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Comments on the Use of 3D Printing Technology in the Design of an AUV Destined for the Identification and Destruction of Underwater Mines

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Abstract

The International Maritime Organization and the North Atlantic Treaty Organization are today, enforcing increasingly stringent rules for maritime safety and security on a national and international scale. The need for security in the Black Sea has increased, the degree of danger has risen, and the risk of loss of life and destruction of ships or other surface or submersible marine vehicles cannot be overlooked. Autonomous underwater vehicles (AUVs) have various civil applications (targeting economic, industrial, and commercial interests), but military applications have recently gained prominence (needs for information, surveillance, and inspection, for the identification and destruction of risk obstacles). Given the high risk of destruction during the operation, solutions are being sought to enable the rapid and cost-free construction of AUVs without compromising their performance and efficiency. The paper's novelty is provided by the mention of 3D printing technologies as a possible solution, taking into account the successes in other essential fields of science and technology. The contribution of the paper was related to the AUV's body extremities (bow and stern), and the following factors were considered: geometric design using computer-aided design methods; hydrodynamic analysis of forms using computational fluid dynamics methods; and prototype manufacturing using 3D printing.

Keywords: 3D printing technology, Autonomous underwater vehicles, Mine counter measure, Computer-aided design, Computational fluid dynamics

1. Introduction

Autonomous underwater vehicles (AUVs), which are part of the major group of submersibles (see Figure 1), are becoming more popular due to their ability to perform a significant variety of both civilian and military missions, including scientific research, industrial and commercial interests, information, safety, and security objectives.

Due to their advantages, they have undergone an extremely diverse architectural evolution, and the very wide range of applicability has dictated the accentuated dynamics of the construction of these types of vehicles. AUVs, with remotely operated vehicles (ROVs), are members of the complex group of unmanned underwater vehicles (UVs). Their design and construction involve interdisciplinary studies, which include computerized architecture design, computational dynamics of fluids, modeling, and control of systems, robotics, image processing, and so on. With the emergence and development of informatics-cybernetics-computerization and robotization over the last decade, the use of calculation and analysis methods of computational fluid dynamic (CFD) type has established itself as a fast, reliable, and cost-quality-efficient tool in the design and evaluation of hydrodynamic performances of submersible vehicles.

The design and construction of an AUV prototype intended for the detection and destruction of underwater mines were approved as part of the Sectoral Plan for Research and Development of the Romanian Ministry of National Defense. The approved project will be carried out in three stages (see Figure 2), as follows: in 2022, the hydrodynamic

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design of the AUV's body will be completed; in 2023, the hydrodynamic design and construction of the propulsion and governance system are targeted; and in 2024, the project will be completed with the final execution of the AUV and testing under real operating conditions.

Figure 1. *Constructive types of AUV's and ROV's [1]*

AUV: Autonomous underwater vehicle, ROV: Remotely operated vehicle

This study highlights the project's first-year results (Figure 2). The bow and stern domes of the body were the ones that received CAD hydrodynamic design and CFD simulation. In the second year of the project, after the CAD hydrodynamic design of the propulsion and governance system, the CFD simulation will be resumed and the results of model testing in the wind tunnel will be compared. Early and partial results from the second year of the project were also revealed.

2. Literature Review

The subject of UVs has sparked widespread (in terms of time) and intense (in terms of the number of published documents) interest in the world scientific community, civil and military, engineering, and other fields. If there is a single consecrated in this complex field of study, then it would undoubtedly be Thor Fossen, which has consistently addressed the issue of UVs in its publications [2-4], representing a significant bibliographic reference for any researcher interested in this topic.

The following summative results obtained by researchers interested in the field will be presented, with the selection made based on the subjects that have been approached in this study: architecture (dimensions, shape) of an AUV, ensuring nautical qualities; advanced methods of calculation, modeling, and CFD hydrodynamic simulation; equipping with on-board systems and equipment; use of 3D printing technology.

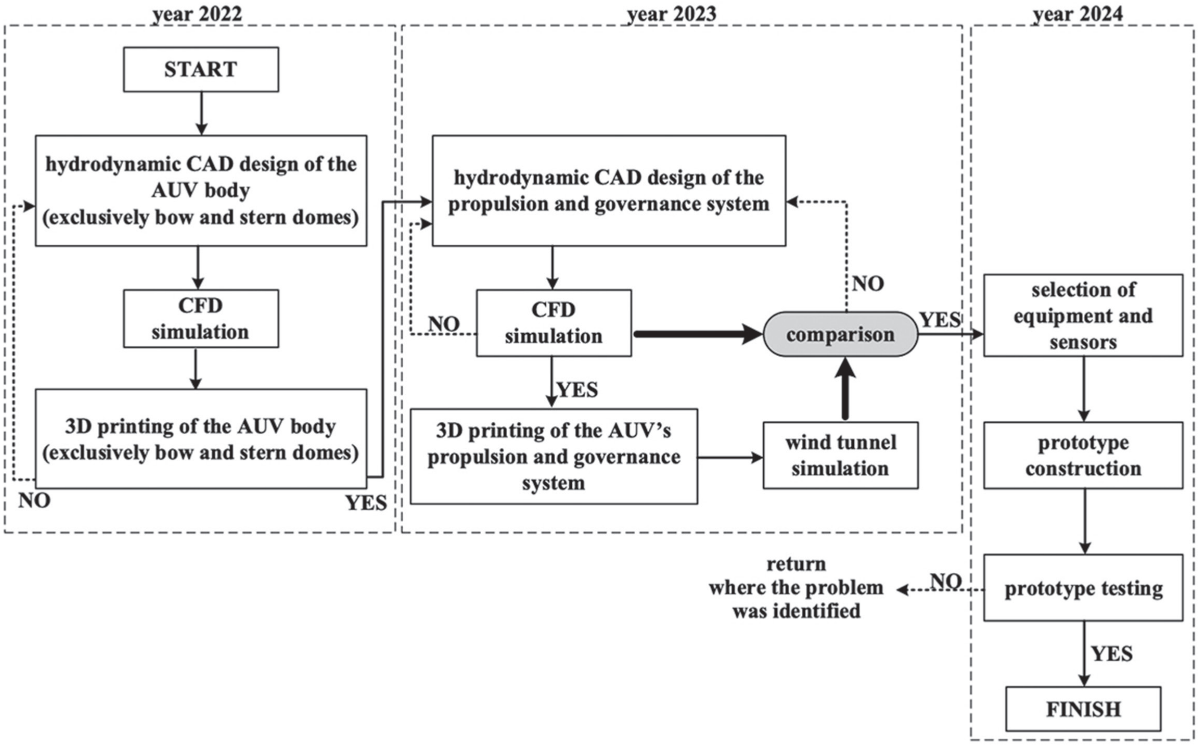

Figure 2. *Flow chart of the project*

CFD: Computational fluid dynamic

To develop the design of an AUV [5], the perspective of correlating the dimensions (of available space and equipment transport capacity) with the speed of movement was imposed (energy consumption). The parameters of an efficient design proved to be the dimensions and profile of the forward (nose) and aft (tail) structures and the dimensions of their reinforcers [6]. The optimization of the shape of an AUV is usually a multi-objective decision-making problem and is essential for determining its nautical qualities. The authors of this paper [7] recognize that the shape of an AUV is dictated by its functionality and has evolved from classical torpedo forms to special, unconventional forms.

UVs with hybrid propulsion, designed to develop an ultra-wide range of speeds, are presented in the literature [8], as is a conventional autonomous underwater glider with a propeller. A spheric amphibian vehicle is a spherical robot that is capable of operating in two different environments: terrestrial and underwater. Controlling the movement of a spherical robot is a difficult task, hence, it is designed with only two degrees of freedom: can move forward/backward and left/right [9].

More cutting-edge research proposes a bio-inspired architecture, with the shape optimized using the response surface method to obtain body sampling points [10]. The design of modular and reconfigurable AUVs aimed at improving their usability by extending their versatility and adaptability to new situations and missions is of great interest. This is achievable with a modular system design of hardware and reconfigurable software [11].

To reasonably design an AUV, the problem of stability during diving on a spiral trajectory was studied and the static, kinematic, and dynamic characteristics of diving were analyzed using MATLAB/Simulink software [12]. The relationship between net buoyancy, longitudinal center of gravity movement, metacentric height, and trajectory diving stabilization parameters was analyzed. The hydrodynamic performance of an AUV, particularly forward resistance (which is conditioned by the body's architecture), is an important factor in determining the power requirements and body shape of an AUV. The hydrodynamic performances of an AUV as well as the distribution of velocities and pressure of water particles around the body were studied [13] using CFD methods and various geometric shapes. According to Bono and Buttaro [14], the performance of an UV is conditioned by its forward resistance (drag), which is a crucial factor in the preliminary design phases to determine the hydrodynamic shape of the vehicle leading to the achievement of the operational requirements.

Maneuverability is an important dynamic nautical quality of an UV, and its prediction is essential for preliminary design. The purpose of this study [15] is to examine the maneuvering capacity of a UV during diving, lifting, or space spiraling movements. The paper [16] proposes the design of a hydrodynamic profile (using the "Myring" equations) for unmanned submersible devices, by numerical simulation, to achieve a highly maneuverable vehicle, capable of moving horizontally and vertically.

The main performances (such as the speed of movement correlated with the drift phenomenon, dynamic stability, gyration diameter, maneuverability, spiral immersion trajectories, etc.) become easily and efficiently predictable with the help of CFD modeling and simulation methods, [17]. These numerical methods must be validated by comparing them to the results obtained in the towing tanks on the models and after real-sea trials on the prototypes.

Small UVs have unique advantages in ocean exploration. Hou et al. [18], and the other members of the research team believe that the vehicle's strength and volume are key factors affecting its underwater operating time. The hydrodynamic performance of a small UV is numerically analyzed using CFD methods by which the value range of the design variables related to the body is determined. A fully detailed methodology to identify the hydrodynamic parameters of an autonomous underwater mini-vehicle and evaluate its performance using different controllers (based on the theory of handling arms in robotics) is presented in the bibliographic reference [19]. The authors investigated the effects of the head shape (nose) on the hydrodynamic performance of an AUV-type vehicle in their conducted study [20]. The essential features of vehicle nose architecture are presented and discussed, considering pressure distribution and complex friction phenomena. The results obtained by the authors can be used as a guide to improving the design of architectural forms for AUV models.

The design of AUVs is very complex due to the high demands of the marine environment, such as the range of working depths, forward resistance, and energy efficiency. Amory and Maehle [21] present a hydrodynamic analysis and simulation of fluid flow on the surface of the body of a micro AUV using CFD methods to establish a three-dimensional (3D) model and the ANSYS Fluent software for hydrodynamic properties analysis. To maximize the operation time, the AUV body must be so designed and equipped to withstand harsh environmental conditions while minimizing hydrodynamic resistance. According to [22], the main factors influencing AUV design are the pressure distribution on the body and hydrodynamic resistance. With the results obtained based on CFD simulations but also with empirical estimates, it was possible to obtain optimum parameters relating to vehicle buoyancy and drag, to reach optimal energy consumption.

The influence of the angle of attack (tilt) on the robot's trajectories in the entrance and exit phases of immersion, was studied [23], as well as the speed, pressure distribution on the body's surface, and the suction coefficient. Honaryar and Ghiasi [24], in their paper present the hydrodynamic characteristics of an AUV designed for inspecting submarine pipelines and cables. The authors were interested in the stability of this bioinspired AUV (the shape of a sea cat), whereas this nautical quality could be affected by various disturbances, such as marine currents, during the inspection process. The findings show that, when compared to other submersible bodies with the same axis of symmetry, the proposed model is about 99 more stable; thus, it is ideal for inspecting submarine pipelines and cables. In the study of [25], the effects of the free surface on the hydrodynamics of submersibles operating at various depths are investigated. It has been concluded that the diving depth has a significant role in the resistance components for a Froude number greater than 0.7, and the various appendixes arranged on the body have little effect on the deformations of the body surface.

This paper [26] describes the hydrodynamic modeling of a multi-body UV. This special construction (a set of heterogeneous bodies with known dynamic parameters that are rigidly connected) can be used when configuring the robot controllers or intervening to fix (possibly multiple) failures. It was discovered [27] as early as 1987 that any component failure must be corrected by an automatic system for an UV to operate fully autonomously. Thus, the software architecture was conceived, and this sets out the performance requirements for command-and-control hardware.

Finally, the use of 3D printing techniques in this field should be given a suggestive reference. This paper [28] describes the design and construction of two AUV models. The 3D printing technique was used to fully achieve the sections and annexes of the models, with each necessary step for design and construction being presented in the paper. The technology of 3D printing has also piqued the interest of researchers in the maritime military field, who have discussed publicly [29] about "3D printing capsules" housed in shipping containers and which create portable 3D printing facilities, usable for a wide range of military needs, such as rapid production of spare parts or destroyed military components. Problems that arise during crises can be solved quickly and cheaply by creating such on-site 3D printing facilities.

Paragraph 23 of the "NATO 2022 Strategic Concept" [30] stipulates: "Maritime security is key to our peace and prosperity. We will strengthen our posture and situational awareness to deter and defend against all maritime threats, maintain the freedom of navigation, secure maritime trade routes, and protect our main lines of communications."

Furthermore, the European Union (EU) created the European Defense Agency (EDA). This was established on July 12, 2004, by a joint action of the Council of Ministers "to support the Member States and the Council in their effort to improve European defense capabilities in the field of crisis management and to sustain the European Security and Defense Policy as it stands now and develops in the future" [31]. EDA currently has three initiatives: coordinated annual review on defense; permanent structured cooperation (PESCO); and the European defense fund.

The project maritime (semi-) autonomous systems for mine countermeasures (MAS MCM), which includes 10 European countries, was proposed and approved under PESCO initiatives. The MAS MCM will deliver a world-class mix of (semi-) autonomous underwater, surface, and aerial technologies for maritime mine countermeasures. The project will enable Member States to protect maritime vessels, harbors, and offshore installations while also ensuring freedom of navigation on maritime trading routes. The development of autonomous vehicles, using cutting-edge technology and an open architecture in a modular configuration, will contribute significantly to the EU's maritime security by helping to counter the threat of sea mines [32].

Therefore, the initiative to develop a prototype of an AUV destinated for the identification and destruction of underwater mines using 3D printing techniques to achieve the body is justified.

3. Materials and Methods

3.1. Body Design

The vehicle was designed using AUTODESK FUSION 360 [33] and SOLIDWORKS [34] software licenses. The design was engineered with two hydrodynamic domes, with several working variants considered (Figure 3 illustrates three of them). The variants of CAD models for the AUV's body bow and stern structures were also subjected to CFD analysis, and a final choice was made, namely a modified version of variant no. 2 shown in Figure 3. In this stage of the research, the focus was on a proper modeling of the geometric shapes of the extremities of the AUV's body and ensuring the optimal flow of fluid around the theme. The next steps will bring significant changes, following the addition of other components parts of the AUV (propulsion and governance system, floaters, sensors, specific equipment et al.).

The first utility software, AUTODESK FUSION 360, was used to develop the original architecture for checking tolerances and for the detailed design of the components, while the second, SOLIDWORKS, was used to generate the work file required for ANSYS [35] software to simulate (via CFD methods) the flow of fluid around the vehicle, which ultimately allowed the choice of hydrodynamic shape (Figure 4).

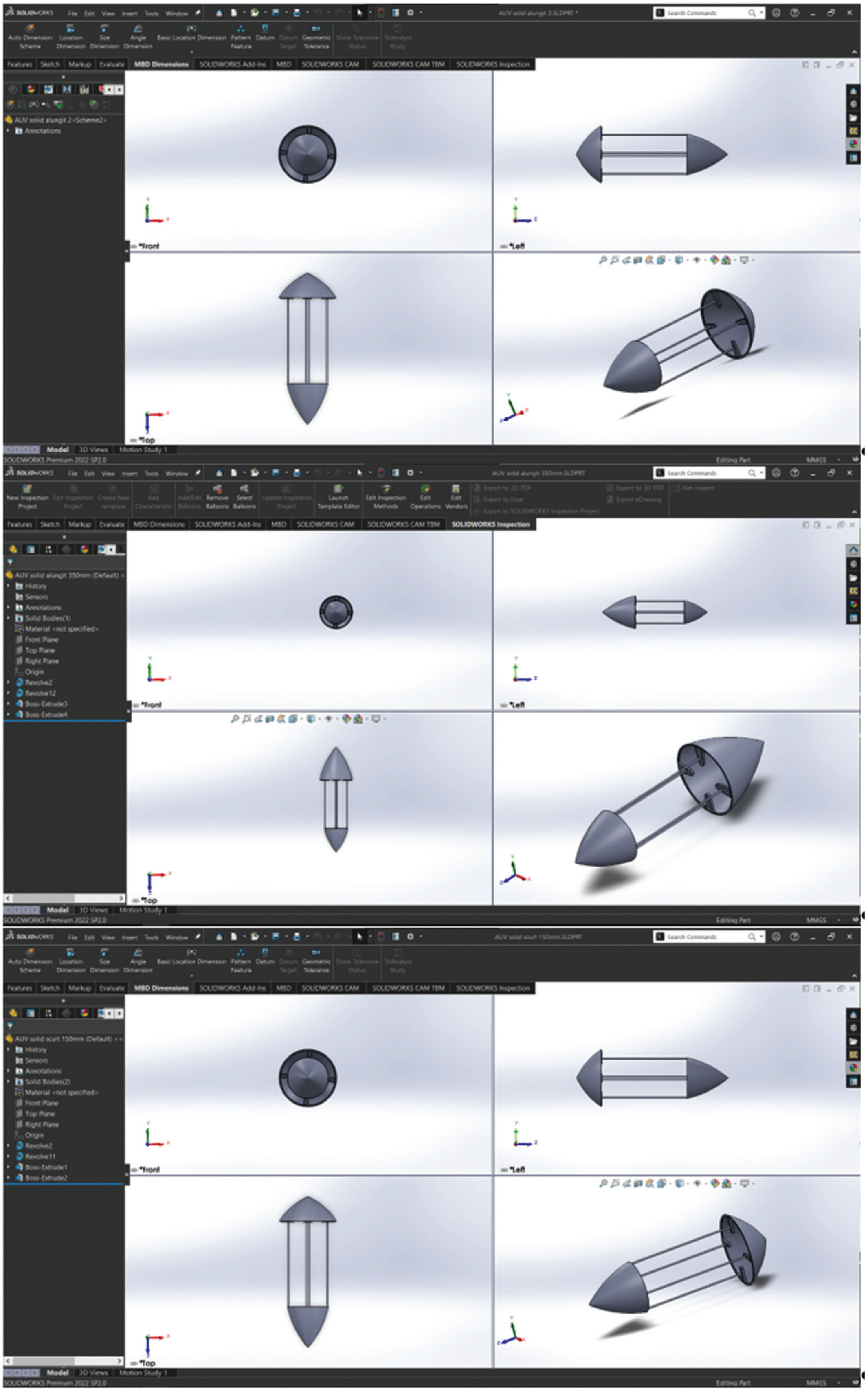

Figure 3. *Shape variants for AUV*

AUV: Autonomous underwater vehicle

We anticipate that the propulsion will be provided by two "brushless" engines located on the sides of the assembly, attached to the threaded bars through sleeves/collars and hydrodynamic profiles. Figure 5 shows the CAD design of those engines, which will be necessary for further CFD simulation (see Figure 2). The engines have more power in comparison to the gauge of the AUV, can operate underwater without problems, and only require short-term maintenance at the end of the mission.

The possibility of manually changing the position of the engines in the longitudinal plane has been ensured using M8 nuts before the operation, which determines the AUV's good maneuverability. Furthermore, by varying the engine rotative speed, a curvilinear trajectory of the vehicle can be ordered, thereby eliminating the need for a governing body (rudder). The engines included protective hulls with a NACA hydrodynamic profile, which improves efficiency, reduces propeller noise in the water, and ensures the safety of the crew or diver operating nearby.

The trajectory of the AUV during immersion (depth and angle of inclination) is controlled by two other engines (Figure 6), of the same functional type (brushless,) located in the vertical plane (one in the bow area and one in the stern area).

All components of the autonomous UV (domes, bars, engines, sleeves, and oil/air floaters) will be dimensioned in such a way that the buoyancy of the robot is positive. As a peculiarity, (immersion is ensured using vertically located motors; if a malfunction occurs or control of the robot is lost, for any reason, all engines will stop and the vehicle will slowly rise to the surface due to the buoyancy with which it was provided). The robot will be modular, allowing it to have different configurations depending on the tactical situation, resulting in different weights. The buoyancy will be maintained by adding or removing oil/air floaters.

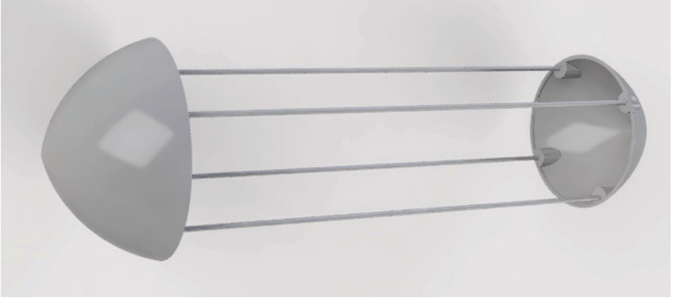

Figure 4. *View from the bow semi-profile of AUV*

AUV: Autonomous underwater vehicle

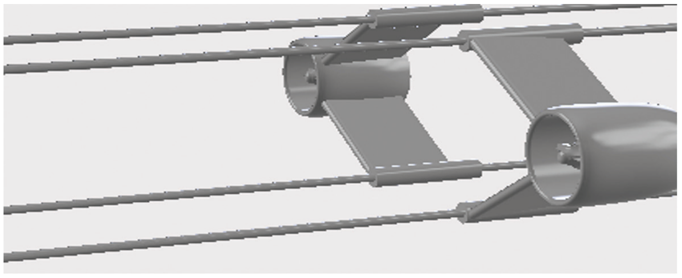

Figure 5. *View from the bow semi-profile of AUV with the propulsive system*

3.2. Hydrodynamic Analysis

Fluid dynamics are used in a wide range of fields where the behavior of gases and liquids must be studied. CFD modeling generates 3D, time-accurate data about fluid movement in general, as well as particle trajectories or surface dynamics. Simply put, if there is a geometric model (3D CAD model) of the system to be studied and information on fluid properties can be used, then various aspects, such as velocities, flow rates, trajectories of current lines, the pressure distributions of certain contours, and so on, can be successfully studied. The study of fluid-structure interaction focuses on the flow of the fluid as well as its encounter with a solid structure. Modeling with ANSYS involves, in principle, going through clear stages of work, but it should be noted that detailing the process is practically impossible. The essential steps of the way of working with ANSYS have been completed for the hydrodynamic analysis of the designed vehicle (the shape was defined with the command "Geometry"; the surface was processed with the command "Mesh" and boundary conditions have been set; the variables were determined, and the solution was processed by launching the command "Execution calculation"). "Results" is a CFD post-processor that visualizes how the analyzed object will behave in various real-world scenarios through simulated demonstrations.

It should be emphasized from the start that in the previously mentioned project, CFD simulations will be carried out in two stages (see Figure 2): for the bow and stern extremities of the AUV's body in the first year of the project (and these elements are illustrated briefly below); for the AUV equipped with the propulsion and governance system in the second year of the project (and which are not completed at this time), although some elements of propulsion and governance system design are presented in the paper (see Figures 5 and 6). The CFD simulations performed will be compared to the wind tunnel tests.

Therefore, the CFD analyses presented in this study are affected by the fact that they are made for the two domes (bow and stern) that are currently modeled in an open architecture. The purpose of including these results in this work serves to broaden the subsequent stages.

Three studies were completed, for which an underwater ambient temperature of 25° and a working depth of about 10 m below sea level (hydrostatic pressure of 1 atm.).

In the first case analyzed, the AUV moves in a horizontal plane on a linear trajectory (forward/backward, left/right) at a speed of 2 m/s.

In the second, the AUV moves horizontally on a curved trajectory (the vehicle turns right at an angle of 45°), with a resultant of speed 1.41 m/s for this compound horizontal movement.

In the third study, AUV performs a compound spatial motion (exit from the immersion at a speed of 2 m/s while performing a right turn with an angle of 45°), with the resultant speed of 1.16 m/s used in the simulation.

Only the most recent case analyzed, considered the most complex, is presented for rational sizing in this work. Some general comments are required, without entering the details of the simulation.

The computational domain around the experimental hull body is represented by a sphere (Figure 7) with a radius of 4 m, filled with water at a temperature of 25 °C, and modeled as an incompressible fluid.

The physics of the computational domain is presented in Table 1.

The vehicle body was rigid and completely submerged in water (without wave and current disturbance). Before performing the CFD, the mesh size and the shape of the boundary must be defined properly. It is recommended that the mesh size be small enough to capture the geometry of the AUV. In this case, the mesh information consisted of 167578 elements and 29474 nodes. The body vehicle has a smooth wall roughness and no-slip wall. The domain has a boundary-type opening, subsonic flow regime, and medium-intensity turbulence.

The main boundary physics is presented in Table 2.

The figures below show the graphic results of the simulations for: the variation of the velocity of the streamlines (Figure 8); the variation and the values of the drag force (Figure 9); and the pressure gradient (at the bottom of Figure 10).

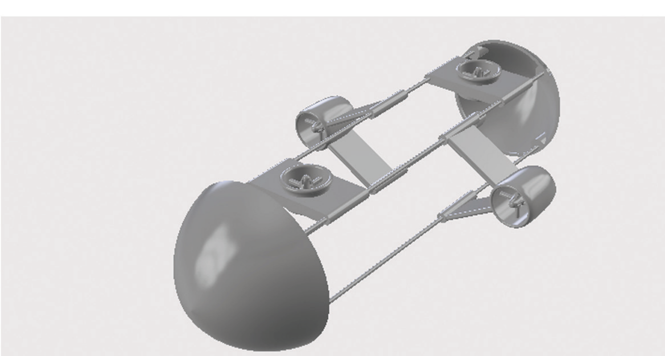

Figure 6. *View from the bow semi-profile with the entire propulsion system mounted*

3.3. 3D Printing of An Autonomous Underwater Vehicle

In Figure 11, several stages of printing of the forward dome of the AUV are illustrated.

A 3D printer (Snapmaker model) was used to create a prototype of an AUV, which can print objects in spaces ranging from (230 x 250 x 235) mm to (320 x 350 x 330) mm, with a layer resolution of 50 to 300 microns. The printer is a part of a modular group that can do everything from 3D printing to laser engraving and numerical control command

Table 1. *Computational domain physics*

Domain - Default domain	
Type	Fluid
Location	B121
Materials	
Water	
Fluid Definition	Material Library
Morphology	Continuous Fluid
Settings	
Buoyancy Model	Non-Buoyant
Domain Motion	Stationary
Reference Pressure	1.0000e+00 [atm]
Heat Transfer Model	Isothermal
Fluid Temperature	2.5000e+01 [C]
Turbulence Model	Shear Stress Transport - SST
Turbulent Wall Functions	Automatic

Table 2. *Boundary physics for CFX 2*

Domain	**Boundaries**	
Default domain	Boundary - sphere	
	Type	OPENING
	Location	F122.121
	Settings	
	Flow Regime	Subsonic
	Mass and Momentum	Cartesian Velocity Components
	U	1.1600e+00 [m s^−1]
	V	1.1600e+00 [m s^−1]
	W	1.1600e+00 [m s^−1]
	Turbulence	Medium Intensity and Eddy Viscosity Ratio
	Boundary - AUV	
	Type	WALL
	Settings	
	Mass and Momentum	No Slip Wall
	Wall Roughness	Smooth Wall

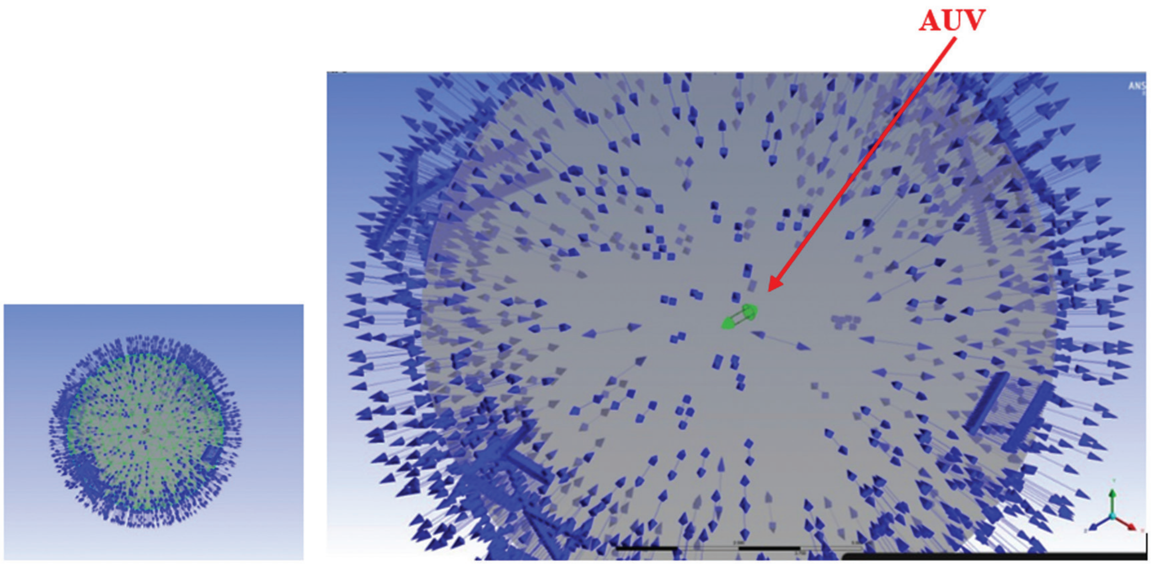

Figure 7. Computational domain

AUV: Autonomous underwater vehicle

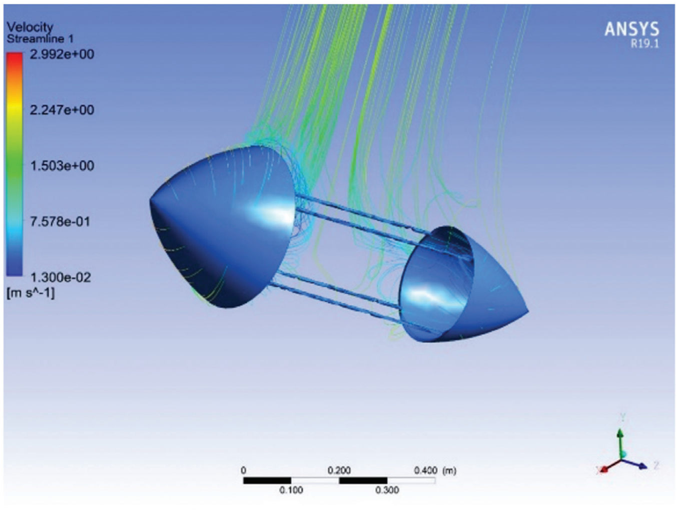

Figure 8. *Velocity variation*

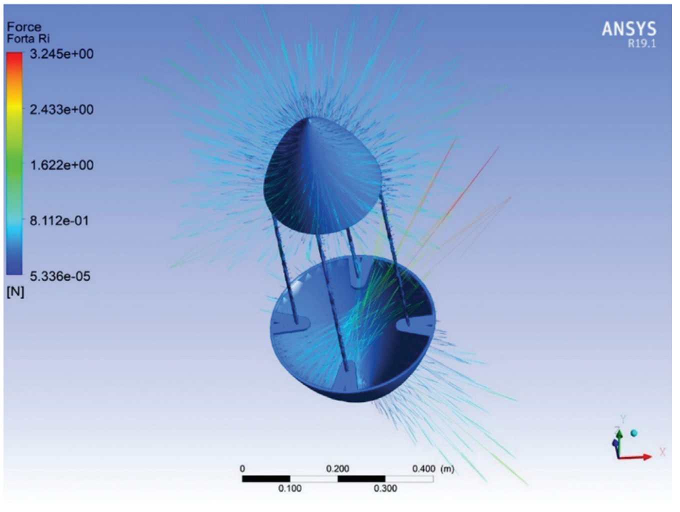

Figure 9. *Drag force variation*

cutting. The proximity sensor probes and obtains data for multiple points on the work platform, and the software calculates and compensates for microscopic irregularities in real-time, ensuring a consistent, correctly applied base layer, for 3D printing as performant as possible.

The 3D printing and installation of brushless propulsion engines, sleeves, and hydrodynamic profiles are suggestively shown in Figure 12.

4. Conclusions and Perspectives

3D printing is a technology that superimposes successive layers of material under the control of the computer (which reads a CAD file), resulting in a 3D object. As 3D printing processes have evolved and new solutions and technologies have emerged, the advantages of this technology have become more clear, as also have the disadvantages or, better said, the possible limits. The advantages are related to design freedom, rapid prototyping, personalized printing, waste minimization, and environmentally friendly processing, all of which involve efficiency, which is translated into time and cost. Technology allows for the development of design ideas, as well as a faster production process, and a higher final product quality. The disadvantages (for the moment, because 3D printing technology is advancing and the present limits will be exceeded) concerns, in particular, the high production costs for serial production, the limitations of the material s that can be used (plastic, although many metals are suitable for technology), and printer performance (which conditions the resistance of the product or the accuracy of the product).

This prototype will contribute to efforts to strengthen national and European defense and it may be used to defend and secure territorial waters, as well as joint missions to defend and secure the international EU's waters of the NATO Allied Forces. The AUV-type system can also be used for civilian purposes, such as inspection and protection of all maritime and port infrastructure.

A solution consisting of two hydrodynamic bodies joined together with threaded bars was chosen for the general architecture of an AUV, which has advantages in terms of modularity and simplicity in construction and access to components.

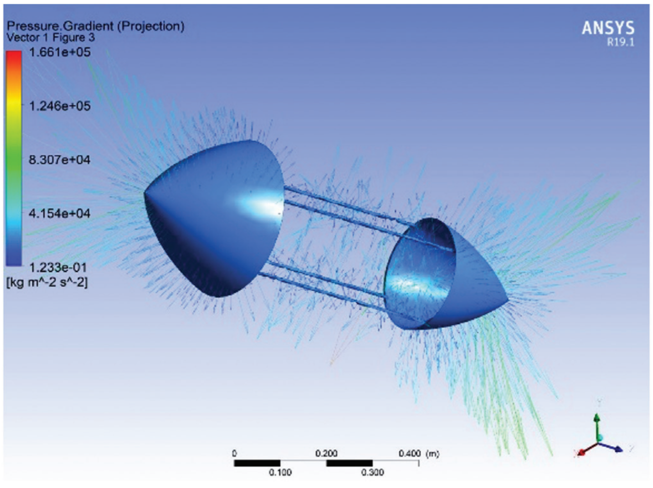

Figure 10. *Pressure gradient*

As previously stated, several architectural variants were considered, for which hydrodynamic analyses of fluid flow on the body's surface (bow and stern) were also performed. The average size, with a forward dome height of 150 mm and the height of the aft dome of 125 mm, produces the desired performance at a vehicle movement speed of 2 m/s, according to simulations.

Figure 13 shows the completed prototype, with printing at 1:2 scale. The forward dome (right side in Figure 13) has a diameter of 300 mm and is intended to form a low-pressure zone around the components behind it, to reduce friction. The aft dome (shown on the left side of Figure 13) has a diameter of 250 mm and is intended to close the pressure lines while also reducing friction. The 4 bars are 1 m long and are threaded for an M8-type assembly.

The main difference between the prototype proposed within the project accepted by the Romanian Ministry of National Defense and that made at the level of the consortium of European countries is that of the reduced consumption of resources (human, financial, production time, and so on.). The idea of the achievements of an underwater robot

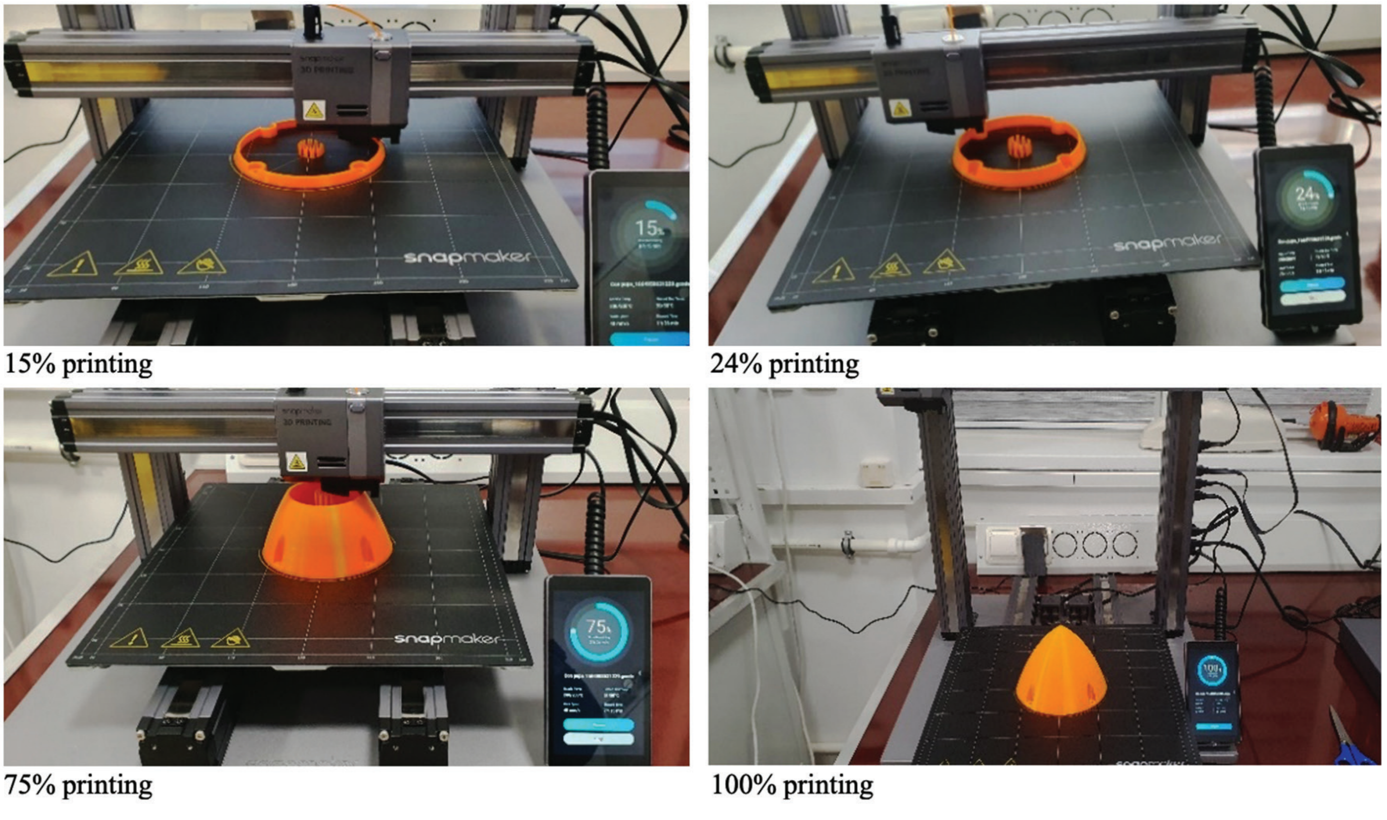

Figure 11*. Printing stages of the AUV's forward dome*

AUV: Autonomous underwater vehicle

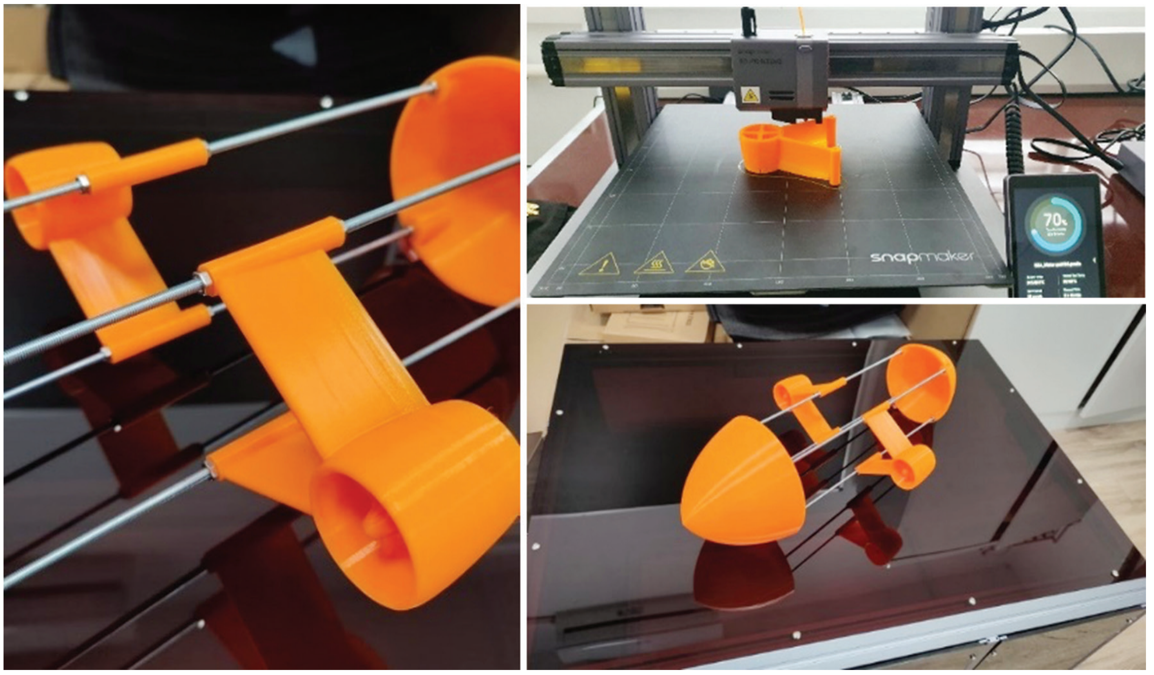

***Figure 12**. Stages of printing and installation of AUV propulsion engines*

AUV: Autonomous underwater vehicle

***Figure 13**. Autonomous underwater vehicle-3D printed prototype*

produced quickly and with free market equipment resulted in the context of the presence of sea mines in areas of national responsibility in the Black Sea (in the context of the armed conflict between Russia and Ukraine) and the lack of the expected final result from the MAS-MCM project. Under these conditions, the Romanian National Naval Forces were forced to intervene in the discovery and destruction of sea mines using non-compliant resources (ships from the military fleet), thus exposing both ships and personnel to very high risks.

The greatest advantage of this AUV (which is, in fact, a multifunctional underwater platform) is its modularity and architecture, which allows for the rapid installation of a robotic arm, cameras, projectors, and various sensors, among other things.

Of course, there are still steps to be taken between the prototype and the final product. This study present the results of the architectural design of the AUV body (the goal was to obtain a new underwater robot open-case (form) with optimal length and form for good hydrodynamic) as well as the advantages of using the 3D printing technology in this phase prior to the actual construction of such a vehicle.

Following that are the steps depicted in Figure 2: design and construction of the propulsion and steering system, equipping appropriate to the mission undertaken, completion of the final concept, and testing the prototype under real-world operating conditions.

The authors are convinced that they will return in a future paper with new results.

Peer-review: Externally peer-reviewed.

Authorship Contributions

Concept design: M.G. Manea, O. Cristea, Data Collection or Processing: C.-P. Clinci, O. Cristea, Analysis or Interpretation: M.G. Manea, C.-P. Clinci, O. Cristea, Literature Review: M.G. Manea, Writing, Reviewing and Editing: M.G. Manea, C.-P. Clinci, O. Cristea.

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