lengths per second. We obtain a required force of 3mN.
To have zero acceleration, our fish needs to produce 3mN. This first result doesn't seem excessive in regards to other results obtained elsewhere in the research field.
To be able to accelerate, the robotic fish will need to be able to produce forces above this calculated value.

We can do a similar calculation for the drag of the fin. Indeed, it is essential that the motor chosen is able to "push" the water. the difference is in the chosen C_D, closer this time to 10 ("flat plate" in the same book), and

the speed being a rotational speed.
However, as our fish will be similar to the one presented in Bonnet *et al*[1], we can approximate this by using the same values calculated there. This gives us the need to select a motor with a torque available above 2mNm.

3.2 Archimedes and gravity

The Archimedes force and the gravity are the two vertical forces applied on the fish's body. Their expression is shown in equations 2 and 3 below.

$$F_{Arch} = \rho_{water} \, V_{displaced} \, g \tag{2}$$

$$F_{grav} = m_{fish} \, g \tag{3}$$

For these two forces to cancel at equilibrium, we need to have $m_{fish} = \rho_{water} \, V_{displaced}$. This is equivalent to having a robot with a density of $\rho_{fish} = \rho_{water}$, as $V_{displaced}$ is the volume of the fish. Without this constraint, the fish would not be able to float statically in the water.
If these two forces are not perfectly equal, we can think about applying weights or air bubbles to the fish. however, obtaining a equilibrium without using additional aids would be better for the fish exterior look.

The second point to address is the application point of these two forces. The Archimedes force is applied at the barycenter of an immersed solid, while the gravity is applied at its center of mass. If these two are not the same, it will create a rotational moment.
For the difference in y, we need to have the center of gravity below the barycenter. As such, when the fish will rotate in roll, pitch or yaw, the rotational moment created will bring it back in its original attitude. Having a bigger vertical difference will result in a bigger moment of rotation, hence a better stability.

The difference in x is the main point of study our this research. Using the same rotational moment described in the last paragraph, having a center of mass forward in comparison to the barycenter will make the robotic fish lean down. This will be the mechanism used to enable the 3D movement.
In section 4 we will now show exactly how to change this horizontal distance between barycenter and center of mass.

4 Solution for 3D movement

In section 2 we have explained the reason to choose an internal moving weight instead of a moving fin to enable 3D movement. Now we will have to question how we can make a moving weight move in a restricted space.

4.1 Matlab script

The first thing to do is a first dimensioning of the system. Indeed, before knowing how to move the weight, we need to figure out an approximation of its mass and course. These first calculations were done using a *Matlab* script.

The inputs of this script are the characteristics of most of the components of the robotic fish, or an approximation when no information is known. For example, we know the weight m_{batt} of the battery used in Bonnet *et al.*. We can take as an approximation (with a factor of growth of 1.2) a new fish weight as $m'_{batt} = m_{batt}(1.2)^3$.

For the element placement, we can make a first approximation of the location of the components. We know that the moving weight system will be bulky and will need some space. For this reason, in the script, we first consider that it takes most of the bottom of the fish center. We also know that the caudal fin actuator needs to be at the back, that the battery needs to be in the center as it is relatively heavy in comparison to the rest of the fish, and that the PCB will take all space possible as it is used there as a mechanical structure for the fish.

For the moving weight mass, we can take a first assumption of a third of the fish's mass. This may seems quite important, but it is required. Indeed, if the weight is relatively light in comparison to the robotic fish, it will need to have a very long course to be able to shift the center of gravity of an appropriate distance. We made a first estimation for the total mass of the fish at 9 grams, which puts the weight at 3 grams.

Below in table 2 you can find a short summary of the main elements taken into consideration in the *Matlab* script. Note that the position (0,0) corresponds to the geometrical center of the approximation of the fish shape as an ellipse, positive x corresponds to the back of the fish, and positive y corresponds to its top. The size of the exterior ellipse at this stage is 78x20x12mm, corresponding to a factor of growth of 1.2.

Element	**Mass [g]**	x **position [mm]**	y **position [mm]**
Battery	1.5	0	5
Caudal fin actuator	0.6	20	0
PCB	1	-10	3
Moving weight	3	x_m	-6
Moving weight actuator	2	-20	-6

Table 2: Main elements for the robotic fish

The goal of this script is to compute the angle α_{x_m} corresponding to the angle of the robotic fish when the mass is in position x_m. This will enable us to do a first parameter optimization.
Below in figure 13 and 14 you can find schematic drawings of the researched angle, the goal is to be able in the end to achieve an angle of 45° from both sides. Indeed, we want the fish to be able to be pointed up or down of approximately 30°, taken with a safety factor of 1.5. This safety factor accounts for the fact that with the water friction, the center of mass and barycenter won't precisely align. It could be possible to do without this factor by doing complex fluid dynamics study, far above my level.

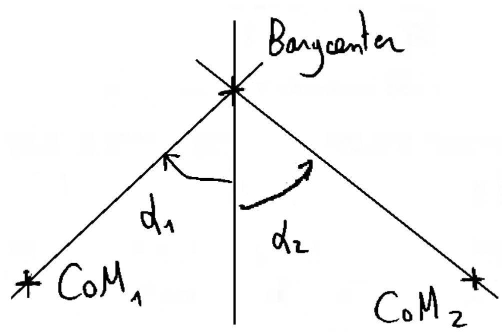
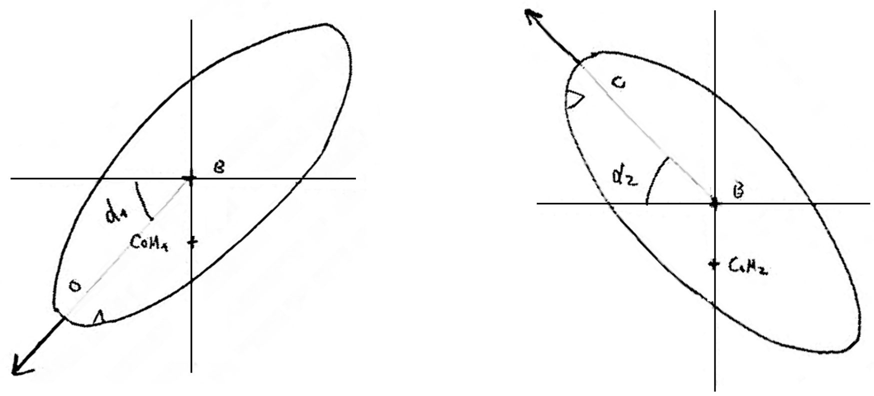


Figure 13: α depending on the position of the CoM



(a) CoM in the front, pointing down (b) CoM in the back, pointing up

Figure 14: Fish pointing up or down depending on the position of the CoM

For this first use of the *Matlab* script, we obtained different results, presented below. Unfortunately, due to an overwrite of the script for further optimization (see section 4.4), I can't show the script, or the exact results obtained.

1. the ratio of 1/3 between moving weight and total weight is coherent for the parameters taken

2. the moving weight needs to be as low as possible to create an higher angle

3. the course needs to be relatively long, between 14 and 20mm depending on exact robotic fish's weight and exact position of the mass

4. the other elements need to be symmetric in term of mass, so that the barycenter and center of mass are aligned when the mass is centered

4.2 Solutions available

We now have an approximation for the weight and its required course: three grams moving on between 14 and 20 millimeters. The next step is to find the best solution to move it. Different solutions are available, with the one we judged most optimal listed below:

- a commercial (linear) servomotor directly moving the weight (cf. figure 15)
- a motor with a high reduction ratio turning a worm-drive on which is placed the weight (cf. figure 16)
- a motor rolling up a "string" attached to the weight and pulling/pushing it (cf. figure 17)
- a magnet-in-coil based solution to move the weight in a rotation (cf. figure 18)

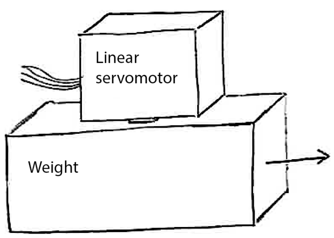


Figure 15: Commercial linear servomotor solution

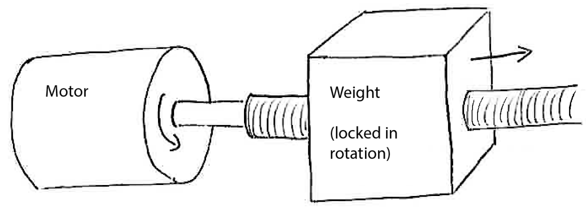


Figure 16: Worm drive solution

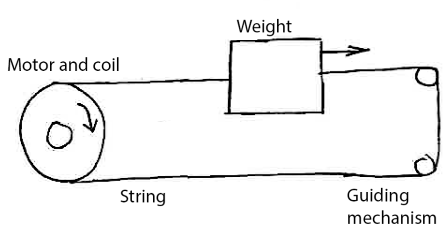


Figure 17: String mechanism, as seen from above

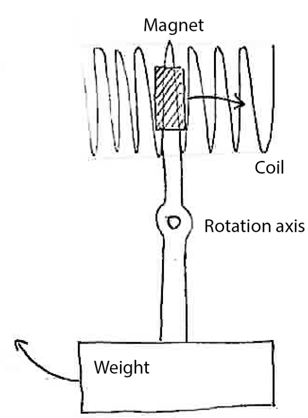


Figure 18: Magnet-in-coil solution

To sort these solutions, two criterion are essential here. The first is the space occupied by the mechanism, and the second is the course it can execute. Indeed, we have a very limited space to work with, and we will need a weight that can move a relatively high course.

To achieve a long course, the solutions based on a rotative movement have a drawback. Indeed, a part of the course is ”lost” due to the cosinus component of the movement in x. Some testing in *Matlab* proved that the length of the arm required to move the center of mass by a adequate distance would make the magnet-in-coil and the non-linear servomotor impossible or difficult to implement in our robotic fish.
In addition, for the magnet-in-coil, the rotation axis could be difficult to implement in our PCB.

The three other solutions have their own advantages and drawbacks.
A linear servomotor, such as the VS-19 for example, would be very easy to use from an electrical point of view. For example, it already has a build-in solution to find the position of the weight. However, it is very bulky relative to the scale of our project. As such, it is not usable as it is, and would need to be extensively adapted in order to fit inside of our fish.

The string method is light, and would ”simply” require a pulley coupled with a motor. Its course is also unlimited from a technical point of view, which would make it a very good applicant. The problem lies in the string itself. First, as it is not rigid, the system would need to be push-pull, so a pair of strings is needed. Moreover, the two strings will need to be both sufficiently resistant to last enough actuation periods, while staying thin as to not take much space when rolled. The guiding mechanism in itself will also be difficult to machine at this scale.

The last solution is the worm-drive solution. From a technical perspective, it is approximately equivalent to a linear servomotor, however we are not constrained by the market solutions. The course is limited only by the worm drive machining capabilities. The main drawback of this solution is that we need to find a solution to obtain the position of the weight, or at least when it is in end-course. From a space perspective, the worm-drive it itself can be very compact, but a motor with a high reduction ratio is often long. Another solution would be to use a stepper motor.

In view of these arguments, we decided to investigate more the worm-drive solution. Indeed, with the arguments above, it appeared to be the most adapted for this project.

4.3 Worm-drive and weight dimensioning

The weight in itself has to have a weight between two and three grams. We decided to fix the dimension of the weight according to what can fit inside the robotic fish. For preliminary dimensions of 12x4x5mm, obtained with pen and paper schematics as something that can fit at the bottom of the fish, the obtained volume is 240mm^3. This gives us a mass of 2.2 grams with brass, or 2.7 grams with lead. The choice of the different materials could be done later to adjust the system.
The course of $\pm$7mm was computed for the brass weight, so increasing the weight by using lead could be a solution for increasing the angle α produced if required.

With our first design (a plate on the worm drive), we need a worm-drive fillet length of 20 millimeters. Indeed, the minimum required course of the center of the weight is 14mm. The addition of 6mm makes it possible for the weight to be engaged of three quarter of its length when it is in end-course. To machine this length, the screw needs to be relatively thick. After discussion, we fixed an external radius of 4mm. With this size, a coherent tooth depth is 0.5mm, which gives us an internal radius of 3mm.
This sizing can be changed later on if required.

We can do calculations for the torque required by the motor to move the screw with the weight attached to it, done using the *Matlab* script found in annex B.
This script returns the value of the torque required to be able to turn the screw. When run, it returns approximately 1.5mNm. With this value in mind, we decided to use the same stepper motor used in the caudal fin to move the weight, knowingly a Seiko MF03G.
Indeed, it is sufficient in term of power, as it is capable of generating torque up to minimum 2mNm. It is also quite compact, considering that a motor would need a gearbox to fit our rotation requirements. In addition to that,

it is available at the LSRO, and known how to work with it in a PCB.

The screw part will also need to have a section to attach to the motor, and another used for guidance. The weight will overshoot the screw by 3mm on each side when in end-course. On the motor side, we can count 3mm for the linkage with the motor gear. On the other side, we can take 2mm to link it to the bearing.
Below in figure 19 you can find a first representation of the screw design.

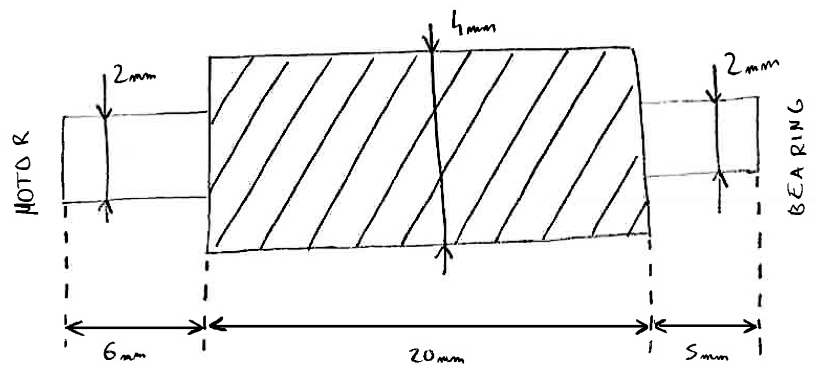


Figure 19: Screw's first schematics

This representation is very simple, but will help to determine the screw's weight, as well as help place the elements inside the CAD files.
It will be improved when included inside the CAD in relation with the other components. In particular, as of now, the link with the motor and the bearing is not implemented.

4.4 Second Matlab script

At this stage, we know the characteristics of most of our system's components. The only things remaining will be the exact dimensions for the screw and weight.
However, the goal of this second script is to check if all the components can fit inside the fish's volume, in particular if the course chosen is possible.

For this, I updated the *Matlab* script of section 4.1 with all the now known weights and dimensions. You can find the *Matlab* code attached in appendix A.

For now, the exact sizing of the weight is not fixed, but this will depend on how it is doable in term of machining, as well as on the space available inside the fish.
The factor of growth in comparison to the previous robotic fish is 30%. This was needed as the elements didn't fit with a growth of 20%. The main bottleneck was the battery. In previous versions, it was placed in a way impossible here due to the space taken by the moving weight mechanism. A solution would have been to use a battery much longer than it is large, but such battery are not available in these dimensions. The solution adopted here is to use the same battery sideways. As such, the thickness of the fish needed to be bigger that what was allowed by a factor of 1.2.

The results are shown in figure 20. We can see all the elements of the robotic fish, except the small electronics.
The PCB mass was estimated using its approximate volume and density, taking into consideration a certain weight for the small electronics (IR receiver, resistors, micro-controller, etc.).

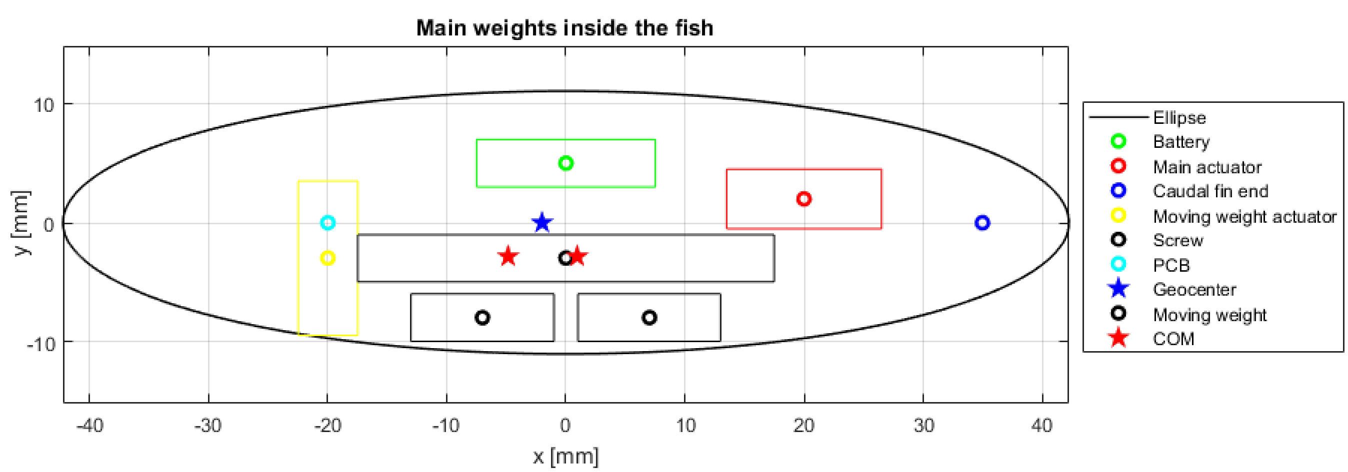


Figure 20: *Matlab* script resulting figure

The angle of interest α corresponds to the angle between the center of mass (red star) and the barycenter (blue star). The center of mass was computed for the two end-courses ($\pm$7mm), which explains the two red stars and the two moving weights in the graph of figure 20.
Note that the barycenter is not in the exact center of the ellipsoid to account for the caudal fin's latex skin's compressibility.

For the chosen course of $\pm$7 millimeters, the script computed angles of -47 to 44°, with an angle of -1.5° when the weight is centered. These angles corresponds to a computed movement of $\pm$2.5mm from its equilibrium position.
This is adequate for this project, and well within our expected angle of 30° with a safety factor of 1.5, so we can consider going forward implementing this solution.

5 Integration

The tasks to do to implement the solution are as follows:

- update the electrical schematic from the previous version
- create a PCB from this schematic
- create CAD files for the mechanical elements to position and dimension them in regards to each other
- determine the exact worm-drive and weight dimensions
- find the best solution to encapsulate the robotic fish

The two first steps will be done using *Altium Designer*. The third will use *SolidWorks*, while the fourth task will again call for a *Matlab* script in conjunction with the CAD files. The last one will mainly be critical thinking with the solutions available.

In term of order, it will be required to do the CAD files before creating the PCB. Indeed, the difficult part is that the PCB is used as main support

for the mechanical components, such as the worm-drive or the stepper motors. As a result, it is required to take all interactions between the parts into consideration when creating it.
To do the positioning of the electrical components, we need a first draft of the PCB shape, which will be done in *Altium* by importing a CAD file.
Sizing the worm-drive will be done concurrently to the CAD files creation.

5.1 Electrical schematics

The *Altium Designer* files for a previous version of the robotic fish was given. This version already had a second H-bridge for a second actuator, that was used to move pectoral fins. The actuator used was a magnet-in-coil.
To this file, we have to change the wiring for the second H-bridge to use for our 4-contact motor. Indeed, it was wired to power a coil with two connections.

In addition to that, we also need to add the wiring for the end-course localization.
This is made in a manner similar as what was done for the tail actuator in the previous versions. The schematics of this circuit is shown in figure 21. Two pairs of pads are located on the side of the PCB, one of these pair wired to a pin of the micro-controller, set to an internal pull-up (*ContactButee*). The second is wired to the ground (*GND*).
When the weight is on the pad, it creates a contact bridge between the two pads, that can be detected in the micro-controller. With a set of two pad in the front and in the back, we are able to detect when the weight is the its end-course. We can tell if it is on the front or back pad by knowing the direction in which we were moving the weight when it created a contact. However, we are not able to precisely locate it on its course.

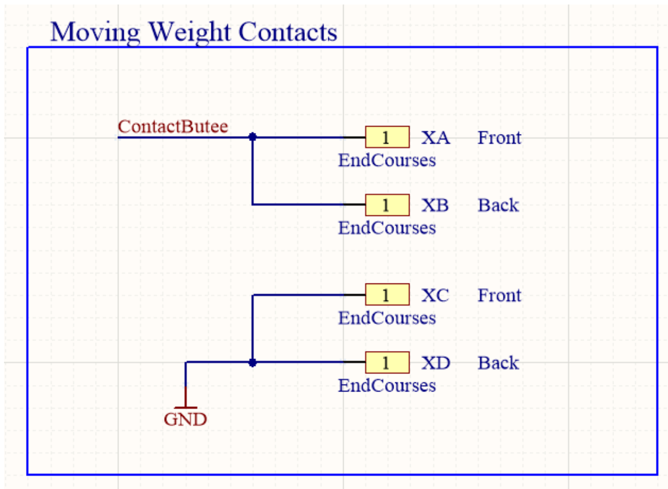


Figure 21: Contact schematics

Note that for this solution to work, the weight (or at least the part in contact with the PCB) needs to be in a conductive material. The material of choice would be for example brass. Another solution would be to do it in a low-friction material such as POM, and add a small copper wire to connect the two pads in end-course.

The updated schematics can be found in full in annex C.

5.2 CAD representation

The CAD files will enable us to have a better representation of the space inside the robotic fish, as well as the space taken by each component.
One of the objective will be to obtain the final shape of the PCB, in order to import it on *Altium*.
Some elements (such as the motor(s), the caudal fin pinion and the battery), were taken from a previous version of the robotic fish. The others need to be modeled.

The worm drive was originally planned to be a dented plate on a worm-drive with an external diameter of 4mm. The weight would have been suspended to this plate. This solution was difficult to design and machine, so

we had to think of a new method.
The new one consists of a two-fillet M2 screw that can be machined much easily using die on a steel rod. The use of a die makes it much easier to guarantee the circularity and linearity of the final worm-drive. In this solution, the weight can simply be composed of a block of metal (brass) in which we tapped a hole to the dimension of the M2 screw.
The main advantage of this solution is the ease of machining, but it also enables us to create a larger weight, as it is a solid part that we simply tap. The screw is also much smaller than the previous design, which frees space for the weight.
We can make new calculations to check the motor capacity to move the weight, but as the external diameter is smaller, the force required will also be smaller. Running the script returns a value of 1.1mNm, a decrease of approximately 30% from the last computed values.
It would have been possible to reduce further the external diameter for the screw. From a machining point of view, M1 could have been possible. The issue then would have been the time of travel for the weight. The Seiko MF03G can move at a maximum of 2'400 steps a second. From the datasheet, each step is 0.342°, which gives us a time time of 15 seconds to travel the full course, with a M2 screw (module of 0.4). Reducing further the screw to M1 would double this time already high. We are aware that this time won't allow for a very nimble robotic fish, however by this time the end of the semester is close and we preferred to have results even if not perfect.

Another part essential to the moving weight mechanism is the support part that comes at the back of the screw. the role of this part is to guide the screw in a good position and to limit the friction between screw and PCB. This part will need to be fixed to the PCB and be guided into correct position using slits. It will be machined in POM.

On the motor side, a "dome" linked to the screw will come on top of the gear. The internal dimensions of this part will need to be decided in accordance to the motor gear datasheet, in order to have a tight fit.

The resulting moving weight assembly is shown in figure 22 below.

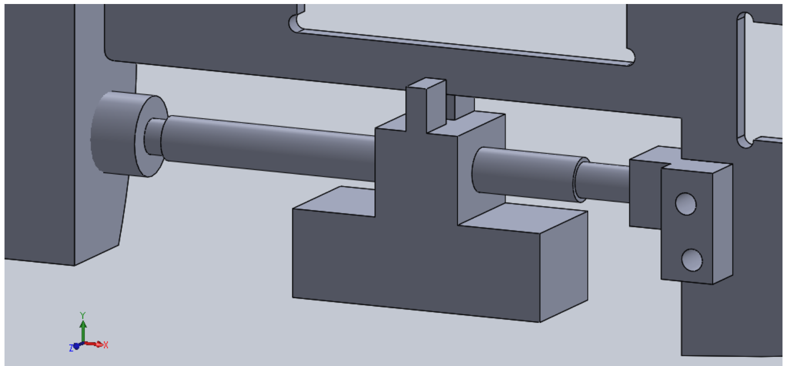


Figure 22: Moving weight assembly

A part is attached to the caudal fin actuator. It is required to have this part in metal for the switch system to work. Indeed, the robot is turned on by establishing a contact between two pads on the PCB with the help of this part. As it will be taken directly from a stock 3D printed in a previous project, this part design cannot be changed. However, we will add a plastic 3D printed cap on top to make it symmetric between up and down.

We can also take into consideration that the PCB will need a hole for the IR receiver, and contacts for the programming. The four programming pins were placed at the front. We can copy the size of these two features from a previous design.

The result is the parts annexed in section D. The assembly obtained is shown in figure 23.

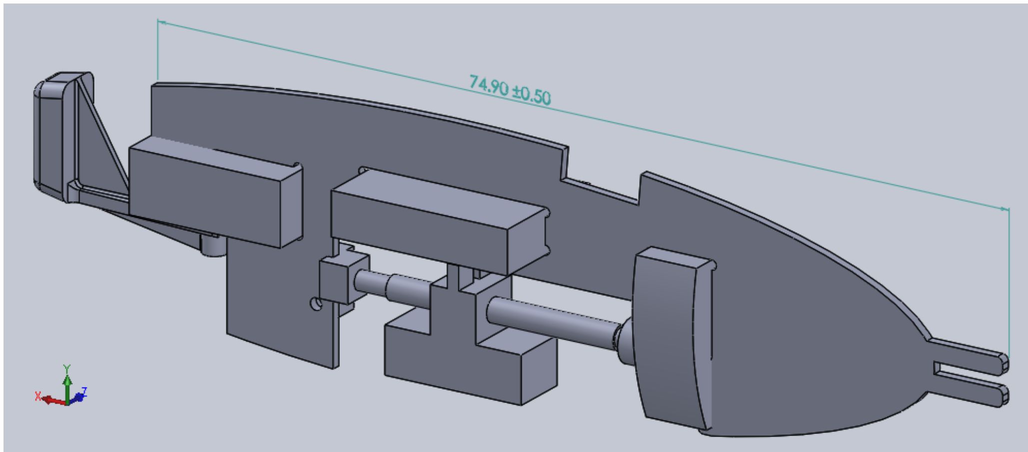


Figure 23: Assembly obtained

5.3 PCB

After importing the PCB shape to *Altium*, the task is to wire the components together on the PCB. The PCB is fixed at two layers, and has some thin parts where it will be difficult to pass a lot of tracks.

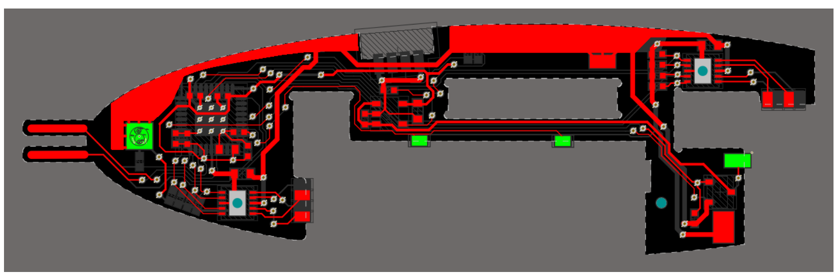
The key points to take into consideration are as follows:

1. the main power consumer are the H-bridges, so the lines from V_{bat} to them must be large
2. the big components in terms of space are the micro-controller, the H-bridges, and the IR receiver
3. it will be machined at the STI-PAT workshops, so their machining capabilities need to be taken into account
4. the decoupling capacities needs to be placed next to the correct micro-controller pin (according to the micro-controller datasheet)
5. space need to be left at the edges in case small filing is required to fit components

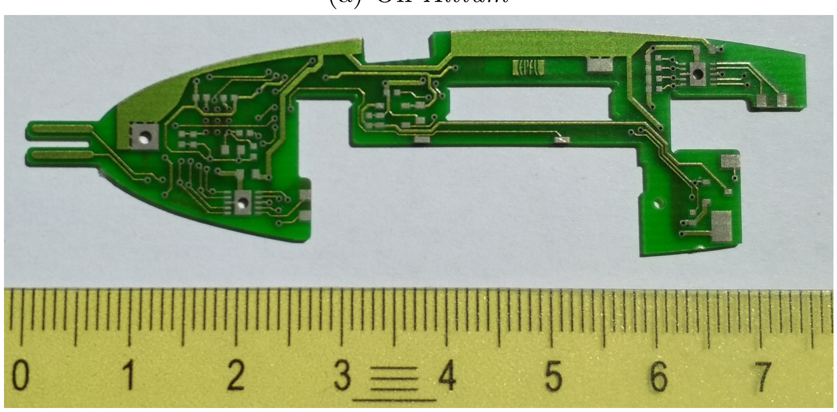
Some choices were made in term of element placement on the PCB. First of, the micro-controller was placed at the front (in the "head" of the fish) as

it was the place were a maximum of space was available.
The pins were placed in the front to be close to the PCB and easily accessible for re-programming if required.
Finally, the IR sensor needs to be on the top.

With all of these requirements and choices, we obtained the PCB files shown below in figure 24a. The *Altium* files will be joined in the annex.
The PCB produced by the STI-PAT labs is shown in figure 24b. The next step will be to solder all the components on this PCB.
Some modifications may also be needed. For example, a small one millimeter hole was created during the CAD drawings to support the POM part, but it may need to be moved a bit. We also may require to file some places to fit the components.



(a) On *Altium*



(b) After production, without components

Figure 24: The final PCB

5.4 Encapsulation

For the robotic fish to be able to go into the water, we need to encapsulate it.

In previous occurrences, the PCB and electrical components were sinked inside a polyurethane volume. For the caudal fin to move, the back of the fish was not filled with PU, but instead received a latex skin, enabling movement while staying waterproof.
The advantage of this solution is that the components are perfectly isolated from water. However, the PU's density is much higher that the water's. As a result, if we were to use this same solution, the fish will have a high density, and will sink at the bottom of the tank. In addition to that, we need to consider that the moving weight needs to be able to move.

Different methods were considered for the encapsulation.
One first method was to create a 3D printed shell. This shell can be made in two section, then glued together to make it waterproof. A preliminary example of shell design can be found in figure 25. At the back, the latex skin could be used similarly to what was done in previous versions.
The problem of this method is that it would be difficult to regulate the robotic fish's buoyancy. Indeed, its volume will be fixed by the shell size, but it will be difficult to change its weight.

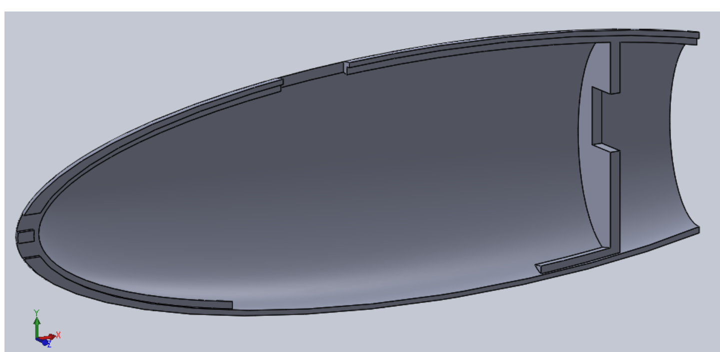


Figure 25: First shell design

The next solution we thought of is that instead of encapsulating the whole fish, we only encapsulate the moving weight mechanism. This will be done similarly to the method stated above, with a 3D printed cage. At the back,

a ring around which the latex skin will come can also be 3D printed. With the cage in place and the latex skin done, the rest of the robotic fish can be covered by a silicon layer to make it waterproof.
The main advantage of this method is it is very easy to change the fish's weight or volume. To increase its weight, we can add another layer of silicon. To increase its volume, we add air bubbles between layers of silicon.

The cage fits inside the rectangular hole in the PCB. This will still guarantee enough course for the weight, while enabling good sealing.
It also has a circular hole in the front where the motor gear will come, with 5/10 of a millimeter clearance on each side. In the back, a square hole support the POM part. A slit to welcome the PCB is also present on its top.

You can see the moving weight cage in figure 26. Note that to be able to see the component inside, only half of the cage is shown here. It is 3D printed like that, and fits with a second symmetric part.

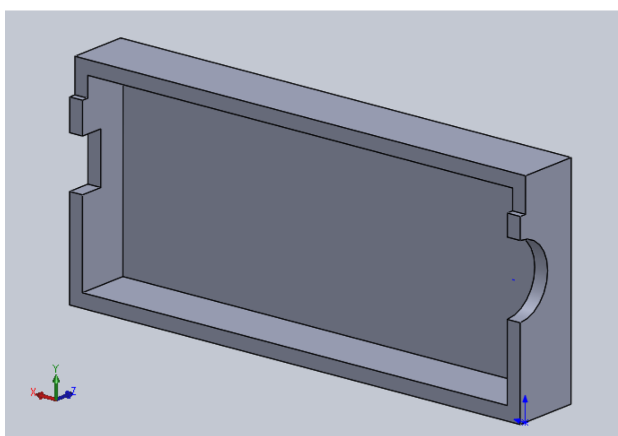


Figure 26: Half cage for moving weight sealing

In figure 27 the assembly with the cage and the rear ring is shown. Once again, for the sake of visibility, the second half of the cage is not present.

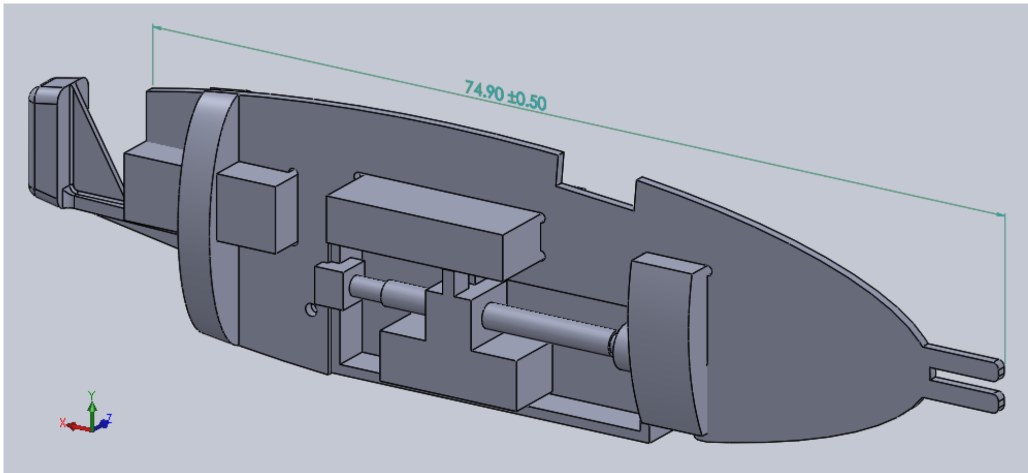


Figure 27: Assembly obtained

To have a better biomimeticity, we decided to use the two solutions conjointly. The second "cage" shown in figure 27 to ensure a good sealing for the moving weight, and a second external shell to look like a fish.
Two things are possible: create the second shell as waterproof, or not. With this choice, we can regulate the volume/weight of our fish. With our external shell not watertight, its volume will fill with water, and will be only aesthetic. If the shell is waterproof, it will increase the volume of our fish.
We can use these options to regulate our buoyancy.

With the external shell closed, our CAD design looks like the model shown in figure 28, which begins to look like a fish.

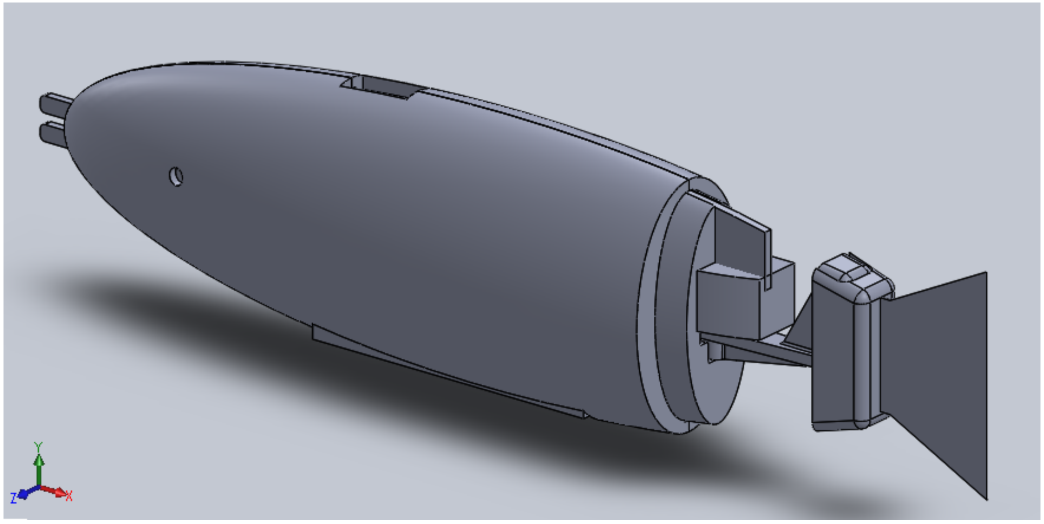


Figure 28: Final model

The new outside shell has holes where the inner cage will come, for the charging eyes, and a for the IR receiver. It comes at the border of the rear ring, where it can glued using silicon for sealing if required.

6 Results

The different results will be separated in different categories. First we will see the electronic results, followed by the mechanical ones. Finally, we will showcase our finished project.

After this, a discussion will be done to go further and think of what will be to improve for a next project.

6.1 PCB and electronic results

After soldering the different components and programming the micro-controller, done by Frank Bonnet and Daniel Burnier in the LSRO, we were able to test our motors.

The robot can be turned on using the caudal fin contact. When turned on, an IR transmitter can be used to turn the different motors on and off, as well as change the actuation frequency for the caudal fin actuator. These actions work as intended. This proves that a major part of our PCB is wired as it should.
The battery also charges, and we are able to correctly program the robot using the programming contacts at the front of the fish.

The end-course contact's signals can be detected inside the micro-controller when triggered manually with a wire. We will need to assemble the fish as a whole to test with if the weight establish the contact, which we will do in subsection 6.3.

A problem arose concerning the LDO. In the previous design, the second H-bridge was used to control a solenoid coil, whereas in this project, it drives a stepper motor. We failed to think about the difference in power consumption between these two devices. As a result, it is impossible to direct current to both actuators at the same time. When the moving weight actuator is in function, activating the caudal fin actuator puts too much strain on the circuit, which resets the micro-controller.

This problem will need to be fixed in a next project, but is enough to test our proof-of-concept. Indeed, even with this constraint it is possible to move the weight, then actuate the caudal fin. However, the robotic fish won't be as nimble nor as agile as a real zebrafish.

6.2 Mechanical results

The main checkpoint for this testing will be passed if all the parts fit together as they are intended. Mainly, the big issue to address is concerning the tolerances of the moving weight mechanism.

In the figure 29 below, you can find a view of our moving weight system without any encapsulation.
We can see that all the parts fit together, and with enough tolerance to move. The weight seems to establish a link between the two end-course contacts as intended.

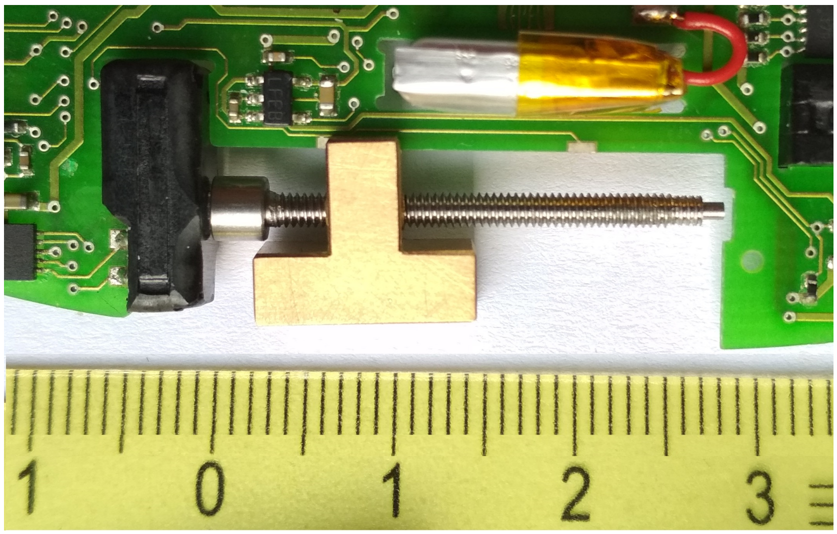


Figure 29: Moving weight mechanism

One small issue comes at the interface between the screw and the POM support part. The screw machining being small as it is, it is difficult to obtain a perfectly straight one. The machined part is a bit twisted, so that it doesn't turn perfectly correctly without the support part. Adding the support part will result in a more guided weight and is essential, but it will also increase the torque required to turn it.
This is the reason for this part to not be shown in figure 29.

For the 3D printed encapsulation parts, the inner cage fits as it should in relation to the PCB and the moving weight. It gives enough freedom for the weight to move, while being held in place correctly by the PCB and the motor.
We didn't consider the electronics present on the PCB while designing the parts, so it brought a conflict between the LDO and one side of the cage. This issue could be easily solved with a small file.
Another area of progress is the linkage between the two cage sections. As it was designed, the two parts just go to the middle of the PCB. Better design would have been to make them assemble like puzzle pieces, which would guarantee a better fit between them. The same remark can be done concerning the outer shell.

The 3D printed outer shell should fit on the PCB perfectly, but we have to consider that a thin layer of silicon will come on the PCB to seal the components. In its CAD design, we took that into account by making the "PCB hole" a bit wider and deeper.
As a result, the 3D printed part fits nicely on the PCB.

The rear ring slides on the PCB. We will be able to then glue the latex skin directly on it. It should come right at the end of the outer shell, to which it will be fixed with the silicon sealing layer.

Another point is the final machined weight's mass. we chose to machine the moving weight with brass, with a density of $8.73g/cm^3$. From the CAD model, its weight should be approximately 2.75 grams. The weight of the produced part is a bit higher, at 2.98 grams.
This is due to the impossibility to remove a certain section of the weight, namely the part that creates the junction with the two contacts to create the end-course signal. As a result, the course will be a bit shorter, but the weight will be a bit heavier.

6.3 Final implementation

We now are able to put together the fish and check some of its characteristics.

One important point to note is that the motor is powerful enough to move the weight. The friction is low enough at the machined POM part, as well as between the weight and the PCB on the upper part.

We can now test the movement of the center of mass with the fish without encapsulation. This was done by placing the robotic fish in a stable point and measuring the center of gravity position from the center.
The stable point measure was effectuated using a simple mechanism: by suspending the robot to a metal wire by one point of contact. When the fish is horizontal, the wire is at the center of mass in x.
The results of this experiment is found in figure 30 below.

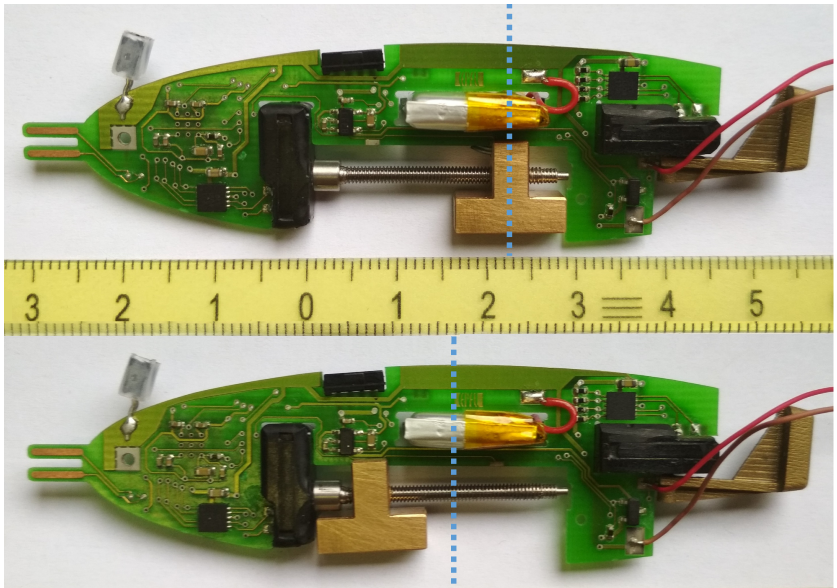


Figure 30: Center of mass movement

This was tested without the encapsulation, so final results may differ a bit.
We can see that the measured change is approximately six millimeters (from 16.5 to 22.5 millimeters from the back of the actuator). In the previous section, the *Matlab* simulation obtained an angle of $\pm45°$ with a change of center of mass of ±2mm. The results obtained experimentally here are a bit above this, with a change of ±3mm, a promising result!

We can however see a small discrepancy in the center of mass' position as compared with our *Matlab* model. From these measures, the center of mass seems a bit more back than what was initially computed. This probably comes from the caudal fin actuator pinion that is heavier than what was put in the simulations. Indeed, the measured weight of this part corresponded to a plastic 3D printed part used in a previous project, whereas this present project uses its heavier metal counterpart.
Another point is that the PCB components are not as front-centered as what was entered in the simulations. These two facts results in the back-heavy robot presented here.
This could be fixed later on during the mass/volume adjustments that will be done to regulate the robot's buoyancy.

6.4 Encapsulation

In figure 31 below you can see our encapsulation method. Only half of it is shown on an naked PCB for the sake of visibility.

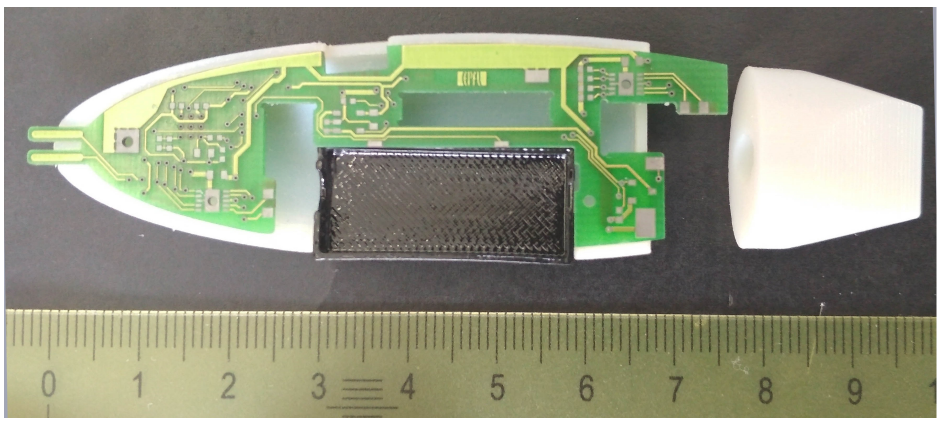


Figure 31: Encapsulated PCB

In white below the PCB, we can see the outer shell, in black the inner cage, and in gray the rear ring. We can see than all the parts fit on the PCB without seamlessly.
The white part at the back of the fish is used to mold the latex skin. It is dipped in a liquid latex solution, the skin is then heated and removed from this mold and glued to the rear ring.
All of these parts were 3D printed in the EPFL workshops.

We can then fit these parts on our robot and fix everything together using silicon, used both as a glue and as a sealant.
The idea to regulate the robotic fish's buoyancy is to add layers of silicon to increase the fish's mass. Its volume should be fixed by the outer shell and the latex skin.

At this stage, the robot's weight is 12.63 grams. It's quite high as compared to the previous iteration (9g), mainly due to the added moving weight and its actuator, and to the robot bigger size.

The volume of the full ellipsoid is 18.7 square centimeters, but due to the latex skin deformation, we will consider a volume of 15cm^3 for our buoyancy adjustments.
To match the water density and have a stable fish , we need to add approximately 2.4 grams of silicon.

Unfortunately, by the time of this report, we didn't have the time to finish this encapsulation.

finish encapsulation

6.5 Issues

Some issues arose on the end-course detection.
The first comes in the fact that we decided to use only one micro-controller pin for the contacts in front and back. As a result, the micro-controller cannot distinguish between contact in the front or in the back.
During the circuit conception, we thought it would be possible to use the present direction of the motor to know which contact produced the signal, but this revealed more difficult than expected.

As mentioned earlier, another problem is in regards to the contact placement. Due to an impossibility to machine the moving weight as it was designed, the weight's contact are a bit bigger that intended. With the PCB contacts placed according to the CAD, and not to the real machined part, the contacts are not placed exactly where they should. As a result, the distance between the two end-courses detected by the micro-controller is only eleven millimeters. The mechanical end-courses created by the inner-cage result in a course of 14mm as it should have been, but the contact pads are a bit too close to each other to use this whole distance.
The increase in the moving weight's mass should balance a part of this, but not everything. By running our Matlab script, we can see that the displacement of 2.75 grams on 14 millimeters produced angles of $\pm$ 45° (30° with a safety factor of 1.5). With a weight of 2.98 grams and a course of 11 millimeters, the angle is of ± 38 degrees.
We think that the difference won't be too much of an issue when testing our robot.

The main issue of the produced robot is the time required to move the weight. In a previous section, we have shown that it would be too high for this robot to obtain fish-like motion. We can measure the time between the two end-course, and we obtain approximately 35 seconds.
Ideally to model the fish perfectly, this time would have to be extremely small. Observation of zebrafish showed that they can shift they moving direction many times in a second. However, they use flexible muscles and deformable fins, so we can't expect to be that fast. Reducing the moving time would be a challenge to address in the next iteration of this project.
This reduction could be done by using another (non-stepper) motor. In this project, the use of the Seiko MF03G brought simplicity in the implementation, as it as was known by the LSRO staff, as well as in timing as it was in stock. For a proof-of-concept, this motor makes a good job, but will have to be changed to obtain fish-like motion.

7 Discussion

This project produced in the end a result. However, this robotic fish is far from perfect.

Globally, the main problem was the timing. My original timing gave a lot of time for the preliminary state of the art and physics studies. While an essential base on which to start the project, the time allocated on these parts was too long, and if this project was to be done again from scratch, the time allocated to these will be diminished.
In addition to that, a lot of time was lost trying to do a first screw dimensioning where not all the rest was done. It would have been much more efficient to do the work later on directly in association the CAD files. This resulted in a loss of a bit less than a week.

The produced prototype can be enhanced a lot. The main issue and hence point of improvement is the motor used. We used this stepper for simplicity, but it is not ideal for this application. We could think of using micro DC motors such as the one used in small radio-controlled planes or helicopters. These hobby motors are small, but not very powerful, so the use of a small

gearbox may be required. Fitting such a motor, relatively long and thin can also be difficult.
Some system used in RC helicopters integrate a DC motor, gearbox and graphite track for position sensing, and can be an inspiration for a further project.

8 Conclusion

This project was very interesting from start to finish. The state of the art and fish physics study were essential to draw a good base for the rest of the project. With these two foundation, we could then begin designing the fish. The research of solution required open-mindedness to think about the different possibilities. The implementation in a small form-factor required 3D thinking in CAD, as well as a bit of calculation and planning for the PCB tracks routing.
Putting everything together at the end, and see the result of one semester of work was also thrilling.

From the existing fish design, used as an inspiration and a base from an electronic viewpoint, we obtained a robotic fish capable of shifting its center of gravity mechanically. The created system needs improvements for the robotic fish to be used in its field of operation: a water tank with other real biological fishes.
However, it serves as a proof of concept to show the feasibility of this method to obtain 3D movement in a body of water.

finish conclusion when all done

9 Acknowledgements

Many thanks to Frank Bonnet for his helpful feedback all along this project, and to Daniel Burnier and Norbert Crot for their help discussing the fish mechanical and electrical design.
Without their help on the hardware side of things, I also wouldn't have been able to solder the components, or machine the mechanical parts.

A *Matlab* script for weight repartition

Below you can find the *Matlab* code for the script of section 4.4.

```
clear all; close all;

LENGTH = 1;
HEIGHT = 2;
WIDTH = 3;


%% dimensions of new fish
dim0 = [65, 17, 10];        % in mm
m0 = 9;                     % in g
V0 = 4/3*pi*dim0(LENGTH)/2*dim0(WIDTH)/2*dim0(HEIGHT)/2;

factor = 1.3;               % factor of growth

dim1 = factor * dim0;
V1 = factor^3 * V0;
m1 = V1/1000;


%% weight repartition

% ellipse
theta = 0:0.01:2*pi;
x = dim1(LENGTH)/2 * cos(theta);
y = dim1(HEIGHT)/2 * sin(theta);

% battery
batt_m = 1;
batt_x = 0; batt_y = 5;
batt_h = 4; batt_l = 15;

% actuator
act_m = 0.6;
act_x = 20; act_y = 2;
act_h = 5; act_l = 13;

% pinion on actuator
act2_m = 0.2;
act2_x = 35; act2_y = 0;

```

```
% moving weight
mov_m = 2.25;
mov_x_tab = [-7,-5,0,5,7]; mov_y = -8;
mov_h = 4; mov_l = 12;

% moving weight motor
mov2_m = 0.6;
mov2_x = -20; mov2_y = -3;
mov2_h = 13; mov2_l = 5;

% screw
scr_m = 0.5;
scr_x = 0; scr_y = -3;
scr_h = 4; scr_l = 35;

% PCB and other electronics
pcb_m = 1;
pcb_x = -20; pcb_y = 0;

% geocenter
geo_x = -2; geo_y = 0;


% plot all except COM
fig1 = figure;
plot(x, y, 'k', 'LineWidth', 1); axis equal; grid on; hold on; % ellipse
plot(batt_x, batt_y, 'go', 'LineWidth', 2); % battery
rectangle('Position', [batt_x-batt_l/2, batt_y-batt_h/2, batt_l, batt_h], 'EdgeColor', 'g');
plot(act_x, act_y, 'ro', 'LineWidth', 2); % actuator
rectangle('Position', [act_x-act_l/2, act_y-act_h/2, act_l, act_h], 'EdgeColor', 'r');
plot(act2_x, act2_y, 'bo', 'LineWidth', 2); % stuff on actuator
plot(mov2_x, mov2_y, 'yo', 'LineWidth', 2); % moving mass motor
rectangle('Position', [mov2_x-mov2_l/2, mov2_y-mov2_h/2, mov2_l, mov2_h], 'EdgeColor', 'y');
plot(scr_x, scr_y, 'ko', 'LineWidth', 2); % screw
rectangle('Position', [scr_x-scr_l/2, scr_y-scr_h/2, scr_l, scr_h], 'EdgeColor', 'k');
plot(pcb_x, pcb_y, 'co', 'LineWidth', 2); % PCB
plot(geo_x, geo_y, 'bp', 'LineWidth', 2); % geometrical center

for i=1:4:length(mov_x_tab)
    mov_x = mov_x_tab(i);
```

```

    % CoM calculations
    tot_m = batt_m + act_m + act2_m + mov_m + mov2_m + pcb_m +
    scr_m;
    CoM_x(i) = (batt_x*batt_m + act_x*act_m + act2_x*act2_m +
    mov_x*mov_m + mov2_x*mov2_m + pcb_x*pcb_m + scr_m*scr_x) /
    tot_m;
    CoM_y = (batt_y*batt_m + act_y*act_m + act2_y*act2_m + mov_y
    *mov_m + mov2_y*mov2_m + pcb_y*pcb_m + scr_m*scr_y) / tot_m;

    % plotting
    plot(mov_x, mov_y, 'ko', 'LineWidth', 2); % moving mass
    rectangle('Position', [mov_x-mov_l/2, mov_y-mov_h/2, mov_l,
    mov_h], 'EdgeColor', 'k');
    plot(CoM_x(i), CoM_y, 'rp', 'LineWidth', 2) % COM

    angle_obtained(i) = (180/pi) * atan(-(CoM_x(i)-geo_x)/(CoM_y
    -geo_y));
end

% legends
title("Main weights inside the fish");
xlabel("x [mm]"); ylabel("y [mm]");
legend("Ellipse", "Battery", "Main actuator", "Caudal fin end",
    "Moving weight actuator", "Screw", "PCB", "Geocenter", "
    Moving weight", "COM");

pos_fig1 = get(groot, 'Screensize')/2;
set(fig1,'Position',pos_fig1);
```

Listing 1: *Matlab* script for weight repartition

B *Matlab* script for screw dimensioning

Below the *Matlab* script for the screw dimensioning.

```
%% check is torque sufficient to move weight
r_out = 1; % outer radius
h = 0.2;   % thread depth
r_in = r_out - h;
r_m = (r_in + r_out)/2;

L = 2*pi*h; % thread pitch (*2 for double helix)
```

```
alpha_rad = atan(L/(pi*2*r_in));
alpha_deg = 180*alpha_rad/pi;

omega_deg = 15; % angle of thread
omega_rad = pi*omega_deg/180;

T = 3*r_out*10^-3; % torque corresponding to the weigth of 3g
R_c = ((tan(alpha_rad) + 1/cos(omega_rad))/(1 - tan(alpha_rad)/cos(omega_rad)))*r_m;         % thread constant
W = T / R_c;     % load parallel to screw thread axis

% T_advance needs to be below 2mNm to work
T_advance_required = 1000*W*r_m*((-tan(alpha_rad) + 1/cos(omega_rad))/(1 + tan(alpha_rad)/cos(omega_rad))) % torque to advance, mNm
```

Listing 2: *Matlab* script for screw dimensioning

C *Altium* schematics

Below the *Altium* schematics file for the robotic fish's PCB.
The corresponding *Altium* project files will also be joined with this report.

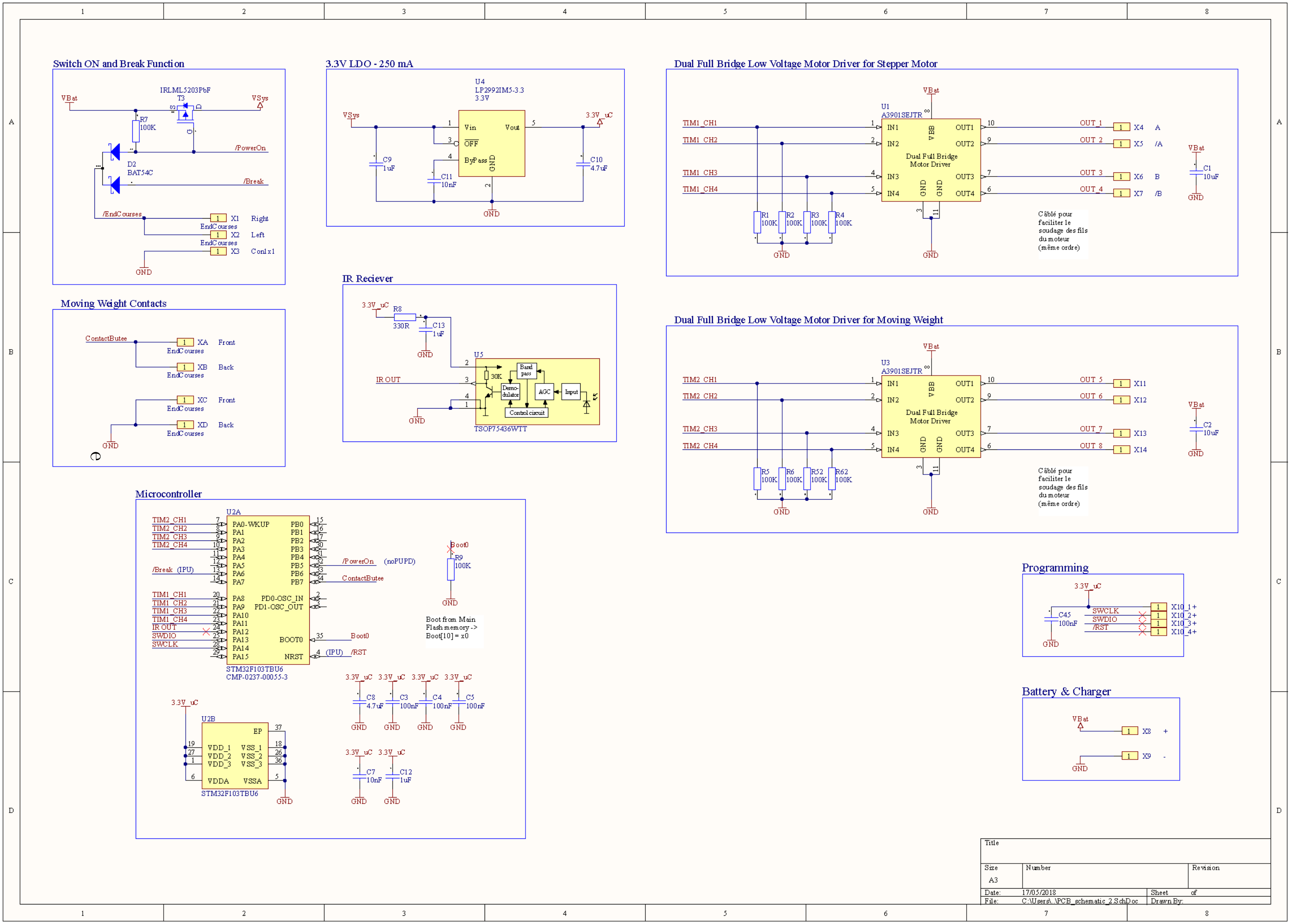


Figure 32: *Altium* schematics

D CAD representation

You can find attached to this report file the *SolidWorks* parts for the project. The files present in the compressed folder *Delafontaine_CAD.zip* are presented in table 3. In addition to that, the technical drawings send for machining are listed in table 4, and are also present in the compressed folder stated above.

Part name	**Role in CAD**
Assem1	global assembly
battery	robot's battery
guignol-fin	metal 3D printed part for caudal fin
motor	Seiko MF03G
v_cage2	inner cage
v_coque2_a	left side of the outer shell
v_coque2_b2	right side of the outer shell
v_fin	plastic caudal fin, ornemental in the CAD
v_guignol2	plastic part coming on guignol-fin for symmetry
v_latex	part used as mold for the latex skin
v_PCB	project's PCB
v_ring	rear ring to support the latex skin
v_screw	moving weight's screw
v_support2	POM support part for the screw
v_weight2	brass moving weight

Table 3: CAD files

File name	**Corresponding part**
draw_screw	*v_screw*
draw_support	*v_support2*
draw_weight	*v_weight2*

Table 4: Technical drawings

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