Development of an Autonomous Underwater Profiler for Coastal Areas

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***Abstract*—One of the most common ways of collecting ocean data is to deploy sensors from the surface, allowing to understand the variation of water properties with depth. Autonomous vertical profilers are robotic vehicles that replace human operators in this task. They form a particular class of autonomous underwater vehicles that move predominantly along the vertical axis, typically with reduced control on the horizontal axis. This paper describes a propeller driven autonomous underwater profiler, optimized for shallow waters. The vehicle has no fins or other control surfaces, and uses four independent thrusters to provide both vertical and horizontal motion, including hovering in the water column. The paper describes the main subsystems, including the hardware implementation, the software structure, and the motion controllers, with experimental data from the first trials.**

***Index Terms*—Autonomous Underwater Vehicles, Autonomous Underwater Profilers, Vertical Profilers.**

I. INTRODUCTION

Monitoring the oceans is critical to understand our planet and data on water properties need to be gathered to better understand oceans phenomena. One of the ways of collecting these data is through vertical profiles of the water column that allow to understand variation of water properties with depth. Taking into account the difficulties of obtaining measurements by human operators, various autonomous profiling vehicles were developed to perform these tasks in a systematic and more reliable way, with minimal human intervention.

An underwater profiler is thus a vehicle that moves predominantly along the vertical axis, and typically drifts along the horizontal plane with the currents. Underwater profilers are a particular class of Autonomous Underwater Vehicles (AUVs), with a design that minimizes drag in the vertical direction.

This paper presents the development of a new autonomous profiler for coastal areas. The main objective was to acquire profiles up to 200m of depth, while maneuvering also in the horizontal plane. The vehicle has no fins, and uses four independent thrusters to provide both vertical and horizontal motion, including hovering in the water column.

The paper is organized as follows: Section II provides an overview of the main efforts that have been made to develop underwater profiling vehicles. Section III summarizes explicitly the main requirements for the development of this new vehicle, while Section IV details the components of the system, including the hardware implementation and the software structure. Section V presents the hydrodynamic model of the vehicle and the controllers designed for the maneuvers. Section VI describes the syntax of the available maneuvers for the operation of the vehicle during a mission, and Section VII provides the first results from our experimental validation. Lastly, Section VIII presents the concluding remarks and future research directions.

II. RELATED WORK

Vertical profiles are important for studying the variation of water properties with depth, for instance to obtain the temperature-depth relationship typically used in oceanography. Autonomous profilers have been developed to replace human operators in obtaining these data, and they have been designed both for deep waters [1], and also for shallow depths [2]. Although their main operation mode is profiling in the vertical direction, they have also been developed with the ability to maintain a fixed distance above seabed [3]. These operational characteristics are directly related to some of the design aspects of existing solutions, mainly in terms of propulsion systems and motion control.

A. Propulsion

To drive a profiler in the vertical direction there are two propulsion systems commonly used: adjusting the buoyancy or using thrusters. Buoyancy driven profilers move by changing their submerged volume which causes the vehicle to either sink or rise [4], [5], [1], [6], [7], [8]. The main advantage of this type of propulsion is that it only uses energy to change its buoyancy state, making them extremely energy efficient on great descents [1]. However, since the buoyancy of the vehicle depends on water density, this type of propulsion is not suitable for shallow water environments where water density varies greatly and affects the performance of the vehicle [5]. Thruster driven profilers use propelled thrusters to move the vehicle [2], [9], [3]. The vertical performance of the thruster is not affected by the water density as much as the buoyancy, since it's easier to control descent rate with the appropriate thruster control [3]. The main disadvantage of using a thruster is that it is an active propulsion system that constantly needs energy to drive the profiler, making it inefficient for dives in greater depths.

B. Motion Control

To perform the required maneuvers, a profiler must run algorithms that controls the propulsion system. In the buoyancy driven profiler described in [5], a task implements a

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PID controller using the measurements of depth and altitude above seabed. This controller computes an intermediate depth trajectory using basic filtering to keep the depth changes within the dynamic capabilities of the profiler.

To acquire a profile of the water column, the vehicle described in [9] runs at a constant speed and, as it nears the target depth, ramps down the thruster voltage to zero bringing the profiler close to the target depth. Then, the profiler ascends using the positive buoyancy defined on construction. The vehicle described in [2] operates in a similar way. The Autonomous Vertical Profiler described in [9] can also hover at a fixed depth. It uses a controller comprising of Linear Quadratic Regulator (LQR) in combination with a complementary filter, as described in [3].

III. MAIN REQUIREMENTS

The list of prototype requirements took into account the following guidelines: the autonomous profiler construction should follow a modular design and allow low logistics operation during transportation, deployment and recovery. This system should be designed to operate on coastal areas (and shallow waters) without any physical connection with an operator. The requirements considered for the development of the vehicle were divided in two subsections: a) Operational requirements, related to the maneuvers that the profiler should perform and its operation; and b) Safety requirements, that should reduce the risk of fault and minimize their impact in the behaviour of the vehicle.

A. *Operational Requirements*

The system should allow a defined set of maneuvers taking into account the considered usage scenarios. Therefore, the vehicle should be able to perform the following maneuvers:

- profile in the same position (estimating drift caused by currents and returning to reference position);
- acquire profiles with arbitrary angles;
- hovering at a fixed depth or fixed height above sea bottom;
- profile within 2 different depths without surfacing.

Moreover, the profiler should satisfy the following requirements related with the logistics of a mission:

- The profiler should require a single operator for launch and recovery (weight in air limited to 30Kg and length limited to 1.5m);
- Battery life should be sufficient to perform 10 profiles to 200m depth with a velocity of 1m/s along 24 hours;
- At the end of the mission, the vehicle should communicate its position to be recovered;
- The mission plan should be communicated using a wireless connection;
- The vehicle batteries should be rechargeable without opening the pressure housing.

B. *Safety Requirements*

As a first step towards safe operation, the profiler should have a positive buoyancy to return to the surface in case of malfunction. Additionally, it should detect situations that can cause harm to the system. The profiler should then be able to detect or measure the following faults and act accordingly:

- Detect water ingress;
- Detect overheating inside the pressure case;
- Detect the sea bed to avoid collision;
- Report battery status;

IV. IMPLEMENTATION

A. *Mechanical Architecture*

1) Weight and Buoyancy: In order to minimize the energy spent in changing the depth of an underwater vehicle, the vehicle should be neutrally buoyant. However, a typical safety measure is to operate underwater vehicles with a little positive buoyancy, to ensure that it returns passively to the surface in case of a major fault. Since buoyancy depends on water density, which can vary significantly in coastal waters, a typical margin of 1–2% of dry weight is typically employed. To accommodate different vehicle configurations and to make final adjustments in weight and buoyancy, the profiler was designed with free volumes in flooded sections, both at the top and at the bottom, to insert flotation material or lead weights.

The passive attitude of an underwater vehicle is determined by the relative position of the center of mass and center of buoyancy. In order to achieve the desired attitude (vehicle pointing downwards), all heavier subsystems have been installed towards the nose cone, equally distributed around the vertical axis.

2) Mechanical Modules: The mechanical design was based on a modular system used for the assembly of autonomous underwater vehicles [10]. This system has been used to assemble multiple configurations of AUVs, such as the MARES AUV, in operation for more than 10 years [11]. In the case of the profiler, the mechanical sections are revolution shapes with 120mm of diameter, that can stack to each other and propagate the male/female coupling system. They can be designed to carry wet sensors and thrusters and they are fully interchangeable, which allows for very easy sensor swapping and/or repositioning.

The most critical parts, like the pressure housing, were machined in polyacetal copolymer (POM), a very strong technical plastic. Others, like the supports for the thrusters or the nose of the profiler, were printed using a 3D printer. Figure 1 presents the final configuration of the profiler, with a total mass of 11.3kg and 1.35m long.

The pressure housing has 8 holes in each end cap, to accommodate standard bulkhead connectors, to install sensors in contact with the water, and to pass cables using cable penetrators. All underwater cables are routed within the flooded sections, for protection and to minimize drag. Figure 2 shows the arrangement of interfaces in the top end cap.

The electronics are mounted inside the pressure housing fixed to an aluminum frame (figure 3). The batteries are mounted at the bottom to lower the center of gravity of the vehicle and are fixed in the tray using 3D printed supports.

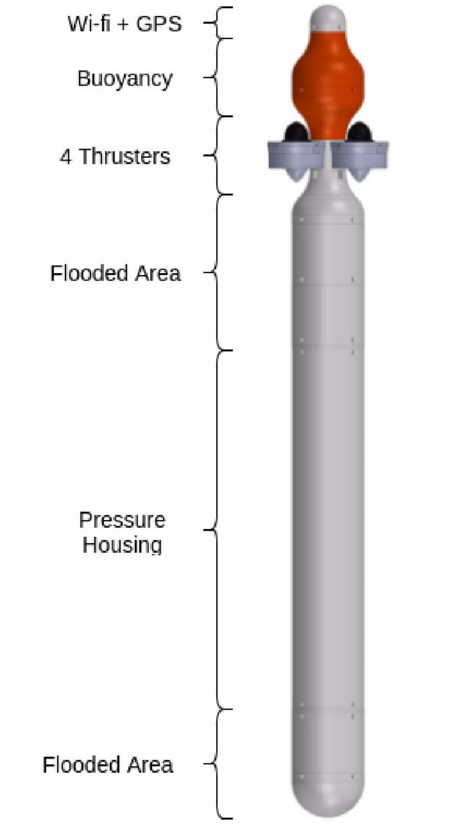


Fig. 1. Final configuration of the profiler.

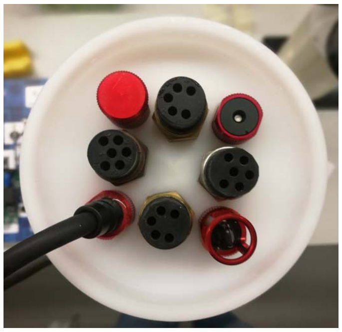


Fig. 2. External view of the top end cap of the pressure housing, with sensors, underwater bulkheads, and cable penetrators.

Fig. 3. Profiler prototype and inner frame.

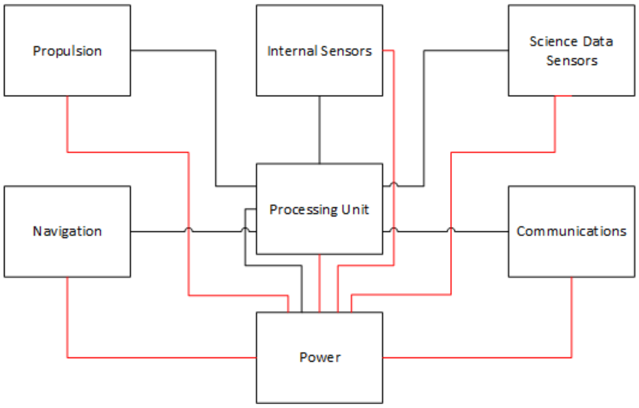


Fig. 4. Subsystems of the profiler.

B. Hardware Architecture

The vehicle is composed by a set of interconnected subsystems as depicted in figure 4.

1) Power System: This subsystem, located inside the pressure housing, includes the batteries, voltage converters and power buses needed to power all the profiler devices. The batteries are two Li-Ion BA95HC-FL packs, connected to a BBDC-02R Dual Battery Controller with ATX Power Supply, all from OceanServer. Each battery pack has 95Whr of energy at a nominal voltage of 14.4V. They were selected as a tradeoff between the available volume and the desired duration and the power consumption of the other subsystems. They can be recharged using an underwater connector available at the top part of the profiler. This subsystem represents a significant volume and weight, therefore it was be placed in the bottom part of the pressure housing.

2) Processing Unit: The processing unit is a BeagleBone Black single board computer (SBC) that runs the onboard software on a Linux distribution. This SBC features a AM335x 1GHz ARM processor and has 4 GB of onboard storage. For the selection of the processing unit, the main selection criteria were: lowest power consumption; reduced size and weight; and interfaces available to communicate with the other components.

3) Propulsion System: The propulsion system is composed by four BlueRobotics T100 thrusters mounted on top of the vehicle (figure 5), with alternate reversed propellers to minimize torque during profiles. Each thruster can provide up to 25N of force, and they are independently actuated with electronic speed controllers installed inside the pressure housing. The independent actuation of the thrusters allows to control the vertical velocity of the profiler, as well as pitch and roll angles, as described later.

4) Navigation System: The navigation system includes the sensors that allow the profiler to estimate its position, heading

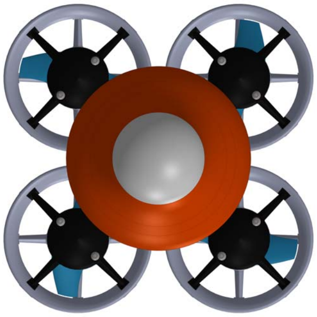


Fig. 5. Top view of the profiler.

and attitude. In the current configuration, the profiler uses a BlueRobotics Bar30 pressure sensor to estimate depth, with a maximum range of 300m. For linear and angular accelerations, the profiler has a tiny ITG3200/ADXL345 6DOF IMU inside the pressure housing. To obtain the absolute position at the surface, an Amaryllo GPS receiver has been potted in epoxy and placed in the topmost part of the profiler, as indicated in figure 1.

5) Scientific Data System: A set of payload sensors can be installed in the profiler to acquire the desired scientific data. When these sensors need to be in direct contact with water, they have to be installed in one of the end caps, or in separate flooded sections. There are still 5 physical ports left to interface sensors with the processing unit, but this number may increase by splicing cables and/or adding interfacing boards. In order to install a new sensor, both power and communications need to be routed from the sensor to the relevant port and there are several alternatives in terms of voltage levels and interface protocols. In the current configuration only a water temperature sensor has been installed, the BlueRobotics Celsius Fast-Response Temperature Sensor. This allows the profiler to obtain temperature-depth curves for a given water column.

6) Communication System: The communication system supports all data exchange between the profiler and a user or base station, including the transmission of the mission plan, the download of mission data, and the communication of the profiler's position at the end of the mission. In the current version, the profiler uses a standard USB WiFi transceiver, potted in epoxy close to the GPS receiver, at the top of the profiler. For long range, open ocean operations, it is possible to replace the WiFi transceiver by an Iridium modem.

7) Internal Sensors: A set of internal sensors have been installed inside the pressure housing to monitor possible faults. These include, for instance, a water ingress sensor and a temperature sensor to detect overheating.

C. Onboard Software

The software architecture was implemented to allow an easy accommodation of new sensors. This software runs in real-time and has multiple processes to ensure that different tasks are performed in useful time. The software implemented is divided in 3 main modules as depicted in figure 6. These modules share a block of shared memory, where the data and the timestamp associated with each measurement is available.

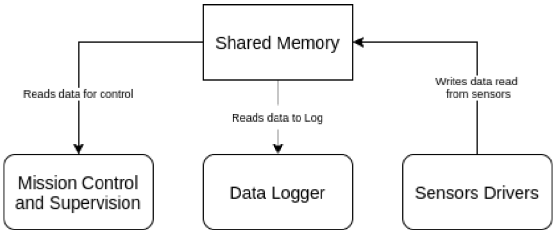


Fig. 6. Onboard software modules.

Each module has a different purpose: the sensors drivers module is responsible to acquire the data from all the sensors available and write it to the shared memory, the data logger logs the data and the timestamps during the operation of the profiler and the mission control and supervision module is responsible to read and execute the mission plan, control the vehicle and detect possible faults on the operation of the system.

V. DYNAMIC MODEL & CONTROLLERS

The 6 degrees of freedom (DOF) model that describes the movement of the vehicle follows the approach presented in [12]. To properly analyze the system, it is convenient to define two coordinate frames: a moving coordinate frame fixed on the body (body-fixed frame) and an inertial reference frame (earth fixed frame) as presented in figure 7.

The motion of an underwater vehicle can be described in the body fixed frame using a matrix representation as follows:

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

$$\dot{\eta} = J(\eta)\nu \tag{2}$$

where M represents the inertia matrix, $C(\nu)$ is the matrix of Coriolis and centripetal terms, $D(\nu)$ is the damping matrix, $g(\eta)$ is the vector of gravitational forces and moments, and τ is the vector of control inputs.

A. Speed Controller

In order to perform the defined maneuvers, it is necessary to control the speed of the profiler as this is one of the parameters of the mission plan.

The speed controller controls the velocities in z, pitch and roll. It was designed using Lyapunov theory, which allows to conclude about the stability of a system and designing control laws, overcoming the limitation of linear controllers that only are guaranteed to work around the selected operating points [13], [14], [15]. Lyapunov theory states that if ”*there exists a scalar function V of the state x with continuous first derivatives such that $V(x)$ is positive definite, $\dot{V}(x)$ is negative definite and $V(x) \to \infty$ as $x \to \infty$, then the equilibrium point at the origin is globally asymptotically stable*” [16].

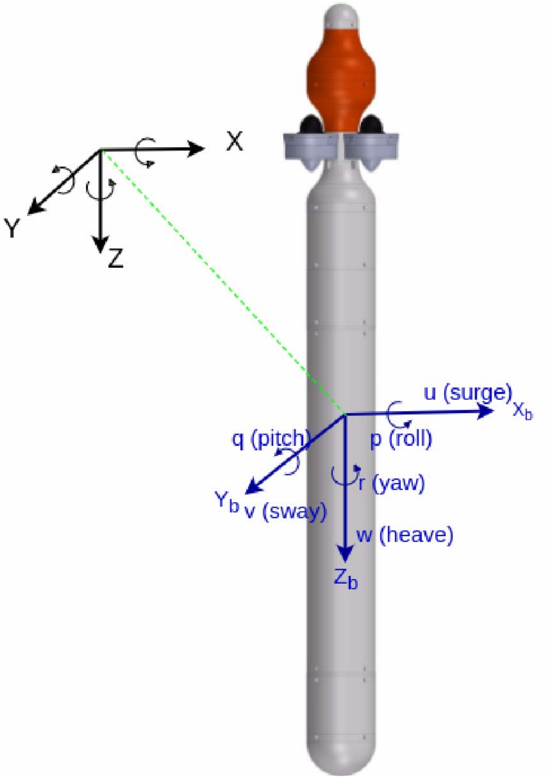


Fig. 7. Reference coordinate frames for the vehicle model.

The profiler is controlled using four thrusters and it was assumed that the thrusters can instantly apply force to the vehicle. Although this is not exact in reality, this assumption was made to simplify the model and it is justified since the time constants associated with the actuation are smaller than the ones associated with vehicle motion [15].

In order to simplify the determination of the speed controller, the order of the model was reduced eliminating lines and columns of the matrices that have low influence on the motion of the vehicle.

To control the velocities in z (w), roll (p) and pitch (q), an error vector is defined as $e = v_r - v_{ref}$:

$$e = [w - w_{ref}, p - p_{ref}, q - q_{ref}]^T \tag{3}$$

Then the Lyapunov candidate function V is defined as:

$$V = \frac{1}{2} e^T e \tag{4}$$

In which the time derivative is:

$$\dot{V} = e^T \dot{e} = e^T (\dot{v}_r - \dot{v}_{ref}) \tag{5}$$

To guarantee the stability of the system, $\dot{V}$ must be negative definite which imposes:

$$e^T (\dot{v}_r - \dot{v}_{ref}) < 0 \Rightarrow (\dot{v}_r - \dot{v}_{ref}) < -k_e e \tag{6}$$

where $k_e \in \mathbb{R}, k_e > 0$.

To satisfy (6), we cannot vary the error variable instantaneously. Therefore, we define a new error variable α as:

$$\alpha = \dot{v}_r - \dot{v}_{ref} + k_e e \tag{7}$$

That imposes the time derivative Lyapunov function to be:

$$\dot{V} = e^T (\alpha - k_e e) \tag{8}$$

Substituting $\dot{v}_r$ in equation (7) for the expression for $\dot{v}$ given in (1) yields:

$$\alpha = M^{-1} [(C(v_r) + D(v_r)) \cdot v_r + g(\eta) + M(\dot{v}_{ref} - k_e e) + \tau] \tag{9}$$

Considering that τ can be actuated using f, to guarantee that $\dot{V}$ is negative definite, τ is:

$$\tau = (C(v_r) + D(v_r)) \cdot v_r + g(\eta) + M(\dot{v}_{ref} - k_e e) \tag{10}$$

B. Position Controller

The position controller controls the position on the 3 DOF: depth, pitch and roll. The position controller feeds the speed controller by passing the speed references to it (see figure 8).

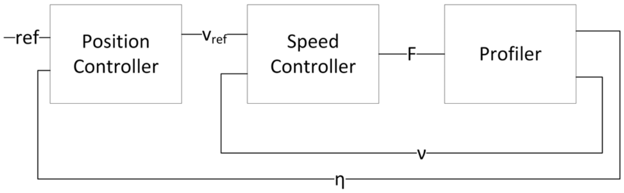


Fig. 8. Block diagram of the controllers.

Starting by defining the errors in depth, pitch and roll as:

$$e_z = z_{ref} - z \tag{11}$$

$$e_\phi = \phi_{ref} - \phi \tag{12}$$

$$e_\theta = \theta_{ref} - \theta \tag{13}$$

The references for the speed controller are then defined as:

$$w = K_{pz} e_z + K_{iz} \int e_z dt + K_{dz} \frac{de_z}{dt} \tag{14}$$

$$p = K_{p\phi} e_\phi + K_{i\phi} \int e_\phi dt \tag{15}$$

$$q = K_{p\theta} e_\theta + K_{i\theta} \int e_\theta dt \tag{16}$$

where $K_{pz}, K_{p\phi}, K_{p\theta}, K_{iz}, K_{i\phi}, K_{i\theta}, K_{dz}, \in \mathbb{R}^+$ are proportional, integral and derivative gains, respectively.

The integral part of the controller is used to eliminate the steady state error to the reference. For the depth controller, it was also considered a derivative term to prevent overshoot, since during the descent the integral part of the controller accumulates error that makes the profiler overshoot.

For each maneuver, the controller gains were determined considering velocities saturation. Since the dynamics of each maneuver are different, the considered gains were determined for each maneuver.

Changing abruptly the position reference of the controllers makes the vehicle accelerate abruptly, causing significant peaks in power consumption since the vehicle needs to accelerate quickly to meet the speed reference. To ensure that the position reference for the controllers is not made abruptly, the position reference is generated using a ramp with a slope equal to the desired velocity for the profiler. This makes the profiler go to the desired speed and position more smoothly.

C. Controller Simulations

Using the model and the controllers described above, the overall performance was estimated through simulation before actually trying in the real profiler. Figures 9 and 10 present the results of the simulation, using the full 6DOF model of the vehicle, where it was instructed to descent to 3.5 meters with a speed of 0.3 m/s (gotoz maneuver).

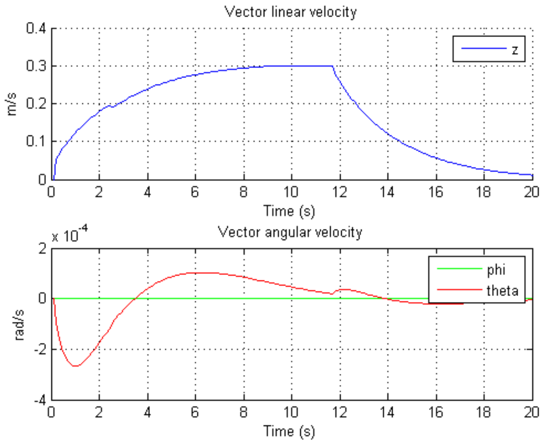


Fig. 9. Speed during gotoz maneuver with 0 in pitch and roll.

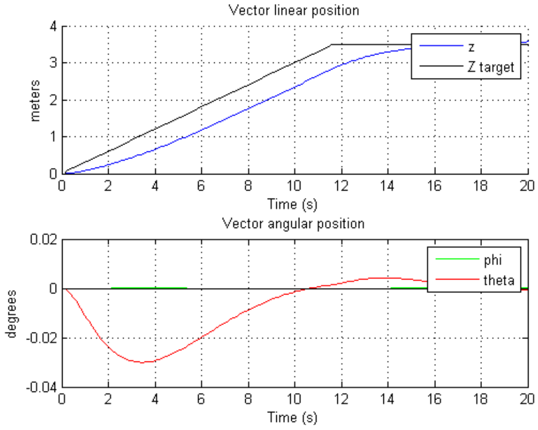


Fig. 10. Position during gotoz maneuver with 0 in pitch and roll.

Figures 11 and 12 present the results where the profiler was instructed to descent to 3.5 meters with a speed of 0.3 m/s (gotoz maneuver) and with 20 degrees in pitch and roll.

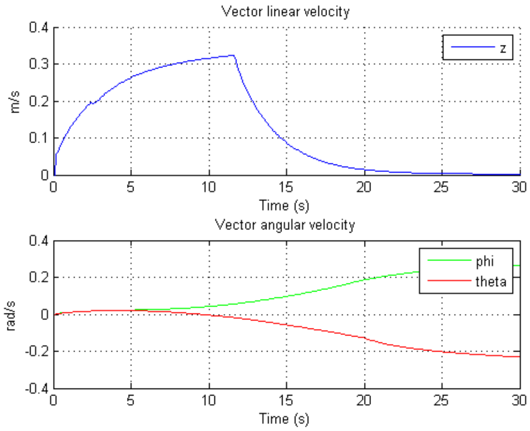


Fig. 11. Speed during gotoz maneuver with 20 degrees in pitch and roll.

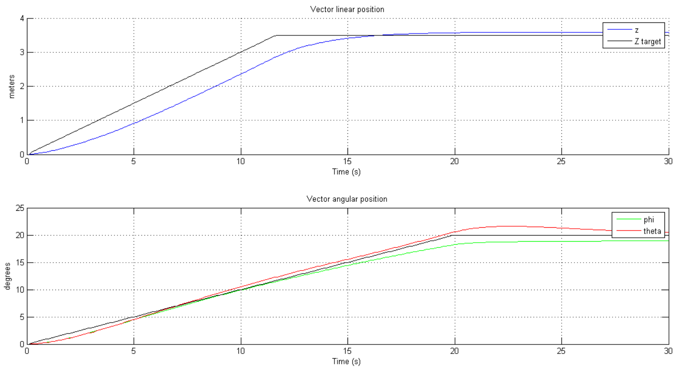


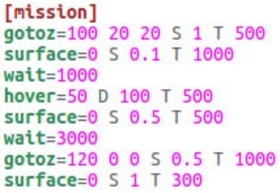
Fig. 12. Position during gotoz maneuver with 20 degrees in pitch and roll.

VI. OPERATION OF THE VEHICLE

To plan a mission on the vehicle, the user must create a mission file with the name config.ini (as shown in figure 13). This file must be started with [mission] and the following commands are available:

- gotoz=<depth> <pitch> <roll> S <descent_rate> T <timeout> — command that allows to profile to a certain depth (in meters) controlling pitch and roll (in degrees) and descent rate (m/s).
- surface=<depth> S <ascent_rate> T <timeout> — command to make the profiler surface with a defined ascent rate (m/s).
- wait=<seconds> — command to wait for a determined period of seconds. Allows to set intervals between different maneuvers. Since the vehicle has a positive buoyancy, the vehicle waits at surface.
- hover= <depth> D <duration> T <timeout> — command to hover at fixed depth during the number of seconds defined in duration.

For each motion command, a timeout must be set, in seconds. In case the profiler does not complete the maneuver on time, the mission passes to the next command.



```
[mission]
gotoz=100 20 20 S 1 T 500
surface=0 S 0.1 T 1000
wait=1000
hover=50 D 100 T 500
surface=0 S 0.5 T 500
wait=3000
gotoz=120 0 0 S 0.5 T 1000
surface=0 S 1 T 300
```

Fig. 13. Example of a possible mission configuration.

VII. Experimental Validation

In the experimental tests described in this section, data was logged to a log file named DataLog<time>.txt, with a period of 250ms. This file was retrieved from the profiler using the Wi-fi connection and was then processed to obtain the figures shown. All these tests were conducted in July 2017, in test tanks at INESC TEC facilities (figure 14).

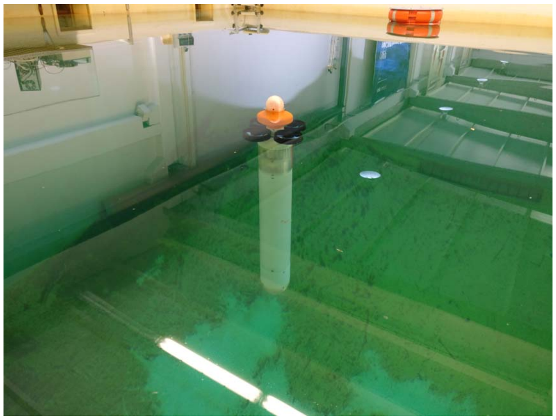


Fig. 14. Profiler at the surface in one of the test tanks at INESC TEC.

In the following figures, the target depth of the profiler is represented together with measured data, to verify that it controls its speed, following the reference during the maneuver. All the tested maneuvers are preceded by a wait command of 5 seconds to allow the vehicle to reach a steady state. Moreover, the profiler waits 2 seconds to initialize the Electronic Speed Controllers resulting in a delay of 7 seconds before the profiler starts a maneuver.

A. Go To z Test

To test the Go To z maneuver, two different tests were performed: one where the profiler dives to a defined depth completely vertical (ie, pitch and roll are both zero) and another where the dive is made with an angle in pitch and roll different than zero. The maneuver is considered completed when the profiler is within 10 cm of the target and the angle error is lower than 2 degrees.

For the first test, the profiler was instructed to dive down to 3.5 meters. The results show that the profiler achieves its target depth with a controlled speed while, at the same time, controlling pitch and roll angles close to zero (figure 15).

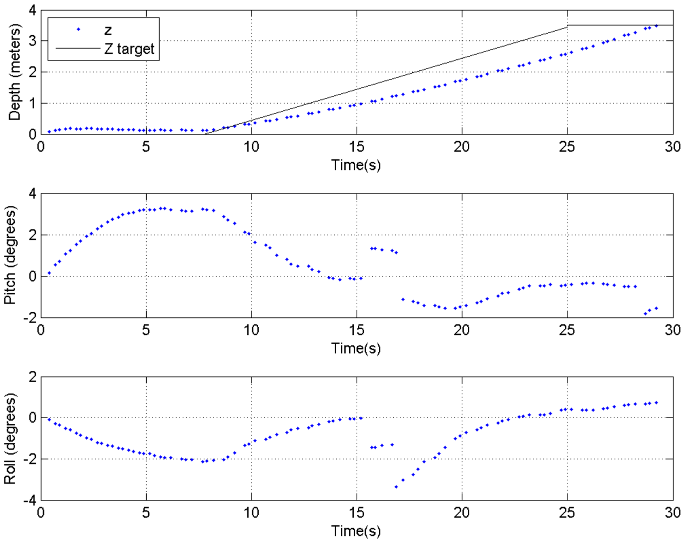


Fig. 15. Depth, pitch and roll during gotoz to 3.5m.

For the second test, the profiler was commanded to dive to 0.4 m depth with an angle of -30 degrees in pitch and 30 degrees in roll. It is possible to observe in figure 16 that the profiler exceeds its depth target. This happens because the forces needed to provide a rotation of the vehicle, also make the profiler dive deeper. Once the angles in pitch and roll are reached, the profiler goes to the desired position.

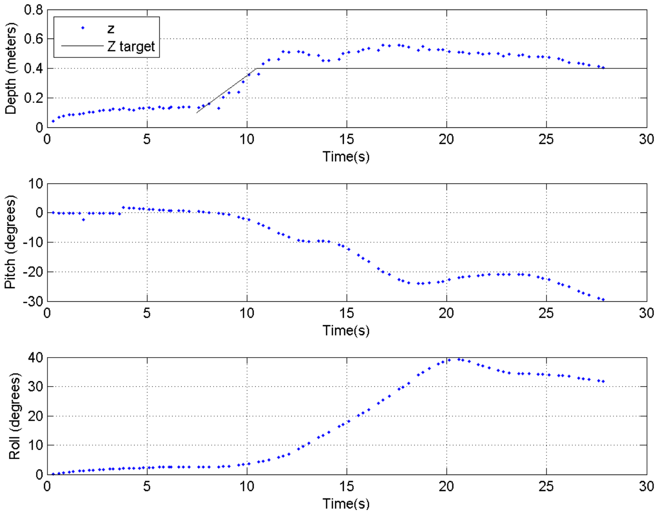


Fig. 16. Depth, pitch and roll of the profiler when diving up to 0.4m.

B. Mission

To test a sequence of maneuvers, the vehicle was instructed to hover at three different depths: 1.5, 2.5 and 3.5 meters followed by a surface with an ascent rate of 0.5 m/s. Figure 17 shows the results and it is possible to confirm that the vehicle hovers at the desired depths and then, after completing the maneuvers, rises with a controlled speed to the surface.

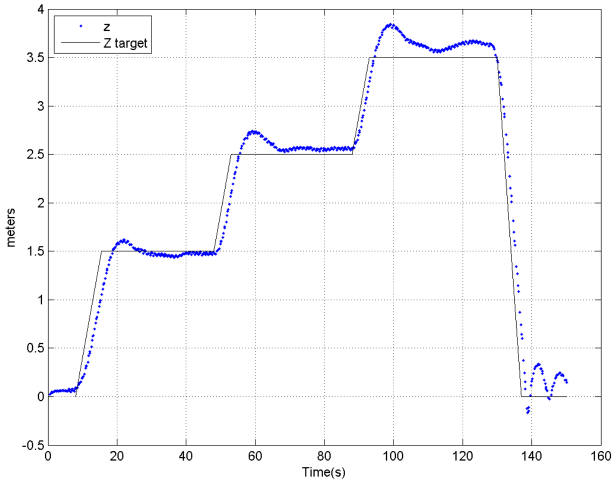


Fig. 17. Hover at three different depths in one mission.

VIII. CONCLUSION AND FUTURE WORK

This paper presents the development of a new autonomous profiling vehicle for coastal areas. A fully functional prototype was developed using a systems engineering approach, following three different phases in an iterative process: design, implementation, and validation.

The development of the prototype focused on the physical implementation, fulfilling the main requirements: it is a portable vehicle capable to perform profiles up to 200m of depth and the software implementation allows the vehicle to autonomously operate, executing a mission plan and gathering data from its set of sensors. The modularity of the vehicle allows to easily add new sensors, using the ports available in the endcaps. These can be integrated in the vehicle's software by implementing a device driver and incorporating the measurements in the shared memory and the logfile.

To design and validate the motion controllers, a 6 DOF model was considered, describing the profiler dynamics and kinematics. This model was used to tune and test the controllers before deployment in the test tanks. The performance of the profiler during the experimental tests demonstrate the adequacy of the controllers and the accuracy of the model.

Taking into account the results presented above, it is possible to conclude that the profiler is already able to perform basic maneuvers and can be used as a platform to collect ocean data. However, the developed system can still benefit from further testing to improve overall performance. For example, the parameters used for the hydrodynamic model can be refined based on experimental tests and identification techniques, to yield a more accurate model of the vehicle. This improved model will result in simulations closer to reality, that can be used to improve the performance of the controllers.

One limitation of the profiler is the rotation in yaw caused by the torque of the propellers. To overcome this effect, it is possible to replace the IMU for a 9 DOF version, and measure the yaw angle. The rotation could then be independently controlled, granting full control of the profiler heading.

In order to increase the usefulness of the profiler at sea, there are a few possible improvements. The first is to add more sensors, like a down-looking camera, an altimeter to measure altitude above sea bottom, and water quality sensors. Another is to design an user interface for mission planing, to start a mission and to analyze retrieved data. An Iridium module would also be useful to expand the communication capabilities of the profiler at the surface. Considering the modular architecture of the developed system, the profiler is ready for a swift integration of all these subsystems.

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