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DORSAL FIN INTERACTION ANALYSIS OF A BIOINSPIRED SURFPERCHE ROBOT

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ABSTRACT

Marine species such as fish have a morphology that has been adapted over time to reduce resistance in underwater displacement as well as staying submerged, therefore the present research focuses on the study of the bluebird fish robot, under four parameters of analysis, hydrodynamics, hydrostatics, kinematics and dynamics, to submerge the robot in the Amazonian rivers where the habitat of this species is found, there is in the future to monitor underwater life. A dorsal fin of 2 degrees of freedom was designed an built using a 3D printer, the rigid fin was driven by a servomotor and control system, all of them were waterproofed, the body can stay underwater near to zero buoyancy with tendency to submerge, the reaction of the movement of the dorsal fin and the reaction of the robot displacement was determined via some tests.

Keywords: *Dorsal fin, bioinspired robot, underwater vehicles, robot stability.*

1. INTRODUCTION

Most of the earth's surface is covered by water, to be more specific, two thirds of it. The oceans are not only a source of raw materials, food and resources, but also allow the transport of products between countries [1]. Scientific understanding of ocean waters is growing in a dizzying way with the use of a variety of technologies. The first scientific explorations were carried out by underwater vehicles manned by humans [2], [3]. More recently, underwater type robots have begun to revolutionize seafloor exploration, offering better information at a reduced cost. On the seabed one of the species that has predominated and explored are fish, which after thousands of years of evolution have developed an amazing ability to move in aquatic environments, this ability motivates several researchers to improve the performance of robotic systems [4]–[6].

There is a diversity of thousands of different fin designs that are largely a product of natural selection for locomotive performance. Many species of fish have fins that show remarkable locomotive properties. For example, the tail of the scombrid fish (tuna and relatives) is a high-performance hydroelectric sheet that allows rapid propulsion [7].

The dorsal and caudal fins of the fish can interact hydrodynamically to improve thrust production, the dorsal fins are used by the fish to generate off axis forces during turning manoeuvres [8]. The paired pectoral fins of the teleosteal fish work as flexible slats under complex motor control allowing swimming and high performance manoeuvres [9], [10] while the pectoral fins of other species, such as sharks and sturgeon function, improve maneuverability at low speed. [11], [12] . The elongated ribbon-shaped fins of knife fish and catfish function as different undulating propellers of the body [13], [14]. Therefore, it is natural to consider fish fins in general, and pectoral fins in particular, as a model system for a design component of an autonomous underwater vehicle. [15].

Teleost species such as tarpon or trout, the dorsal fin is supported by soft fin rays of a similar character to those that support the tail. However, in a large group of teleost fishes with spiny fins, the dorsal fin retains the soft portion, but a new spiny dorsal fin is produced in which the fin membrane is supported by multiple rigid spines [16]. The soft, spiny dorsal fins may be held together by a thin membrane of connective tissue or may be separated as shown in Figure 1. During stable swimming, the spiny dorsal fin usually folds and is not propulsive, but the soft dorsal fin generates thrust and lateral forces during stable swimming, and is also important during maneuvers [17]–[19]. The function of the spiny dorsal fin has not yet been studied experimentally.

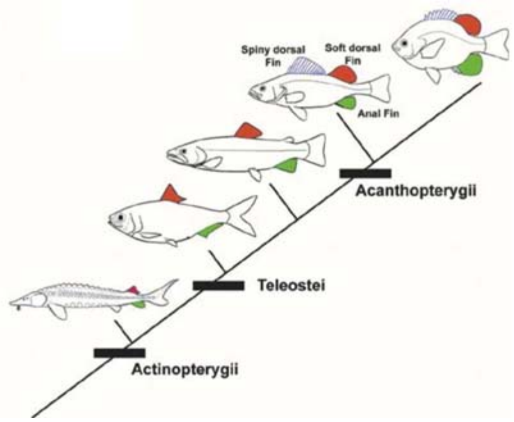

Figure 1: Types of dorsal fins in fish

The main objective of the article is to design and implement an underwater prototype with a dorsal stabilization mechanism that emulates that of the fish with the name of blue mojarra fish Figure 2, designing and developing at the same time the electronic systems based on the results obtained from previous research prior to the realization of the final model.

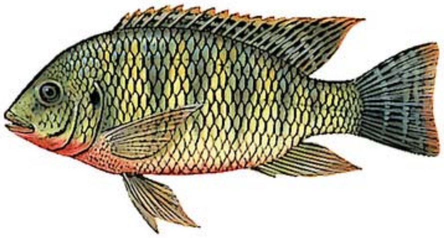

Figure 2: Blue mojarra fish

1.1 Art State

Each of the investigations concerning the underwater robots has provided significant information about the design, construction, locomotion, and hydrodynamics of the marine species, which has served as a guideline for future research.

To do this, it is necessary to have knowledge of research related to the subject as a reference for possible solutions to problems. Paired pectoral fins, and medial dorsal, anal and caudal fins provide important forces for thrust and stabilization during aquatic displacement in fish. Therefore, underwater robots have their origin in the early fifties, exactly in the year 1953 with the appearance of the so-called POODLE, a remotely controlled underwater robot developed by Dimitri Rebikoff in France. It is evident that these robots had to be controlled remotely, which is why the term ROV/(Remotely Operated Underwater Vehicles) was born [8].

Human needs produce a variety of technology for the solution of problems such as the oil extraction through the ROV support, the first robots for this service were the RCV-225 and RCV-150 developed by HydroProducts in the United States [8][9]. Today ROVs are an essential part of oil extraction, reaching ever greater depths with great reliability [10]. It is necessary to understand what has happened in the last decades about the development of the AUVs. That is why we will make a brief summary of the development of this technology over the years. The technological advances have initially focused on morphology and locomotion, focusing on the resemblance of aquatic species.

The beginning of this branch of research is based on a series of publications that have their origin in the year 1926 when C. M. Breder published his monograph on fish locomotion. Even over time this approach endures especially for aquatic vertebrates because of their general body size and shape (Webb, 1989; Kerfoot and Schaefer, 2006; Langerhans, 2008; Rivera, 2008; Carlson and Lauder, 2011), however (Gosline, 1997; Lauder, 1989; Lauder and Liem, 1983) also study fish morphology focusing on

skeletal support structures for the general movement of study fish tails [8][11][12].
This article describes the development of a robotic fish, where the caudal propulsion is designed in a system 1 DOF (Degrees of Freedom) and that, to test its functionality, they sealed and tested the electrical devices, in addition the design of the pieces was developed in Solid Works and printed in 3D. Once the robot fish was built, a series of underwater tests were carried out to check if its movement is equal to its biological similarity [13].

That document directed the fish movement by means of the fins, however, in 1930 it determined the difference in swimming modes with respect to the fin of each living organism in marine habitat. In other research it establishes that the movement of the fins is based on the posture and shape of the body. They agree that the dorsal fin of a fish can benefit stability in addition to providing movement. [14][15][16].

Complementarily in 1973 Eric von Holst, observes the general movement patterns of fish fins, and shows that the knowledge of the coordinated function of the fin in the already existing underwater robots is still poor [4][18].

Harris (1936, 1937), Breder and Edgerton (1942), Arreola and Westneat (1996), Gordon et al. (2000), Consi et al. (2001), Hove et al. (2001) and Liao (2002) have provided important information on the use of multiple fins during locomotion in fish, but another interesting contribution is the understanding of the body surface with the study of kinematics and hydrodynamics, thus determining that information on how fish coordinate the use between their fins is limited and even scarce [17].

In many fish with spiny fins, the dorsal and anal fins are composed of an anterior spinous portion and a posterior more flexible region, often referred to as soft dorsal and anal fins. The spiny parts of these fins can be lifted and depressed, but not moved laterally, while the soft dorsal and anal fins have tilting muscles that drive lateral movement (Geerlink and Videler, 1974; Jayne et al., 1996). The tilting muscles are active during constant swimming and maneuvering, and dorsal fin movement.
The shape of the fin has important consequences for the mechanics of fin pushing related to its role in fast swimming versus maneuverability in slow swimming species. Walker and Westneat [19], [20] demonstrated that a paddle stroke is capable of producing stronger thrust transients for maneuvers when performed with a more rounded fin , distally widened, paddle-shaped . In contrast, a thinner, tapered, wing-shaped fin is best suited for swimming at higher sustained speeds using a dorsoventral finning motion. There are several key fin-shaped parameters that are associated with the movement of the fin and the locomotive apparatus as a strategy, following the 1980's and even in the 1990's, prototype experimentation was established as a new stage in the development and elaboration of underwater robot prototypes [21] [22] [9].

With the passage of time robotics covers new fields and one of them is the automation and for its ease and efficiency should also be included in devices exposed to an aquatic environment and therefore between the years 1970-1980 is produced in a potential way the AUVs that are autonomous underwater vehicles, this topic takes greater force during the first international symposium of submersible technology where it was analyzed the development of controls for the autonomy of water robotics [10].

According to the Development Community it exceeded the technology available at that time, however, significant progress was made in the development of the AUVs. Between 1990 and 2000 much more technology was generated for the growth of AUVs, moving from experimentation or testing to the first generation of available guided vehicles to perform and complete defined tasks in real environments. Entering a commercialization stage implies the generation of a new era for robotics that is consolidated from the year 2000 in which through the use of technology programs are launched to build, operate and make money using AUVs. This turn in robotics shows how a research topic and even an environmental commitment can become a trade in the ocean industry.

Today, technology in AUVs has reached very important points as they are becoming better known and are becoming a more profitable commercial option. Lately, there has been a lot of interest from the oil and gas industry, as they are spared many problems, costs and risks associated with underwater inspection and sampling activities by using this type of technology. This has led to joint efforts by private companies as well as teams from leading global organizations to make AUVs an operational part of the oil and gas industry, thus increasing the marketing and demand for these types of technologies. [2] [8].

The main objective of the article is to design and implement an underwater prototype with a dorsal stabilization mechanism that emulates that of the fish with the name of blue mojarra, designing and developing the electronic systems based on the results obtained from a prototype developed prior to the realization of the final prototype model with an anticipated research. Later the execution of movement actions with the integrated system to evaluate the results of the performance of the prototype.

2. METHODOLY

2.1 Hydrostatic pressure on the buoyancy of the robot fish

The experimentation with the operation of the fish robot requires the arrangement of water at rest, which leads to a physical variable called hydrostatics and the pressure that is exerted under these conditions. Hydrostatics is based on density and pressure concepts under Pascal and Archimedes principles. This last principle should be considered with greater emphasis for the study of the buoyancy of the fish robot. By virtue of the force that will be exerted on the body (fish robot), Archimedes principle is analyzed in which he says that every body immersed in a fluid suffers a vertical and upward force equal to the weight of the fluid that dislodges the immersed part of the body. Based on the following mathematical equation it will be possible to determine the thrust force that water exerts on the robot fish [20].

$$F_e = M_l * g \qquad (1)$$

$$F_e = V_l * d_l * g \qquad (2)$$

Where:

Fe = Force of water pushing on the fish
Ml = Mass of displaced liquid
Vl = Volume of liquid dislodged
dl = dislodged liquid density
g = gravity

The study guarantees require consideration of the buoyancy height using the following equation:

$$F_e = (S * h) * d_l * g \qquad (3)$$

Where **S** is the surface of the rigid body (fish robot) and **h** is the height between the liquid level and the upper limit of the fish

$$F_e = (S \times 0.01m) * 997\frac{kg}{m^3} * 9.81\frac{m}{s^2} \qquad (4)$$

$$F_e = 132.35\,N \qquad (5)$$

Once determined the thrust force that in this case we consider that of the water that establishes the weight necessary for the buoyancy of the fish robot on it. As it is an irregular rigid body, the best way to determine the volume is by experimenting with submerging the body in a container full of water and subjecting it to the introduction of the body, the difference between the full container and the new amount of water will correspond to the volume of the robot fish.

According to Archimedes principle, for a body immersed in a liquid to be in equilibrium, the thrust forcé and weight must be equal in magnitude and, furthermore, must be applied at the same point

2.2 Kinematics of the blue mojarra fish robot

The study of the dorsal fin is governed under two degrees of freedom with which we will have a position, speed and acceleration of the fixed link, that is, there is a single mobile joint governed by an actuator which in this case is given by a stepper motor. The previous study of a direct kinematics allows determining the position and orientation of the dorsal fin with respect to a system of coordinates known the geometric parameters of the fish robot.

The position of the dorsal fin is determined by the angular variables of X, Y, Z that can be obtained later by its respective sensor. It is worth mentioning that the position of the second joint is a fixed value that will always be in relation to the position of the first joint.

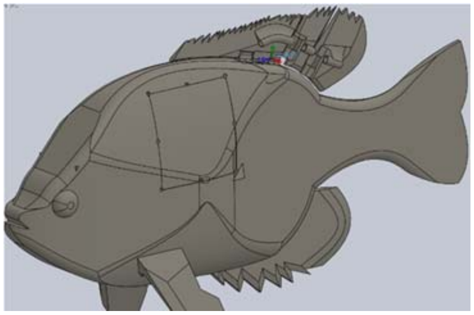

Figure 3: Fish robot reference system

The distances are anatomically visible and referenced to the center of masses of the moving parts of the dorsal fin. A reference system is established as shown in Figure 3, for the study, the Denavit Hartenberg parameters are also determined with the consideration of their respective positions in Table 1.

$$x_1 = l_1 \cos(\theta_1) \quad (6)$$

$$y_1 = l_1 \sin(\theta_1) \quad (7)$$

$$x_2 = l_2 \cos(\theta_2) \quad (8)$$

$$y_2 = l_2 \sin(\theta_2) \quad (9)$$

Table 1: DH parameters for direct kinetics

θ	D	A	α
θ_1	0	l_1	0
θ_2	0	l_2	0

The analytical development by Denavit Hartemberg determines the homogeneous transformation matrix shown below.

$$A_2 = \begin{bmatrix} \cos(\theta_1+\theta_2) & -\sin(\theta_1+\theta_2) & 0 & l_1\cos\theta_1 + l_2\cos(\theta_1+\theta_2) \\ \sin(\theta_1+\theta_2) & \cos(\theta_1+\theta_2) & 0 & l_1\cos\theta_1 + l_2\cos(\theta_1+\theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Obtaining the position of the final effector of the fish robot, the center of mass of each dorsal fin joint must be considered in the study so we refer the positions to a center of mass in each joint

$$x_{c1} = l_{c1} \cos(\theta_1) = 6.31\,mm \quad (11)$$

$$y_{c1} = l_{c1} \sin(\theta_1) = 4.10\,mm \quad (12)$$

$$x_{c2} = l_{c1}\cos(\theta_1) + l_{c2}\cos(\theta_1+\theta_2) = 28.64mm \quad (13)$$

$$y_{c2} = l_{c1}\sin\theta_1 + l_{c2}\sin(\theta_1+\theta_2) = 6.53mm \quad (14)$$

On the other hand, the preliminary study should contain the development of the inverse kinematics of the fish robot whose objective is to find the values that should take the articular coordinates corresponding to the dorsal fin of the fish robot so that its end is positioned and oriented according to a determined spatial location. Regarding the above mentioned, the two articular positions of the fish robot for the dorsal fin were determined considering the following parameters.

$$\sigma = tan^{-1}\left(\frac{y}{x}\right) \quad (15)$$

Where σ is the angle of the slope of the end effector, that is, the angle of the position where the end effector is located. For ease of calculation, an R variable is estimated that contains information regarding the position and orientation of the end of the fish robot.

$$R^2 = l_1^2 + l_2^2 - 2\cos\varphi \quad (16)$$

The angular positions when an inverse kinematics is performed at the end of the dorsal fin of the blue mojarra fish robot correspond to the following equations, taking into consideration the already mentioned that the angular position θ_2 , is always referred to the position θ_1.

$$\theta_1 = \sigma - \cos^{-1}\left(\frac{l_1^2 - l_2^2 + R^2}{2Rl_1}\right) \quad (17)$$

$$\theta_2 = \cos^{-1}\left(\frac{-l_1^2 - l_2^2 + R^2}{2l_2l_1}\right) \quad (18)$$

With these previous studies it will be possible to establish the direction of the movement of the dorsal fin for the direction of the blue mojarra robot fish.

2.3 Dynamic out of the water of the blue mojarra fish robot

The dynamics of robots is carried out with the aim of sizing the actuators, performing a control and developing a simulation. In the present investigation, control over the movement of the dorsal fin will not be developed. For the design of the simulation, direct dynamics is considered in order to know the movement as a function of the angular acceleration once the torques of each joint are known. This is how the simulation is developed to determine the oscillatory type movement of the dorsal fin, from which it is possible to determine the matrix of inertial masses of the two joints.

Mass = 1.36 grams
Volume = 1360.81 mm^3
Surface area = 1353.23 mm^2

Mass center

$$X = 6.31\,mm$$
$$Y = 4.10\,mm$$
$$Z = 0.04\,mm$$

Main axes of inertia and main moments of inertia: (grams * square millimetres)
Measured from the mass center.

$$I = \begin{vmatrix} -0.27 & 0.96 & 0 \\ -0.96 & -0.27 & 0 \\ 0 & 0 & 1 \end{vmatrix}$$

$$Px = 20.31$$
$$Py = 79.56$$
$$Pz = 93.24$$

Moments of inertia: (grams * square millimeters). Obtained at the mass center and aligned with the coordinate system of results.

$$m_{c1} = \begin{bmatrix} 75.38 & -15.17 & 0.01 \\ -15.17 & 24.49 & -0.07 \\ 0.01 & -0.07 & 93.24 \end{bmatrix}$$

Moments of inertia: (grams * square millimeters). Measured from the output coordinate system.

$$m_1 = \begin{bmatrix} 98.23 & 20 & 0.31 \\ 20 & 78.63 & 0.13 \\ 0.31 & 0.13 & 170.23 \end{bmatrix}$$

While the inverse dynamics allow the dimensioning of the actuator and the pulley effect that has been developed to establish the undulation in the second joint.

Mass = 3.05 grams
Volume = 3050.86 mm^3
Surface area = 2205.62 mm^2
Mass center:

$$X = -13.74\,mm$$
$$Y = 9.35\,mm$$
$$Z = 0.00\,mm$$

Main axes of inertia and main moments of inertia: (grams * square millimetres). Measured from the mass center.

$$I_2 = \begin{vmatrix} -0.40 & 0.92 & 0 \\ -0.92 & -0.40 & 0 \\ 0 & 0 & 1 \end{vmatrix}$$

$$Px = 103.23$$
$$Py = 255.08$$
$$Pz = 343.84$$

Moments of inertia: (grams * square millimeters). Obtained at the center of mass and aligned with the resultant coordinate system.

$$m_{c2} = \begin{bmatrix} 231.20 & -55.28 & 0 \\ -55.28 & 127.11 & 0.02 \\ 0 & 0.02 & 343.84 \end{bmatrix}$$

Moments of inertia: (grams *square millimeters). Measured from the output coordinate system.

$$m_2 = \begin{bmatrix} 497.86 & -447.09 & -0.05 \\ -447.09 & 702.82 & 0.05 \\ -0.05 & 0.05 & 1186.21 \end{bmatrix}$$

The inspired robot will have an aquatic application, where one of the challenges is the incorporation into the water and the blue mojarra locomotion, for this it is necessary to take into account aspects such as the hydrodynamic force, the morphology of the robot and the locomotion of the dorsal fin.

2.4 Design

The design of the fish is based on the Figure. 2 which describes a Blue Mojarra fish, the drawing's limit points are taken into account in the solidworks software, to extend on the z-axis, so that in this way generate a 3D body, then decrease the square shape of the object by means of the limits on the axes, referring to the points obtained.

In the figure. 4 you can see the design of the fish for the printing with an internal emptying to introduce the electronic elements inside the body and achieve the movement of the robot. The fin is built independently in separate planes, so that it can be attached to the fish at the time of final assembly.

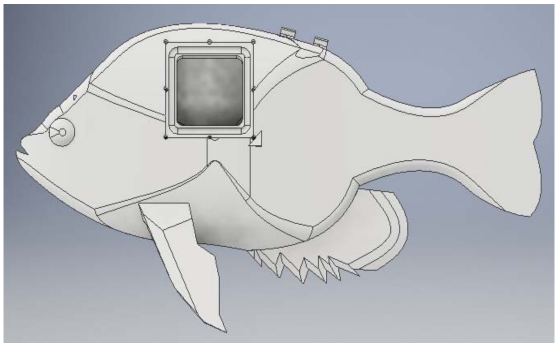

Figure 4: Modeling of the fish with an empty inside

2.1 Fish morphology

Robotics today has reached a crucial point in its evolution from technology, although from the beginning the idea of creating robots was based on the similarity to the morphology of living beings. For the present research, the study of fish robots is required. This document refers specifically to the different types of species that exist, as each species has a different shape which leads to each limb being used in a different way. So previous research has been devoted to analyzes of the physiology, mechanics of the functioning of the structure and kinematics of swimming [16].

Biological fish have undergone millions of years of evolution and therefore exhibit diversification of thrusters in terms of fin shape, body size and form of use. The blue mojarra fish is a product of this evolution and therefore has different characteristics from the other members of its family called Cichlidae, Morphologically it has an oval-shaped body in a compressed way, when they reach maturity they can measure a maximum of 30 cm, so they are peaceful animals and many times they are used as pets in fish tanks, the ecosystem in which they live tends to be rocky. The research aims to analyze the importance of the dorsal fin of the mentioned fish, by which they make the direction of their movements maintaining the respective balance.

3. RESULTS

4. In the design, simulation tools are used where studies are carried out that show an acceptable percentage of guarantee for the robot's operation. For the design, parameters such as the center of mass are considered, which guarantees the stability of the links and the body of the robot and the locomotion, by means of the drive of a servo-motor with the highest possible acceptance to the similarity in the movement of the dorsal fin of the blue mojarra fish.

The implementation requires only the movement of the dorsal fin and for its effect an actuator (servo-motor) performs this movement, which by means of the effect of pulleys on each motor shaft will perform locomotion to two links of the dorsal fin, achieving a slightly wave-like movement. With the exception of the dorsal fin, all the body mass of the robot is rigid, so for the study of locomotion and obtaining data from the movement system, an external propulsion is required at a constant speed.

The research is interested in achieving the effect of movement by including the action of the dorsal fin of the robot, using data collected by the MPU 6050 through an arduous UNO Fig 5. For further analysis through a graphical interface provided by the software of the same.

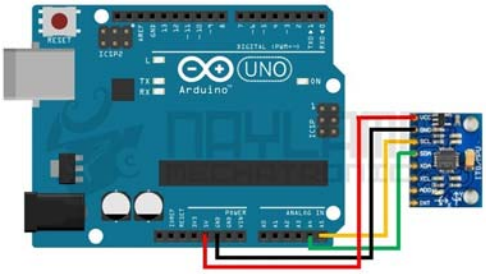

Figure 5: Fish robot data acquisition and control circuit

To obtain the data , the experiment was first carried out with the fin placed vertically, that is, in the original system, and then with the rotation of the fin in its two different positions, either to the right or to the left. In such a way that it is possible to observe the direction in which the fish robot advances according to the direction that the dorsal fin is placed.

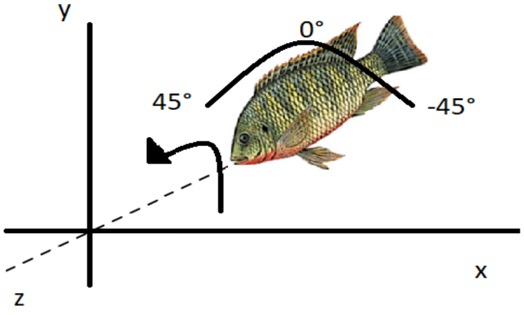

Figure 6: Rotation direction evaluated during the experiment.

For the study, we propose four different angular positions of the pectoral fin in which the effect of its movement will be evaluated in relation to its roll orientation as shown in figure 6, the first one in which the fin is perpendicular to the body of the fish 0°, after that the movement of the vane to the right at 15°, 30° and 40°, for the experiment a propulsion system is implemented that after reaching the speed of 2m/s remains constant, once this speed is reached we proceed to take a reading of the data, the averages of the data given by the MPU 6050 were registered in table 2:

Table 2: Results in different forward trajectories at different degree of fin position

	Angular position (°)			
Time (t)	**0°**	**15°**	**30°**	**40°**
0	-2,63	0,03	-0,19	-0,29
1	-2,59	0,06	0,64	4,17
2	-1,78	1,11	4,12	14,12
3	-1,55	2,82	11,81	21,23
4	-1,35	5,91	19,39	29,30
5	-1,09	9,53	26,46	35,33
6	-1,40	13,17	30,51	37,82
7	-1,18	21,63	41,27	48,46
8	-1,13	23,25	46,21	49,45
9	-1.16	23,13	46,02	48,13
10	-1,15	22,98	46,19	49,12

If the dorsal fin is maintained at 0°, there is a slight inclination of the fish body, this inclination is close to 0°, after modifying the angular position to 15°, the fish begins to rotate until it reaches the maximum angular position of 22.98°, at the beginning it presents a small oscillation and later it shows an inclination of the robot fish. The third experience considers an angle of 30° of the dorsal fin, for the third time there is a small initial oscillation of the fish to later incline and reach a maximum oscillating angle of 46.19°. In the fourth experience the initial oscillation is presented again, later the fish turns until reaching a maximum inclination of 49.45°.

In the last 2 experiments it can be observed that the maximum angles reached do not differ too much, this is due to the fact that by construction the fish is not capable of turning beyond that angle, what can be observed is that the turning speed does differ among all the tests performed, depending if it is directly on the angular position of the dorsal fin.

5. CONCLUSIONS

The blue mojarra robot fish presents a locomotion whose propulsion is based on the movements of the caudal fin, its middle and dorsal fins are used mainly for stability and support in the rotation, in the present investigation a bioinspired fish robot was designed with the purpose of analyzing the action that exerts the movement of the dorsal fin during the displacement, for it the design was implemented using 3D printing and waterproofing the actuators and electronic devices for its operation under water.

For the bio-inspired robot to be submersible, parameters such as hydrodynamics and hydrostatics were considered so that we could analyze the weights and forces to maintain the robot's buoyancy close to null. It should be noted that a dynamic system was not designed to obtain this buoyancy; with the materials and their analysis, the immersion time was reduced, for the tests under water, a nylon thread was used that kept the robot at an adequate depth.

The dorsal fin of the blue mojarra fish robot is rigid, its movements significantly influencing the movement of the fish robot, as expected. The main incidence of the fin is in the rotation in warping, the present investigation has determined its incidence in the displacement giving step to raise new topics of investigation related, this incidence can and must be taken advantage of for a better maneuverability of underwater vehicles, in future investigations will be used and will value systems of control of displacement with the interaction of systems of propulsion based on tail fin and stability and maneuverability with pectoral and dorsal fins.

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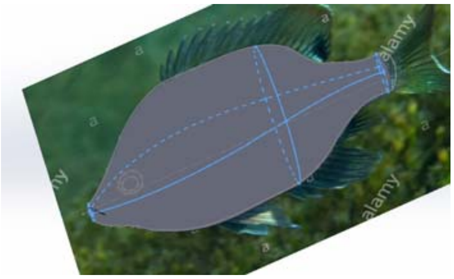
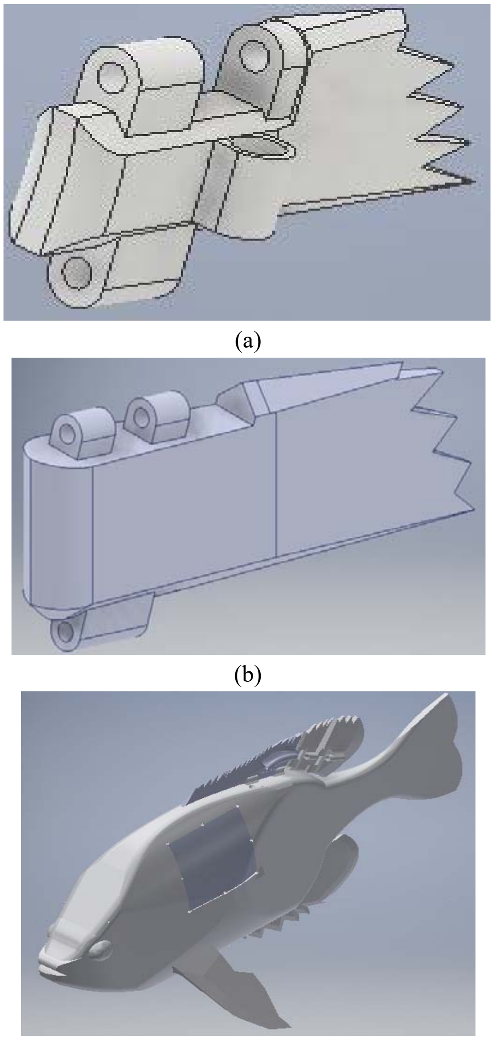
ANNEXES



Annex 1. Obtaining the reference points for the design

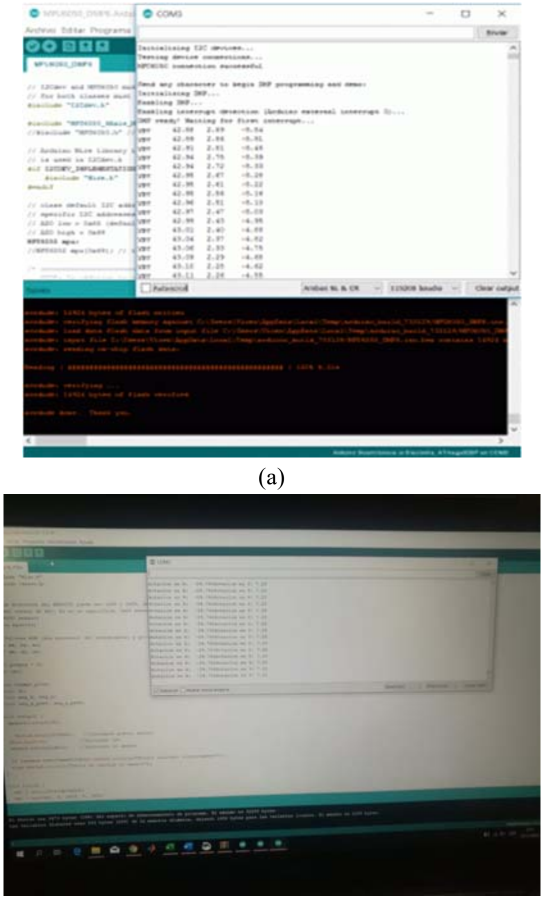


(a)

(b)

(c)

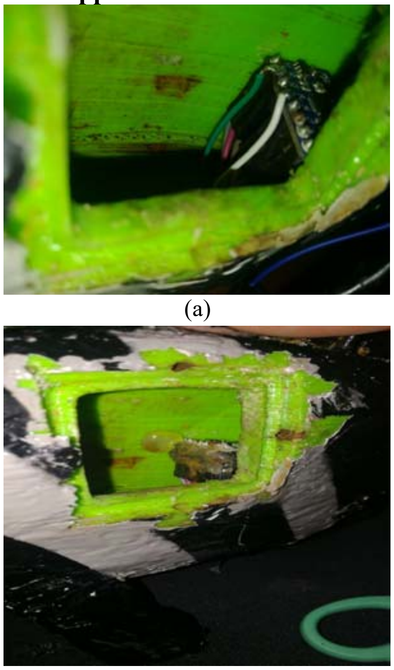
Annex 2. (a) dorsal fin intermediate part, (b) dorsal fin end piece, (c) dorsal fin assembly mechanism



(a)

(b)

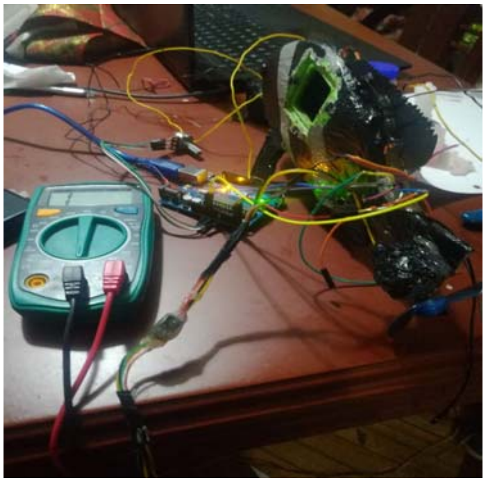
Annex 3. (a) Results obtained through the MPU with a base programme. (b). Real data obtained with application to the fish robot.



(a)

(b)

Annex 4. (a)Placement of internal components. (b). internal waterproofing of components.



Annex 5. Programming set up prior to full waterproofing.

Annex 6. total waterproofing of the fish robot.

Annex 7. Immersion test.