EXPERIMENTAL RESEARCH ON UNDERWATER VEHICLE MANOEUVRABILITY USING THE AUV PIRAJUBA

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Abstract. *Free model tests are extensively used in the identification process of marine vehicles manoeuvrability. During this investigation the self-propelled model performs a number of preprogramed manoeuvres in order to provide data for estimating the vehicle dynamic model. Their use can be extended to autonomous underwater vehicles, AUV, although several considerations about the manoeuvres, environment and the sensors feedback must be considered. This paper presents an investigation on the main factors that affect the manoeuvrability of AUVs, presenting the methodologies adopted in the analysis of sea trials of the vehicle Pirajuba, an AUV developed by the mechatronics department of the Polytechnic School of the University of São Paulo. The horizontal and vertical plane dynamics are investigated separately, since the typical vehicle geometry and usual manoeuvres make coupling effects negligible. The manoeuvres considered for the horizontal plane are the straight line, zigzag, and turning circle. For the vertical plane, it is studied the pulse response and the oscillatory manoeuvre induced by a pseudo-random binary signal (PRBS) input. Furthermore, a review on the identification manoeuvres, vehicle and environment conditions, the sensors characteristics and their influence in the identification process are presented. Those aspects are applied in the analysis of the sea trials carried out with the Pirajuba AUV, in the Angra dos Reis bay area.*

Keywords: *AUV, manoeuvrability, sea trials, identification.*

1. INTRODUCTION

The autonomous underwater vehicles, AUVs, represent specialized class of robots capable of navigate underwater for long periods of time, without communication to a human operator. These vehicles are used as assistance tools for several types of biological, physical and chemical oceanographic missions (Williams et al., 2012).

The AUV Pirajuba was developed by the Unmanned Vehicle Laboratory (LVNT, in Portuguese) at University of São Paulo in order to be used as a test bed for investigations on dynamic identification, controllability, and navigation (de Barros et al., 2012).

The first versions of the vehicle were used mainly for hydrodynamics research (de Barros et al., 2008a, 2008b and 2012a) and in the development of technologies in the field of underwater robotics, such as manufactory of pressure vessels, propulsion system, fins actuators, sensing, communication and embedded system (de Barros et al., 2010 and 2011). In its latter version (de Barros et al., 2012b), the AUV Pirajuba was considered to be in development stage for oceanographic related field missions, in which the first navigations sensors were being integrated in the embedded hardware and software systems, performing functionality and verification tests in the Olympic pool of University of São Paulo.

After these tests the AUV Pirajuba had its mechanical project, embedded hardware and software improved in order to conduct sea trials. These sea trials were used in order to investigate the AUV hydrodynamics, autopilot and navigation system. This paper presents the results and methodologies used in these investigations for the third version of the AUV Pirajuba, seen in Fig. 1 during the sea trials, as well as the overall improvements in the mechanical and hardware projects to accomplish these tests in the sea environment.

The AUV hydrodynamics were investigated performing several pre-established manoeuvres, applying deterministic (Nomoto, 1960; Journée, 1970) and stochastic (Ljung, 1999) identification algorithms to the sensors and actuators signals in order to estimate the vehicles dynamics. The horizontal and vertical plane dynamics are investigated separately, since the typical vehicle geometry and usual manoeuvres make coupling effects negligible. The manoeuvres considered for the horizontal plane are the zigzag, and turning cycle. For the vertical plane, it is studied the pulse response and the oscillatory manoeuvre induced by a pseudo-random binary signal (PRBS) input.

All the identification tests were performed using a simple autopilot system. The AUV Pirajuba autopilot system are divided in vertical and lateral planes, controlling the vehicle depth and heading angle, respectively. Straight line tests were used in order to adjust the gains controllers in order to enhance the response performance.

The navigation tests were performed by the use of an addition sensor that measures the vehicle velocity components. The algorithms were applied to the same identification manoeuvres in order to estimate the vehicle position in an inertial frame. The navigation algorithms were only tested offline for better estimate of its parameters, however all navigation components (e.g., hardware, sensors and software) were embedded in the vehicle.

All the results presented in this paper were obtained by two sea trials in Angra dos Reis bay area, as seen in Fig. 1. This environment was chose due to low incidence of waves and currents. All tests were supported by the Brazilian Navy, providing technical assistance during the sea trials.

This paper is organized as follows: Section 2 shows an overview of the improvements in AUV mechanical and hardware projects in order to accomplished the sea trials. The section 3 presents the weight and control surfaces trimming methodology. Section 4 describes autopilot design and presents its results. Section 5 the results obtained by the identification manoeuvres. Section 6 the results achieved by the navigation algorithm. Finally, section 7 provides a critical review of the progress achieved so far and proposes future developments for the AUV project.

Figure 1. Pirajuba AUV during the identification tests.

2. THE AUV PIRAJUBA

The AUV Pirajuba was developed by the Unmanned Vehicle Laboratory (LVNT, in Portuguese) at University of São Paulo in order to be used as a test bed for investigations on dynamic identification, controllability, and navigation (de Barros et al., 2012). Without a payload the AUV has an autonomy of 10 hours at the cruising speed of 1 m/s.

This torpedo-like AUV uses a free flooding design, in which an external hull made of fibreglass and flotation foam is used to form its hydrodynamic shape and to hold secure the vehicle pressure vessels, allowing the entrance of water in its interior. Its hull uses the Myring (de Barros et al., 2010 and 2011) semi elliptical and cubic relationship as nose and tail profile, respectively, and a cylindrical middle body, its main parameters are presented in Tab. 1.

Table 1. Main parameters of the Pirajuba hull.

Features	Dimension
Bare Hull Length (m)	1.742
Hull Maximum Diameter (m)	0.234
Base Diameter (m)	0.057
Nose Length (m)	0.217
Middle Body Length (m)	1.246
Myring Body Parameter θ (°)	25
Myring Body Parameter n	2

The vehicle uses three custom made aluminium vessels: main, manoeuvring and thrust vessels. The main vessel carries the ARM based computer units, lithium polymer batteries, communication and power electronics, and liquid presence and motion sensors. During the tests the AUV Pirajuba used an Inertial Measuring Unit (IMU) to measure the AUV angular rates, together with a compass to acquire the vehicle heading angle. The AUV Pirajuba also includes a less accurate AHRS (Attitude Heading Reference System), as a redundancy for both systems.

In addition to these sensors, the AUV Pirajuba also has a pressure gauge sensor, used as feedback of the depth control, a Doppler Velocity Logger (DVL), which measures the vehicle velocity, and an Ultra-Short Base Line (USBL), used to locate the vehicle underwater. However, both acoustic sensors (DVL and USBL) were not used in the identification tests, as their transducers affect the flow around the vehicle, and consequently change the vehicle dynamic behavior.

Table 2. Main parameters of the Pirajuba hydroplanes.

Features	Dimensions
Height	0.016 m
Root Chord	0.090 m
Tip Chord	0.060 m
Position[1]	1.373 m

[1]: Distance from the leading edge to the hull nose tip

The Pirajuba uses four control surfaces in the cruciform configuration, positioned in its stern, with its dimensions presented in Tab. 2. The servo mechanisms used to control these surfaces are installed inside the manoeuvring vessel, together with the thruster electronic driver. The thruster vessel carries a 150W DC motor, which moves a polyurethane propeller made by a rapid prototyping manufacturing system. The propeller parameters were selected from the Wageningen series, and its geometry defined in a CAD based numerical tool. All the vessels structures were calculated for operating at a depth of 100 m. The AUV inertia parameters were first calculated by a (Computer-Aided Design) software being later measured by a bifilar pendulum experiment. The results with and without the DVL sensor are presented in Tab.3.

Table 3. Pirajuba AUV mass and inertia parameters.

	Method	X pos.* [mm]	Y pos.* [mm]	Z pos.* [mm]	Mass [kg]	Ix [kg.m²]	Iy [kg.m²]	Iz [kg.m²]
Without DVL	CAD results	932	0,23	9,4	52,7	0,457	8,121	8,167
	Bifilar pendulum	897	--------	--------	53,8	--------	8,660	8,704
With DVL	CAD results	899	0,22	10,5	55,6	0,457	9,046	8,996
	Bifilar pendulum	872	--------	--------	54,4	--------	8,760	8,704

Centre of gravity position related to the body nose tip.

In Fig. 2. is presented the actual vehicle used during the tests with the main and electronics vessel exposed, and in Fig. 3. is presented the vehicle layout drawing with its main dimensions. The vessels present a blue coloration due to the use of an anodising process, that was used to enhance the corrosion resistance of the vessels by increasing the thickness of the aluminium oxide layer. This process is important due to the high corrosion levels on the sea environment.

Figure 2. The Pirajuba AUV external hull, pressure vessels, external sensors and wireless communication hardware. Inside the vehicle, it is shown the maneuver and the main vessels.
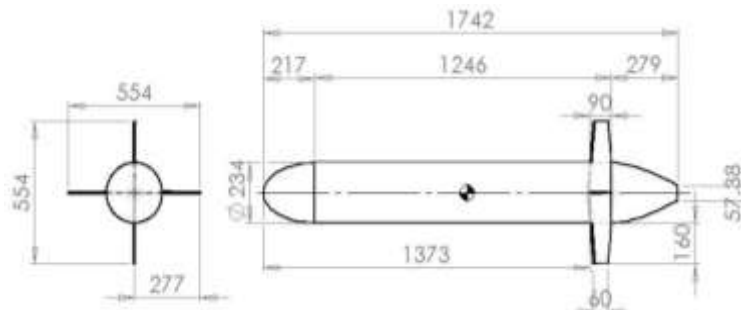
Figure 3. Drawings of the AUV Pirajuba (dimensions in mm).

3. TRIMMING METHODOLOGY

Before navigate in sea, an AUV must be trimmed to a condition wherein is possible to navigate in a straight line without the use of the control surfaces and external disturbances. The most common trims for an AUV are related to the excessive weight or buoyancy, when totally immerse, the misalignment of the control surfaces, and the residual moment generate by the propeller. In the next sections are presented the trim methodology used for all cases in the AUV Pirajuba.

3.1 Weight trimming

The weight trim is performed to achieve a vehicle horizontal static stability, i.e., the AUV will not present an ascent or descent movement due to a difference between it weight and buoyancy.

In the AUV Pirajuba this was done by the addition of lead in the interior part of the external hull. The first estimative of this weight was calculated using a CAD software, considering all the parts and equipments of Pirajuba in addition to the weight of water in its interior. However, the final weight adjustment should be done in the field, adding small weights of lead to compensate the water density and other parts that cannot be correctly modelled.

3.2 Control surface trimming

The control surfaces are trimmed in order to enable straight line navigation without any deflection. Due to the difficult of trim small angles (less than 2 degrees), this procedure is performed executing several straight lines manoeuvres, in which the trim angle is varied at every manoeuvre until the AUV present a small deviation. In this way, the control surfaces can present a trim angle that is not aligning with the AUV hull, due to its eventual axisymmetric imperfections.

3.3 Propeller trimming

When a propeller rotates is generated a residual torque due to the blades drag. In cases of AUVs with only one propeller, this residual torque is transferred to the AUV causing a roll angle. Depending of the amplitude this roll angle can prejudice the autopilot performance and the manoeuvres identification process.

Normally, this angle can be compensated by applying all the trim weight in the lower part of the AUV. However, in the case of the Pirajuba, this procedure resulted in a roll angle between 3 to 5 degrees, seen in Fig. 4, with could impair the identification analysis. In order to reduce this angle the trim weight was shifted to the lateral direction, increasing the restoration moment generated. This shift only modifies the overall mass center in about 15 mm, which should not interfere significantly in the AUV dynamics.

This trimming is executed at the AUV cruising speed. The relation between the propeller rotation and the vehicle speed was obtained empirically by external measurements.
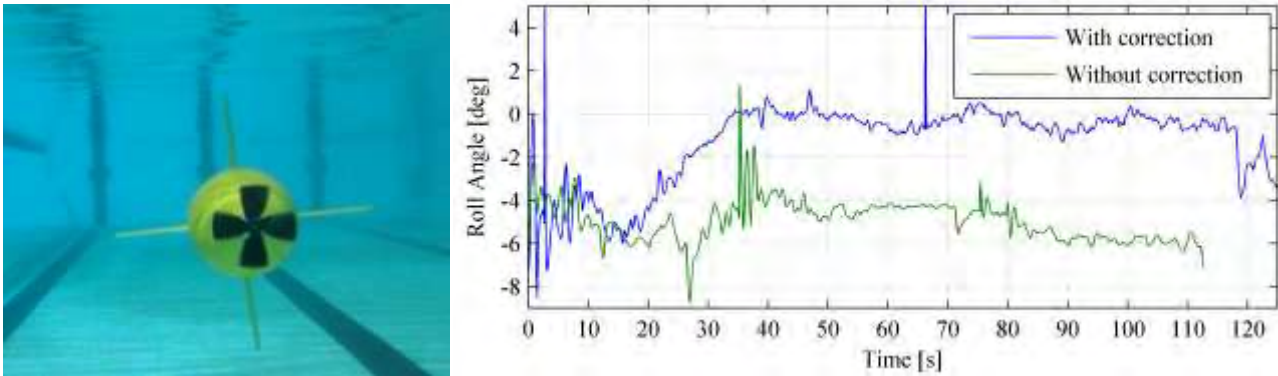
Figure 2. At left, a picture of the Pirajuba AUV with an excessive roll angle in a pool test. At right, graphs showing the roll angle time series with and without the lateral shift in the trim weight.

4. THE AUTOPILOT SETUP

The autopilot was design to control the AUV Pirajuba depth and heading during the identification and navigation manoeuvres. The controls were used to ensure a minimal interference between the movements in different planes, e.g., the control was designed to keep the AUV at a constant depth during the lateral manoeuvres in order to do not generate addition hydrodynamic efforts. The same is valid for the vertical motion.

Each control was developed individually and validated in straight line tests, after the trimming procedure. The controls were developed using a simple PID (Proportional-Integral-Derivative) structure, in order to present a straightforward implementation in the embedded system with a fast and reliable tuning procedure, and avoiding eventual implementation problems that could result in the loss of the equipment. Both controls are presented separately in the following sections.

4.1 Lateral control

The lateral control uses the feedback from the compass heading angle (ψ_{CPS}) and the IMU yaw rate (r_{IMU}). If the movement only occurs in the lateral plane the yaw rate is equal to the heading angle derivative, indicating a control with a PD structure.

The IMU yaw rate signal was used by exhibit a lower noise than the derivation of the compass heading angle, however the IMU signal must have its random bias (b_{rIMU}) subtracted to not present a control derivation. This sensor bias was calculated when the sensors is started with a stationary vehicle. As the IMU present a very low bias variation over time (bias stability), it was not corrected.

The control signal from the rudder (δ_{rud}), the vertical control surfaces, is calculated as

$$\delta_{rud} = K_\psi \left(\psi_{ref} - \psi_{CPS} \right) + K_r \cdot \left(-r_{IMU} + b_{r_{IMU}} \right) , \qquad (1)$$

where K_ψ and K_r are the control gains in the heading angle and yaw rate feedback, and the variable ψ_{ref} represents the heading reference signal, that was used as reference to control the heading in the navigation manoeuvres. The control gains were chosen in order to present a fast response without the control saturation, which was defined to be in 20 degrees.

An example of this control regulation was presented in Fig. 5, in which the vehicle undergoes a great push that was applied by a diver, after the acceleration period.
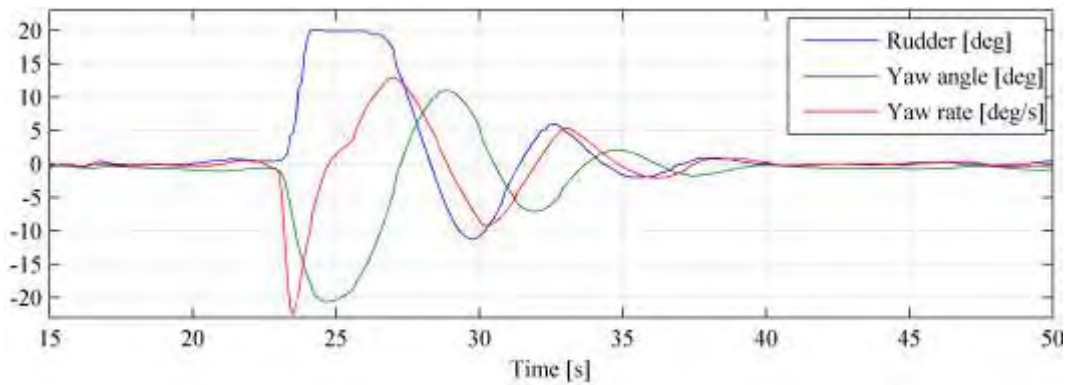
Figure 5. Verification of the controlled rudder action in a straight line manoeuvre.

4.2 Vertical control

The vertical control was defined by a complete PID structure, as seen in Eq. 2, with the error e_z (Eq. 3) defined by the difference between the depth reference signal (z_{ref}) and the AUV depth (z_{pre}) feedback, which was obtained by the pressure gauge sensor.

$$\delta_{sp}(t) = K_{Pz} \cdot e_z + K_{Iz} \cdot \int e_z dt + K_{Dz} \cdot \frac{de_z}{dt} \tag{2}$$

$$e_z = \left(z_{ref} - z_{pre} \right) \tag{3}$$

The depth PID gains (K_{Pz}, K_{Iz} and K_{Dz}) were estimated by several tests in an Olympic pool (de Barros, 2010; de Barros, 2011), representing a controlled environment, and later on they were readjusted for sea trials. On both events the control gains were estimate in order to obtain a fast response with low overshoot, preventing an eventual hit in the bottom or trespassing the water surface in immersion or emersion manoeuvres.

An example of the control regulation was presented in Fig. 6 for a 1.5 m immersion manoeuvre from the sea surface. This figure shows that the AUV depth was well controlled during the manoeuvre, presenting a low overshoot. However, the stern plane output signal presented high frequencies oscillations (chattering behaviour), probably due to the depth signal derivation. For the next tests the control gains should be adjusted in order to not presenting this behaviour and wear the stern plane actuators.
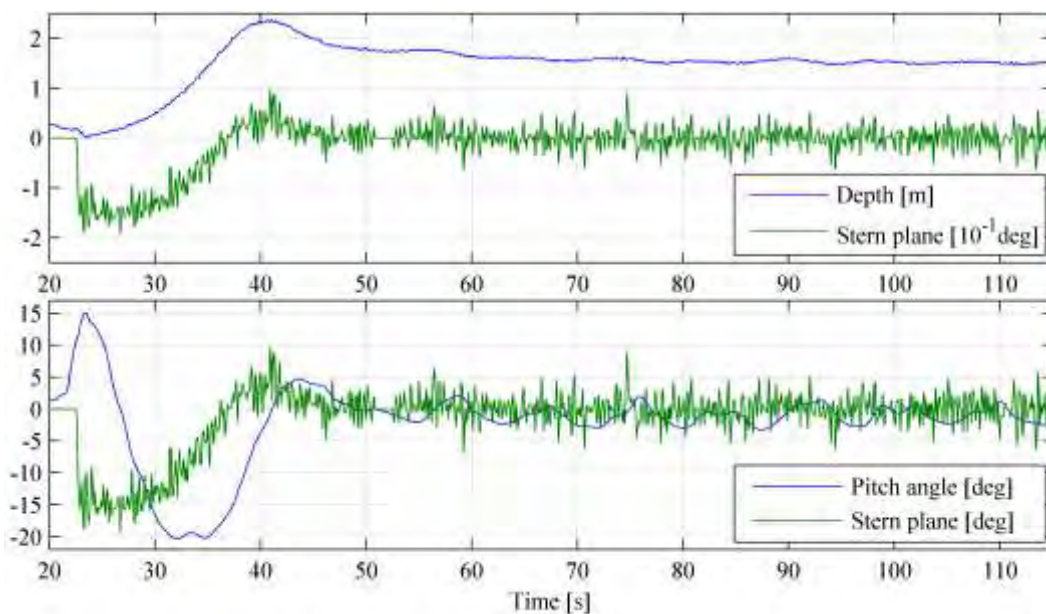

Figure 6. Verification of controlled stern plane action in a straight line manoeuvre in the immersion phase.

5. IDENTIFICATION MANOEUVRES

The identification manoeuvres were a group of manoeuvres that are used mainly to identify the vehicle dynamic model, using deterministic and stochastic methodologies (Nomoto, 1960; Ljung, 1999). The manoeuvres are divided in order to identify independently the lateral and vertical motion dynamics. Each set of manoeuvres are presented in the following sections, but first an overall test methodologies are presented.

5.1 Test methodologies

All manoeuvres were performed considering six stages, limited by empirically chosen time periods. These stages are qualitatively presented in Fig. 7.
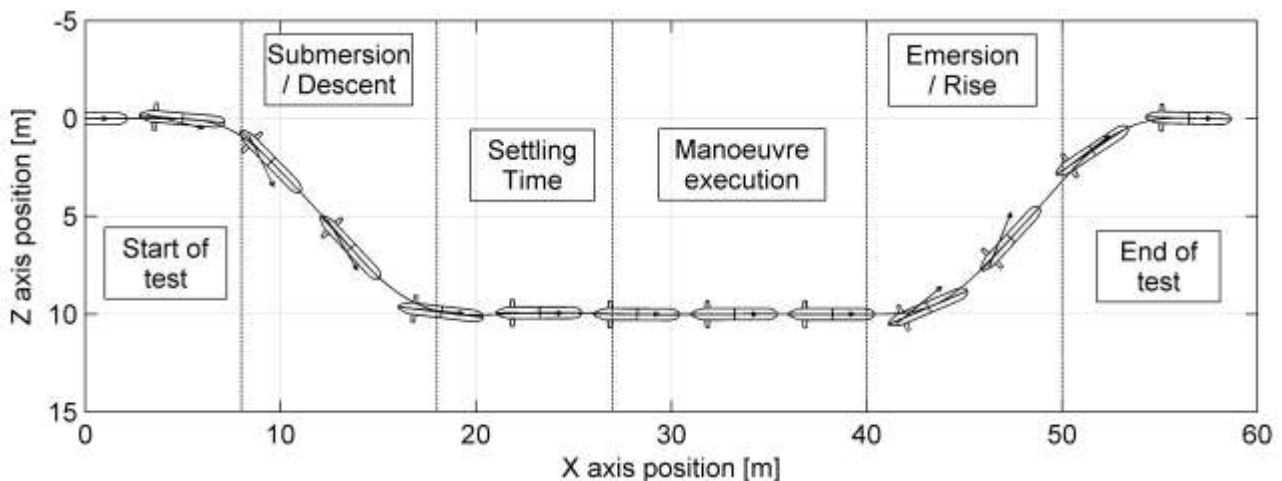
Figure 7. The six stages considered during the identification manoeuvres of the AUV Pirajuba. The presented displacements do not represent the actual time relation of each stage.

The lateral and vertical controls were used in all non-manoeuvring stages in order to guarantee a low variation in the initial condition and in the final estimated AUV position. As a secure measure the manoeuvres present a time limit and a depth limit. If the manoeuvre exceeds the set time, or the secure depth limit, the embedded system cancels the current manoeuvre and return to the surface.

In order to verify the influence of nonlinear effects, all manoeuvres were performed with four different deflection angles: 5, 10, 15 and 20 degrees. The nonlinear effects are expected to be more significant in the 15 and 20 degrees manoeuvres, as the resulted angle of attack in the rudder can exceed its stall angle (Dantas et al., 2011). Additionally, each manoeuvre was repeated at least four times in order to have a better stochastic description of the dynamic model and the environmental disturbances.

5.2 Lateral manoeuvres

The lateral manoeuvres were performed with two different types of manoeuvres: the turning circle and the zigzag (Nomoto, 1960; Fossen, 2002).

The turning circle is a classic naval manoeuvre that is performed by a constant rudder deflection, resulting in a uniform circular motion. This manoeuvre was used principally to identify AUV dynamic steady states characteristics.

In the zigzag manoeuvre (Kempf, 1932) the AUV executes an oscillatory motion defined by the rudder deflection and the heading angle. The manoeuvre starts with a constant rudder deflection that changes direction when the heading angle reaches the same value, as summarized in Eq. 3. This manoeuvre was used to best identify the AUV transient responses.

$$\delta_{rud} = \begin{cases} +\delta & \rightarrow & \psi \geq +\delta \\ \delta_{rud} & \rightarrow & -\delta < \psi < +\delta \\ -\delta & \rightarrow & \psi \leq -\delta \end{cases} \tag{3}$$

Figure 8 and Fig. 9 present the results obtained by the AUV Pirajuba in the turning circle and zigzag manoeuvre, respectively. Oscillations in the yaw rate are induced by the wave perturbations in the AUV motion.
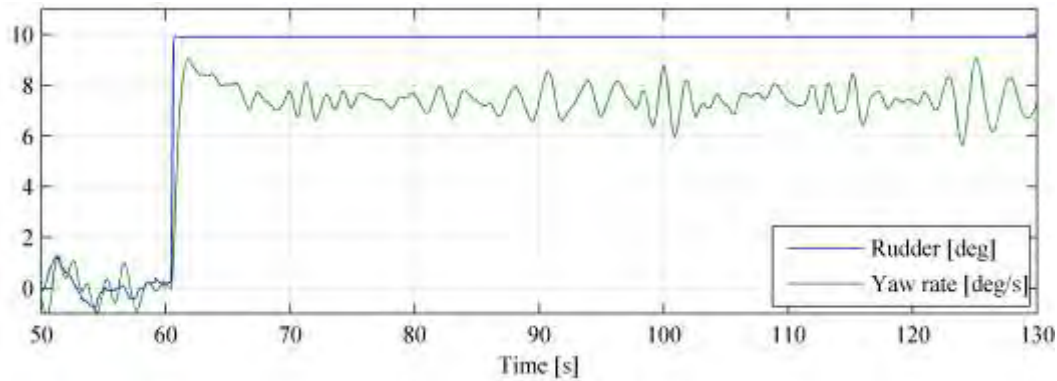
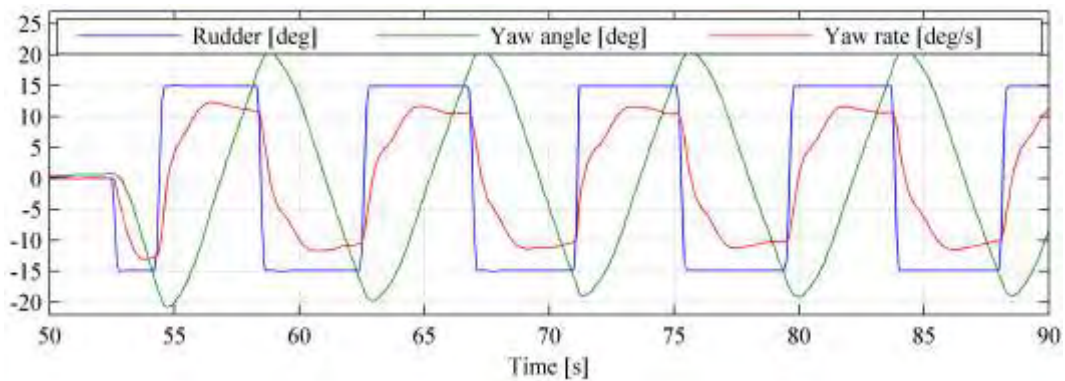Figure 8. Measurement of the yaw rate and rudder deflection for a 10 degrees turning manoeuvre.

Figure 9. Measurement of the yaw rate, yaw angle and rudder deflection for a 15 degrees zigzag manoeuvre.

5.3 Vertical manoeuvre

The vertical manoeuvres are limited by the local sea bottom and the water surface, as the vehicle must present a distance from these limits in order to avoid the wall effects and the free-surface suction (Fossen, 2002), which would prejudice the identification process.

Considering the standard bottom depth of Angra dos Reis coast (4 to 6 m) is impossible to submersible vehicle execute a step-like manoeuvre in the vertical plane (like the turning manoeuvre), as the vehicle will hit the bottom or the sea surface. To substitute this manoeuvre was used the pulse response test (Booth, 1975), in which the stern plane is deflected to a constant value in a short period of time, and the data is collected until the AUV reach the stady state. The simplicity of the pulse manoeuvre does not allow a total identification of the dynamic responses in all frequencies, being better used as a validation manoeuvre.

The AUV Pirajuba pulse manoeuvres were implemented considering an amplitude of 5 and 10 degrees and periods between 1 and 3 seconds, due to the imposed limits. An example of the depth and pitch angle results obtained by this manoeuvre is presented in Fig. 10, for a 3 s / 10º deflection, starting in the bottom and going to the surface. The same wave induced oscillations seen in the turning and zigzag manoeuvres (Figs. 8 and 9) are observed in the depth and pitch angle.
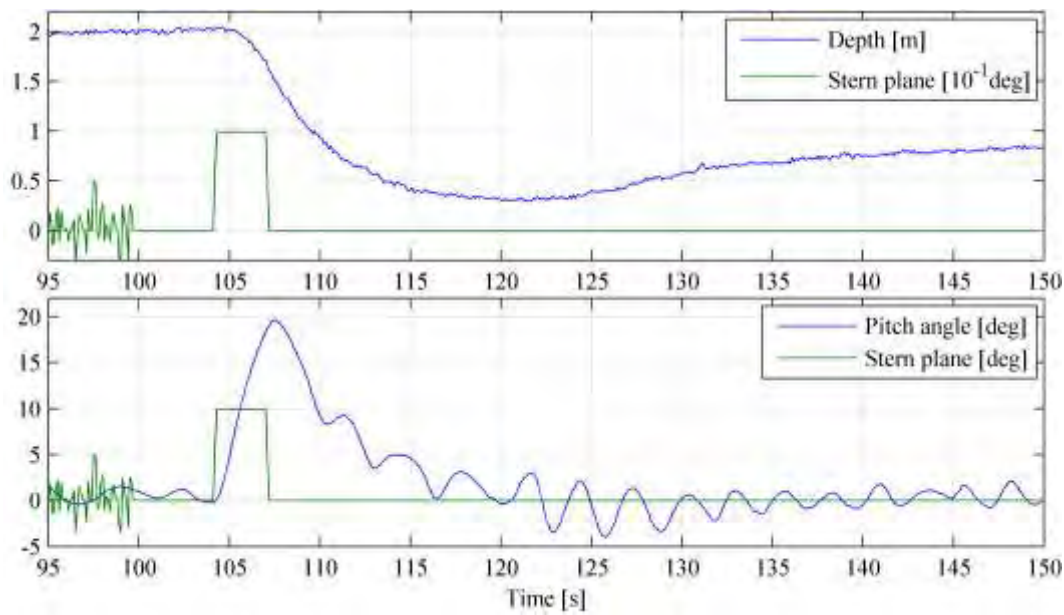
Figure 10. Measurements of the depth (above chart) and pitch angle (below chart) during a 3 second / 10 degrees pulse manoeuvre.

The zigzag manoeuvre can be used in order to identify the AUV dynamics in the vertical plane, considering the feedback from the depth or pitch angle. However, in the AUV Pirajuba vertical identification manoeuvres were used the pseudo random binary sequence (PRBS) tests, in which the stern plane angle switches between the same positive and negative deflection angle using predetermined random periods. The PRBS signal has a broader excitation frequency than the zigzag signal, which can result in a better identification of the AUV vertical dynamic in all frequency modes. The PRBS manoeuvre was only used in the vertical plane as the AUV vertical dynamic model present a more complex structure than the lateral (Fossen, 2002), which can be simplified to a linear first order system (Nomoto, 1960).

In order to avoid an impact to the sea bottom or the water surface, the PRBS signal was considered in the depth reference rather than the stern plane angle. In the Pirajuba trials the PRBS was set to generate a depth reference signal of 1 or 2 meters with a period of 2 seconds. An example of the PRBS manoeuvre is presented in Fig. 11.

Figure 11 shows the same high frequency oscillation from the depth control graph (Fig. 6) was presented in the stern plane deflection, showing the disadvantages of using a PRBS depth reference signal than the stern plane deflection. Despite this problem the AUV presented atypical PRBS oscillation that can be used by identification algorithms (Ljung, 1999).
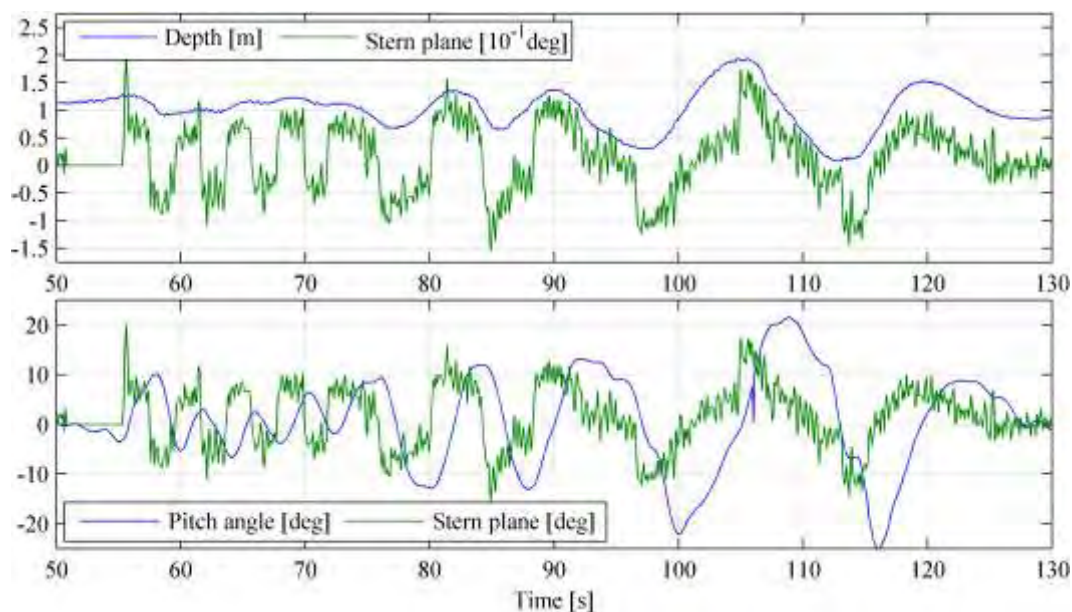
Figure 11. Measurements of the depth (above chart) and pitch angle (below chart) for a PRBS manoeuvre with a depth reference of 2 and 1 m and period of 2 seconds.

Other manoeuvre that can be used in the identification of a submersible vehicle vertical dynamic is the harmonic response (Tinker, 1979), which is composed of several tests performed with different frequencies of a sinusoidal signal applied to the stern plane deflection. However, this test was not used for the AUV Pirajuba as its execution demands a number of tests in order to range all the AUV frequencies, increasing the overall cost and time demanded by the experiment.

6. NAVIGATION RESULTS

This section presents the results of a dead reckoning navigation algorithm (de Barros et al. 2012) that was applied to the manoeuvres executed by the AUV Pirajuba. Although the vehicle has a specific embedded computer responsible to the navigation calculations, the results presented in this section are obtained by offline calculations.

The navigation calculations were performed considering the measurements of the IMU, compass, DVL and depth gauge sensor at 10 Hz, which represents the embedded recording frequency.

In short terms, the navigation algorithm uses the IMU accelerometers and gyroscopes information to determine the AUV orientation, using the compass heading measurement to correct the yaw/heading angle. The velocity given by the DVL is integrated with the orientation angle to estimate the AUV position in the inertial frame, which the vertical component is corrected by the depth measurement.

Using this algorithm the longitudinal and lateral position will drift over time, requiring a position measurement to correct this estimation. However, as the DVL and IMU presents low drifts, less than 2 mm/s and 1 degree/hour, respectively, the position estimation will present a small drift for manoeuvres with less than 3 minutes, providing enough information to validate the algorithm.

Examples of this algorithm application are presented for the turning and zigzag manoeuvres in Fig. 12. The drift in the beginning of the manoeuvre could have occurred due to a real drift of the vehicle, as at the manoeuvre star the vehicle has no propulsion and can be carried out by the sea current.
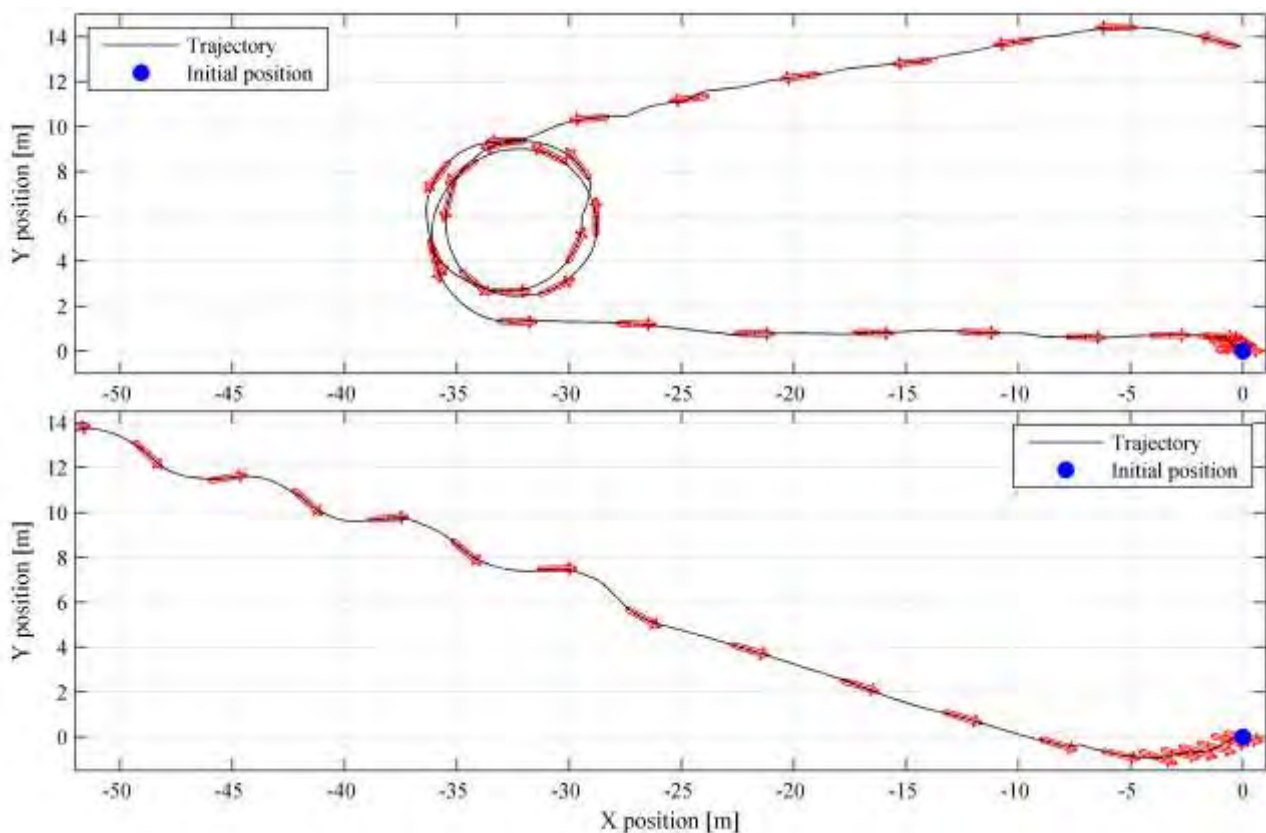

Figure 12. Position and yaw angle estimation for the AUV Pirajuba in a 20 degrees turning (top chart) and zigzag manoeuvre.

This drift can also be generated in the navigation algorithm initialization, which had not stabilized their internal states, or due to errors in the DVL measurement that was not considered in the navigation algorithm (Miller, 2010). As can be seen in Fig. 13, the DVL can present dropout signals (velocities are not measured) or a measurement errors, induced wrong estimations of the AUV position. However, these errors occurred only a few times during all the Angra dos Reis sea trials, and most of them occurred in beginning of the manoeuvre, in which the vehicle oscillates more.
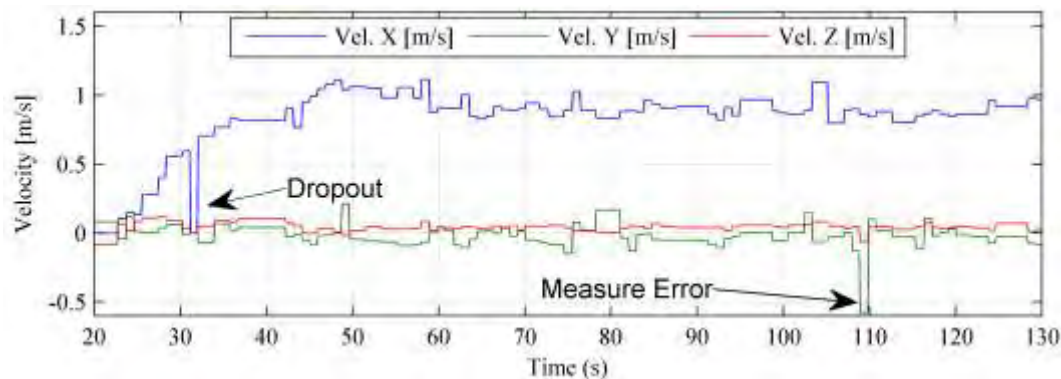

Figure 13. Velocity DVL measurements of the Pirajuba DVL in a acceleration phase of a zigzag manoeuvre.

For longer and deeper manoeuvres the embedded algorithm can use the position information measured by the USBL system in order to correct this information. Another option is to equip the AUV with GPS (Global Position System) module, and program the AUV to emerge on the surface and correct the position estimation when the navigation system indicates a large estimation error.

7. CONCLUSION

All the identification manoeuvres were well executed in the sea trials, allowing the use of deterministic and stochastic methods to identify the AUV Pirajuba dynamic model. Even the problem in the stern plane angle of the PRBS manoeuvre can be overcome using an identification methodology that uses a specific model for wave disturbances.

The experiments in Angra dos Reis coast also showed that it is possible to conduct missions with the AUV Pirajuba in a calm sea environment, showing that the vehicle is prepared to be used in oceanographic missions. In order to be used in longer missions, the navigation algorithm should incorporate the measurements sensor characteristics, like the DVL dropouts, and the position sensors, e.g., the USBL and the GPS.

A next version of the Pirajuba AUV will include an imaging acoustic sonar and water quality sensors to provide capabilities for the vehicle to perform oceanographic missions.

8. ACKNOWLEDGEMENTS

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