Design and Manufacturing of a 3D-Printed Underwater Robot through parameters CAD/CFD and Stress Analysis for Optimization and Performance[*]

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Abstract

This project focuses on the design and development of an open-structure ROV (Remotely Operated Vehicle) using 3D printing technology. The implementation of this technology as a cost-effective and pioneering alternative in submarine construction was explored, contrasting with traditional methods that often use conventional metals or plastics. CAD/CFD analyses were conducted to optimize the design, eliminating vortices and turbulent flow, and stress tests were performed to ensure proper distribution of the structure. Additive manufacturing allowed for the creation of 25 PLA parts for the ROV assembly, facilitating an intuitive and practical process. The resulting ROV demonstrated three degrees of freedom and successfully passed submersion and buoyancy tests, showing navigational capability both at the bottom of the pool and on the water surface. This project not only expands knowledge about open-structure submarines but also opens new possibilities for the application of 3D printing technologies in underwater engineering.

Keywords

ROV, 3D Printing, Open-Structure, CAD, CFD, Stress Analysis, buoyancy, underwater.

1. Introduction

In recent years, there have been advances in the designs of unmanned underwater vehicles, primarily reflecting remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) [1]. Specifically, the ROV is an unmanned underwater robot capable of maneuvering in the water and is controlled by an operator on the water's surface. ROVs are rapidly evolving alongside science and technology, allowing for the possibility of building ROVs of different innovative designs and sizes [2].

The oceans cover just over 70% of the Earth's surface, containing abundant biological and mineral resources [3]. However, exploration, maintenance, and inspection are limited by confined spaces and uncomfortable areas inaccessible to humans. In response to this challenge, various submarines have been developed and researched to meet established needs. Yet, the high cost of a watertight metal structure and a lack of structural analysis limit the development of further prototypes.

Some research has faced certain limitations, including focusing only on analyzing the direct or linear movement of the underwater robot, neglecting the rotational aspect [4]. Additionally, a simplistic design can lead to unsmooth movement and vortex formation. Affecting the stability of an ROV and thereby restricting its ability to submerge and maneuver underwater.

This work is undertaken to design, manufacture, and optimize an open-structure underwater robot, manufactured through 3D printing, with an efficient hydrodynamic design for navigation in

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water, integrating electronic systems for precise control of the thrusters. The choice of an open structure optimizes navigation efficiency, while 3D printing, being less dense than metals, reduces material consumption, resulting in an economical approach. The combination of innovative design and sustainable technology enhances the robot's performance, allowing for its navigation and control in water.

The document will include a comprehensive literature review on underwater robots, providing a detailed context on their evolution, applications, and relevant technologies. The method to be implemented for the submarine's development will be outlined, from the initial design to manufacturing and subsequent testing. The research results will be presented comprehensively, covering both achieved progress and areas identified for future improvements. The data collected during the development process will be analyzed, highlighting the submarine's strengths as well as any limitations or challenges encountered. Finally, a robust conclusion summarizing the main findings of the research will be provided.

2. State of Art

Industrial activity generates waste that, when combined with sediment in rivers and lakes, affects water quality and causes massive fish and other organism deaths, disrupting the ecological balance [5]. The increase in aquatic accidents has driven the development of underwater robots, not only for rescue purposes but also for applications in fishing, archaeology, cleaning, defense, and oil and gas exploration [6]. This has led researchers, scientists, and engineers to work on the development of underwater robots to address these challenges.

Unmanned Underwater Vehicles (UUVs) such as Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs) are used in oceanic exploration [3]. AUVs are crucial for marine exploration, featuring rounded or symmetrical designs that include bow, midsection, and stern [4]. ROVs have open or closed frame structures: open-frame ones are stable and can carry more weight, but they struggle with complex movements; closed-frame ones are more mobile but less stable, primarily used for specific tasks [7]. Creating ROVs and AUVs presents challenges; ROVs are more adaptable and, requiring human interaction, which makes them more cost-effective than AUVs.

Submarine observation entails risks such as inaccessible areas and contaminated waters, necessitating robots capable of operating in these environments. Cooperative control combines automation and human manual control, offering a promising option for man-machine systems [8]. An article proposes a methodology for researching and designing underwater robots, focusing on mechanical design, stress testing, fluid dynamics, and dynamic modeling [9]. With this methodology, underwater robots with an ideal structure can be developed, allowing for agile and fluid movements within the water.

Advancements in 3D printing have streamlined the creation of underwater robots with intricate geometries through CAD designs, reducing design complexity and costs [10]. Hydrodynamic performance is crucial for the stability and speed of an energy-constrained underwater vehicle, with Computational Fluid Dynamics (CFD) being key to optimizing its shape; although modeling hydrodynamic features is challenging, the CFD method provides precise analysis [11]. CFD is crucial for underwater stability; adjusting key parameters and achieving the ideal shape can be laborious, requiring repetition of the modeling, meshing, and calculation process [4]. The application of CAD and CFD tests allows direct interaction with the model, benefiting developers in terms of costs and time.

Calculating hydrodynamic coefficients is essential for the stability of underwater vehicles, reflecting changes in force and torque with linear and angular velocities; Computational Fluid Dynamics (CFD) is effective in simulating fluid flow over the vehicle in a numerical environment to determine hydrodynamic forces and torques [12]. This method is primarily implemented in SolidWorks software, which enables the extraction of different parameters and coefficients used to optimize and improve the model.

The development of an underwater robot system requires meticulous consideration of various factors to ensure its functionality and efficiency in the underwater environment, where operators need advanced skills [8]. In the complex seabed environment, the maneuverability and agility of underwater vehicles are crucial indicators of their performance underwater; agility refers to the efficiency and speed in changing speed, direction, and location, while maneuverability includes the ability to change these aspects while maintaining stability [13]. The performance of an underwater robot in water is quite challenging, so a body inspired by aquatic animals has always been a reliable and efficient solution.

The design of an underwater robot involves compromises between mobility, stability, maintenance, performance, and budget, seeking a long metacentric height to counteract abrupt attitude changes due to external forces such as waves [7]. In robotic systems, obstacle avoidance is crucial, where fixed bases prevent collisions and objects within their workspace, while floating bases such as USR or ships focus on avoiding static and dynamic obstacles [14]. The hydrodynamic properties of marine organisms, such as speed, resistance, maneuverability, and dynamic stability, impact the design of underwater robots, with features such as long dorsal fins for stability and a flexible tail that keeps the fluid flow attached, enhancing hydrodynamic efficiency [12]. Despite the complexities in water currents, the design of an underwater robot benefits from inspiration from marine organisms to improve its hydrodynamic performance.

3D printing has emerged as a manufacturing method that offers greater freedom in designing complex geometries compared to other methods, with soft robots typically composed of easily deformable materials such as fluids, gels, and reactive polymers [13]. There are robots that have used a hull structure, with these robots increasing flexibility and stability [6]. Regarding 3D printing, its emphasis on using 100% infill to prevent leaks and breaks based on stress testing shows practical consideration for material integrity in underwater environments [10]. 3D printing technology allows the creation of three-dimensional objects based on digital models, ideal for manufacturing a submarine robot model.

Submarine detection technologies are essential in marine engineering and resource exploration, addressing aspects such as environmental perception, autonomous navigation, and object detection; these technologies include acoustic, light, electromagnetic signals, and bionic sensors, constantly evolving in underwater robots. Communication systems are essential for underwater vehicles, but the complexity of these systems affects their development due to challenges of illumination and alterations at sea [1]. Submarine autonomous navigation is challenging due to properties of the aquatic environment: attenuation of electromagnetic waves and limited visibility restrict wireless communication and light-based perception, while sonar, although useful, provides noisy and less descriptive acoustic images, complicating navigation [15]. Additionally, the arrangement of cameras in waterproof housings with glass interfaces is crucial to ensure accuracy in 3D coordinates in underwater environments [16]. Various technologies applicable to underwater robots require efficient waterproof systems, and signals are often affected by water currents.

The teleoperation method for surface movement, UART communication emerged as a simple way to teleoperate and tests were successful in operator and submarine communication [9]. Bearing this in mind, a submarine robot was designed and manufactured with a 3D printer, equipped with eight piezoelectric sensors on its side to detect water pressure; the direction of the pressure source is calculated using feedback data from these sensors [17]. Like the design of this submarine, several researchers have developed different models based on all the research conducted.

A mechanism of concentric shaft transmission was proposed to overcome interior space limitations; navigation and maneuverability tests demonstrated satisfactory performance of the flapping and propeller system, allowing the vehicle to navigate in diverse environments [18]. We also have the design of an underwater robot for cleaning large ships, where the robot design must be hydrodynamic for proper assessment and cleaning of the ship's bottom [19]. The design of a Mini ROV integrates various design processes, including software, mechanical and electronic planning, and construction [2]. Different articles have shown their point of interest when designing and manufacturing underwater robots, focusing on mechanics, hydrodynamics, or the technology to be implemented. Mechanics is crucial for ensuring the structural integrity, hydrodynamics plays a role in optimizing the robot’s performance underwater and the technologies is essential for the communication underwater.

3. Method and data

The main objective is to design, manufacture, and optimize an open-structure underwater robot using 3D printing technology. The focus is on developing an efficient hydrodynamic design that ensures smooth and agile navigation in challenging aquatic environments. Special attention is given to the integration of advanced electronic systems for precise control of the turbines, which will allow optimal manipulation of the underwater robot's movement and speed. This comprehensive approach aims not only to improve the robot's performance in terms of speed and maneuverability but also to ensure its durability and reliability in extreme underwater conditions.

3.1. CAD/CFD for mechanical modeling and Flow Simulation

The method outlines the process for developing an open-structure underwater robot made from 3D printing, utilizing CAD/CFD parameters to accurately analyze both the construction and behavior of the submarine. One methodology suggests employing CAD/CFD using high-level engineering software such as SolidWorks, to reduce costs and estimate enhancements in the robot [10]. These parameters enable a more precise study of how the structure would behave in water, besides, 3D printing manufacturing allows for precise customization of the structure, facilitating optimization for hydrodynamic efficiency and buoyancy.

TABLE 1: CAD Parameters [10]

Parameter	**Symbol**	**Dimension**	**Obtain**
Mass	m	kg	CAD
Buoyancy	B	N	Calculated
Weight	W	N	Calculated
Inertia	l_x, l_y, l_z	$kg \cdot m^2$	CAD
Inertia	l_{xx}, l_{yx}, l_{zx}	$kg \cdot m^2$	CAD
Inertia	l_{xy}, l_{yy}, l_{zy}	$kg \cdot m^2$	CAD
Inertia	l_{xz}, l_{yz}, l_{zz}	$kg \cdot m^2$	CAD
Volume	v	m^3	CAD
Length	L	mm	CAD
Width	a	mm	CAD
Height	h	mm	CAD

3.2. Stress–strain analysis

Stress tests simulate the physical conditions of the environment to which the robot will be subjected, showing potential points of deformation. These tests include mechanical displacement, von Mises stresses, and safety factor calculations. If the design exhibits weak points or fails to withstand the intended pressure, the CAD design must be modified to enhance its performance. One of the most important parameters to consider is the fluid pressure exerted on the structure. Pressure simulations can be conducted in SolidWorks to determine the effectiveness of the ROV's mechanical design under specific conditions [20]. Stress tests may unveil areas where additional reinforcement is needed to ensure the structural integrity of the ROV during operations in harsh environments, thus informing targeted design enhancements for optimal performance.

Figure 1 illustrates the procedure for constructing a 3D-printed ROV. This involves applying simulations, additive manufacturing, umbilical communication, assembly, and integration.

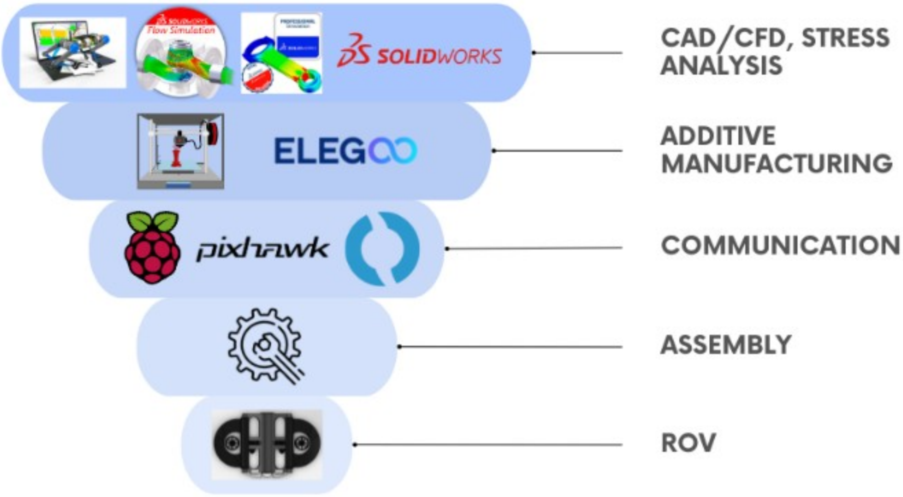

Figure 1: Procedure for ROV Design and Manufacturing

4. Development and Results

4.1. CAD Design

The first step in development is the CAD parameter, where a prototype of the final product is designed. This design then undergoes various simulations and tests to determine how optimal and hydrodynamic it is for navigating through water. To reach the result, several prototypes were designed, which did not meet the requirements and needed significant improvements, until obtaining the final prototype that met all the navigation and hydrodynamic movement requirements.

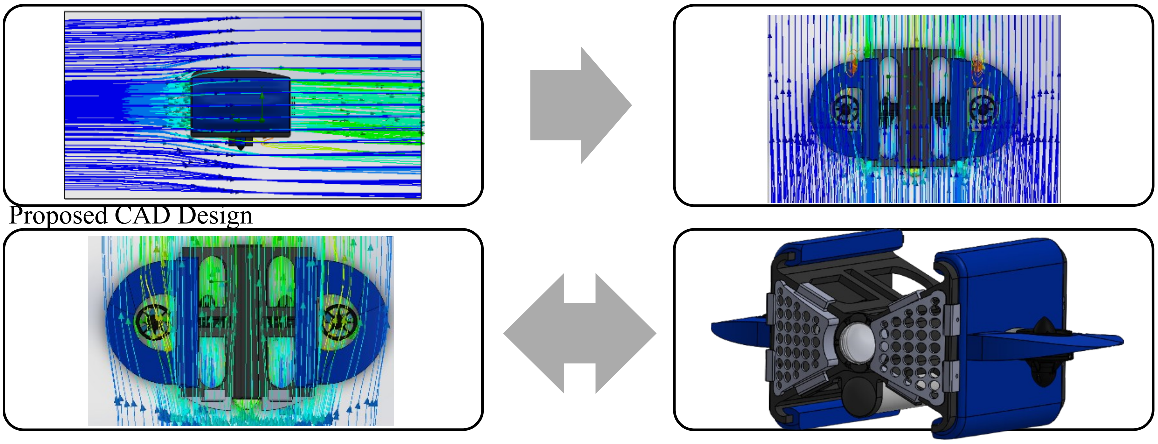

Figure 2: CAD Designs

Figure 2 shows the evolution of the design throughout the research. Starting with a design without wings and a square style, resulting in instability and the creation of vortices. The next image we have a design where the square is eliminated, but the side walls are kept creating wings for greater stability; however, vortices were still created that would affect the submarine's operation. Finally, we have the proposed CAD design for this project, where a piece is created at the front to displace water and eliminate vortices, resulting in a hydrodynamically capable submarine to navigate in water.

Once we have the design, we can obtain the CAD parameters provided by SolidWorks for the submarine, obtaining the mass, moments of inertia, volume, and lengths. The only two parameters that need to be calculated are buoyancy and weight.

TABLE 2: Results of CAD Parameters

Parameter	**Symbol**	**Dimension**	**Obtain**
Mass	m	kg	13.6
Buoyancy	B	N	130.3
Weight	W	N	133.416
Inertia	l_x	$kg \cdot m^2$	0.23823849
Inertia	l_y	$kg \cdot m^2$	0.41007389
Inertia	l_z	$kg \cdot m^2$	0.49175804
Inertia	l_{xx}	$kg \cdot m^2$	0.23823849
Inertia	l_{yx}	$kg \cdot m^2$	2.083E-05
Inertia	l_{zx}	$kg \cdot m^2$	-8.03E-06
Inertia	l_{xy}	$kg \cdot m^2$	2.083E-05
Inertia	l_{yy}	$kg \cdot m^2$	0.49175353
Inertia	l_{zy}	$kg \cdot m^2$	0.00060728
Inertia	l_{xz}	$kg \cdot m^2$	-8.03E-06
Inertia	l_{yz}	$kg \cdot m^2$	0.00060728
Inertia	l_{zz}	$kg \cdot m^2$	0.41007841
Volume	v	m^3	0.0129734
Length	L	mm	440
Width	a	mm	720
Height	h	mm	300

To calculate buoyancy, we must consider the volume obtained from the parameters, we also need the gravity and the density of the fluid where the submarine will be submerged, in this case, the density of water. In the case of weight, we must consider the mass obtained and the gravity.

To develop the equations, we need the following parameters:

$$\rho = 1.024\, kg/m^3$$

$$g = 9.81\, m/s^2$$

$$V = 0.129734\, m^3$$

$$m = 13.6\, kg$$

Once we have the parameters, we can develop the equations and obtain the buoyancy and weight:

$$Buoyancy\ Equation: f_b = \rho g V \tag{1}$$

$$Buoyany\ f_b = 130.3\, N$$

$$Weight\ Equation: W = mg \tag{2}$$

$$Weight\ W = 133.416\, N$$

4.2. Stress Test

The stress analysis proposes testing the structure of the submarine at different depths and therefore at different pressures. Submarines must have the ability to operate at various depths so that they can perform tasks that a person could not. In this test, the structure was tested at 3 different depths: 10, 25, and 50 meters, with pressures of 29.39, 51.43, and 88.17 psi respectively.

TABLE 3: Depth Parameters

DEPTH	PRESSURE	DEFORMATION
10 meters	29.39 psi	0.0024 mm
25 meters	51.43 psi	0.0042 mm
50 meters	88.17 psi	0.0072 mm

TABLE 3 indicates the parameters considered to test the pressure resistance of the structure. Three main depths were taken as reference, as the depth increased, the pressure increased; however, the deformation remained minimal. This result shows that the structure is designed correctly, and there are no critical points at these depths.

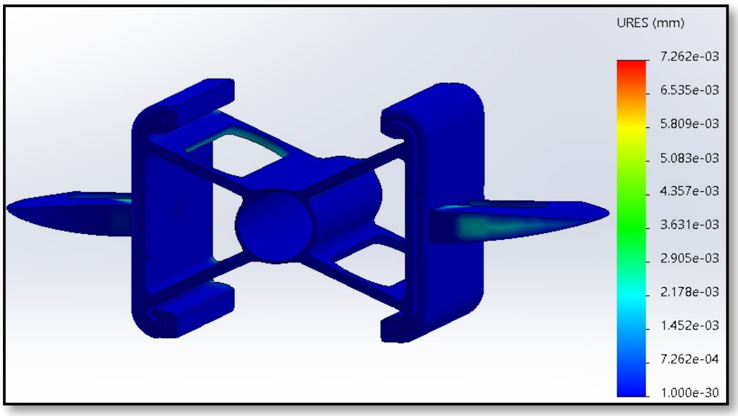

Figure 3: Stress Test at 50 m depth

Figure 3 shows the results of the stress test at 50 meters depth, indicating that the integrity of the structure remains unaffected, with only a minimal deformation of 0.0072 mm observed at the front of the wing.

4.3. Flow Simulation (CFD)

The CFD flow analysis helps us determine how an object would behave when in contact with a fluid. In this case, the submarine was tested at different fluid velocities ranging from 0.5 m/s to 2.5 m/s. With this CFD study, we can determine if the object has a hydrodynamic design for navigation.

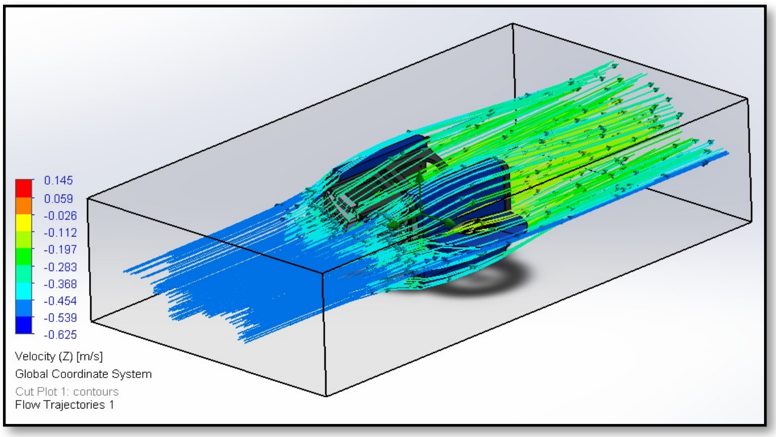

Figure 4: CFD Test (Velocity Z = 2.5 m/s)

Figure 4 illustrates that the fluid impacts the submarine and maintains a stable trajectory in relation to the submarine's geometry. No vortices or scattered fluid lines are created, indicating that the submarine will be able to navigate under good conditions.

4.4. Translational or rotational motion

The performance of the robot when moving linearly or rotationally along a specific axis can be assessed through simulations at various velocities. Throughout these simulations, data of the force and torque experienced by the robot at each velocity along the axis are collected. Velocities ranging from 0.5 m/s to 2.5 m/s were tested.

Velocity (Z)	Force (N)	Torque (Z)
2.5	-134.981	12.6275
2	-86.4403	11.9858
1.5	-48.5458	11.4905
1	-21.5517	11.1303
0.5	-5.41683	10.9505

TABLE 4: Forces and Torque at Axis Z

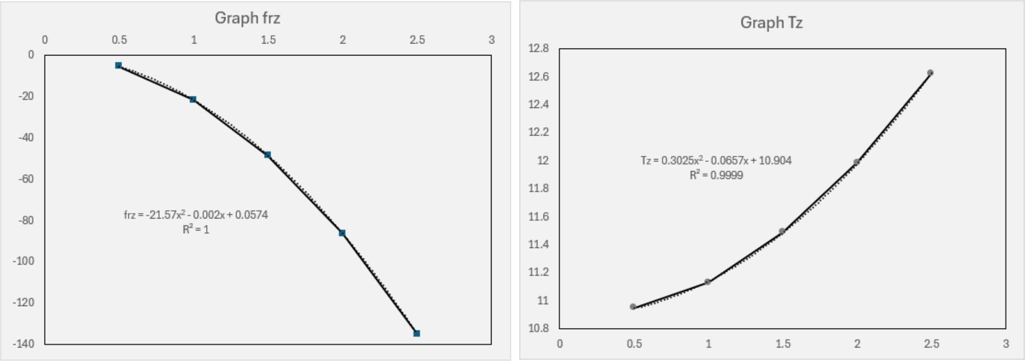

Figure 5: Polynomial graph (Axis Z)

Figure 5 displays the polynomial graphs obtained from the CFD simulations along the z-axis shown in Table 4. Same studies were conducted on each axis, and these graphs provide equations derived from the linear and rotational motion of the submarine.

Translation Movement X, Y AND Z AXIS

1) $frx = -64.935\, v_x^2 - 6.4103\, v_x + 2.6772$
2) $fry = 193.47\, v_y^2 + 4.9401\, v_y + 114.89$
3) $frz = -21.57\, v_z^2 - 0.002\, v_z + 0.0574$

Rotational Movement X, Y AND Z AXIS

1) $Tx = -0.4067\, w_x^2 + 0.3498\, w_x - 14.463$
2) $Ty = -0.7356\, w_y^2 + 0.3266\, w_y - 0.1046$
3) $Tz = 0.3025\, w_z^2 - 0.0657\, w_z + 10.904$

4.5. Fabrication and Testing

Figure 6: Open Structure ROV Assembly

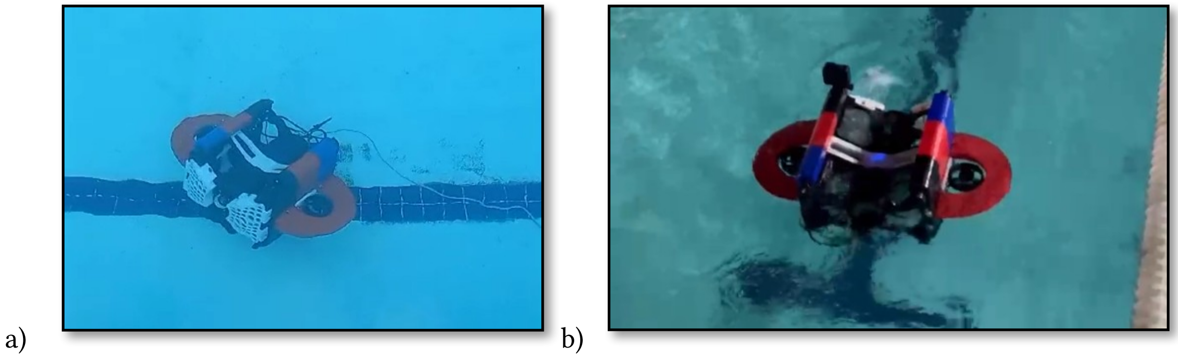

Figure 7: Submersion and buoyancy test

Figure 6 illustrates the assembled submarine undergoing testing in the university pool. The material used was PLA with 35% infill coated with epoxy resin, with a manufacturing time of 110 hours. Figure 7a demonstrates how the submarine has the ability to submerge to the bottom of the pool, while Figure 7b shows how the submarine floats in the water, fulfilling navigation requirements in both states.

5. Discussion

This research aims to significantly contribute to the field of underwater robotics through an innovative design and development of an open-structure submarine, a less explored area compared to closed-structure submarines. For example, in the case of closed-structure ROV research named “The preliminary of Design and Movement of Remotely Operated Vehicle (ROV)”, stability in water was compromised due to the geometry of its body. This investigation also adopts an approach that focuses on implementing 3D printing for submarine construction. This decision not only represents a more cost-effective alternative but also introduces a pioneering perspective in research, as most research on open-structure submarines is typically fabricated using conventional metals or plastics such as PVC. My contribution to science will not only expand the knowledge of open-structure submarines but also open possibilities for the application of 3D printing technologies in underwater engineering.

6. Conclusions

Submarine robots have emerged as an essential tool in maritime exploration, deployed to carry out various tasks across multiple industry sectors. The application of CAD/CFD parameters has demonstrated significant improvements in design, eliminating critical points identified during simulations. Furthermore, stress analysis has confirmed a submarine design capable of withstanding various pressures, making it ideal for subsequent testing in physical environments.

These results enabled the utilization of additive manufacturing for the creation of the submarine. 3D printing arises as a response to this need, capable of creating different custom designs of complex geometry. To increase its hardness and impermeability, epoxy resin was used, applied across the entire surface of the submarine. Continuous studies and proper manufacturing allowed for the creation of a submarine capable of navigating in water smoothly and consistently.

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