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Hybrid Unmanned Aerial Underwater Vehicle: Modeling and Simulation

Paulo L. J. Drews-Jr[1,3] Armando Alves Neto[2] Mario F. M. Campos[3]

Abstract— **The complete modeling and simulation of an unmanned vehicle with combined aerial and underwater capabilities, called Hybrid Unmanned Aerial Underwater Vehicle (HUAUV), is presented in this paper. The best architecture for this kind of vehicle was evaluated based on the adaptation of typical platforms for aerial and underwater vehicles, to allow the navigation in both environments. The model selected was based on a quadrotor-like aerial platform, adapted to dive and move underwater. Kinematic and dynamic models are presented here, and the parameters for a small dimension prototype was estimated and simulated. Finally, controllers were used and validated in realistic simulation, including air and water navigation, and the environment transition problem. To the best of our knowledge, it is the first vehicle that is able to navigate in both environment without mechanical adaptation during the medium transitions.**

I. INTRODUCTION

Nowadays, unmanned autonomous vehicles have been the focus of many development efforts, with a large range of applications. The amount of resources applied has improved their capabilities, especially in the military field. Remotely operated or autonomous Unmanned Aerial Vehicles (UAVs), for example, were used in recent military operations around the world [1]. But they were also used in non-military activities, like agriculture [2] and surveillance [3]. Another important robotic platform are the Unmanned Underwater Vehicles (UUVs), whose the most known are the Remotely Operated Vehicles (ROVs). This kind of vehicles can also be applied in several commercial field operations [4], e.g. oil and gas extraction in ultra deep waters [5].

Both kind of vehicles are well adapted to work in their own environment (air and water, respectively), but some situations may require a single vehicle capable of working in both environment. Such requirement commonly appears when is necessary to perform maintenance on partially or fully submersing structures, as ship hull or risers. A typical approach includes using auxiliary vessels to transport ROVs that will make the inspection of offshore target regions. This problem is harder in partially submersed structures. In such situations, where the usage of auxiliary ships is difficult and expensive, underwater robots equipped with wheels or tracks are recommended.

[1]P. Drews-Jr is with the NAUTEC, Centro de Ciencias Computacionais, Universidade Federal do Rio Grande, RS, Brazil. E-mail: paulodrews@furg.br

[2]A. Alves Neto is with the Telecommunication and Mechatronic Engineering Department, Universidade Federal de São João del-Rei, MG, Brazil. E-mail: aaneto@ufsj.edu.br

[3]M. Campos and P. Drews-Jr are with the VeRLab, Computer Science Department, Universidade Federal de Minas Gerais, MG, Brazil. E-mail: mario@dcc.ufmg.br

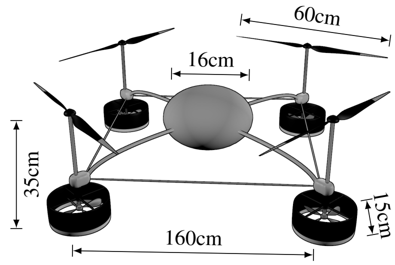


Fig. 1. A proposal design for our Hybrid Unmanned Aerial Underwater Vehicle (HUAUV).

Here we propose a novel, efficient and cheaper design for robots capable of navigating in both, air and water, environments. Figure 1 provides an image of the conceptual platform we will discuss through the paper. It is called Hybrid Unmanned Aerial Underwater Vehicle (HUAUV) and presents several advantages when compared with another hybrid vehicles presented in the literature. To the best of our knowledge, it is the first vehicle able to navigate in both environment without mechanical adaptation during the medium transitions. It allows the vehicle to make rapid transitions and be prototyped in large range of sizes. The application set of our proposed vehicle is wide, but, as an example, we cite the mapping problem of remote areas – as the Antarctica continent or the Amazon rain forest. It is a typical challenge that includes aerial and underwater mapping, almost at the same time. In such inhospitable regions, the access to boats can be costly and difficult, but it is required to transport underwater vehicles to explore and map. However, our HUAUV could be launched from control stations on the ground or on the ships, and then fly to the target place, where the vehicle submerges to accomplish the task.

II. RELATED WORK

There are many different works dealing with the problem of modeling and simulating UUVs [6], [7], [8] and UAVs [9], [10], [11]. However, vehicles with hybrid (air-water) characteristics are less investigated. Some underwater vehicles with flying capabilities or aerial vehicles with diving features were proposed through the history. Between World War I and II, it was published an article in the American Modern Mechanics Magazine concerning a hybrid vehicle, developed and tested by the Denmark Navy [12]. In fact, the physical vehicle was never presented, just its conceptual project. In 1934, a Russian naval cadet proposed a vehicle called Flying Underwater Boat, capable of carrying three persons and weight up to 15 ton [13]. It also was never built.

In the 1960's, the engineer Bruce Reid built the first hybrid air-water vehicle, called Reid Flying Submarine (RFS-1). It was a single-seat craft capable of air and underwater navigation. The pilot needed to use an aqualung for breathing underwater. During its first tests, the vehicle flew 10 m in altitude and submerged 2 m in depth [14].

In the last decade, the USA Defense Advanced Research Projects Agency (DARPA) funded a project from Lockheed Martin Company called Cormorant MPUAV [15]. As the name says, it was an multi-purpose aerial vehicle with payload of 450 kg. The idea was to have a vehicle that could be launched from submarines, capable of flying with jet propulsion. It would return to the submarine with the aid of ROVs. The project started in 2006, but the contract was cancelled in 2008, before the prototype was built.

In 2008, the DARPA specified a canonical mission for submersible airplanes in a Broad Agency Announcement [16] and [17] proposed a conceptual design that theoretically fulfilled all requirements. It needs eight operators and equipment totaling 2,000 pounds of payload. In the project, two different devices were proposed: a turbo-fan engine and two electrical motors for aerial and underwater navigation, respectively. In order to submerge, valves are opened to flood all of the interior space within the structure. Differently from our proposed vehicle, it is hard to miniaturize and performs slow transition, requiring different mechanical device in each environment.

Recently, the MIT Lincoln Lab has designed a Hybrid Aerial-Underwater Vehicle [18] which is an unmanned vehicle capable to fly, plunge dive into water and navigate underwater by folding its wings. Compared to our proposal, the vehicle presents complex design and control; it is not able to take-off from water and needs to change their mechanical design to navigate underwater. Similar to this project, [19], [20] proposed an hybrid vehicle capable of taking-off from the water using balloon inflation. Some limitations remain present as the complex mechanisms, and the need of mechanical adaptation to transit between both environments.

It is possible to see that all of these vehicles present complex mechanics, what makes their existence almost impractical. But the main problem of such platforms concerns the transition environment process, i.e. the changes that must be done to the vehicle structure in order to allow it to transpose from air to water, or vice-versa. This and other characteristics were taken into account when we perform the design of our vehicle. In the next section, we begin by choosing one among several classical robotic platforms, seeking to point out the most appropriated to work in both environments.

III. METHODOLOGY

In order to define a suitable methodology to build a hybrid air-water vehicle, we study the available architectures, taking into account different parameters such as payload and modification issues of the primary structure, among others. An important aspect of the project is the platform choice. We based this question on the possibility of adapting an existing aerial platforms to do underwater navigation or underwater platforms to fly.

A. Platform Selection

As presented in [21], we begin by defining some available architectures. Two lists of possible alternatives are given below, followed by Table I where we compiled ratings from 1 to 5 – 1 for the worse case and 5 for the better – to find the best candidate. Those values were arbitrarily and empirically chosen, based on our researches and knowledge of several characteristics of the problem.

1) Aerial Vehicles:

- Fixed-wing airplanes – as main characteristic, these platforms present the need for constant air flow through their wings, providing lift force during fly process. They also need great obstacle-free areas to take-off and landing, a significant constraint to our application. They do not allow hovering or stable control at low altitudes in small areas, but present high aerodynamic efficiency and high speed navigation at high elevations.
- Tail rotor helicopter-like vehicles – helicopters are very complex mechanisms compared to airplanes. They are expensive to buy and maintain, navigate at low speeds, present low energy autonomy and payload. As advantages, they have good maneuverability and can do hover fly near to the ground at small areas. They also allow vertical taking-off and landing, a very important advantage to missions in uneven environments.
- Coaxial rotor helicopter-like vehicles – these are rotary-wing devices with basically the same advantages and disadvantages of the previously presented, except for the fact they are more compact and mechanically simpler, something desirable in our project. However they have more complex aerodynamic behavior and limited maneuverability.
- Quadrotor-like vehicles – these are aerial platforms boosted by four propellers with fixed angle of attack. Their motion control is performed by the unbalance on the rotor speeds and the consequent thrust generated by them, which make the vehicle stable and maneuverable. Their main advantages are high payload/vehicle volume ratio, and the capability of low altitude and hover navigation like helicopters. However, they present high energy consumption, due to the number of propellers employed, and are more susceptible to wind disturbances.
- Blimps, balloons and aerostats – this kind of vehicles (also known as lighter-than-air aircrafts) are platforms sustained by large cavities filled with gas less dense than air, such as helium. Their main advantage is the low energy consumption and noise disturbance. However, they have a great disadvantage when considering underwater environment. Their navigation may be impossible due to the large volume filled with an element very much lighter than water.
- Bird-like vehicles – these are relatively novel platforms, inspired in biological motion dynamics of nature, like birds and bugs. Their main advantages are the possibility

of build small devices, with low energy consumption and little noise interference. They also present low payload capability and complex dynamics, with actuator systems very difficult to design and build. And, though there are fishes with this kind of underwater behavior, the hydrodynamic of wing in dense fluids are not efficient.

2) Underwater Vehicles:

- Torpedo-like systems – these are underwater "vehicles" characterized by their closed architectures, like submarines and fish-like missiles. They have good payload capabilities and can navigate at high speeds due to their hydrodynamic design. However, due to their high value of added mass (we will discuss it later), they need powerful actuators and, consequently, present high spend of energy in navigation tasks.
- ROV-like systems – unlike torpedoes, these are underwater vehicles based on open (or non-closed) structures. Because of this feature, the environment fluid (air or water) can pass through their body, causing low values of added mass and drag. However, they present bad aero and hydrodynamic profiles, and are normally heavier than common aerial and underwater vehicles, with unsatisfactory payload/weight ratio.

As far as these platforms are concerned, we elaborate the Table I, with our classification to each vehicle according some desired characteristics to maximize the design of our project. For reasons we cited before, blimps and ROVs were eliminated from our analysis, basically due their hydro or aerodynamic inefficiency.

TABLE I
PLATFORM CLASSIFICATION.

Features / Platforms	*Airplane*	*Helicopter*	*Quadrotor*	*Coaxial*	*Bird-like*	*Torpedo*
Aerial controllability	4	2	3	2	2	2
Underwater controllability	2	2	3	1	1	3
Payload/Vehicle volume	2	3	5	4	2	2
Energy consumption	3	2	1	2	3	2
Mechanical simplicity	4	2	3	2	1	4
Hovering	1	5	5	5	3	1
Low speed navigation	1	3	4	4	2	1
Environment switch-over	3	3	4	4	5	5
Modeling simplicity	3	2	3	2	1	3
Env. (noise) interference	2	1	1	1	2	2
Weight (added mass)	3	3	4	3	3	3
Aerodynamic modeling	3	2	4	2	2	3
Hydrodynamic modeling	3	1	3	2	1	4
Structure modification	2	2	3	3	3	1
Miniaturization	3	3	3	4	2	3
Final score	39	36	**49**	41	33	39

This qualitative analysis presents us the quadrotor as the winner. I.e., it is the best candidate to our hybrid aerial-underwater robot. It presents simple mechanical structure and mathematical model, good maneuverability and controllability, high payload score and allows hovering. However, it has a high energy consumption and significant velocity constraints.

B. Propellers Design

Propeller design is a key task in the project of aircrafts (especially rotary-wing vehicles) and underwater systems, once it represents the main source of thrust. Even for fixed-wing airplanes and lighter-than-air vehicles, propellers are responsible for providing acceleration forces, and they must be designed according to desired behaviors of each project. Equivalent importance can be seen at the design of propellers for underwater crafts. Traction forces provided by them are responsible for maintaining the vehicle under the water and producing forces to move it.

Aerial and aquatic propellers present quite distinct shapes from each other, since the environments in which they operate have different characteristics, such as density and viscosity. In our study, we used a propeller design software called *JavaProp* to project both propellers of our hybrid quadrotor. This software is based on the methodology of optimal propeller design presented in [22].

The main parameters describing a propeller are: (i) the thrust coefficient c_f and (ii) the power coefficient c_w. Both were calculated based on the density ρ (in kg/m^3) of each environment, the rotation speed $\mathbf{\Omega}$ (in revolutions per minute – rpm) and the diameter D (in meters) of the propeller itself, as shown in Equations 1 and 2, respectively:

$$c_f = \frac{\mathbf{f}}{\rho\,\mathbf{\Omega}^2\,D^4}, \tag{1}$$

and

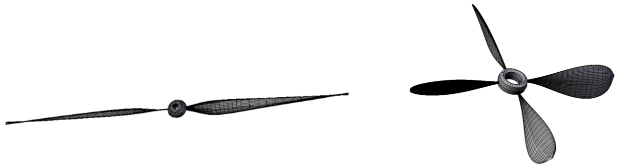
$$c_w = \frac{\mathbf{w}}{\rho\,\mathbf{\Omega}^3\,D^5}. \tag{2}$$

where $\mathbf{f}$ represents the provided thrust (in Newtons) and $\mathbf{w}$, the consumed power (in Watts) applied to the propeller.

1) Aerial Propeller: Initially, efforts were concentrated on the design of the aerial propeller, empirically expected to be larger than the water one. In the air, the thrust provided by the set of four rotors is the only force available to support the vehicle. In the absence of other forces (such as buoyant, completely insignificant in the air), traction should be sufficient to overcome the weight force of the drone. These propellers are also the main sizing factor on quadrotor-like aircrafts. Therefore, we sought to design a propeller that generates the force required with the smallest size possible, thus reducing the overall length of the vehicle.

Another important point is the power system, which also represents a limiting factor to the force generated by the propellers. This also depends on other factors, such as efficiency of engines and the energy delivered by the battery module. Figure 2(a) presents the aerial propeller designed to our vehicle. With D = 0.60 m, we chose a two-bladed propeller able to provide 6.23 N at rotation speed of $\mathbf{\Omega}$ = 2,000 rpm, and $\mathbf{w}$ = 50 W. Moreover, four propellers produce enough power to sustain a weight of 2.6 kg. The air density in this case was estimated as $\rho_{\text{air}} \approx 1.29\,\text{kg/m}^3$.

2) Aquatic Propeller: Next, we concentrated on the design of the aquatic propeller. For this case, buoyant force is more expressive than in the air, due to its dependency of the medium density ρ, the gravitational magnitude $\|\mathbf{g}\|$, and the body



(a) Aerial propeller (b) Aquatic propeller

Fig. 2. *JavaProp* three-dimensional design of (a) the aerial (diameter of $0.60\,\mathrm{m}$) and (b) the aquatic propeller (diameter of $0.15\,\mathrm{m}$).

volume V. Supposing buoyant larger than weight, the thrust to submerge the robot will be smaller than to sustain it in the air. On the other hand, density is directly proportional to the drag force and the added mass, which creates resistance to the vehicle's movement. Thus, the aquatic propeller needs to generate enough force to allow the navigation with a desired speed.

Due to the water density[1], approximately $1{,}025\,\mathrm{kg/m^3}$, it is possible to generate high thrust forces with reduced size and rotation speed. As ρ_{water} is around one thousand times larger than ρ_{air}, the parameters c_f and c_w will be very different from the previous one. Figure 2(b) shows the designed aquatic propeller with diameter of $0.15\,\mathrm{m}$ and four blades. Considering a rotational speed of $500\,\mathrm{rpm}$ and the same power, it experiences forces of about $7\,\mathrm{N}$.

C. Robot Modeling

The next step is to define the mathematical model of our robot. We used the Newton-Euler formalism to establish this model in a workspace $\mathcal{W} \equiv \mathbb{R}^3$. It was considered a state vector $\mathbf{x} \in \mathbb{R}^{12}$ consisting of positions and orientations of the vehicle, and their respective derivatives, in the Lie Group SE(3), such that $\mathbf{x} = [\mathbf{p}\ \mathbf{v}\ \boldsymbol{\psi}\ \boldsymbol{\omega}]^T$. Here, $\mathbf{p}$ and $\mathbf{v}$ are linear position and velocity vectors of the center of mass of the vehicle, respectively, related to the world's reference frame $\{\mathcal{W}\} \in \mathbb{R}^3$, $\boldsymbol{\psi}$ is the orientation vector in SO(3), also related to $\{\mathcal{W}\}$, and $\boldsymbol{\omega}$ is the angular velocity vector related to the body reference frame $\{\mathcal{B}\}$ attached to the center of mass of the quadrotor.

The vehicle input vector, $\mathbf{u} = \boldsymbol{\Omega} \in \mathbb{R}^4$, is composed of the angular velocities – in rpm – applied to the rotors. Positive values of $\boldsymbol{\Omega}_i$ mean thrust in the air propellers, while negative values mean thrust in the water propellers. Details of the propulsion system are described in [23][2] (patent pending). It is also important to establish $\mathbf{p}_{\text{ref}} = [x_{\text{ref}}\ y_{\text{ref}}\ z_{\text{ref}}]^T$ as the reference position control in the $\mathbb{R}^3$ workspace, where $z = 0\,\mathrm{m}$ is the surface between air and water.

1) Added Mass: Added mass is an effect that often appears in modeling problems of underwater vehicles. It basically represents the force necessary to accelerate the vehicle against a fluid with volume equal to its own geometric volume, V, making its inertia bigger than the real one. However, estimating the value of the mass flow moving with the robot is a non-trivial task, once it varies with the complex and non-symmetrical geometry of the vehicle. For simplicity reasons, we assume the sphere of the central part of the vehicle as the main volume to be moved (Figure 1), with radius $R = 0.08\,\mathrm{m}$. It allows us to calculate the added mass (Eq. 3) and the added inertial matrix (Eq. 4) of our robot:

$$m_a = \frac{4}{6}\pi\rho R^3, \tag{3}$$

$$\mathrm{I}_a = m_a R^2 \begin{bmatrix} \frac{1}{5} & 0 & 0 \\ 0 & \frac{1}{5} & 0 \\ 0 & 0 & \frac{2}{5} \end{bmatrix}. \tag{4}$$

2) Restoring and Drag Forces and Moments: Restoring forces (in a passive way) provide equilibrium states for physical systems without the need of actuation. The weight force in the air or in the water depends exclusively upon the vehicle's mass – both are equal. In contrast, the buoyancy force depends upon the medium density ρ. Therefore, it is non negligible in the water. Both forces are exerted along the Z axis in the space. Underwater robots are normally projected such that the buoyancy force is slightly larger than weight [24]. This is important for safety reasons, because the vehicle can automatically return to the surface if power supply fails.

Another important issue is related to the location of the center of buoyancy and center of gravity. The stability of the vehicle depends on the relative lines of action of these two forces (pitch and/or roll moments can be generated by the unbalance). Thus, the center of buoyancy needs to be exactly above the center of gravity. In this situation, the vehicle is considered unconditionally stable. Our proposed vehicle has all of these features.

In other hand, drag forces and moments are effects that resist to the motion of the vehicle. It is an important topic in fluid dynamic area due its relevancy in projects of aerial and underwater vehicles. Similar to added mass and buoyancy force, drag forces and moments depend upon the medium density, being significant in water. While restoring forces improve the stability of the vehicle in the medium, drag makes the movement harder.

3) Vehicle Dynamics: The robot's linear motion can be written as

$$\dot{\mathbf{p}} = \mathbf{v}, \tag{5}$$

$$\overline{m}\dot{\mathbf{v}} + \mathrm{C}\rho\mathbf{v}|\mathbf{v}| + (m - \rho V)\mathbf{g} + (\mathbf{v} \times m\boldsymbol{\omega}) = \mathrm{R}\begin{bmatrix} 0 \\ 0 \\ \sum_{i=1}^{4} \mathbf{f}_i \end{bmatrix}, \tag{6}$$

where $\mathbf{p}$ is defined in meters and $\mathbf{v}$ in meters per second. Also, $\overline{m} = (m + m_a)$, C is the matrix of drag coefficients, $\mathbf{g}$ the gravity vector, V the quadrotor volume, R the SO(3) rotation matrix of the vehicle in the three-dimensional space from $\{\mathcal{B}\}$ to $\{\mathcal{W}\}$, and $\mathbf{f}_i$ the force provide by the i-th motor

$$\mathbf{f}_i = c_f \boldsymbol{\Omega}_i^2, \qquad \forall i = 1 \ldots 4, \tag{7}$$

with c_f been the propeller coefficient given by Eq. 1.

[1]Water temperature of $25\,^{\circ}\mathrm{C}$.

[2]In english, "Air-Water Propulsion Device for n-Rotor Amphibian Vehicles", number: BR 102012023897-7 – Brazil

Similarly, the angular motion can be described by

$$\dot{\boldsymbol{\psi}} = \mathrm{B}\boldsymbol{\omega}, \tag{8}$$

$$\bar{\mathrm{I}}\dot{\boldsymbol{\omega}} + \mathrm{C}\rho\,\boldsymbol{\omega}|\boldsymbol{\omega}| + (\boldsymbol{\omega}\times\mathrm{I}\boldsymbol{\omega}) = \begin{bmatrix} l(\mathbf{f}_2 - \mathbf{f}_4) \\ l(\mathbf{f}_3 - \mathbf{f}_1) \\ \sum_{i=1}^{4}(-1)^{i+1}\mathbf{m}_i \end{bmatrix}, \tag{9}$$

where $\boldsymbol{\psi}$, in radians, is the Euler angular vector and $\boldsymbol{\omega}$, in rad/s, is the angular speed vector. We used the ZYX Euler angular representation, where ϕ, θ and ψ are the roll, pitch and yaw moments, respectively. Also $\bar{\mathrm{I}} = (\mathrm{I} + \mathrm{I}_a)$ is the total inertial matrix of the robot – diagonal due to the vehicle's symmetry – B is the matrix that transforms angular velocities from $\{\mathcal{B}\}$ to $\{\mathcal{W}\}$, l is the distance between each rotor and the center of the vehicle, and $\mathbf{m}_i$ is the moment provide by the i-th motor, given by

$$\mathbf{m}_i = c_f l \boldsymbol{\Omega}_i^2, \qquad \forall i = 1\ldots4. \tag{10}$$

4) Control Laws: We used simple Proportional-Derivative (PD) and nonlinear controllers to stabilize and navigate the HUAUV through the environment. Similar control designs for quadrotors can be seen in [25], [26]. All controllers here were obtained by adequate linearization of Equations 5, 6, 8 and 9 at operating points corresponding to hover conditions [26].

The rotor speed (input) vector can be rewritten as

$$\boldsymbol{\Omega} = \begin{bmatrix} \delta\Omega_T - \delta\Omega_\theta + \delta\Omega_\psi \\ \delta\Omega_T + \delta\Omega_\phi - \delta\Omega_\psi \\ \delta\Omega_T + \delta\Omega_\theta + \delta\Omega_\psi \\ \delta\Omega_T - \delta\Omega_\phi - \delta\Omega_\psi \end{bmatrix}, \tag{11}$$

where $\delta\Omega_T$ is the nominal thrust speed that provides lift and $\Delta\Omega_{\boldsymbol{\psi}} = [\delta\Omega_\phi,\ \delta\Omega_\theta, \delta\Omega_\psi]$ is the speed deviation vector that causes roll, pitch and yaw angular moments, respectively. These propeller speed deviations are computed by the PD attitude control law

$$\Delta\Omega_{\boldsymbol{\psi}} = \Lambda_{\boldsymbol{\psi}}\left(\boldsymbol{\psi}_{\text{ref}} - \boldsymbol{\psi}\right) - \Lambda_{\boldsymbol{\omega}}\mathrm{B}\boldsymbol{\omega}, \tag{12}$$

with $\boldsymbol{\psi}_{\text{ref}}$ been the desired orientation vector (limited to small angles). Here, $\Lambda_{\boldsymbol{\psi}}$ and $\Lambda_{\boldsymbol{\omega}}$ are gain diagonal matrices positive definite for aerial stabilization and negative definite for underwater stabilization.

As far as position control is concerned – more specifically the altitude control – the motors thrust speed $\delta\Omega_T$ can be defined by the desired altitude $z_{\text{ref}} \in \mathbf{p}_{\text{ref}}$ according to the nonlinear control law

$$\delta\Omega_T = \frac{\lambda_1\left(z_{\text{ref}} - z\right) - \lambda_2\dot{z} + \sqrt{\frac{(m-\rho V)\|\mathbf{g}\|}{4c_f}}}{\cos\phi\cos\theta}, \tag{13}$$

where positive z_{ref} means flying commands and negative means submerging commands. Also, λ_1 and λ_2 are proportional and derivative control gains.

Finalizing the position control, reference angles ϕ_{ref} and $\theta_{\text{ref}} \in \boldsymbol{\psi}_{\text{ref}}$ are determined according to desired positions x_{ref} and $y_{\text{ref}} \in \mathbf{p}_{\text{ref}}$ respectively

$$\begin{bmatrix} \phi_{\text{ref}} \\ \theta_{\text{ref}} \end{bmatrix} = \lambda_3 \begin{bmatrix} x_{\text{ref}} - x \\ y_{\text{ref}} - y \end{bmatrix} - \lambda_4 \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix}, \tag{14}$$

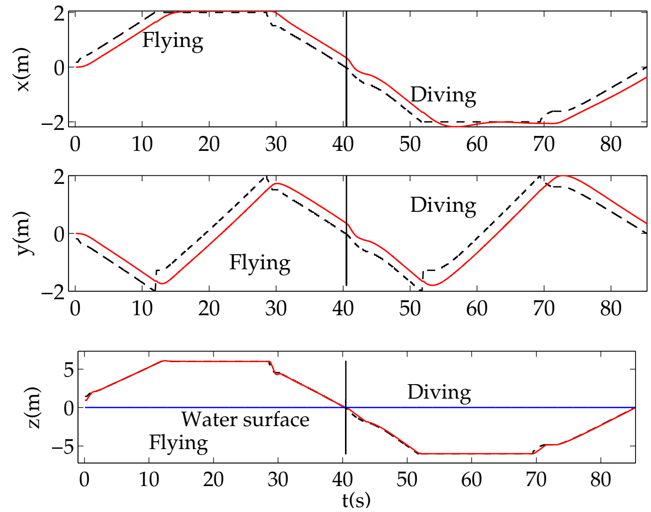


Fig. 3. Position control of the HUAUV along x, y and z axes. Dashed black lines represent the $\mathbf{p}_{\text{ref}}(t)$ trajectory, while red continuous lines are real robot positions (vertical black lines mark the point where the robot makes the transition of mediums).

while ψ_{ref} is set to zero for simplicity reasons. Similarly to the altitude control, λ_3 and λ_4 are also positive control gains for aerial navigation and negative for underwater motion.

IV. EXPERIMENTS

In this section, we present some results for the position control of our simulated Hybrid Unmanned Aerial Underwater Vehicle. Table II summarizes the parameters we used to compose the model. The command diag $(\cdot)$ means diagonal matrix.

TABLE II
PARAMETERS SPECIFICATION OF THE MODEL.

Parameters	Variable	Values
Mass	m (kg)	2.0
Volume	$V\,(\mathrm{m}^3)$	$2.1{\times}10^{-3}$
Wing span	l (m)	0.45
Inertial matrix	I $(\mathrm{kg{\cdot}m^2})$	diag $(3.6, 3.6, 6.6)\times10^{-2}$
Drag matrix	C	diag $(-3.3, -3.3, -3.3)\times10^{-3}$
Control gains (air)	$\Lambda_{\boldsymbol{\psi}}$	diag $(10, 10, 0.6)$
	$\Lambda_{\boldsymbol{\omega}}$	diag $(3, 3, 5)\times10^{-1}$
	$\langle\lambda_1, \lambda_2, \lambda_3, \lambda_4\rangle$	$\langle 10, 0.2, 0.05, 2\rangle$
Control gains (water)	$\Lambda_{\boldsymbol{\psi}}$	diag $(-5, -5, -0.1)$
	$\Lambda_{\boldsymbol{\omega}}$	diag $(-0.05, -0.05, -2)$
	$\langle\lambda_1, \lambda_2, \lambda_3, \lambda_4\rangle$	$\langle -5, -0.1, -0.05, -2\rangle$

Figure 3 presents the control response, in $\mathbb{R}^3$, given an arbitrary trajectory vector $\mathbf{p}_{\text{ref}}(t)$. It was chosen to command the robot to fly from the water surface to the altitude of $6\,\mathrm{m}$, return to the surface and dive into the water at the depth of $-6\,\mathrm{m}$, returning once again to the surface.

One can see dashed black lines representing the command trajectory $\mathbf{p}_{\text{ref}}(t)$, and red continuous lines representing the real robot position, measured by its sensors. Vertical continuous black lines mark the time where the robot makes the transition of environments (air to water) and it is possible to see that this transition happens almost immediately, one of our primary goals.

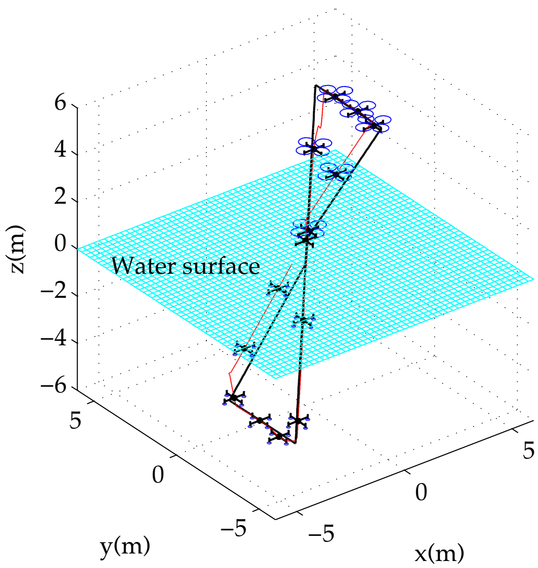


Fig. 4. Three-dimensional trajectory of HUAUV flying above the water and diving into it. The dashed black line represents the $\mathbf{p}_{\text{ref}}(t)$ trajectory (detailed in Figure 3), while the red continuous line is the real robot path execution.

Figure 4 presents the same experiment in $\mathbb{R}^3$ space. More about this project, including videos with other experiments, can be found in `http://verlab.dcc.ufmg.br/projetos/huauv/index`.

V. CONCLUSION AND FUTURE WORK

This paper proposed a novel design approach to Hybrid Unmanned Aerial Underwater Vehicles based on quadrotor-like platforms. To the best of our knowledge, this is the first time quadrotors are used also in underwater environments. The main advantages of using such structures are the facility of control provided by the vehicle and its ability to change from water to air (or vice-versa) in a sparingly fast and simple way. The main limiting factors (disadvantages) are the weight constraint of the vehicle (especially during the flight) and the high energy consumption.

With respect to the use of quadrotors under the water, another advantages like simplicity of modeling and simulation, employ of open structures (low additional mass), and the high payload/volume ratio, are taking into account. Some main disadvantages would be high (noise) interference environment and speed constraints attributable to drag forces.

As future work, we intend to build an actual model as a proof of concept, to test and identify some real problems concerning the switch-over behavior between air and water environments. Furthermore, from the mechanical point of view, other constraints like sealing and pressure compensation methods must be faced when in deep water is concerned.

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