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Design of vectorial propulsion system for Guanay II AUV *

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Abstract—The autonomous underwater vehicle (AUV) Guanay II was designed to navigate on the surface of the sea, and in specific points stop and realize a vertical immersion. This vehicle has three thrusters located on stern, oriented to provide propulsion and yaw control on the horizontal plane. The used immersion system is based in the change of buoyancy of the vehicle, by using a piston system. Due to this design, the vehicle does not have the ability to navigate in immersion, considering that the inclination of the vehicle (pitch angle) cannot be controlled. In this work, we show the design of the vector propulsion system for the vehicle Guanay II, which will allow to control the pitch in immersion. To this end, we have provided to the two laterals thruster the possibility of varying their propulsion angle on the vertical plane, by the use of servomotors. Next, we will show the design and the results obtained.

Keywords—vertical immersion; vector propulsion system; AUV, GUANAY II.

I. INTRODUCTION

At present, there are different types of immersion systems for autonomous underwater vehicle (AUV): immersion by mobile rudders (MAYA [1], Iver 2 [2]), immersion by fixed vertical propulsion ion (SPARUS II [3], MONSUN II [4]), immersion by vector propulsion (ODYSSEY IV [5], DORADO [6]), immersion by buoyancy control, etc.

For an AUV to be able to navigate in immersion, it's necessary to be able to control the depth of navigation and its inclination. The immersion systems by control of buoyancy can control the depth, but in most cases do not allow the control of vehicle inclination. This leads to the implementation of hybrid immersion systems (Qianlong I [7], Theseus AUV [8], Urashima AUV [9]). These systems use the buoyancy control system, to adjust the trimming or to perform vertical immersion, but for the navigation in immersion, use movable rudders or vectorial propulsion (Thrust vectoring).

The vehicle Guanay II (Fig. 1), is a vehicle developed by the research group SARTI of the UPC*. Initially designed to navigate the surface and at specific points perform vertical dives. The maximum speed achievable by this vehicle is 1.2m/s.

The Guanay II has a propulsion system based on three motors located at the stern, the control of the yaw is realized varying the speed of the lateral thrusters. The four stabilization surfaces located on the horizontal plane are fixed and allow greater stability in navigation; reducing rolling movements.

This vehicle's immersion system is based on the change of buoyancy, which allow for vertical immersion, but does not allow to control the inclination of the vehicle, making it impossible to navigate in immersion.

To enable the navigation in immersion of the vehicle, we propose in this work, the development of a vector propulsion system. We have discarded the use of mobile control surfaces for the following reasons: a) due to its low effectiveness at low speed [12] [13]. b) due to the current structural characteristics of the Guanay II AUV, the incorporation of a vector propulsion system is much more feasible, compared to the structural modifications required to convert the stabilizing surfaces to control surfaces.

The proposed vector propulsion system is based on the control of the orientation of the two lateral propellers. We will provide a rotating motion on the vertical plane to each of the lateral thrusters, with this we obtain the control of the inclination (pitch angle). In the next section, we explain the characteristics of the system designed, and in section III, we show the results obtained.

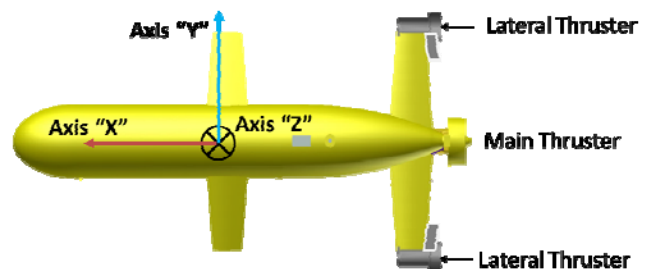


Fig. 1. 3D of AUV Guanay II, Description of the propulsion system

II. DESIGN OF THE VECTORIAL PROPULSION SYSTEM

The proposed vector propulsion system consists of providing the lateral thrusters with a circular motion on the vertical plane, this makes possible to orient the propulsion flow

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at different angles on the vertical plane. Consequently, the thrusters generate a force applied on the stern, in the plane "xz", generating a pitching moment over the center of gravity (axis "y").

To provide this motion to the thruster, we have analyzed different commercial actuators, we value the possibility of being coupled to the vehicle and its economic cost. From this study, we have found that the best option for this application is the use of servo motors (SAVOX SW-1211SG) [14].

This type of servomotors only has the IP67 certification, therefore, to be able to be used to depths up to 20 meters, we have made some modifications. These modifications have consisted in reducing the compressive stress suffered by the servomotor and its connections, replacing the air inside the servomotor with oil, and covering all the seals and cables with vulcanized tape.

The correct operation of these servomotors, with these modifications has been verified in a hyperbaric chamber up to a depth of 20 meters. To mount the servomotor to the thruster, we have designed a support structure and mechanical coupling. Its parts are shown in fig. 2 and its final assembly in fig. 3 and fig. 4. This structure was designed in Autodesk Inventor and manufactured in PLA, in a fast prototype printer. The range of circular motion is $\pm 25^\circ$.

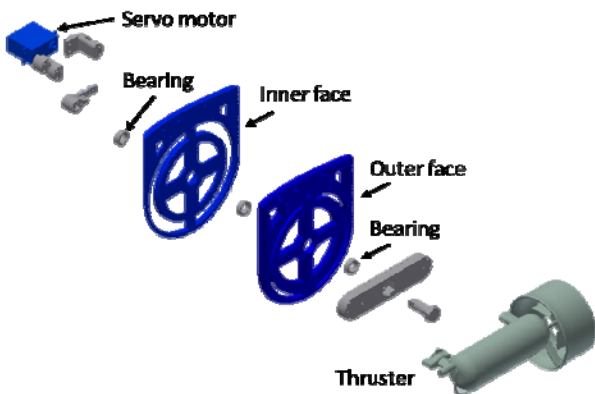


Fig. 2. Parts and pieces of the structure (model 3D - Autodesk Inventor)

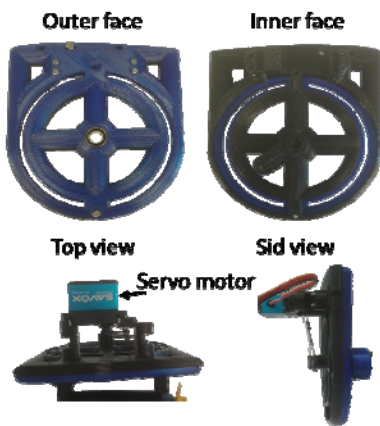


Fig. 3. Parts and pieces of the structure (real model)

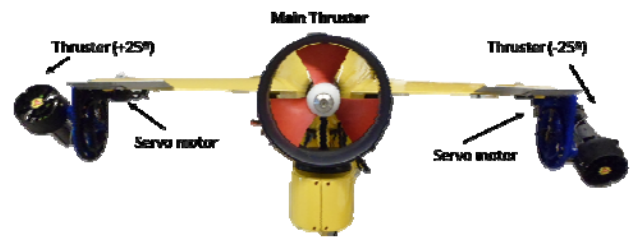


Fig. 4. Photographs of the stern of the AUV Guanay II, fixed propulsion system (main thruster) and vectorial (lateral thrusters).

In figure 5, we show the block diagram for controlling the orientation of the thrusters. The power required for the operation of these servomotors is 6 Vdc (see fig. 4), the position of the drive shaft is adjusted according to a PWM signal, with an amplitude of 5 volts, 50 Hz frequency and a positive duty cycle of 6% to 11%. The control unit has a serial output interface (RS232) and we use a RS232 to PWM driver of 2 channel. This allows independent control of the servomotor located in the left aft stabilizer, to the one located in the right stabilizer. To measure the inclination reached by the moving vehicle, we use an inertial system (INS) located in the center of mass of the vehicle.

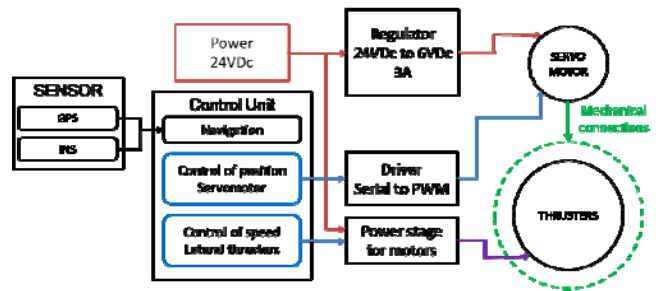


Fig. 5. Block diagram of the system; Measurement of the inclination of the vehicle and control of the orientation of the lateral thrusters.

III. TESTS AND RESULTS

The first tests have been developed in the Olympic channel of Castelldefels - Barcelona - Spain. These tests consisted in making linear paths of approximately 18 meters in length, using the configuration of angle of the servomotor, percentage of power of propulsion and buoyancy, given in the Tables I and IV.

The buoyancy of the vehicle has been adjusted to values close to neutral buoyancy (represented in Tables I and IV by +) and to more positive values (represented in Tables I and IV by +++).

The first test consists of three stages according to the positions of the servomotors given in Table I. The first stage starts from a state of repose, where the laterals thrusters are activated at 100% and the main thruster at 30%, with an angle of the servomotor of 0° , during a period of 20s. In the second stage, the propulsion percentages of the thrusters are maintained, but the angle of the servomotor is changed from 0° to -25° , during 20s. Finally, in the third stage the propulsion percentages are still maintained, but the angle of the

servomotor changes again to 0° . This test is performed for two different buoyancy adjustments.

In figures 6 and 8, we show the evolution of the pitch angle of the vehicle for different buoyancy adjustment. In both graphs, we observe a change in the inclination of the AUV, generated by the action of the servomotor. In Table II, we detail the dynamics of this variable in each of the stages of the actuators. In Figure 8, in which we analyze the case 2, which has less positive buoyancy, it is confirm that the pitch angle is greater.

In figures 7 and 9 we show the evolution of the vehicle depth for different buoyancy adjustment. In Table III we detail the depth dynamics in each of the stages of the actuators.

TABLE I. CONFIGURATION PARAMETER FOR THE TEST 1

# Test	Time[s]	Parameter	Value
1	20 (Stage 1)	Angle of servomotor	0°
		Power of Lateral Thrusters	100%
		Power of Main Thruster	30%
		Buoyancy case 1	++++
	Buoyancy case 2	+++	
	20 (Stage 2)	Angle of servomotor	-25°
		Power of Lateral Thrusters	100%
		Power of Main Thruster	30%
		Buoyancy case 1	++++
	Buoyancy case 2	+++	
	20 (Stage 3)	Angle of servomotor	0°
		Power of Lateral Thrusters	100%
Power of Main Thruster		30%	
Buoyancy case 1		++++	
Buoyancy case 2	+++		

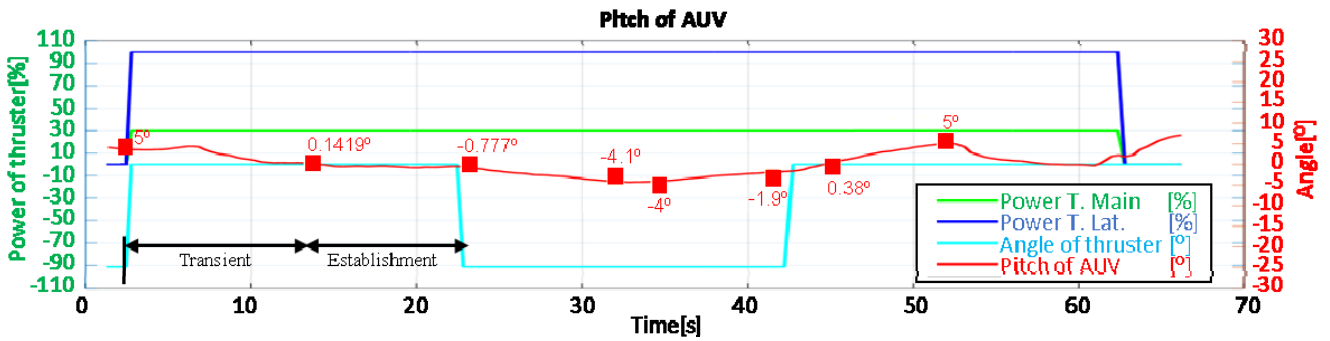


Fig. 6. Result obtained test 1, case 1, Pitch angle of AUV.

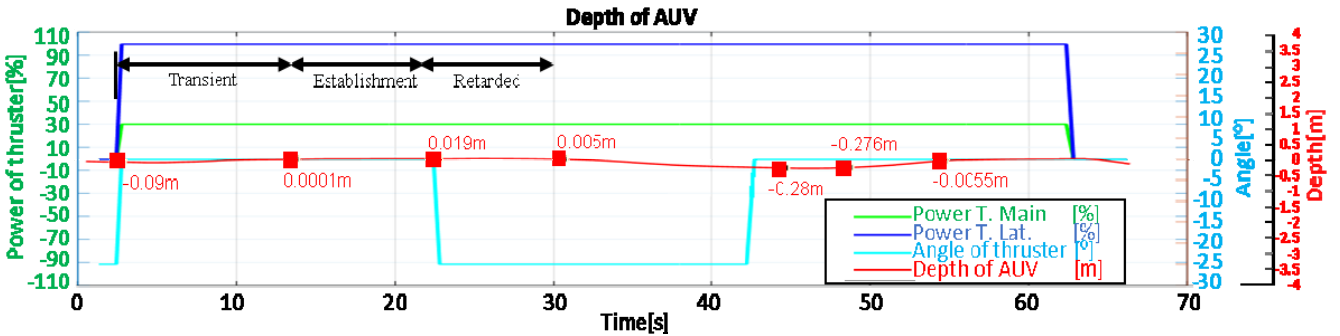


Fig. 7. Result obtained test 1, case 1, AUV behavior on the vertical plane.

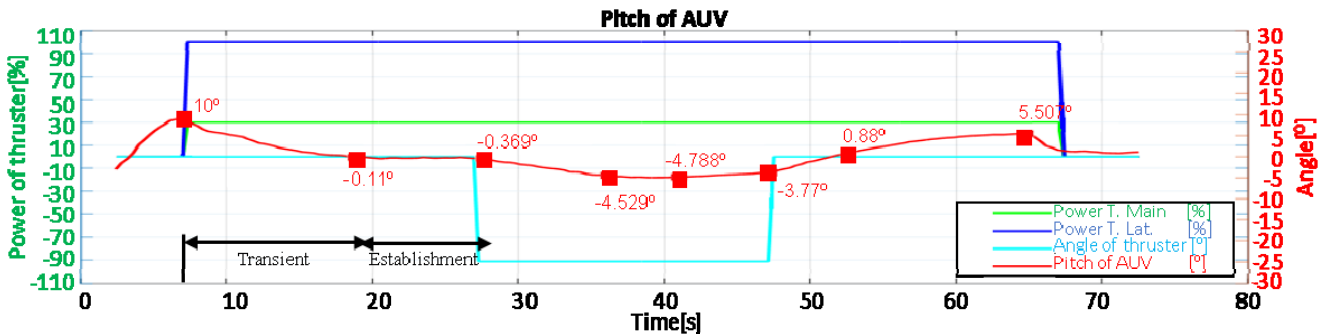


Fig. 8. Result obtained test 1, case 2, Pitch angle of AUV.

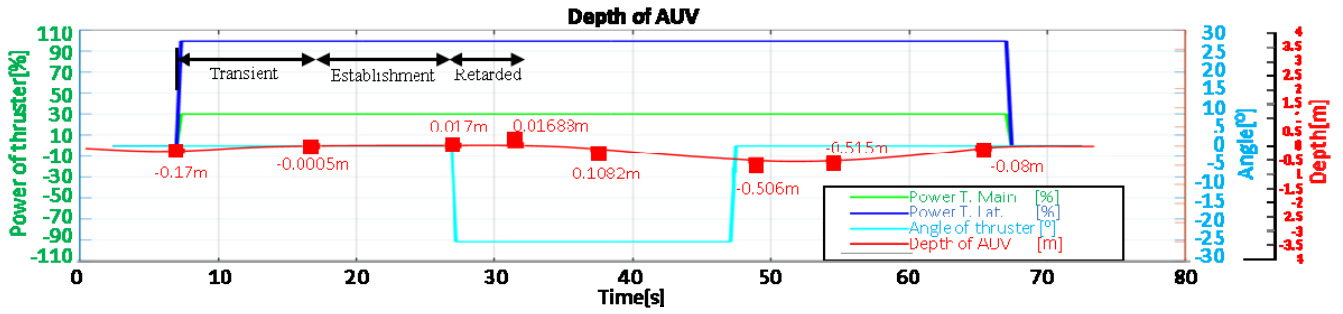


Fig. 9. Result obtained test 1, case 2, AUV behavior on the vertical plane.

When analyzing Table II, III and the previous figures, we can observe that the change in the angle of the servomotor (0° to -25°) generates an instantaneous change in the inclination (pitch) of the AUV, but does not generate an instantaneous change in the vertical plane (depth). We observe that the AUV begins to submerge after a time (delayed) of 7.98s for case one and 4.51s for the case two; after that time, the AUV reaches the force and inclination necessary to overcome the buoyancy force.

When the angle of the servomotor changes from -25° to 0° , we observe that the inclination of the vehicle instantly changes, but does not generate, an instantaneous change in the level of depth. The AUV trajectory maintains the same slope for a few seconds and is subsequently established maintaining the same depth (case one 0.3m, case two 0.5m) for a few seconds (case one 4s, case two 5.6s). Finally, the AUV begins to emerge until reaching the surface, due to the positive buoyancy initially set in the AUV.

The difference between the depth values reached and the times analyzed for transition, establishment and duration in a state depend exclusively on the positive buoyancy adjustment used in each case study.

TABLE II. RESULTS OBTAINED, DECOMPOSITION OF THE SIGNS OF TEST 1, IN TRANSITION, ESTABLISHMENT AND DURATION IN A STATE.

# Test	Stage	Parameter	Pitch	
			Case 1	Case 2
1	1	Transient (time)	10.89s	11.9s
		Establishment (value)(time)	0° 9.11s	0° 8.1s
	2	Establishment (time)(slope)	8.88s -0.38°	8.53s -0.49°
		Establishment (value)(time)	-4° 2.6s	-4.65° 4.92s
		Establishment (time)(slope)	8.52s 0.3°	6.6s 0.17°
		Establishment (time)(slope)	9.92s 0.69°	5.48s 0.85°
	3	Establishment (time)(slope)		12.18s 0.38°
		Transient (value)(time)	NA 10.08s	NA 2.34s

TABLE III. RESULTS OBTAINED, DECOMPOSITION OF THE SIGNS OF TEST 1, IN TRANSITION, ESTABLISHMENT AND DURATION IN A STATE.

# Test	Stage	Parameter	Depth	
			Case 1	Case 2
1	1	Transient (time)	10.97s	9.8s
		Establishment (value)(time)	0m 8.99	0m 10.14s
		Retarded (value)(time)	0m 7.98s	0m 4.51
	2	Transient (time)	0s	6s
		Establishment (time)(slope)	12s -0.02°	9.49s -0.04°
		Establishment (time)(slope)	1.95s -0.02°	1.93s -0.04°
	3	Transient (value)(time)	$-0.3m$ 3.99s	$-0.5m$ 5.6s
		Establishment (time)(slope)	6s 0.04°	10.9s 0.04°
		Transient (value)(time)	0m 8s	0m 1.58s

The second test consists of 4 stages according to the positions of the servomotors given in Table IV. In this test, we use both positive as negative positions for the servomotors. This test is performed for three different buoyancy adjustments of the vehicle.

In the first stage, we set percentages of laterals thrusters at 100% and the main thruster at 30%, these values are used during all four stages of the test.

In figures 10, 12 and 14, we show the evolution of the pitch angle of the vehicle for the different buoyancy adjustments. In the three graphs, we see a change in the inclination of the AUV, generated by the action of the servomotor. In Table V we detail the dynamics of this variable (pitch) in each of the stages of the actuators. In step four, of these figures, we can see the behavior of the vehicle with a positive servomotor angle.

In Figures 11, 13 and 15, we show the evolution of the depth of the vehicle for the different buoyancy adjustments. Table VI details the depth dynamics at each stage of the actuators.

TABLE IV. CONFIGURATION PARAMETER FOR THE TEST 2

# Test	Time[s]	Parameter	Value
2	20 (Stage 1)	Angle of servomotor	0°
		Power of Lateral Thrusters	100%
		Power of Main Thruster	30%
		Buoyancy case 2	+++
		Buoyancy case 3	++
		Buoyancy case 4	+
	20 (Stage 2)	Angle of servomotor	-25°
		Power of Lateral Thrusters	100%
		Power of Main Thruster	30%
		Buoyancy case 2	+++
		Buoyancy case 3	++
		Buoyancy case 4	+

# Test	Time[s]	Parameter	Value
	20 (Stage 3)	Angle of servomotor	0°
		Power of Lateral Thrusters	100%
		Power of Main Thruster	30%
		Buoyancy case 2	+++
		Buoyancy case 3	++
		Buoyancy case 4	+
	20 (Stage 4)	Angle of servomotor	+25°
		Power of Lateral Thrusters	100%
		Power of Main Thruster	30%
		Buoyancy case 2	+++
		Buoyancy case 3	++
		Buoyancy case 4	+

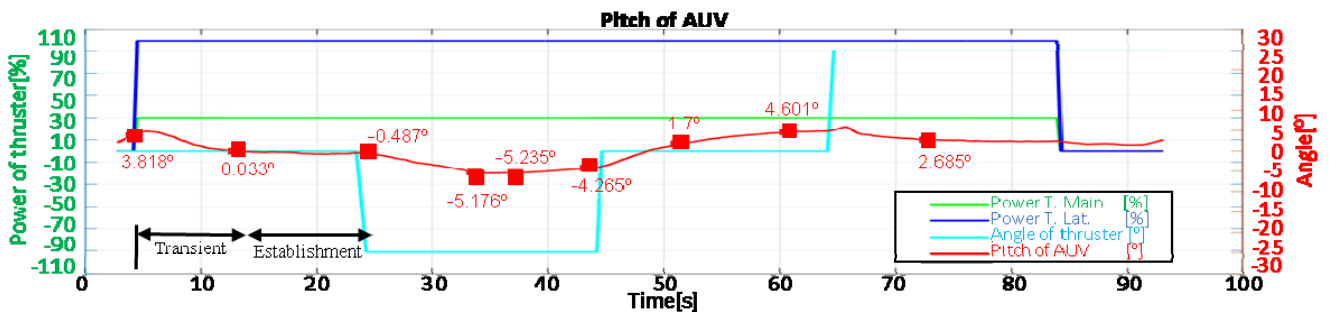


Fig. 10. Result obtained test 2, case 2, Pitch angle of AUV.

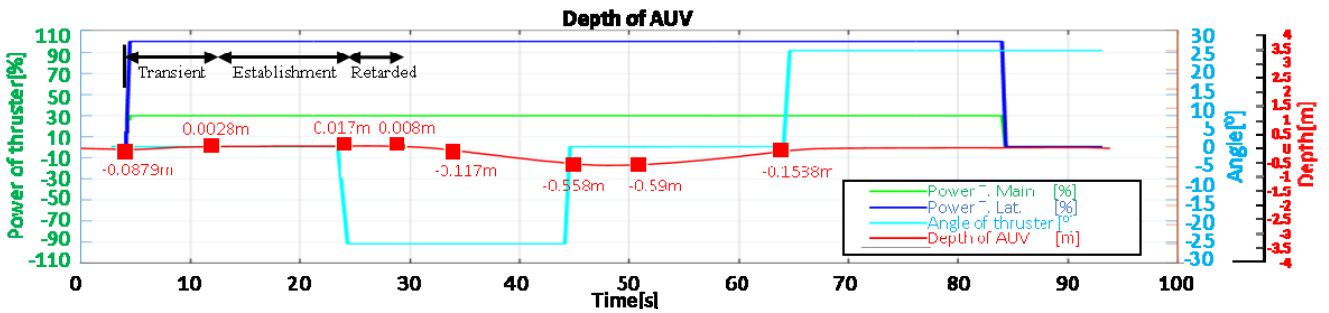


Fig. 11. Result obtained test 2, case 2, AUV behavior on the vertical plane .

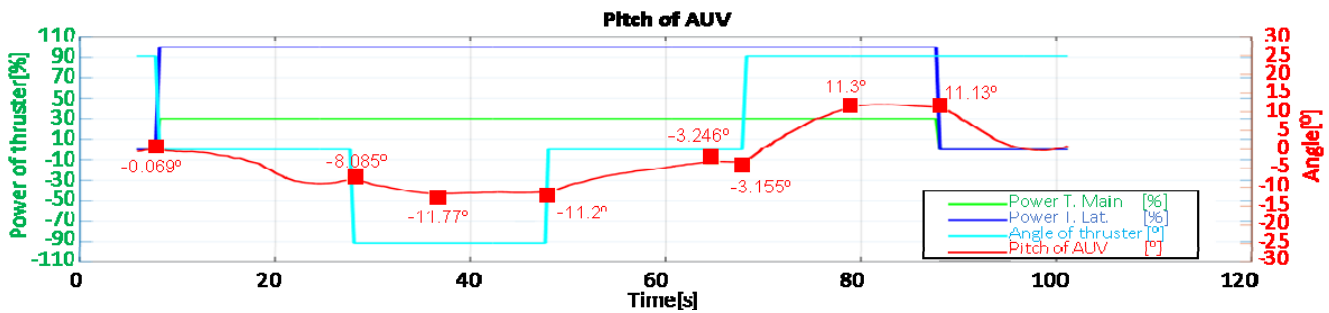


Fig. 12. Result obtained test 2, case 3, Pitch angle of AUV.

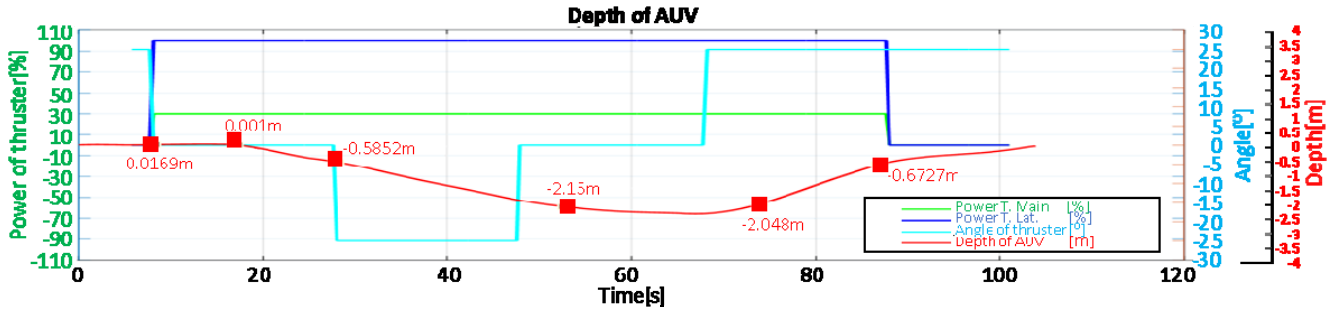


Fig. 13. Result obtained test 2, case 3, AUV behavior on the vertical plane.

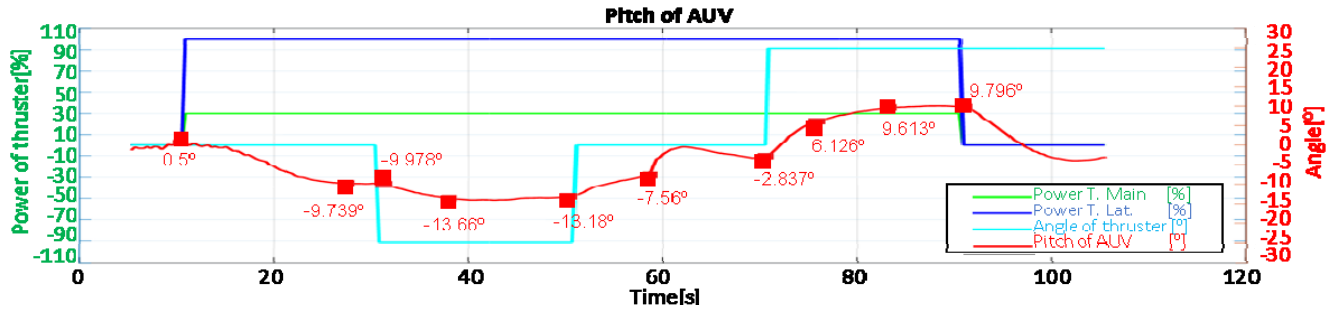


Fig. 14. Result obtained test 3, case 4, Pitch angle of AUV.

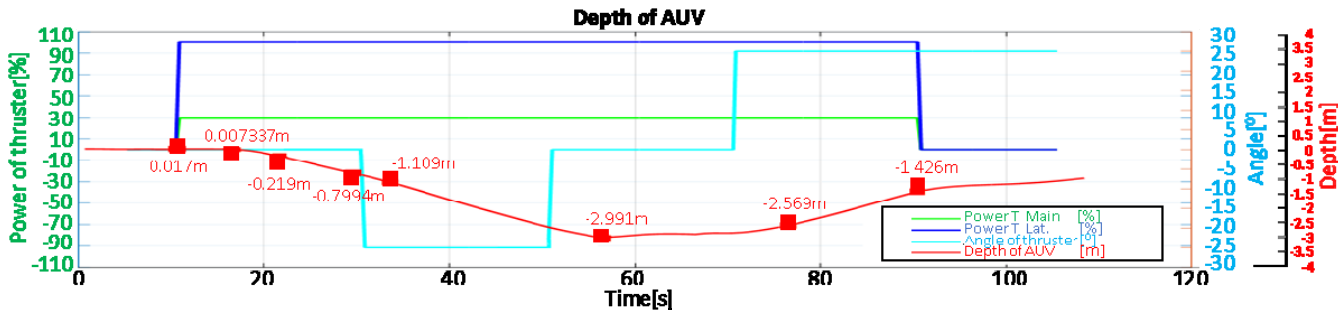


Fig. 15. Result obtained test 3, case 4, AUV behavior on the vertical plane.

TABLE V. RESULTS OBTAINED, DECOMPOSITION OF THE SIGNS OF TEST 2, IN TRANSITION, ESTABLISHMENT AND DURATION IN A STATE.

Stage	Parameter	Pitch		
		Case 2	Case 3	Case 4
1	Transient (time)	8.88s	20s	16.95s
	Establishment (value)(time)	0° 11.12s		-9.8° 3s
2	Establishment (time)(slope)	9.24s -0.5°	8.5s -0.43°	6.7s -0.55°
	Establishment (value)(time)	-5.2° 3.5s	-11.3° 11.5s	-13.4° 13.33s
	Establishment (time)(slope)	7.21s 0.16°		
3	Establishment (time)(slope)	7s 0.8°	16.9s 0.47°	8.34s 0.67°
	Transient (value)(time)		-3.1° 3.1s	NA 11.36s
	Establishment (time)(slope)	10.7s 0.31°		
	Transient (value)(time)	4.6° 3s		

Stage	Parameter	Pitch		
		Case 2	Case 3	Case 4
4	Transient (value)(time)	NA 8s		
	Establishment (time)(slope)		11.11s 1.3°	5.37s 1.67°
	Establishment (time)(slope)		8.89s 11.2°	7.5s 0.5°
	Establishment (value)(time)	2.3° 12s		9.7° 7.14s

With the lowest buoyancy setting, we note in figure 18 that the vehicle has a negative pitch angle, even though the servomotors are at zero degrees. However, when the angle of the servomotor is positive it is achieved that the vehicle emerges. With this buoyancy adjustment, it can be seen in figure 19 that the maximum depth (2.9m) is reached and the ascending dynamic is slower.

Also, we can observe that a greater positive buoyancy appears a delay in the dynamics of immersion, with respect to

the instant where the change in the angle of the servomotor is realized.

TABLE VI. RESULTS OBTAINED, DECOMPOSITION OF THE SIGNS OF TEST 2, IN TRANSITION, ESTABLISHMENT AND DURATION IN A STATE.

Stage	Parameter	Depth		
		Case 2	Case 3	Case 4
1	Transient (time)	8s		
	Establishment (value)(time)	0m 11.97s	0m 8.99s	0m 6s
	Establishment (time)(slope)		10.9s -0.05°	14s -0.07°
2	Establishment (time)(slope)		20s -0.06°	20s -0.08°
	Retarded (value)(time)	0m 5s		
	Transient (time)	5s		
	Establishment (time)(slope)	10.s -0.04°		
3	Establishment (time)(slope)	1.93s -0.04°	4.96s -0.06°	6s -0.08°
	Transient (value)(time)	-0.5m 5s	-2.3m 15s	-2.7m 14s
	Establishment (time)(slope)	13s 0.03°		
4	Transient (value)(time)	3s	2s	1s
	Establishment (time)(slope)		18s 0.1°	19s 0.08°
	Establishment (value)(time)	0m 17s		

IV. CONCLUSIONES

We have designed and implemented a vector propulsion system for the vehicle Guanay II, which has been validated in tests developed in the Castelldefels canal. It has been proven that the mechanical system designed I have implemented in the horizontal stabilizers of stern of the AUV Guanay II, it allows controlling the pitch of the AUV and the depth of navigation. We have established that the difference in the different tests between the depth values reached and the pitch angles of the vehicle depend on the adjustment of the positive buoyancy.

Adjustment of buoyancy also influences the ability of the vehicle to respond to the commands of the propellers. At lower buoyancy, the delay of the behavior of the vehicle at the orders of the actuators is smaller.

We conclude that, in order to optimize the operation of the vector inversion system, it is necessary to adjust the buoyancy of the vehicle, maintaining a slightly positive buoyancy.

This work contributes to the AUV Guanay II, of a vectorial immersion system that allows to control the pitch angle of the vehicle. From the results obtained, we propose as future work the integration of this vectorial immersion system with the initial system of immersion by change of buoyancy, in order to optimize the times of immersion and emersion and energy consumption.

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