BIMODAL UNMANNED VEHICLE: PROPULSION SYSTEM INTEGRATION AND WATER/AIR INTERFACE TESTING

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Abstract

A multi-modal UAV capable of sustained aerial flight, locomotion in water and deployment from a tube filled with compressed air is under development. This paper covers the design and integration process of a CO_2 thruster previously designed in a vehicle designed to fulfil mission requirements in terms of altitude and velocity after water/air transition. The thruster uses a common CO_2 cartridge available off-the-shelf to accelerate water stored inside a water chamber for efficient and sustained thrust. Water is chosen as vectorial fluid since it is available from the surroundings. Analytical model, described in the paper, evaluates water to air transition phase in terms of trajectory, reached altitude and velocity. After thruster performances evaluation thanks to the analytical model, an experimental prototype was fabricated and tested for model validation. High speed camera is used to track vehicle transition and Kinovea software exports resulting data from a recorded video to spreadsheet formats for scientific study and post-processing. A comparison and discussion of the results as future work is also proposed with areas for improvement and development.

1 General Introduction

Nowadays, the Unmanned Aerial Vehicles (UAV) technology can be considered an effective tool which can be exploited for 3D (Dull, Dirty, Dangerous) air missions. UAVs can be used for a wide range of applications such as pollution/air data collection, monitoring, photographic and video recording, border surveillance. Also a set of space applications could fit the UAV capabilities: several studies on vehicles to explore the atmosphere of planets can be found in literature.

One of the new frontiers in the development of UAVs is represented by hybrid or multi-modal UAVs. Such a kind of UAVs is capable to operate in different mediums like air and water, air and ground, ground and water. Bimodal UAVs can avoid the use of two unmanned platforms in a variety of missions [1]. Just to provide an example, the capability of collecting data in sea water and further in the air, in case of chemical/nuclear disaster, could present the advantage of shorten the time required to provide a detailed situation awareness. The missions which can be accomplished in an effective way by bimodal UAVs does not belong to earth only, but they can be suitable for space missions as well. One single vehicle, which could be used to explore the Mars lakes and its atmosphere, could be useful to reduce the payload of the rocket/launcher used to send it to the space.

The multi-modal UAVs described in this paper, called with the acronym BUUAS (Bimodal Unmanned Underwater and Aerial System), starts its mission being launched from a tube filled with compressed air from an underwater vehicle, or dropped from a ship/air vehicle with a parachute. The vehicle collects data in the water and in the further, a transition between air and water starts: this is obtained by jumping from the water, deploying wings and increasing its speed up to cruising velocity in air. When the air mission phase of the vehicle has been completed the BUUAS plunges, folds its wing and it can be recollected by mother ship or vehicle to be used again in a new mission. Eventually, thanks to the relative low cost of the platform, in case of nuclear/chemical contamination the BUUAS can be directed in air to the mother ship to exchange data, and sent to a pre-set destination for landing.

The difference in properties of air and water is a key point to consider in the design of BUUAS: due to this issue, it is straightforward that different aerodynamic configurations [2] should be considered for operations in water and in air, whose density ratio is around one thousand. A UAV operating in air requires a large wing surface to obtain the required lift from a medium presenting a low density. On the other hand, during water operations, such a large surface would produce unuseful lift and increase by far friction and induced drag. As a consequence, a configuration morphing between water and air and vice versa is required to operate in both the mediums with optimal endurance and good flying/diving qualities.

1.1 Multi-modal unmanned vehicles

UAVs operating in the air presents typical configurations, which can be divided in three main classes: fixed-wing vehicles, tail rotor helicopters, and multi-rotors [3]. All these configurations can be potential candidate to for the development of BUUAS.

Fixed-wing requires the take-off from a runway or with a catapult, but they assure a quite long endurance due to a better efficiency.

Tail rotor helicopters present good loitering and hovering capabilities with vertical take-off and landing, but their dynamics is quite complex and unstable. They are sensitive to gusts, the engine provides all the power required to balance the weight in hovering, and finally the mechanics of an helicopter main and tail rotor head is complex: therefore, the endurance and range is low.

Multi-rotors represent a recent answer to the problems of helicopters: they are capable of hovering and loitering, their mechanics is very simple, the propellers are shrouded and arenâĂŹt dangerous. On the other hand, they donâĂŹt exploit the aerodynamic lift to balance the weight, so that a high power is required to allow the fixed-point or low speed flight.

For the design of BUUAS, problems of take-off or landing are negligible due to the launch of the water configuration of the vehicle from a tube filled with compressed air, or from a mother ship/air vehicle to provide initial speed in water. Moreover, one of the requirements of BUUAS is a long endurance and range. Due to these considerations, a configuration based on a vehicle showing a streamlined cylindrical configuration in water and capable of deploying wings after the transition between water and air has been selected.

Reviewing all the informations available on literature, [4] describes a first simplified example of multi-modal vehicle with some limitations, as absence of payload and a structural fuselage, focusing mainly on the challenges to develop such aircraft as the transition mechanism and the plunge diving process.

Another small aerial-aquatic robot model [5] is developed with foldable wings to reduce impact surface with the sea and a water jet propulsion system is designed to transit through the two mediums with good results in terms of feasibility. The drawback is the absence of payload on the robot.

Lockheed Martin Corporation developed the *Cormorant UAV* capable to be released by a Remote Operated Vehicle (ROV) and take off from water thanks to high pressurized gas [6]. To return in water a parachute is used to decelerate, such that the vehicle splashes as cormorants do and finally is retrieved again by the ROV. The dimensions and weight of such multi-modal vehicle were finally enough to install payload and several sensors needed for the operations. Due to insufficient founds the project was suspended, but many years later the University of Alabama tried, accepting the Cormorant project challenges, to design an hybrid UAV with same features using a single turbofan connected to rotors instead of a DC motor to delete the batteries and their weight [7]. A gearbox was designed to be placed between turbofan and propellers to adapt the RPM in different mediums. The lack of this project is the absence of a transition mechanism that is capable to lift the UAV from water making the project obsolete.

1.2 Impulsive thruster

As always happened, human discoveries are inspired by the surrounding nature, studying it and understanding the physical principle behind that specific phenomena. Such approach can be used also speaking about impulsive thrusters that uses water as propellant substance. In fact, few years ago, a group of Japanese researchers from Hokkaido University discovered that there is a specie of oceanic squid that can fly more than 30 metres in the air to escape from predators. (Figure 1)

The *Neon Flying Squid* propels itself out of the ocean by shooting a high pressurized water-jet, before opening its fins to glide, covering as long distance as possible. As they land back in the water, the fins are all folded back into place to minimise the impact [8].

Taking example from this nature application, a short-impulse thruster can be designed and integrated with foldable wings in the same way. In particular, impulsive thruster is a propulsion system that can be used for the purposes of this work due to its high impulse density, fast time response and capability to produce thrust in both air and water continuously thanks to pressurized gases

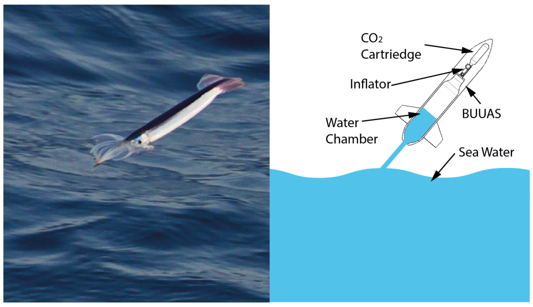


Fig. 1 Neon Flying Squid (www.pelagicodyssey.ca)

For the water/air transition phase, the idea is to use an impulse thruster with pressurized CO_2 cartridge as [9] who developed a transition system for a 70g aerial-water robot that exits water in 3 seconds at a speed of 11 m/s using shape memory alloy to activate the valve to control CO_2 release.

Other hybrid UAV design example involves an impulsive thruster by a chemical combustion with higher efficiencies but with an increase of the overall weight and lower safety for transition phase and vehicle itself [10].

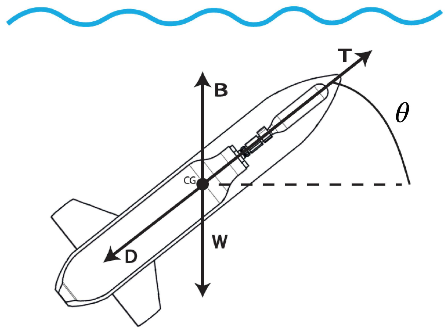
For this project, impulsive water jet solution was be considered since water is directly available by the surrounding without introducing any additional weight [11]. Moreover, this type of system can bypass problems in the transition phase as waves and spray drag especially in open water where this bi-modal UAV is designed to fulfil its mission [12]. Two different ways to implement such system are available. In fact, the thruster can accelerate directly the pressurized gas through a nozzle or indirectly by using propellant water to be expelled out. Thanks to previous work done, indirect short-impulse thruster is the right choice between the two [11]. Such mechanism will be integrated with an optimized propeller for both mediums to have a complete propulsion system for the overall mission.

2 CO_2 thruster requirements

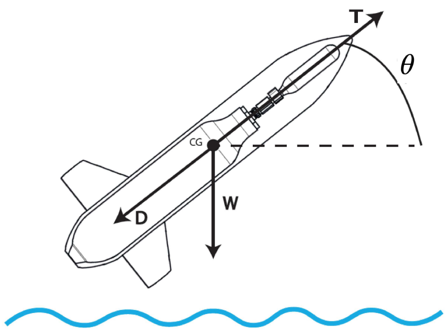
After a preliminary design already accomplished [13], this project focused on the transition mechanism design in a delicate situation as the air/water interface and on its integration with the overall propulsion system taking into account the final prototype characteristics. Some studies on air and water propulsion are already carried out [12] and [11] and BUUAS requirements in distinct mediums can be summarized in Table 1.

Thrust to weight ratio in air	0.6
Thrust to weight ratio in water	0.3
Cruise speed in air	25 m/s
Cruise speed in water	2 m/s

Table 1 BUUAS propulsion system requirements



(a) Forces acting during underwater mission phase



(b) Forces acting during aerial mission phase

Fig. 2 Forces during vehicle transition phase

An impulsive thruster was designed according to these requirements, as described in the following Chapter. To integrate it inside a fuselage for launching tests, a scaled version of the vehicle will be designed and tested. This choice aims to reduce both weight and dimensions, since transition test have never been carried out and also for safety reasons. In addition, foldable wing mechanism will be putted aside for the first experiments to reduce vehicle complexity.

A dynamic model, implemented in Matlab, was used to evaluate the required thrust to reach an altitude of 8 m over the sea level(mean ocean wave height) with sufficient speed to deploy the wings and start the aerial phase of the mission. The same analytical model, going ahead with the design phase, is used to estimate the vehicle dynamics to be expected in launching tests described in the following.

In this analytical model, transition between water and air was assumed very fast and negligible and for this reason only water and aerial phase were considered. The vehicle is assumed as a point particle, with all the force applied to its centre of gravity (Figure 2). Another assumption made at this design stage to simplify the model, is that lift force is negligible because of main wing absence. Moreover, the vehicle is assumed to have a neutral buoyancy ($B = W$).

Eq. 1 is true until vehicle reaches sea level and gives, as outputs, velocity, covered distance and instant of time at which UAV is exiting water, evaluated from the moment of ignition of the transition system. Since the model is referred for a medium which has a density comparable with the body ones, added masses effects where taken into account, considering an "artificial" mass $m_{art} = m(1+k')$ with k' evaluated by a model described in [14].

$$\begin{cases} m_{art}u'(t) = T cos(\theta) - \frac{1}{2}\rho S C_d u(t)^2 cos(\theta) \\ h'(t) = usin(\theta) \\ d'(t) = ucos(\theta) \end{cases} \tag{1}$$

Then these outputs become inputs for the air model (eq. 2) in order to get final altitude and velocity that the vehicle reaches.

$$\begin{cases} mu'(t) = T sin(\theta) - \frac{1}{2}\rho S C_d u(t)^2 sin(\theta) - W \\ h'(t) = usin(\theta) \\ d'(t) = ucos(\theta) \end{cases} \tag{2}$$

2.1 Scaled geometry

As previously mentioned, a scaled and simplified UAV geometry is used for the transition experiments to decrease the overall complexity and weight of the unmanned vehicle (Figure 3).

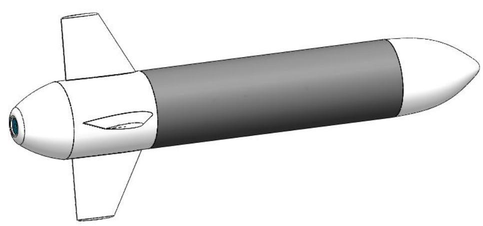


Fig. 3 Scaled geometry design

Nose cone and aft part (fins included) are 3d printed using *FDM technology* in ABS plastic. A this design phase, additive manufacturing is a good choice to produce spare parts with complex geometry, with high repeatability and low weight. Inside fuselage, all the components as LiPo batteries, CO_2 thruster and controller receiver will be positioned taking care of the centre of gravity position that may affect the UAV transition trajectory. In addition, bulkheads are positioned in some portion along fuselage to both increase strength of structure and fix the inner components, as can be seen in Figure 4.

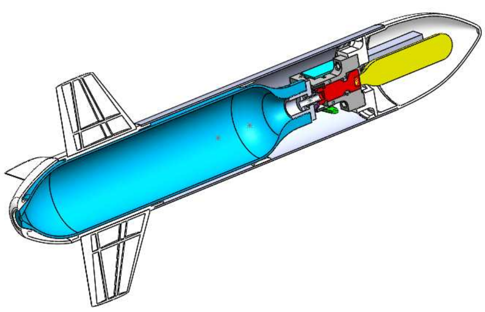


Fig. 4 Sectioned fuselage with thruster inside

3 CO_2 thruster design and tests

3.1 CO_2 thruster design

To acquire desirable thrust for the launching, the CO_2 thruster was designed (Figure 5). In the design process, many easily acquired off the shelf components are used to reduce the period of testing and experiment. A 25 grams CO_2 cartridge is used for providing high pressure gas. The cartridge is screwed into the inflator to be punched. The gas released from the cartridge is stopped by the inflator if the thruster is not activated. The servos, fixed on 3D printing seats, would actuate the inflator to release the gas into water chamber when is necessary. A telescopic adapter is used to connect the inflator and water chamber without moving them. The inflator is actuated only when the front part is pressed into the shell by the servos through the press plate.

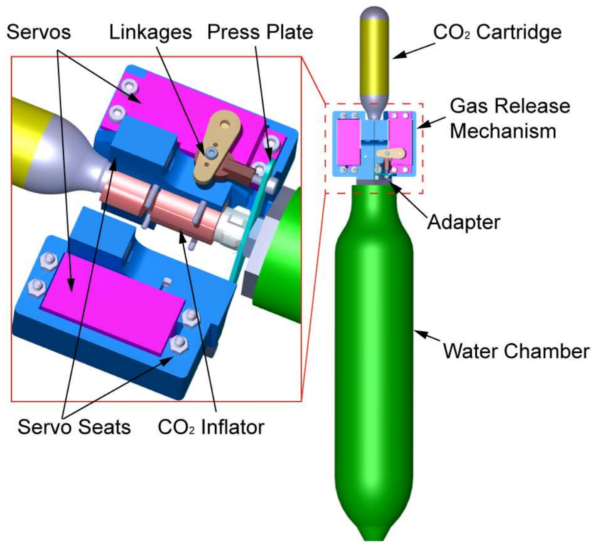


Fig. 5 CO_2 thrust system layout

The water chamber design is very important for the thrust. Moreover, the size of exit area and the volume of water chamber are two critical parameters. The volume, which is 810ml, was fixed by a thrust analytical model to achieve the height as we mentioned. In this case the exit diameter was temporarily designated as 9mm. Combining the resulting thrust behaviour with the analytical model of transition, trajectory of the vehicle launching from 1m depth water was acquired. As the Figure 6 shows, when the volume is 810ml and the launch angle is 60°, the vehicle could reach the specified altitude.

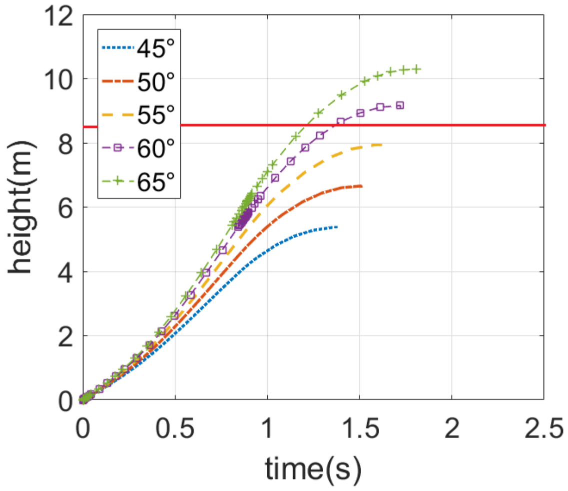


Fig. 6 Trajectory with different angles under the 810ml volume

3.2 CO_2 thruster test

Several tests were conducted for testing the mechanism and evaluate the exit area effects. The whole thruster system was tested on the test rig in the water tank. 5 sets of of tests have been done and the exit diameter 5mm, 7mm, 9mm, 11mm, 13mm were tested. The results are shown in Figures 7 and 8.

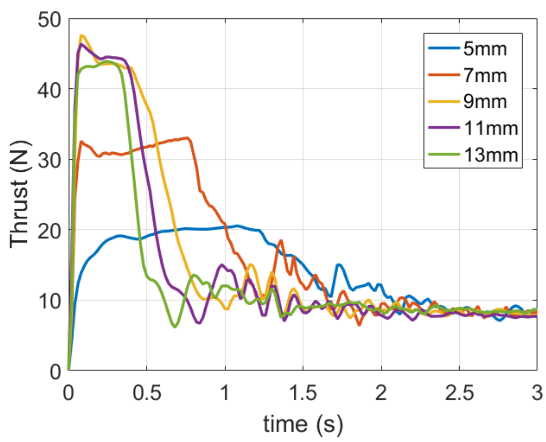


Fig. 7 Thrust test with different exit diameters

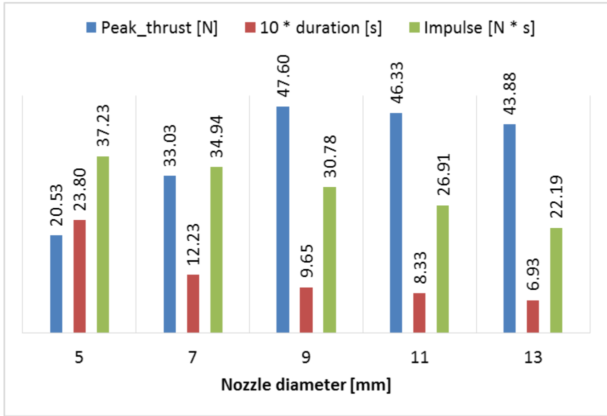


Fig. 8 Test results - Peak thrust, impulse and duration for different exit area size

Based on the results, it is obvious that the exit area have a great effect on the duration and the peak thrust. Both duration and impulse will increase with the increasing of the diameter, but the peak thrust has an opposite behaviour.

For the transition phase, an amount of thrust enough to lift the vehicle is needed and an impulse as big as possible to exit from water. According to the results, the 7mm was chosen as the diameter of nozzle and the 810ml as the volume.

4 Launching experiment

With a thruster completely designed, the following project stage consists in assembly the above-cited system with the proposed scaled vehicle in order to detect overall flying performances during a transition phase simulation in the first portion of flight. In fact, the launched vehicle has not control surfaces, so after leaving the water a randomly behaviour is expected when external secondary disturbances (i.e. wind, thrust axis non perfectly centred, vehicle weight not axysimmetrical distributed..) will act. Nevertheless, the experiment aim is to assure that the generated thrust is sufficient to exit from the water and compare the trajectory and velocity of the analytical dynamic model with the experiment one in the first portion of flight.

Different tests with different launch angles are carried out to comprehend how this important parameter can influence on vehicle performances during a crucial mission phase as the transition one. Obtained trajectories are then compared with the dynamic vehicle model implemented in Matlab (eq. (1) and (2)).

4.1 Experiment setup and plan

The experiment setup consists on a water tank with sufficient dimensions in terms of length and height in which a launch ramp with settable launching angle is positioned to host the scaled vehicle (Figure 9). The tank deep was chosen such that the vehicle, positioned in the ramp, is entirely submerged in water for all the test angles. The vehicle initial position can not be too deep because radio signals from controller to the receiver are not so powerful to be transmitted underwater. For these reasons a compromise was found and the tip nose has be positioned few centimetres under water surface.

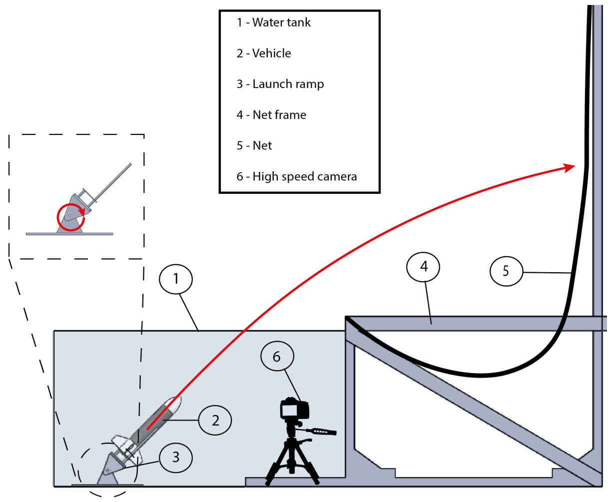


Fig. 9 Experiment layout

To accelerate transition phase and reduce the water drag influence, an optimum range of launch angles is estimated to be from 45° to 70° by vehicle dynamic simulations.

The thruster is hosted inside it and the water chamber can discharge all the water through a hole in the aft part of the fuselage. Batteries, controller receiver and the cartridge are hosted in the frontal part of the vehicle, where the nose cone can be disassembled to allow routine operations by the operator as cartridge replacement.

After first tests, it was noticed that the vehicle trajectory was very sensitive to battery position; to make the flight as straight as possible, the battery was linked under the cartridge, as close as possible to the thrust axis, in order to decrease any moment by this heavy component.

4.2 Experimental results

To refine the dynamic model and validate it with experimental tests, a variable vehicle mass in time is used. In particular the overall vehicle mass follows the eq. (3) where m_b is the empty mass, m_{w0} is the initial water mass inside water chamber and t_b is the burnout time.

$$\begin{cases} m(t) = m_b + m_w(t) \\ m_w(t) = -\frac{m_{w0}}{t_b} \end{cases} \tag{3}$$

In this simple model, the water chamber discharge is assumed to be linear in time since actual mass flow rate from thruster experiment is not available. In addition, burnout time is taken from experimental results according to the method discussed in [11].

To validate the analytical dynamic model described above, experimental tests are conduced and high speed camera videos are post-processed using Kinovea software. In fact, the experiment aim is to assure that the generated thrust is sufficient to exit from the water and a comparison is done between reached altitude and velocity of the analytical model with the experiment ones in the first portion of flight. Videos recorded during the experiments, is post-processed with Kinovea software. It is a free and open-source software, used for sport video analysis, very useful for slow motion videos in which is necessary to study a particular object, or point trajectory. In fact, through a calibration measure introduced by the user, the software can evaluate distances and times manually or using a semi-automated tracking to follow points and check live values or trajectories (Figure 10). Moreover, resulting data can be exported for further analysis to spreadsheet formats for scientific study and post-processing.

Fig. 10 Kinovea tracking example

Knowing object position in time, linear velocity has been calculated through the incremental ratio:

$$v(t_i) = \frac{s(t_{i+1}) - s(t_{i-1})}{t_{i+1} - t_{i-1}} \tag{4}$$

The results are reported from Figure 11 to 16 according to different launching angles. For each angle, a comparison with analytical dynamic model is shown. Each graph represent the vehicle performances until it leaves the camera framing at almost 1.6 meter height from water surface.

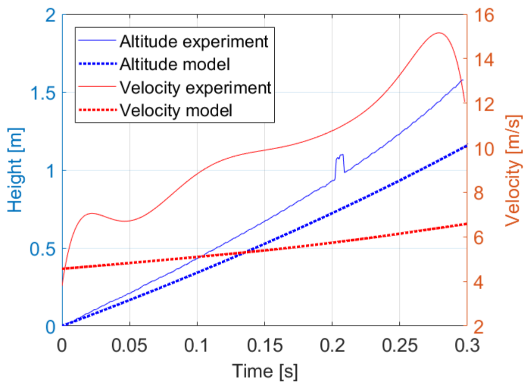


Fig. 11 Altitude and velocity comparison between analytical model and experimental test - Launch angle: 45°

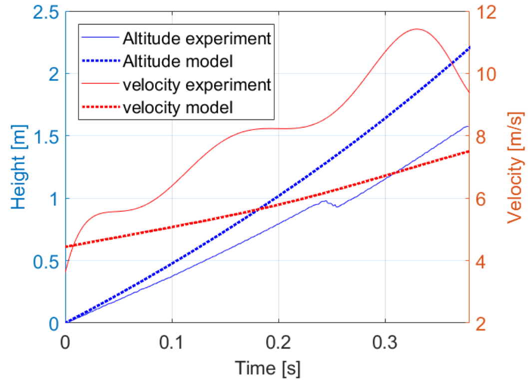


Fig. 12 Altitude and velocity comparison between analytical model and experimental test - Launch angle: 50°

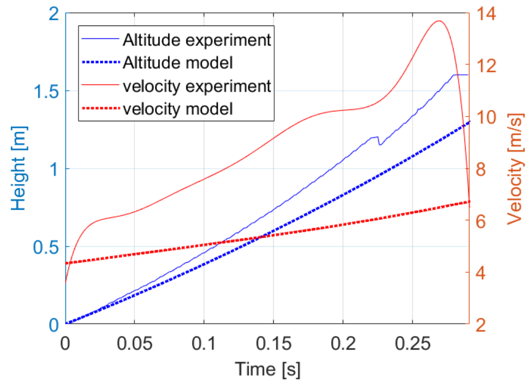


Fig. 13 Altitude and velocity comparison between analytical model and experimental test - Launch angle: 55°

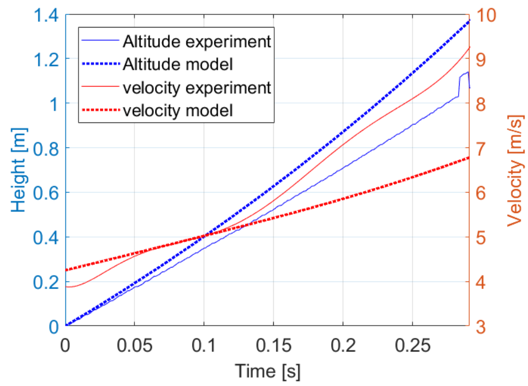


Fig. 14 Altitude and velocity comparison between analytical model and experimental test - Launch angle: 60°

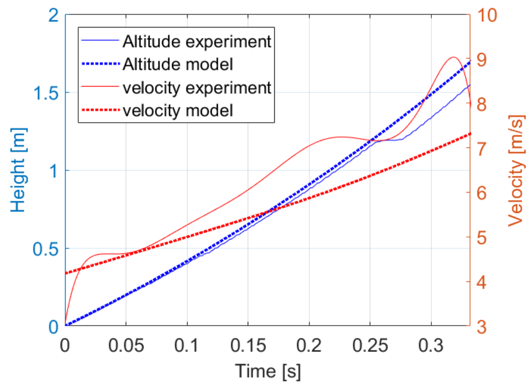


Fig. 15 Altitude and velocity comparison between analytical model and experimental test - Launch angle: 65°

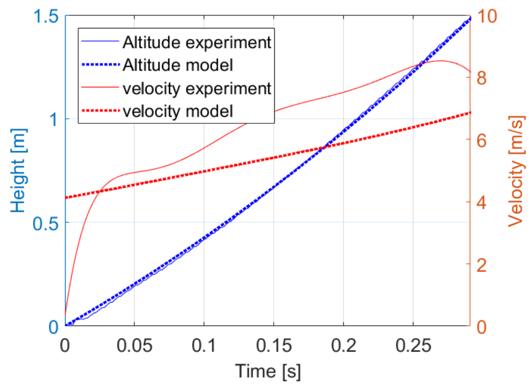


Fig. 16 Altitude and velocity comparison between analytical model and experimental test - Launch angle: 70°

As can be seen from this visual comparison, during the first portion of flight, analytical model and experimental tests match well for high angles (60° to 70°), while the results are a slightly different for smaller angles. This can be explained by the longer distance that vehicle covers underwater if the launch angle is smaller that may affect the vehicle performances, for which a negligible water to air transition could be an assumption far from the reality. Another notable trend is that, increasing the launch angle, the vehicle exits the camera framing at a lower speed, before reaching its maximum value.

5 Future developments

After the transition capability assessment, additional tests, adding some masses to simulate a heavier vehicle could carried out to asses thruster performances. The project could also focus on the integration with a complete propulsion system capable to generate enough thrust to cruise in both water and air at a certain velocity, optimized for the vehicle porpoises, thanks to a pusher propeller, designed to have high efficiency for both mediums (Figure 17).

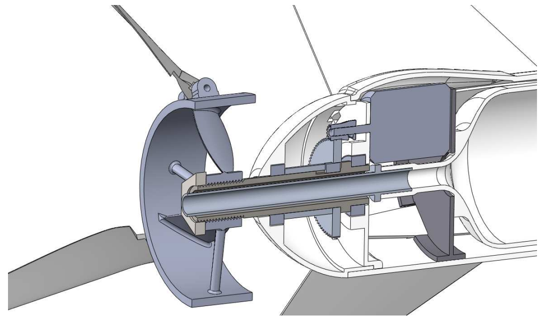


Fig. 17 Overall propulsion system integration with gear box and hybrid propeller

Finally, after the complete design of the propulsion system, foldable wing mechanism could be another wide area of development, to integrate it with the designed vehicle and synchronize the deployment with the transition phase with high frequency response to get high performances from the BUUAS.

6 Conclusion

Experimental test involving the scaled vehicle and the designed thruster in [11] is described. Covering a wide launching angle range, the results coming from the tests are considered good and satisfactory because the force generated by the thruster is sufficient to exit from the water respecting expectations coming from analytical model. The comparison with numerical results demonstrates that in the first portion of flight the performances are almost the same. For security reasons a complete ballistic flight wasn't possible and the vehicle was always slowed down by the surrounding net. In particular the vehicle hits a 3 meter height net and covers almost 6 meters forward. For this reason, these experiments demonstrate that the thruster has great potentiality to reach the altitude requirement with enough velocity for wing deployment.

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