StrEAMLINING Sub-aquatic ROV FABRICATION through Mathematical MODELING, CAD AND CFD ANALYSIS for ENHANCEd PERFORMANCE

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Abstract
Nowadays, robotics research is quickly expanding and developing, allowing increased opportunities to perform studies using advanced technologies such as models and design software. This project aims to design and build a 5-DOF ROV, beginning with mathematical modeling and moving to kinematic and dynamic models to understand its behavior under various circumstances. The ROV designed uses CAD and CFD tools to ensure that it can endure environmental conditions while remaining highly maneuverable, low-cost, and capable of performing user-defined tasks. The body of the ROV is printed with an Ender 3 Pro 3D printer, the electrical system and data are driven by a Raspberry Pi 4, and the propulsion system is powered by six Blue-Robotics T200 Thruster turbines. Communication between the ROV and the land computer is performed via an umbilical cable with 8 pins. The project will facilitate research in the field of robotics, providing valuable insights into the design and operation of ROVs in challenging environments.

Keywords
DOF, ROV, CAD, CFD, mathematical modeling, RaspberryPi 4.

1. INTRODUCTION

Remotely operated vehicles (ROV) are underwater robots designed to accomplish tasks underwater. They are frequently utilized in a variety of sectors, including oil and gas exploration, marine research, and undersea exploration. Building a ROV requires detailed planning and consideration of several elements, including the environment in which it will operate, the activities it will do, and the materials and components utilized in its development [1].

This paper will describe the design and development of a ROV by applying different techniques to achieve an optimal design for any required needs. The robot should have a system capable of maneuvering in conditions of high dynamic requirements. Computer-aided design (CAD) and computational fluid dynamics (CFD) tools will be used to calculate the pressures to which the robot will be subjected, as well as a better hydrodynamic design based on fluid dynamics

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calculations. The manufacturing process for ROVs involves complex design requirements with stringent performance and cost-effectiveness criteria. This can streamline the ROV fabrication process and enhance performance while ensuring cost-effectiveness.

Developing a mathematical model where the basic morphology of our robot will be studied, as well as its kinematic model and dynamic model. For the electronic operation, the use of a Raspberry Pi would satisfy the need for electronics communication, which will be responsible for maintaining programming and communication with the various sensors and turbines to be used in the design of the ROV. For the monitoring system, it would count with video modules in a simple way. A Pix-hawk 2.4 controller for more accurate stability control, as well as real-time telemetry monitoring of the ROV [2].

This research will be key for the validation of the method based on CAD and CFD [6], as well as the improvement in the development of these robots for future research, reducing the time and cost of testing and the errors of mechanical designs that fail to meet demanding conditions in environments unfavorable for ROVs. Achieving an advance in underwater research and supplying the fundamental need on which this research is based, which is the constant and high-quality monitoring of the coral reefs of Honduras [3]. Nowadays, with the continuous development of low-cost technologies such as 3D printing and open-source hardware and software, the cost of building an ROV has been further reduced. Autonomous underwater vehicles have grown to be very popular for this purpose as a result of the increased use of remotely operated vehicles around the world, but the cost of controlling these vehicles is significantly higher than that of remotely operated vehicles [4]. This paper will present a valuable resource for researchers and engineers involved in the manufacturing process of ROVs and for anyone interested in exploring the potential of advanced modeling and analysis techniques in underwater technology.

2. Method AND Data

2.1. MeCHANICAL DESIGN based ON CAD

The proposed method attempts to define the required stages for designing a ROV capable of meeting the requirements determined for monitoring corals and marine life off the coast of Honduras. This research is based on a hierarchical method, which is quite useful for complex engineering design models such as mathematical modeling. In high-throughput processes, mathematical modeling and simulations are a fundamental part of achieving a high-quality study [5]. In the case of mathematical modeling, each level represents an equation that is related to the next level [2, 5, 6].

Many designs often involve using software tools to create detailed 3D models of a mechanical product or component. The design is created by defining various parameters and dimensions that specify the shape, size, and material properties of the object. Experimentation with computer-aided models is an increasingly important problem-solving technique. The aim of this method is to reduce costs by developing a customized robot that meets specific details and fits the needs required in different environmental scenarios and that fits specific needs for special tasks, which can be developed in CAD. This would mean considerable savings without the need to purchase a robot in the first instance [7, 8]. This test involves mechanical displacement, Von Mises stress,

Table 1
CAD Parameters

Parameter	Syhmbol	Dimension	Obtain
Mass	m	kg	CAD
Buoyancy	B	N	(Calculated)
Weight	W	N	(Calculated)
Moments of inertia	I_{xx}, I_{yx}, I_{zx}	$Kg \cdot m2$	CAD
Moments of inertia	I_{xz}, I_{yz}, I_{zz}	$Kg \cdot m2$	CAD
Moments of inertia	I_{xy}, I_{yy}, I_{zy}	$Kg \cdot m2$	CAD
Volume	V	m^3	CAD
Lenght	L	mm	CAD
Width	a	mm	CAD
Height	h	mm	CAD

and safety factor calculations. The CAD design must be modified to improve performance if it has flaws or can't withstand the pressure at which it is meant to be submerged. The pressure that the fluid applies to the structure is one of the most crucial factors to be taken into account. The parameters that the CAD model generates are displayed in Table. 1.

2.2. HydroDINAMIC Study

According to D'Alambert's paradox, which states that no hydrodynamic force will act on a body moving with constant velocity in a non-viscous fluid, frictional forces will be present when the solid body is in a viscous fluid, such that the system is not conservative with respect to energy, commonly referred to as interference drag [9, 10].

When a vehicle or solid body is submerged, it is essential to achieve the best possible stability to obtain better control of the vehicle. Sometimes external forces act on the ROV, which can cause a reduction in stability. The longitudinal design of the ROV will be fundamental to determining better stability [11]. The different drag coefficients according to its shape and design are presented for the ROV, where (DC) stands for "drag coefficient" and adopting a particularity of "double the speed, quadruple the drag," this refers to the amount of flow through which the ROV body goes and will increase its drag proportionally to the flow [10, 11].

3. Mathematical MoDELING

3.1. KINEMATIC MoDELING

When designing and manufacturing a ROV, mathematical development becomes a fundamental part when trying to have control in an environment as dynamic as the ocean. Testing a robot is time consuming and costly. Mathematical modeling is useful for simulation purposes and to design control systems that take into account the dynamics of the system before building it [12].

The mathematical model of a ROV requires two fundamental branches of study, these being kinematics and dynamics, the kinematic model consists of various equations which are

Table 2
Damping Coefficient Parameters

Axis	Symbol	Dimension	Symbol	Dimension	Obtain
	Linear Coeficients		Quadratic damping coefficients		
Surge	X_u	$N_{s/m}$	$X_u\|u\|$	$N_{s\ /m}$	PRBS
Sway	Y_v	$N_{s/m}$	$Y_v\|v\ \|$		PRBS
Heave	Z_w	N	$Z_w\ \|w\|$		PRBS
Roll	K_p	$N_{s/m}$	$K_p\|p\|$	N_{s2/m^2}	PRBS
Pitch	M	$NM\ \|q\|$	$_2\ N$	$_{s/m}$	PRBS
Yaw	N_r	$N_{s/m}$	$N_r\|r\|$	N_{s^2/m^2}	PRBS

responsible for relating the different coordinates used to represent the speed of the ROV and the dynamic model is responsible for describing the various forces acting on the ROV when it is in a dynamic environment [13].

ROV's have movements in six degrees of freedom in a marine environment. Knowing the DOF's of the ROV its necesary to begin to identify the coordinates needed for the mathematical model. Fluid simulations (CFD) must be perform to estimate the velocities at which the ROV could move in real scenarios, by doing these, we'll be able to understand the behavior of the robot as shown in Figure. 1. This data is obtained with a method called polynomial regression based on simulations (PRBS) [2]. Different parameters are obtained from the fluid simulations and are shown on Table. 2. Two reference frames must be defined named as NED global reference frame referenced to "The North, East Down world frame" and the B body reference frame denoted as The "body reference frames". In the body NED would be found the first three coordinates being (φ, θ, ψ) and their derivatives (p, q, r) which are used to describe the orientation angles and rotational motion of the ROV. The next three coordinates (x, y, z) and their derivatives (u, v, w) which are based on the translational motion about the x, y and z axes [8, 14, 15].

Taking into account the notation of SNAME the navigation and control system is common to use the notation x, y, z in reference to the earth (n) and the body (b) of reference specified or referred to in Euler angles as for rotations is why the vectors of velocity, torque and position where $v = [v\,1 v\,2]^T$, $n = [n1 n2]^T$ [14, 16].

3.2. Dynamic Modeling

The dynamic model of an ROV brings together the equations of forces and motions acting on the ROV. The Newton-Euler equations of motion to determine the dynamics of a submerged body would be used to obtain part of a dynamic system of the ROV. These bodies are exposed to different types of forces [17]. These are mainly inertial, hydrodynamic and restoring forces. To get an idea of how a dynamic model can be started, a short equation is presented and shown in (1).

$$M v + C(v)v + D(v)v + g(\eta) = \tau \tag{1}$$

To explain the above equation, M is described by a 6 x 6 matrix relating the inertia matrix

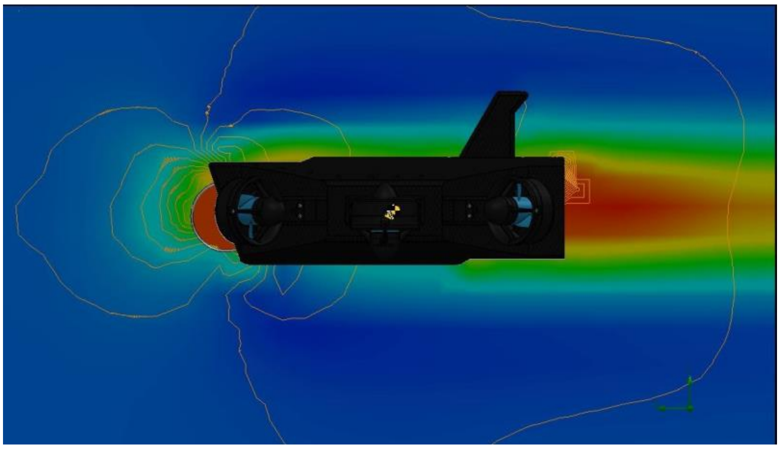


Figure 1: CFD Simulation of surface cutplot

and added masses in (2), C(v) is a 6 x 6 matrix relating the Coriolis matrix and its added masses in (3), D(v) is described as a 6 x 6 matrix in (4) elaborated using the damping forces and g which is represented by a 6 x 1 vector and elaborated using the restoring forces [18, 19]. Each of these matrix are made up of different parameters within each vector and are rewritten in (5), (6), (7).

$$M = M_{RB} + M_A \tag{2}$$

$$C(v) = C_{RB}(v) + C_A(v) \tag{3}$$

$$D(v) = D_L(v) + D_{NL}(v) \tag{4}$$

When deriving the equations of motion of the rigid body by applying Newtonian formulation, the mass matrix of the rigid body is calculated as follows [20] in (8) and (9):

$$M_{RB} = \begin{bmatrix} 8.409 & & & & & \\ 0 & 8.409 & 0 & & & \\ 0 & 0 & 8.409 & 0 & 0 & 0 \\ & & & 12162 & 0.\ 595065 & \\ & & & 0.000595065 & .217961 & -.\ 0257169 \\ 0 & 0 & 0 & -0.00000257171 & 0.0000\ 583 & 0.0000\ 678583 \end{bmatrix} \tag{5}$$

$$C_{RB}(v) = \begin{bmatrix} & & & & 8.4\ 9w & 0.30217 \\ & & & 0 & 0 & \\ & & & -84\ 09w & -8.409u & 0 \\ 0 & 0 & 0 & 84\ 09v & & \\ 0 & 8.4\ 9w & v & 0 & 0.302178r & -0.\ 7961q \\ -8.409w & 0 & -8.409u & -030\ 2178r & 0 & 0.121619p \\ 8.409v & -8.409u & 0 & 0217\ 961q & 0.121619p & 0 \end{bmatrix} \tag{6}$$

Applying hydrodynamic terms, the added mass matrix MA and Coriolis added masses can be derived by applying an energy method based on Kirchhoff's equations [20]. The added masses of the ROV in a fluid are determined by the added mass matrix which is defined as follows:

$$M_A = -\begin{bmatrix} -5.38031 & (& & & & \\ 0 & -5.38031 & -5.3^{0}8031 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ & & & & -0.3916 & 0 \\ 0 & 0 & 0 & 0 & 0 & -0.3916 \end{bmatrix} \tag{7}$$

There are four main sources of hydrodynamic damping in ROV's, these being potential damping, damping due to waves, surface friction between the ROV and the fluid, and damping due to vortex shedding. However, the effects of potential damping and damping due to waves are not taken into account in ROV studies, that is why D(v) can be expressed as a linear damping term DL caused by friction and a quadratic damping term DNL(v) due to vortices, these can be expressed in the following equations:

$$D_L = -diag[X_u, Y_v, Z_w, K_p, M_q, N_r] \tag{8}$$

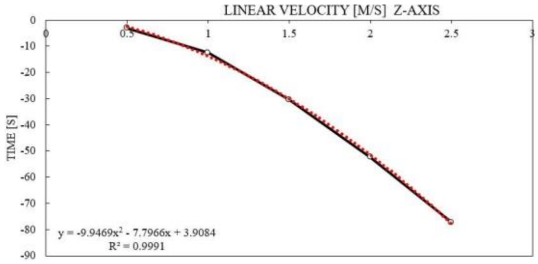
$$D_Q(v) = -diag[Xu|u||U|, Yv|v||V|, Zw|w||W|, Kp|p||P|, Mq|q||Q|, Nr|r||R|] \tag{9}$$

4. Fabrication

The proposed design consists of a closed, hermetic design with a large interior capacity. Its structure consists of a plastic shell, and with the help of Ultimaker Cura software, we were able to modify the parameters of the print, which is printed in poly-lactic acid (PLA) at a rate of 100 percent infill and a 0.2 mm height between printing layers, sealed with epoxy resin to seal any type of opening between the filament [21].

The design consists of 4 thrusters located horizontally and vectored at 45 degrees and 2 vertically, with this configuration the ROV obtain 5 DOF [22]. Although the shape of the robot plays a significant role in its hydrodynamics, the number of degrees of freedom it will have is unaffected. According to [23], an underwater robot's degrees of freedom depend on the quantity and placement of its thrusters. To achieve all degrees of freedom, some designs employ reconfigured vector thrusters (RVT) or a significant number of fixed thrusters. An RVT is described in [23] as a thruster connected to a servomotor inside the underwater vehicle that rotates to adjust the thruster's orientation and force.

The design with the lowest drag coefficient is presented as a streamlined body, which has a drop shape [8], hydro-dynamically more efficient than the other suggested bodies due to its front face when breaking the fluid. It is also observed that the streamlined half body obtains a much lower drag coefficient than the other design types; both designs share many similarities, affected by the angle of attack with which they pass through the fluid and affected by the drag suffered by the half body due to its curvature, which is very similar to a wing, despite this being a design not widely used in ROVs.



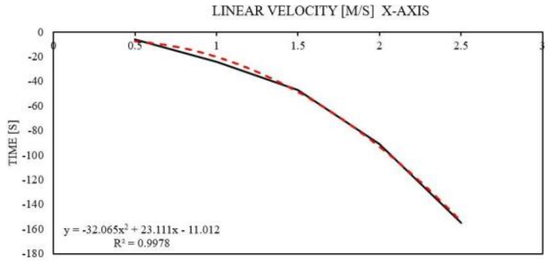


Figure 2: Linear velocity in Z and X axis, data is obtained through Polynomial regression based on simulations in CAD

The rov's primary role is to navigate in different directions underwater, but this is not an impediment to not taking into account the buoyancy of the ROV. If buoyancy is not taken into consideration, the ROV may end up with a very heavy design that will not be able to operate in a good way or a too-light robot that will not be able to submerge, and the design will fail [8,24].

5. Results

The research done in CAD and CFD allowed us to create a hydrodynamic design that can function under challenging conditions. The ROV's design was enhanced to move through water with the least amount of drag and the greatest amount of maneuverability. The results of the simulation indicated that the best performance would come from a streamlined shape with six symmetrical thrusters.

The six thruster configuration helps the robot gain good underwater movement. By making use of the data provided by solid works and performing fluid dynamics, we can describe all the possible movements and velocities that the ROV could operate under different circumstances. As shown in Figure. 2, the displacement of the ROV through the Z, Y, and X axis, was tested at 2.5 m/s against water currents.

Various stress tests were carried out through CAd and CFD calculations obtained in solidworks, tests where performed in multiple depths to ensure the ROV's safety and reliability. The stress study of the first test involved submerging the ROV to depths of 10 meters, 50 meters, and 100 meters. All tests perform with a good rating and a FOS above 1.44. However, at 100 meters depth, the safety factor was equal to 1, the deformation was greater than in the earlier tests. Therefore, in order to guarantee the ROV structure's security, a maximum depth of 100 meters was set.

The decision to use carbon fiber [25], was to add strength to the PLA (poly-lactic acid), the material used to 3D print the ROV, by doing so, the structure could increase the structural rigidity and strength the ROV needs and allow deeper operations by combining a cured carbon fiber layer over the PLA.

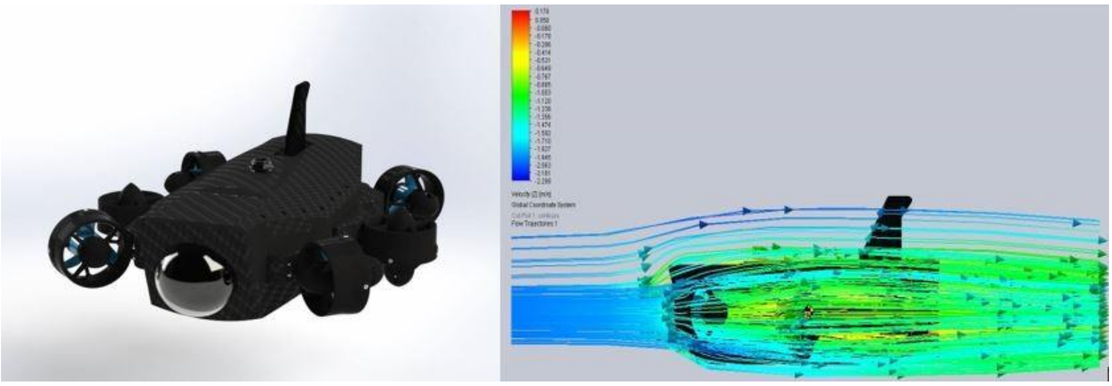


Figure 3: CAD Design and Hydrodynamic test

6. Conclusions

ROVs have become an essential component of sub-aquatic activities in a variety of sectors, including oil and gas research, marine antiquities, oceanography, and military uses. Advanced mathematical modeling, computer-aided design (CAD), and computational fluid dynamics (CFD) research have greatly improved the performance and cost-effectiveness of subaquatic ROVs. A complex process involving design, manufacturing, and testing is needed to create an underwater robot using 3D printing. However, the use of 3D printing technology has many benefits, such as the ability to precisely create custom designs with complex geometries. The robot can withstand the harsh underwater environment thanks to the use of water-resistant materials and waterproofing features. More people and organizations will be able to explore the ocean's depths as 3D printing technology advances and makes it easier and more affordable to manufacture underwater robots, as shown in Figure. 3.

CFD research is critical in the construction of ROVs. CFD analysis can forecast the movement of water and pressure on the ROV's surface by modeling the fluid dynamics that the ROV will encounter. This data can be used to improve the ROV's construction, decreasing drag while increasing speed and maneuverability. CFD analysis can also help improve the structural construction of the ROV, such as its buoyancy and stability, both of which are critical in subaquatic activities. The ability to maximize design and manufacturing processes reduces material and labor costs considerably, and the elimination of the need for tangible samples lowers total production costs.

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