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Parameter Estimation and Control of an Unmanned Underwater Vehicle

F. J. Velasco[1,3,*], E. Revestido[1,4], F.J. Lastra[1,5], J.M. Riola[2,6] and J. J. Díaz[2,7]

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ABSTRACT

In the present article, based on a specific set of trials carried out in the CEHIPAR model basin, a parameter estimation of a torpedo-shaped underwater vehicle is performed. A complete modelling of the underwater vehicle is performed considering the dynamics of the vehicle and its actuators with data acquired in the model basin. Thanks to the obtained model, a heading controller is designed and tested in a guidance system for a manoeuvre defined by way points.

1. Introduction

The use of unmanned vehicles, in the naval field, is widely known in the scientific world, but it is the military and security, sectors that are moving this technology forward in recent years. Fleet formation constitutes one of the basic requirements for the design of a new generation of ships that will be employed in various missions such as mine clearance (Riola and Diaz, 2009) pathways, anti-submarine warfare, perimeter defense, surface warfare, support for special operations forces, etc.

The incorporation of unmanned vehicles to the Defence sector have contributed to the state of the art of unmanned systems (Riola, 2011) for hazardous or high-risk missions, such as tracking, detection and neutralization of mines. Today, the AUV-UUV are of paramount importance, for both defence and civilian applications and procedures for underwater exploration.

It is of great importance in naval construction to obtain as accurate as possible a mathematical manoeuvring model. This requirement is also of paramount importance in motion control applications in which, if the mathematical model used for the control design is not accurate when considering the operational conditions of the vehicle, or if external disturbances exist, it is difficult to tune the controller for a good behaviour of the vehicle.

The aim of this paper is to obtain a mathematical model based on the trials developed in the CEHIPAR installations for the design of a heading controller. The controller is tested in a guidance system for a manoeuvre defined by a sequence of way points.

2. Dynamic behavior of a vehicle

One of the challenges of this paper is the modelling of the dynamic behaviour of an underwater vehicle. To do this, we use a commercial torpedo-shaped vehicle, property of the University of Cantabria (UC), to carry out trials in the ("Canal de Experiencias Hidrodinámicas de El Pardo", CEHIPAR) model basin to determine the parameters of the mathematical model that describes the dynamic behaviour. This section describes the most important elements of the underwater vehicle hardware, and the tests/trials that have been conducted. It also outlines the sea trials performed that verify the dynamic behaviour characteristics of the vehicle obtained in the model basin.

[1] Dept. Electronic Technology & Systems Engineering a nd Automatic Control, Univ. Cantabria. E.T.S. de Náutica, C/ Gamazo 1- 39004 Santander (Cantabria) Spain.
[2] Under-Directorate for Technology and Innovation (SDGTECIN-DGAM);
[3] Email: velascof@unican.es.
[4] Email: revestidoe@unican.es.
[5] Email: fjlastra@tesia.unican.es
[6] Email: jriorod@fn.mde.es.
[7] Email: jdiaher@ext.mde.es.
[*] Corresponding author.

2.1. Unmanned underwater vehicle

The torpedo-shaped vehicle property of the University of Cantabria is shown in Figure 1, it has a maximum length of 1.65 m and a radius of 0.17 m. It weighs 35 kg and has a maximum speed of 6 knots. The bow shape is a hemisphere and has an aft cone with four flat stabilization surfaces. The thrusters have two longitudinal axes that are spaced from the axis of the cylinder 0.36 m. In the central area, it has a vertical propeller and a security mass. The vehicle is autonomous and the power generation system is based on a set of Li-poly (lithium polymer batteries) batteries that provides a range of approximately 1 hour at a speed of 3 knots or 2 hours at a speed of 2 knots.

Figure 1. Torpedo-shaped vehicle (C´Inspector, Kongsberg).

Source: Authors

Propellers commanded by electric motors make up the propulsion system. Two propellers are located in the centre of the vehicle at both sides, for surge and yaw motion. These propellers are mounted within fixed nozzles. The yaw motion is performed by acting on the port or starboard propeller with different numbers of RPM or an inverse number of RPM. A third propeller is also located in the centre of the vehicle perpendicular to the other two horizontal propellers for the depth control. The pitch movement of the vehicle is achieved by displacement of an internal mass in the rear half of the vehicle.

A summary of the variables that define the motion of the vehicle and the sensors used in the measurement is shown in Table 1.

Table 1. Variables and sensors.

Symbol	Measurement	Sensor
Ψ	Heading	Accelerometer
θ	Pitch	Accelerometer
Φ	Roll	Accelerometer
z	Depth	Pressure sensor
N port	RPM port propeller	Tachometer
N starboard	RPM starboard propeller	Tachometer
Vert. Prop.	Vertical propeller	Tachometer
Pos. Mass	Mass position	Potentiometer

Source: Authors

Furthermore, the vehicle provides a side scan sonar (single beam), which is used to perform seabed inspection functions.

The communication with the vehicle is performed through a fibre optic cable that carries data bidirectional. Thus, the operator is able to remotely control the vehicle through the "Human Machine Interface" (HMI), either by commands from the keyboard or using a joystick control unit. For the position of the vehicle, the vehicle provides a "Wideband Acoustic Positioning" (WAP) system that includes a GPS antenna with three hydrophones, which must be submerged at least a meter deep.

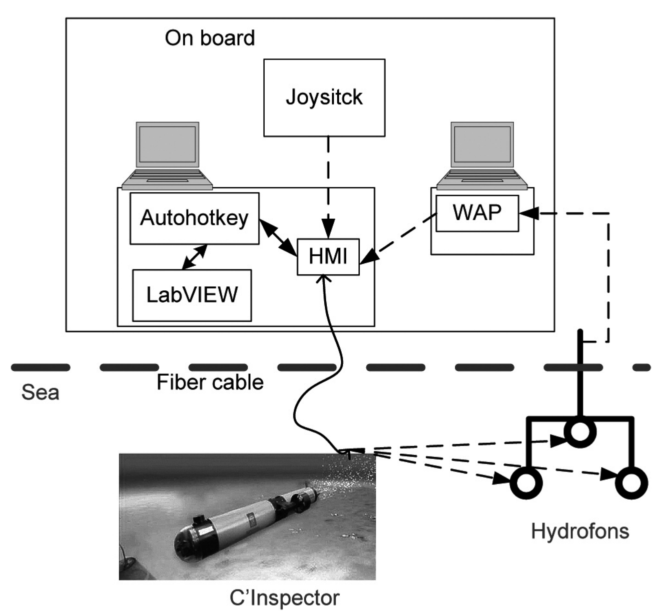
2.2. Sea trials

The construction of a marine vehicle involves the performance of different standard manoeuvres or sea trials (Lewis, 1998). Through them, in addition to evaluating their robustness, it highlights the potential limitations of the control system and the behaviour of the vehicle in emergency situations.

Data from sea trials can also be used for identifying a mathematical model of a vehicle dynamics (Perez et al, 2007; Perez and Revestido, 2010). That is why software has been developed in this work to capture data from the various instruments of the vehicle and to carry out standard manoeuvres automatically acting on the propulsion. In this particular case, Autohotkey free software (Mallet, 2013), which allows the emulation of the data entered via the keyboard, was used. In this way, it is possible to enter commands using the software provided by the Kongsberg company through another software implemented using Autohotkey to act on the propulsion.

The main purpose of the Autohotkey application is to act on the propulsion and capture data from the instruments on board the vehicle. In this way, this application can be used in control loops for motion control. Moreover, the application developed in Autohotkey can be integrated into other programming environments such as LabVIEW (Bishop, 2004).

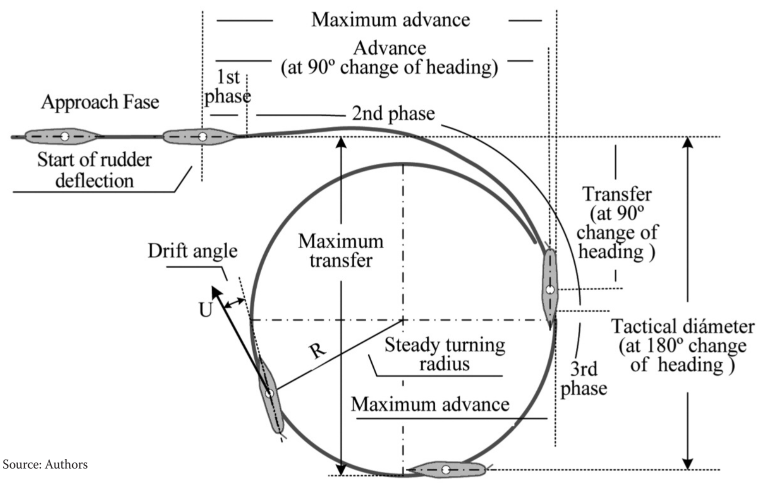
Figure 2. Software integration with the underwater vehicle.



Source: Authors

The sea trials proposed by the International Towing Tank Conference ITTC (2004) and summarized in the article Lopez et al. (2004) include, among others, the turning circle manoeuvre, which is used to calculate the radius of curvature of the vehicle and also to check the behaviour of the propulsion system in change of course manoeuvres. Figure 3 shows the various stages of this manoeuvre, which, due to its simplicity, can be done manually using the joystick unit control.

Figure 3. Turning circle manoeuvre.



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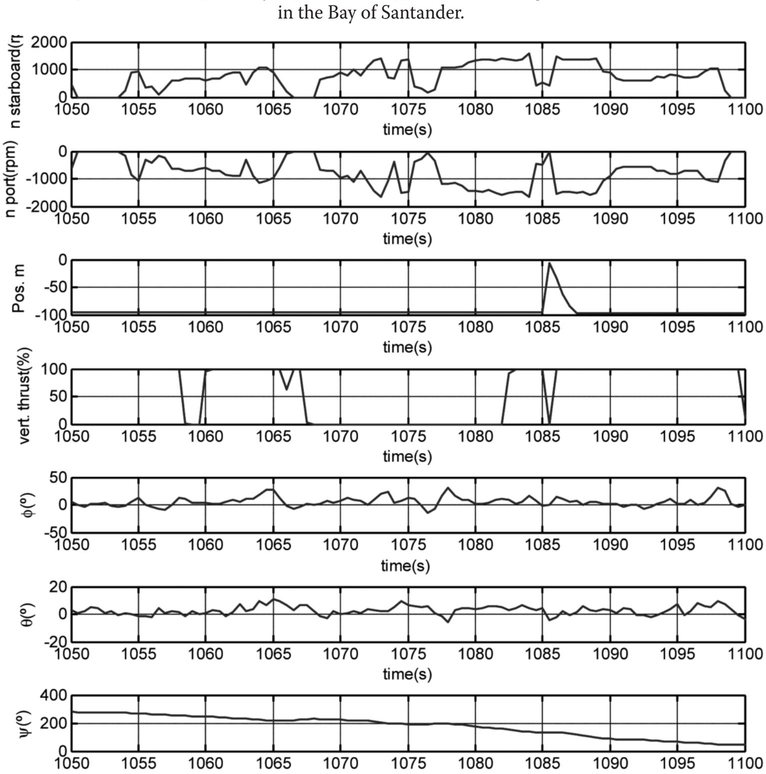
From the above, thanks to the tool developed, the results are given in Figure 4.

Figure 4. Data acquired by the software support for a turning circle manoeuvre in the Bay of Santander.



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2.3. Mathematical model

Underwater vehicles move in six degrees of freedom (DOF). In order to describe the vehicle motion, three translational coordinates are needed and another three to define the orientation. Two coordinate systems are used to study the vehicle movement: one coordinate is fixed to the vehicle and is used to define its translational and rotational movements and another one is located on Earth (inertial) to describe its position and orientation.

The 6 DOF nonlinear manoeuvring model can be expressed in the following form (Fossen, 1994, 2002):

$$M\dot{\upsilon}+C(\upsilon)\upsilon+D(\upsilon)\upsilon+g(\eta)=\tau$$
$$y=\eta+w,\ \dot{\eta}=R(\eta)\upsilon, \tag{1}$$

where $\eta=[x,y,z,\phi,\theta,\psi]^T$ is the position and Euler angles vector, $\upsilon=[u,v,w,p,q,r]^T$ is the linear and angular speeds vector, $\upsilon=[X,Y,Z,K,M,N]^T$are the forces and moments and w is the measurement noise. M is the added mass matrix, $C(\upsilon)\upsilon$ is the Coriolis term, $g(\eta)$ is the restore matrix and $R(\eta)$is the rotation matrix.

The hydrodynamic damping forces are a combination of lineal and nonlinear damping:

$$D(\upsilon)\upsilon=D_l\upsilon+D_{nl}(\upsilon)\upsilon \tag{2}$$

In the present work, an unmanned vehicle (C'Inspector) is used, in which three engines are mounted: two horizontal ones located at the centre of the vehicle for the surge and yaw motion and a vertical one for depth control. The movement of an internal mass achieves the pitch motion. Thus, the thrust can be expressed as:

$$T=\rho D_h^4 K_T(j_0)n\,|\,n\,|\,(1-t) \tag{3}$$

where ρ is the water density (1000), D_h is propeller diameter, n are the propeller revolutions per second, t is the thrust deduction factor (typical values of 0.05 to 0.2) and K_T is the dimensionless coefficient (Fossen, 1994). Based on the thrust equation (3) and yaw moment, the following expression is obtained:

$$\begin{bmatrix}\tau_{x,th}\\ \tau_{N,th}\end{bmatrix}=\begin{bmatrix}1 & 1\\ d_p & -d_p\end{bmatrix}\begin{bmatrix}T_p\\ T_s\end{bmatrix} \tag{4}$$

where $\tau_{x,th}$ is the surge force, $\tau_{N,th}$ is the yaw moment, d_p the distance from the centre of the vehicle to the propeller, T_p is the starboard thrust and T_s is the port thrust. Furthermore, if the roll angle $\Phi\neq 0$, the following equation must be taken into account:

$$\tau_{M,th}=-\left(T_p-T_s\right)d_p\sin(\phi) \tag{5}$$

As a result, the forces generated by the thrusters and the pitch actuator are $\tau = [\tau_X, 0, \tau_Z, 0, \tau_M, \tau_N]^T$.

2.4. Parameter estimation

This section summarizes the tests that were performed in the CEHIPAR for the parameter estimation of the mathematical model defined above. Figure 5 illustrates the assembly of the C'Inspector vehicle in the CEHIPAR installations.

This assembly has a measuring table, on which two cylinders that hold the vehicle is mounted. These cylinders are commanded by electric motors. The cylinders are of the screw type, to provide high precision in the movement. The measuring table is mounted in a system that moves along the CEHIPAR flat-water basin. Before all these basin trials, it was necessary to determine the moments of inertia, the centre of gravity and centre of buoyancy of the vehicle. The values obtained can be found in Table 2, including the weight values with and without security weight.

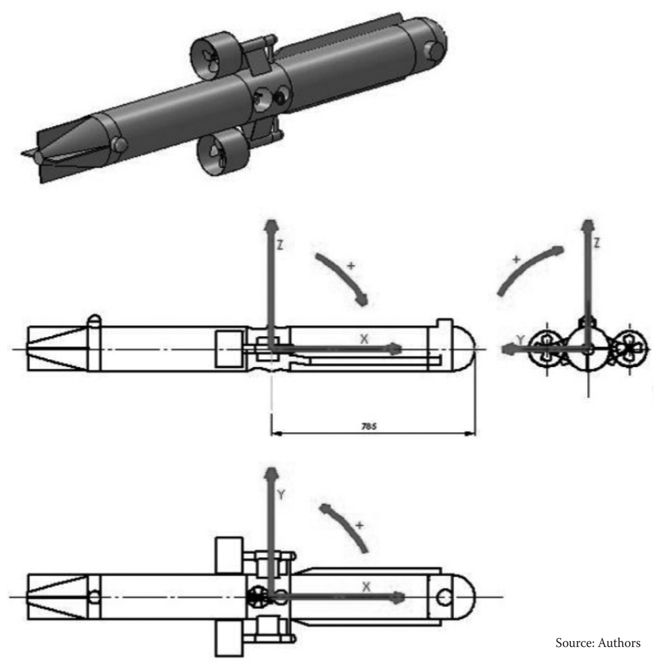
Table 2. Weight distribution.

	Security weight	
	with	**without**
Weight (Kg)	33	34,34
x_g (m)	0,184	0,167
z_g (m)	-0,012	-0,012
I_{xx} (kg m^2)	0,287	0,29
I_{yy} (kg m^2)	7,105	6,945
I_{zz} (kg m^2)	7,233	7,073

Source: Authors

All the estimated parameters are referred to a given orthogonal coordinate system clockwise centered on the axis of the cylinder at a distance of 785 mm from the bow end of the vehicle (at the height of the eye bolt fastening hole located between the vertical thruster and the equalizing orifice). The X-axis is directed towards the bow, the Y-axis is directed to port and the Z-axis is directed upward, see Figure 6.

Figure 6. Coordinate system.



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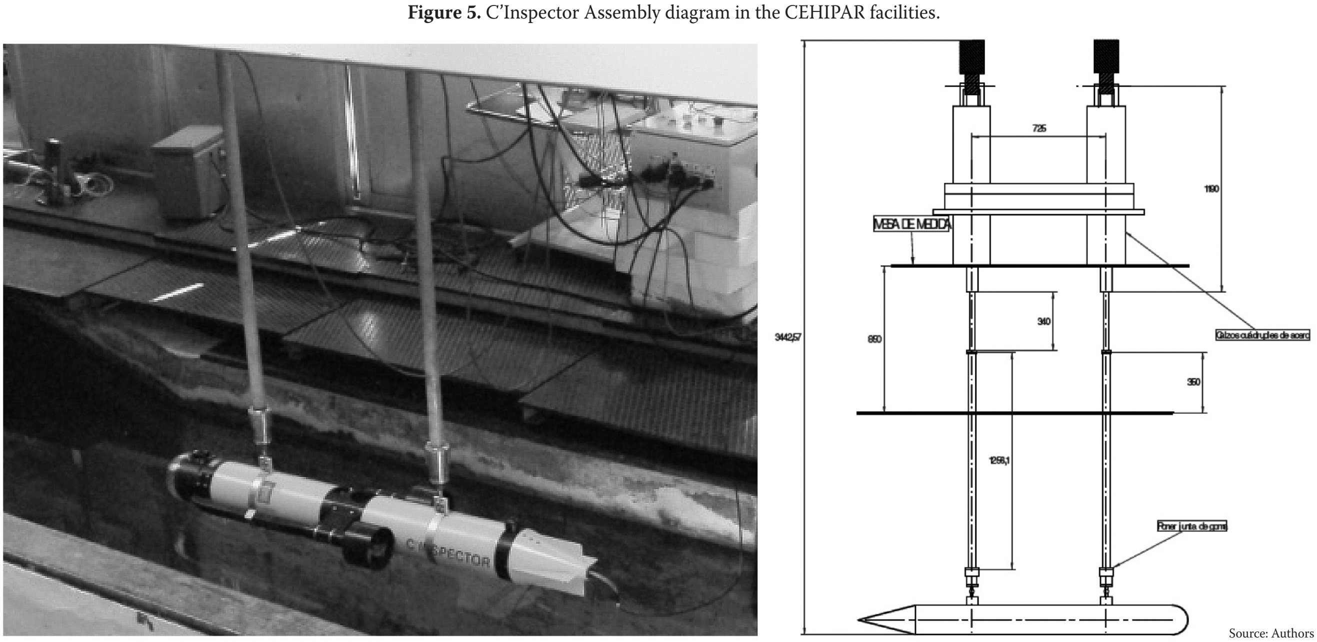
The different trials carried out were the following:
— Towing at different speeds.
— Static drift.
— Static pitch (as above but with the vehicle rotated 90°).
— Dynamic roll.
— Dynamic pitch.
— Dynamic yaw (as above but with the vehicle rotated 90°).
— Acceleration and braking.
— Dynamic sway.
— Dynamic heave (as above but with the vehicle rotated 90°).

Figure 5. C'Inspector Assembly diagram in the CEHIPAR facilities.



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Each of the tests were carried out with two or three amplitudes, as well as additional tests to characterize the thrusters.

The sections below show each of the trials performed to obtain the mathematical model previously defined. The parameters obtained in each of the trials have been estimated using least squares (Ljung, 1999).

2.4.1. Resistance and longitudinal aceleration

The C'Inspector was dragged in upright position at speeds between 0.5 and 2.0 m/s. These speeds were made in a single run, which measures the added mass during phases of acceleration and braking.

The equation for the X force is:

$$X = X_0 + X_u u + X_{uu} u^2 + (-m + X_{\dot{u}})\dot{u} \tag{6}$$

where the resistance at the nominal speed u_0 (1.5 m/s) and $u = U - u_0$, U being the real speed.

2.4.2. Self-propelled and spin thrusters trial

The self-propelled trial is carried out by towing the C'Inspector at the nominal speed while the revolutions of the horizontal thrusters are between 35% and 60% of the maximum speed. If we call T the effective thrust the measured total force is:

$$X = X_n n \tag{7}$$

where n is the difference between the actual revolutions n_r and the nominal revolutions n_n (those for which the total force is zero). The effective thrust T (in Newtons) is expressed as:

$$T = -X_0 + X_n n = -X_0 + X_n(n_r - n_n) \tag{8}$$

where X_0 is the resistance at the nominal speed.

2.4.3. Manoeuvre with vertical propeller

These trials were conducted by leading C'inspector to the nominal speed with the revolutions of the self-propelled point. The revolutions of the vertical propeller ranged from –60% to +60% of the maximum speed. The following model has been adjusted:

$$X = X_{|\mu|}|\mu|, \;\; Z = Z_\mu \mu, \;\; M = M_\mu \mu \tag{9}$$

where μ are the revolutions of the propeller in % of the maximum, with positive value when thrust is upward. There is a clear asymmetry in the force X and in the moment M between the response with the propeller pushing up or down.

2.4.4. Trim weight

This trial was made with the vehicle in a fixed position and moving the internal weight between 0 and 100% of the maximum displacement.

2.4.5. Static and dynamic pitch

The static pitch consists of the displacement of the C'Inspector at the nominal speed and varying at the same time, the angle of pitch (trim). This introduces a vertical speed given by:

$$w = U \sin\theta \tag{10}$$

being U being the nominal speed and θ the pitch angle.

The dynamic pitch corresponds to the performing of a sinusoidal trajectory in the vertical plane so that the longitudinal axis of the C'Inspector is kept tangent to the trajectory all through the trial. Thus, in the C'Inspector axis, there is only a pitch rotational movement. As before, the tests were performed at nominal speed with an oscillation period of 3 seconds. Pitch amplitudes varied between 5° and 10°. The vertical force is set according to the following linear model:

$$Z = Z_{\dot{q}}\dot{q} + (Z_q - mU)q \tag{11}$$

2.4.6. Dynamic heave

In this test, the C'Inspector oscillates in a vertical direction while it is moving into the nominal speed. The oscillation period of 3 seconds was considered as a reasonable estimate of the response time for the manoeuvre. The oscillations were carried out in the same run with amplitudes from 0.05 to 0.15 m. The vertical force is applied with a linear fit of the type:

$$Z = (-m + Z_{\dot{w}})\dot{w} + Z_w w \tag{12}$$

m being the mass and Z_w the added mass.

2.4.7. Static and dynamic yaw

In this test, the C'Inspector was displaced at the nominal speed meanwhile the yaw angle (drift) was varying. This introduces a transverse velocity given by:

$$u = U \sin\psi \tag{13}$$

where U is the nominal speed and ψ the drift angle. The results for the transverse force obtained with the best linear fit present the following form:

$$Y = Y_v v \tag{14}$$

The dynamic yaw was produced by forcing the vehicle to follow a sinusoidal trajectory such that the axis movement of the vessel consisted of a pure yaw oscillatory movement at the nominal speed with the system of self-propulsion thrusters. The same oscillation period was chosen, and the oscillations were performed in the same race with amplitudes ranging from 5° to 10°. The transverse force is modeled in the following form:

$$Y = Y_{\dot{r}}\dot{r} + (Y_r - mU)r + Y_{rrr}r^3 \tag{15}$$

2.4.8. Dynamic sway

In the dynamic sway, the C'Inspector oscillates transversely at the nominal speed with the thrusters in the self-propulsion point. The oscillations were performed in the same race with amplitudes ranging from 0.05 to 0.15 m. The transverse force takes the following form:

$$Y = (-m + Y_{\dot{v}})\dot{v} + Y_v v \tag{16}$$

m being the mass and Y_v the added mass.

2.4.9. Dynamic roll

Finally, the last test was the dynamic roll, where the C'Inspector oscillates around the *X*-axis while moving at the nominal speed and with the thrusters in the self-propulsion point. A period of 3 seconds and amplitudes of 10, 20 and 30 were used. The moment about the *K* axis has made a fit of the type:

$$K = (-I_{xx} + K_{\dot{p}})\dot{p} + K_p p \tag{17}$$

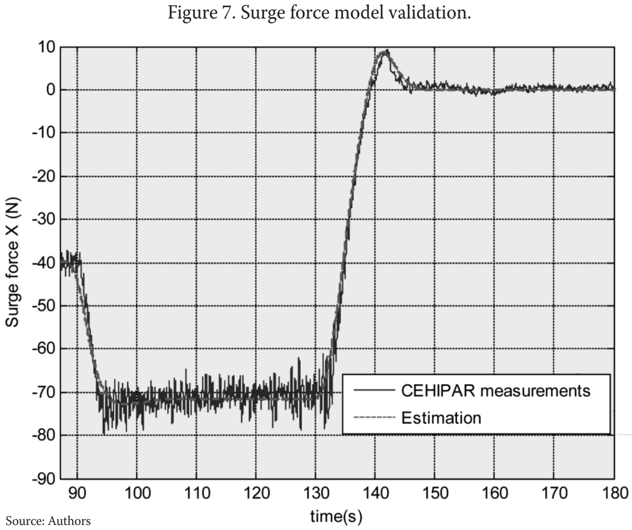
I_{xx} being the inertia moment around the *X* axis.

3. Model validation

In the application of the system identification theory, it is conventional to use for the model validation different data than the data used in the estimation. In this work, for economic reasons in order to avoid a large number of trials, half of the acquired data is used for parameter estimation and the other half for model validation.

There are different ways to validate a model (Ljung, 1999), one of them being to compare in the same graph the acquired measurements with the obtained model. This will verify whether the fit of the model to the data is adequate. Figure 7 shows that for the case of the surge force, the fit is good.

Figure 7. Surge force model validation.



Source: Authors

Another form of model validation is the use of statistical metrics. One metric is the coefficient of determination *R² (%)*, which provides information about the obtained model to the extent that it is able to reproduce the measurement data, and represents the percentage of output variation reproduced by the model:

$$R^2(\%) = \frac{\sum(\hat{D} - \bar{D})^2}{\sum(\hat{D} - D)^2 + \sum(\hat{D} - \bar{D})^2} \tag{18}$$

where D and $\bar{D}$ represent the measured data and its mean respectively, and $\hat{D}$ the data generated by the obtained model.

The following table 3 shows the model validation results, by calculating the coefficient of determination, for each of the performed tests. Thus, it is found that the obtained model is good, because in most of the trials the $R^2(\%)$ coefficient is near to 100%. It must be noted that the $R^2(\%)$ coefficient obtained also depends on the signal/noise measurement ratio corresponding to the test. This happens, for the dynamic sway trial since the signal/noise ratio is high and therefore the $R^2(\%)$ coefficient is smaller than the rest of the degrees of freedom.

Table 3. Coefficient of determination results for the 6DOF trials.

Trial	**Force**	***R²(%)***
Resistance and longitudinal acceleration	X (N)	69,23
Dynamic Pitch	Z (N)	47,93
Dynamic Heave	Z (N)	99,24
Dynamic Yaw	Y (N)	70,47
Dynamic Sway	Y (N)	96,86
	Moment	
Dynamic Roll	K(Nm)	85,55

Source: Authors

4. Control of the underwater vehicle

The control problem for an underwater vehicle is related to heading control. The heading control is usually integrated in a guidance system with the aim of following a predefined trajectory defined by a set of way points. This section outlines the design of a heading controller based on the model obtained in the previous sections and it is tested for a particular manoeuvre delimitated by way points.

4.1. Heading control problem

An automatic pilot must fulfil two functions: course keeping and change of course. In the first case, the objective is to maintain the trajectory of the vessel following the desired heading ($\psi_d(t)$ = constant). In the second case, the objective is to perform the change of heading without excessive oscillations and in the minimum time possible. In both situations, the correct functioning of the system must be independent of the disturbances produced by wind, waves and ocean currents.

The trajectory followed by a vessel can be specified by means of a second order reference model:

$$\ddot{\psi}(t) + 2\zeta\omega_n\dot{\psi}(t) + \omega_n^2\psi(t) = \omega_n^2\psi_d \tag{19}$$

where ω_n is the natural frequency and ζ, the desired damping ratio of the system in closed loop. ζ is typically chosen in the interval ($0.8 \leq \zeta \leq 1$) in order to take into account security issues (Van Amerongen, 1982). In restricted waters and for collision avoidance, the course-changing manoeuvre should have a clear start, in order to show other ships the intention of the manoeuvre and, for that reason, that manoeuvre should preferably be completed without overshoot.

The heading controller used in this work is based on a previous work (Velasco et al., 2013), where a first order network controller is tuned based on genetic algorithms.

4.2. Guidance system: los

Line of Sight (LOS) (Fossen, 1994) is a widely known navigation method, which provides satisfactory results in following a path defined by waypoints. In the LOS method, it is assumed that we want to design a guidance system based on two way points with coordinates $[x_d(t_0), y_d(t_0)]$ and $[x_d(t_f), y_d(t_f)]$, respectively. Hence, the following expression is applied to obtain the desired heading angle:

$$\psi_d = \tan^{-1}\left(\frac{y_d(t_f) - y_d(t_0)}{x_d(t_f) - x_d(t_0)}\right) \tag{20}$$

Equation (20) requires a sign test to ensure that $\psi_d(t)$ is in the proper quadrant. The autopilot follows the heading by guiding the vehicle from way point to way point.

When moving along the path, a switching mechanism for selecting the next way point is needed. The way point (x_{k+1}, y_{k+1}) can be selected on a basis of whether the ship lies within a circle of acceptance with radius R_0 around the way point (x_k, y_k) k being the actual way point. Moreover if the vehicle positions $(x(t), y(t))$ at time t satisfy:

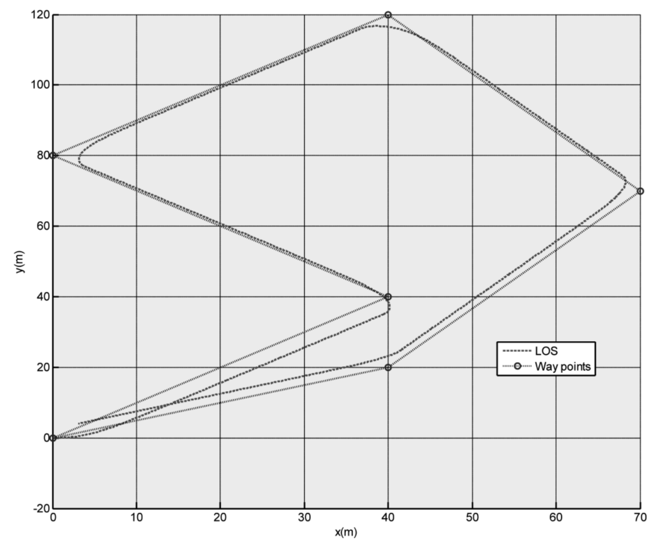
$$[x_k - x(t)]^2 + [y_k - y(t)]^2 \leq R_0^2 \tag{21}$$

A guideline could be to choose R_0 equal to two ship lengths (L_{pp}).

4.3. Simulation results

Figure 8 shows a simulation implemented using the Matlab/Simulink environment. We have implemented the model defined in section two with the estimated parameters and a guidance system based on the LOS method previously indicated. The figure shows that the system follows adequately the predefined way points path.

Figure 8. LOS guidance results with the model obtained in section 2 and the heading controller in section 4..



Source: Authors

5. Conclusions

This paper has highlighted the study in terms of modelling of an unmanned underwater vehicle through an appropriate trials program in the CEHIPAR facilities. Thanks to the acquired data, it has been possible to estimate the hydrodynamic coefficients of a six DOF nonlinear manoeuvring model of a torpedo-shaped underwater vehicle and the thruster coefficients have also been estimated.

The present work is part of a research project that has ambitiously addressed an area of growing interest, allowing the theoretical analysis in the field of simulation, and thanks to it, the design of heading controllers for a guidance system.

Acknowledgments

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