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Measurements of Hydrodynamic Parameters and control of an underwater torpedo-shaped vehicle

Francisco J. Velasco*, Elías Revestido Herrero*, Francisco J. Lastra Santos*,
José María Riola Rodríguez, Juan Jesús Díaz Hernández** and Luis M. Vega Antolín*.**

** Univ. Cantabria. E.T.S. de Náutica, C/ Gamazo 1- 39004 Santander (Cantabria) SPAIN*
(velascof@unican.es, revestidoe@unican.es, lastrafj@unican.es, vegalm@unican.es).
*** Under-Directorate for Technology and Innovation (SDGTECIN-DGAM) Madrid*
Spain (jriorod@fn.mde.es, jdiaher@ext.mde.es)

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. Furthermore, it is proposed a modification of the conventional LOS method that works properly in presence of ocean currents. The modified LOS is applied to the torpedo-shaped model previously obtained and tested under realistic conditions.

Keywords: PMM, parameter estimation, LOS, path following, ocean currents.

1. INTRODUCTION

The use of unmanned vehicles, in the naval field, is widely known in the scientific world. The military and security sectors are the ones 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 underwater vehicles that will be employed in various missions such as mine clearance pathways, anti-submarine warfare, perimeter defence, surface warfare, support for special operations forces, etc.

Today, the AUV-UUVs are of paramount importance, for both defence and civilian applications and procedures for underwater exploration. 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.

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. One way to obtain the parameters of a manoeuvring model is to perform the so-called planar motion mechanism (PMM) tests (Lewis, 1998). There are some articles related to PMM tests performed on underwater vehicles (Phillips, 2007; Guo, 2001). In this work, we have made some modifications in the PMM tests in order to estimate roll coefficients and other actuators parameters.

Based on the cited manoeuvring models path following systems are conventionally developed. Line of Sight (LOS) is a widely known method of navigation that provides satisfactory results in following a path defined by waypoints (Aguiar, 1997; Pettersen, 2001; Refsnes, 2004; Healey, 1993; Fossen, 2003). However, this method has the disadvantage that if the vehicle is operating under realistic conditions such as in the presence of currents, large cross-path errors may occur. In this case, there are no such a large number of publications as much as in the conventional LOS method and the existent contributions that deal with ocean currents are quite complex as in Caharija (2012 a, b) . In this work, we propose a modification of the conventional LOS method that provides satisfactory results in presence of ocean currents by performing a simple procedure.

Our proposed approach differs from the usual approach previously reported in the literature (Fossen, 1994), whereby the line between two-way points is divided in a number of intermediate points selected by a specific criteria and the heading provided by our method varies along the two-way points. In this way, the cross track error is reduced even in the case of ocean currents as is stated in the results given in this work.

2. 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.

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

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

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 and $D(\upsilon)\upsilon$ represents the hydrodynamic damping forces that are a combination of lineal and nonlinear damping. All the matrixes of equation (1) considering the symmetries of the vehicle can be found in Fossen (2002).

In the present work, a torpedo-shaped vehicle 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. Thus, the thrust can be expressed as:

$$T = \rho D_h^4 K_T(j_0) n|n|(1-t) \qquad (2)$$

where ρ is the water density, 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 (2) and yaw moment, the following expression is obtained according to Refsnes (2004):

$$\begin{bmatrix} \tau_{x,th} \\ \tau_{N,th} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ d_p & -d_p \end{bmatrix} \begin{bmatrix} T_p \\ T_s \end{bmatrix} \qquad (3)$$

where $\tau_{x,th}$ is the surge force , $\tau_{N,th}$ is the yaw moment, d_p the distance from the centre of mass 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:

$$\tau_{M,th} = -\left(T_p - T_s\right) d_p \sin(\phi) \qquad (4)$$

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

3. PARAMETER ESTIMATION

This section summarizes the tests that were performed in the "Canal de Experiencias Hidrodinámicas de El Pardo" (CEHIPAR) for the parameter estimation of the mathematical model defined above. To do this, we have used a commercial torpedo-shaped vehicle, property of the University of Cantabria, which has a maximum length of 1.65 m and a radius of 0.17 m.

Figure 1 illustrates the assembly of the vehicle in the CEHIPAR installations. This assembly has a measuring table, on which two cylinders that hold the vehicle are mounted. These cylinders are commanded by electric motors, which are of 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 1 and were obtained by performing some tests in an internal table.

Table 1 Weight distribution of the torpedo-shaped vehicle with and without security weight.

	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 m2)	0,287	0,29
I_{yy} (kg m2)	7,105	6,945
I_{zz} (kg m2)	7,233	7,073

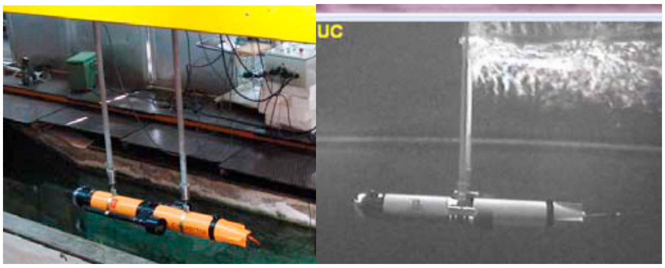

Fig. 1 C'Inspector Assembly in the CEHIPAR facilities.

All the estimated parameters in this section are referred to a given orthogonal coordinate system located 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 parameters obtained in each of the trials have been estimated using least squares (Ljung, 1999).

Since the accelerations of equation (1) were not measured, a local polynomial fixed-point smoother has been applied to estimate them. That is, for each sequential velocity measurement one fits a local polynomial based on a number of measurements close to the measurement of interest,

$$\hat{\upsilon}_j(t_k) = \hat{a}_0 + \hat{a}_1\Delta_{k,i} + \hat{a}_1\Delta + \hat{a}_1\Delta_{k,i} \qquad (5)$$