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DEVELOPMENT AND ANALYSIS OF A ROV DYNAMIC MODEL: CAPTURING THE EFFECTS OF THE PROPULSION SYSTEM

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Abstract. *This article describe the modeling of the kinematics and the dynamics of remotely operation vehicles (ROVs). It evaluates the insertion of the propeller dynamics model and the involving fluid in the model for dynamic position control strategy considering a comparative analysis with existing dynamical position. Vehicle model parameters known are used as reference for the control position simulation. Results illustrate the model stability performance in closed loop feedback control considering parametric uncertainties and external disturbances.*

Keywords: propeller, thrust, dynamical model, hydrodynamics coefficients, parametric uncertainties.

1. Introduction

Any maritime boat to move itself in the water needs a propulsion system. There are some types of propulsion and amongst them propeller propulsion is the most used. The purpose of this work is evaluates the vehicle performance characteristic when the propeller dynamics and the involving fluid are inserted in its model. *Sirene* underwater vehicle model is used for the simulation proposal ”(Aguiar, 1994)”. This vehicle uses fixed pitch propeller, connected to the motor shaft as the propulsion system. The propeller dynamics incorporates delays and non-linearities that the control system may not be able to compensate. The basic dynamic effects introduced by propellers is comes from two active principles: the hydrodynamics ones, caused for the interaction of the propeller blades with the fluid and the electrodynamics ones, function of the DC dynamic motor. The last one is characterized by relatively small time constants and therefore can be neglected. In this context, it is interesting to evaluate if the dynamic of this system can influence the behavior of the vehicle, especially in positioning maneuvers. The forces and moments analysis of the interaction propeller-fluid is a problem of great complexity. The mechanism of forces generation has been studied in steady state, adopting one classic technique known as dimensional analysis “(Newman, 1977)”. The identified results are adjusted for smooth maneuvers, as in the case of great dimension ships. However, this approach is not adequate for situations where fast movements of the propeller can occur (according to changes of the speed of the platform that carries it). This work describes a basic system considering the dynamics of the vehicle, the incorporated model of the propulsion system and the involving fluid dynamics, which was implemented in SIMULINK. The complexity of this system increases if the model of the umbilical cable is included in the vehicle model. A modeling in six degrees of freedom is intended to develop a system of global control of the vehicle considering itself valid for different frames. The control strategy along may not compensate the disturbance produced by the umbilical cable, the parametric variations, as added mass, and others structuralized disturbances, as the speed of the seawater. It is important to observe that these evaluations are based on dynamic positioning.

2. Mathematical Model

Models of underwater vehicles works with two reference systems: one, located in the G.C. (Gravity Center) of the vehicle (body reference or {B}), and another, located in a point of the land (inertial reference, or {U}). The dynamics is shaped in the body reference. During the simulations, the measures obtained in the vehicle are transformed to the inertial reference. In this work, it is adopted transformation for angles of Euler “(Craig, 1983)”. A generic model of a ROV with six degrees of freedom was developed. An usual and consolidated expression used in the literature to describe the kinematics and the dynamics underwater vehicles may be formulated by the following representation “(Fossen, 2002)”

$$M_{RB}\dot{v} + C_{RB}(v)v + D(v)v + G(\eta) = \Gamma_{RB} \tag{1}$$

The kinematics equations can be simplified in the compact form

$$\dot{\eta} = J(\eta)v \qquad (2)$$

where

$$\eta = [x, y, z, \phi, \theta, \varphi]^T$$

$$v = [u, v, w, p, q, r]^T$$

and
M_{RB} inertial matrix generalized of the rigid body
C_{RB} matrix that contains Coriolis terms and Centripetal forces that act on the rigid body
$J(\eta)$ rotational matrix of {B} to {U}
η vector that represents linear and angular positions
ν vector that represents linear and angular speed of the vehicle to the seawater
$D(v)$ vanish and friction forces
$g(\eta)$ gravity force
$\Gamma_{RB} = [X, Y, Z, K, M, N]^T$ vector of external forces and torques applied to the body, expressed in {B}.

2.1. External Forces and Moments

Forces and moments that act on the vehicle have hydrodynamics, gravitational and viscous origin, in function of the weight, shape and blades, beyond forces and moments due to the added mass and the umbilical cable. These forces and moments can be represented in the compact form as

$$\Gamma_{RB} = \Gamma_p + \Gamma_A + \Gamma_D + \Gamma_R + \Gamma_c \qquad (3)$$

where
Γ_{RB} vector of forces and moments applied to the rigid body
Γ_p vector of forces and moments in function of the propeller
Γ_A vector of added mass
Γ_D vector of forces and moments due to hydrodynamics and viscous forces
Γ_r vector of restitution forces and moments due to the gravitational force
Γ_c vector of forces and moments due to umbilical cable

If underwater vehicle activities will occur in great depths, the water column minimizes the wind effect of the waves; therefore the greater ambient effect will be the seawater speed. It means that the ambient phenomenon beyond the maritime current will not be considered, and it will be represented by Γ_D . Moreover, forces and moments that act on the propeller blades are evaluated disrespecting the surface effect and cavitations that may occur.

3. Vehicle for Simulation

The underwater vehicle model used for simulation was obtained from *Sirene*, a vehicle developed by MAST-II project in partnership with Dynamical Systems and Ocean Robotics Lab (DSOR), Lisbon Technical University, Lisbon, Portugal. The tests carried out in the *VWS (Versuchsanstalt fur Wasserbau und Schiffbau)*, Berlin, Germany, in a circulating water channel with changeable speed between 0 and 2 *m/s*. More details in "(Pascoal, 1998)". This vehicle does not possess null resultant for the restorative forces and it is controllable in four degrees of freedom (*x, y, z* and *yaw*). The propellers are distributed in the platform as in Fig.1 below

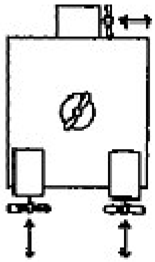


Figure 1 Propellers in the ROV *Sirene*

4. Propeller Dynamic Model

The propeller schematic model is represented in Fig. 2

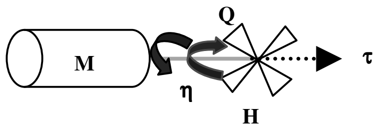


Figure 2 Propeller

where
M - Direct-current motor connected to the propeller H.
η - Rotational angular speed
τ - Propeller force designed thrust
Q -Reaction drag torque of the fluid in the motor
Γ - Motor torque
η - Angular speed of the motor shaft

Forces and torques that acts in this propulsion system model are represented in block diagram in Fig. 3 and the system equations are represented in Eq. (4)

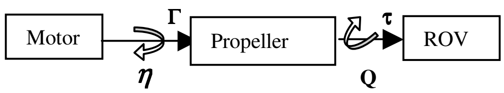


Figure 3 Block Diagram Model.

$$\sum \tau_i = J.\frac{d\eta}{dt}$$
$$K_e.I_s - Q = J.\frac{d\eta}{dt}, se \frac{d\eta}{dt} \cong 0 \Rightarrow \tau_e = Q \tag{4}$$

where
J –motor inertia
K_e - electromagnetic motor constant

It is observed in the equations above that in steady state the generated torque to electric motor is symmetrical to the fluid friction torque. This subject recently received attention in literature, having induced a series of models with increasing order of complexity such as describes in "Yoerger *et al.* (1985)", "Healey *et al.* (1993)", "Bachmayer *et al.* (2000)" and "Fossen *et al.* (2002)".

The dimensional analysis applied to Fig.2 supply the following expressions for force τ and produced torque Q in steady- state

$$T = \rho\eta^2 D^4 k_T(J),$$
$$Q = \rho\eta^2 D^5 k_Q(J), \tag{5}$$
$$J = \frac{u_a}{\eta D},$$

where
k_T – Hydrodynamics force coefficients
k_Q – Hydrodynamics torque coefficients
J - Advance propeller speed
D - Propeller diameter
η - shaft angular speed

The *values* of the coefficients k_T and k_Q are shown in Fig. 4, parameterized in J.

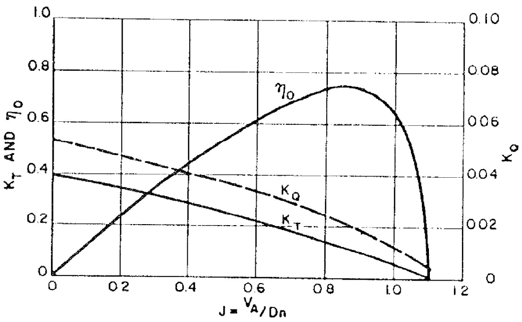


Figure 4 k_T and k_Q hydrodynamic coefficients.

These curves characterize the functioning of the propeller when both the translation speed and the rotational propeller speed are positive. This is the operation regimen more common in sea boats, and for which the efficiency of the propeller is maximized. The values of the coefficients of force *(C_T)* and torque *(C_Q)* are got considering carried through experimental tests in a standard propellers set, and can be gotten in *Wageningen B-Screw Series"*(Van Lammeren, 1969)". It must be observed in the Fig. 4 that when η increases, *J* tends to zero, then, the values for *T* and *Q* also tends to zero, indicating that this graph cannot be used for attainment of force and torque propellers values in case where it is necessary a fine position control. The propeller dynamics representation is carried throughout a model of two states like in "Healey *et al.* (1995)" where the propeller speed η and the fluid speed through the propeller is related by drag and sustentation effects. Controller output signals are setup to each propeller through the inversion of a quasi-static expression having related propulsion τ and the speed η through the expression (6)

$$T = b(n, U_a n \mid n \mid), \tag{6}$$

where

b is a function that depends on the shaft motor speed η and the seawater speed *Ua*. The control effort determined by the controller is used to setup propellers motion according the expression (7)

$$\tau_{crtl=B(b(n,U_a))}u, \quad B \in \Re^{6x6} \tag{7}$$

where

B is a matrix controller mapping signals of the τ_{ctrl} to each propeller through the signal of drive *u*. It is inserted in the vehicle model the dynamics propulsion considering that the electric motor is controlled in electric torque, the total dynamics of the propeller is described by the Eq. (8)

$$\tau_e - k(\eta) = J \frac{d\eta}{dt} \tag{8}$$

where

τ_e is the electric torque

k(η) is the resistance torque propeller rotational

J is the moment of total inertia of the motor /propeller referred to the motor.

k(η) complex function of the axle motor rotational speed.

One notices that

$$\frac{d\eta}{dt} = 0 \Rightarrow \tau_e = k(\eta)$$

It means that in steady state, the electric torque is the total torque of resistance to the rotational movement. "(Yoerger, 1985)" observed that the reaction torque caused by the fluid that involves the propulsion system cause a delay (lag) in the reply in propeller force when input step signal is applied in the electric motor. It was developed a simplified model of the propulsion system, with *k(η)* proportional to the square of the rotationally speed, what leads

$$\begin{aligned} \tau_e - k_{\eta|\eta|}\eta|\eta| &= J \frac{d\eta}{dt} \\ T &= T(\eta, u_a) \end{aligned} \tag{9}$$

It must be observed that "Yoerger *et al.* (1990)" model does not describe the movement of the water mass around the propeller when the it does rotational movements. Moreover, it only considers the simple case where the advance propeller rotational speed propulsion systems in relation to the fluid are positive, that is, the movements of the propeller are restricted to the first quadrant. The relation among these speeds can be observed in Fig. 5 that presents the relation between C_T and *Jo* parameterized for the relation among the propeller rotational speeds and the fluid speed both in direct and reverse movements.

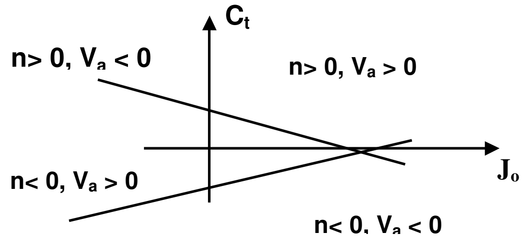


Figure 5 C_T representation in four quadrants

Later, "Healey *et al.* (94)" incorporated the propeller movements to the four quadrants, developing a first-class non-linear model to describe the fluid dynamics around the propeller, in accordance with the Eq. (10)

$$\begin{aligned} &\tau_e - K_\eta \eta - Q = J\,\frac{d\eta}{dt} \\ &m_f\,\frac{du_a}{dt} + d_f(u_a - u_0)\,|\,u_a - u_0\,| = T \\ &T = T(\eta, u_a) \quad and \quad Q = Q(\eta, u_a) \end{aligned} \tag{10}$$

where
u_a fluid speed in the propeller.
u_o speed of the platform that carries out the propeller in relation to the fluid.

It can be observed in the equations above that the drag torque includes a linear term k_η and a non-linear term *Q*. It is important also to notice the fluid speed evolution in the propeller in function of force *T* and the speed u_a. To get *T* and *Q*, it is important to understand that the mechanism of generation propulsion force in a propeller has the same nature that the sustentation force in a wing of an airplane. The screw propeller possesses translation and rotational movement. The propeller propulsion force is obtained in according to the combination results of the components forces of the sustentation and resistance. These forces, called lift *(L)* and drag *(D)*, are gotten in function of the incidence angle of fluid attack in the propellers. A coefficient representation lift (C_L) and drag forces (C_D) is shown in Fig. 6. These forces are got with the association of the Eq. (11)

$$\begin{aligned} &Lift = 0{,}5\rho V^2 A C_{L_{máx}} \sin((2\alpha_e)) \\ &Drag = 0{,}5\rho V^2 A C_{D_{máx}} (1 - \cos(2\alpha_e)) \end{aligned} \tag{11}$$

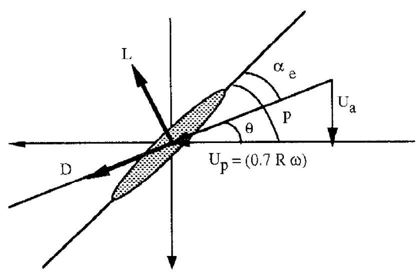
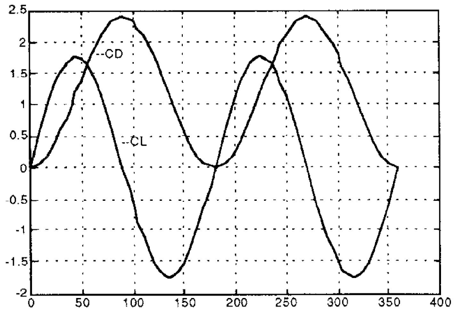


Figure 6 Propeller forces in function of the angle of attack.

where
A - transversal section of the area of the tunnel that protects the propeller
α_e - angle of attack

ρ - fluid density
Ua - fluid speed in the propeller
Up - translation propeller speed in relation to the fluid
V - total propeller speed in relation to the fluid
θ - propeller inclination angle
η - shaft motor speed

It is possible to observe in Fig. 6 that the Lift force is perpendicular to the instantaneous line of the fluid that acts in the propeller and Drag force is a longitudinal force, collinear with this line. The Lift and Drag coefficients are defined in relation to the line of the fluid flow and therefore a rotational conversion is necessary to compute the centerline force and the tangential force (responsible for the hydrodynamic torque). Also it is usual to consider *r=70%R* as the point of maximum incidence of the fluid in relation to the propeller, where *R* is the propeller radius, that is, in this point occurs the maximum effect of the typical radial distributions of the binary forces and torques. The maximum value of Lift and Drag coefficients in relation to the four quadrants propeller operation are gotten experimentally in tests called "*Open Water Tests*", where the propellers are tested in a uniform fluid with constant speed "(Newman, 1977)" and the results may be observed in Fig 7.



Vertical axle: C_D and C_L
Horizontal axle: αe

Figure 7 C_D and C_L coefficients.

The general propeller model may be represented by the blocks diagram in Fig. 8, where is represented the models of *DC* brush motor *(M)*, with electric voltage as input *(Vs)*, the propeller model (Prop), that describes the generating force *T* and torque *Q* mechanism at the four quadrants, beyond the model of the fluid. The propeller model input is the speed signal of the platform that carries them in relation to the fluid *(Uo)*. The explicit identification of the seawater speed also can be got using complementary filters that integrate information proceeding from a *Doppler* unit (to measure the speed of the ROV in relation to the seawater and the deep of the sea), and a system of acoustic positioning. This model shown in Fig. 8 was incorporated in the simulator model developed in this work.

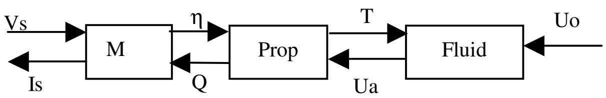


Figure 8 Propeller Model.

5. Umbilical Cable

The umbilical cable is difficult to model due its discontinuous movement, changeable length, nonlinear viscous effect, and the intrinsic capacity to support overload, function of its constructive characteristics. The mathematical model of the cable will be described for discontinuous differential equations. The umbilical cable hardwired between the bird cage and the ROV can present disturbances for the dynamic stability behavior of the ROV when the vehicle is operating in hostile environments, due to sudden appearance of efforts that exert traction and compression on it. As the cables are not projected to support great efforts added throughout its length, these efforts may cause operational difficulties on it. The cables are responsible for the transmission of the energy required for the motors and the optics communication between the ROV and the platform in the water surface, essentials for the drive and the control of the ROV. It must be considered, however, that additional efforts on the cable, exactly of small dimension, can cause attenuations in the optical signals and losses in telemetry. Umbilical cable was not incorporated in the general model of the ROV simulated in this work. Therefore the model adopted for simulation (vehicle *Sirene*) does not present values for the parameters mentioned above. Other models of umbilical cable can be found in "(Kapsemberg, 1985)", "(Nomoto and Hattori, 1986)", "(Driscoll and Biggins, 1993)".

6.Control Strategy

For ROV dynamic positioning control must be observed that diverse parameters of the vehicle are estimated with inaccurate due the difficulty to measure or calculate them through experiments. Considering also that the dynamics of the ROV is non linear and the vehicle is subject to ambient disturbances during the operation, it is necessary to project the controller with highest degree of robustness in relation to the parametric uncertainties and capacity to reject non previsible disturbances ambient (like seawater speed). In function of these particularitities, conventional controllers with fixed gains as P-D and P-D-I can be inadequate for these applications, due to non linearities existents in the system as static attrition, histereses, saturation in the actuators and dead zones, that cause problems to the robustness performance of the controllers., presents a high degree of robustness in relation to the parametric uncertainties and great capacity to reject disturbances "(Slotine, 1998)". To avoid this problems, this work uses a robust methodology called Sliding Mode Control, treated here as CMD, which is supported in the Lyapunov stability theory. This technique is based on the trajectories of balance (that is, with constant command inputs) of the underwater vehicles parameterized by the module of the linear speed of the vehicle, yaw dates, and the angle of flight (angle between the total vector speed and the horizontal line). One also that this work may be applied to different structures of ROVs. Similar strategies was applied in " (Healey and Lienard, 1993)" and" (Jalving, 1994)".

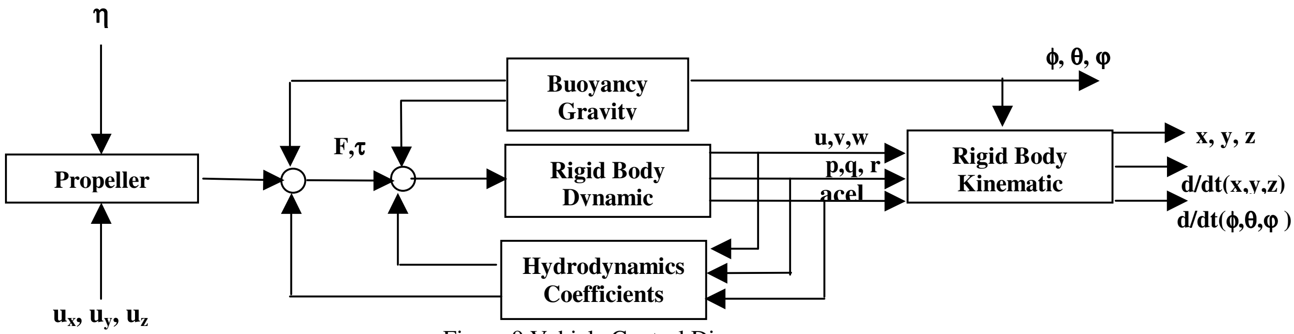


Figure 9 Vehicle Control Diagram.

7.Simulation

The problem of following trajectories using non-linear control techniques presents some difficult problems of resolution due to the hydrodynamic effect and the influence of the seawater speed, that cause disturbance in the movement of the underwater robot. It is intended to get a necessary control of pursuing trajectories and dynamic positioning of the ROV through the dynamic model of vehicle propulsion, seen in Fig. 10. The controller command signal inputs receives the forward speed of the vehicle in relation to the seawater, the orientation of the vehicle controlled by main propellers functioning in several ways (or conjugated with the action of the lateral propeller), and the depth, controlled by the vertical propeller.

The model used to simulation the kinematics of the vehicle *Sirene* was carried out in MatLab/Simulink and is presented in Fig. 10

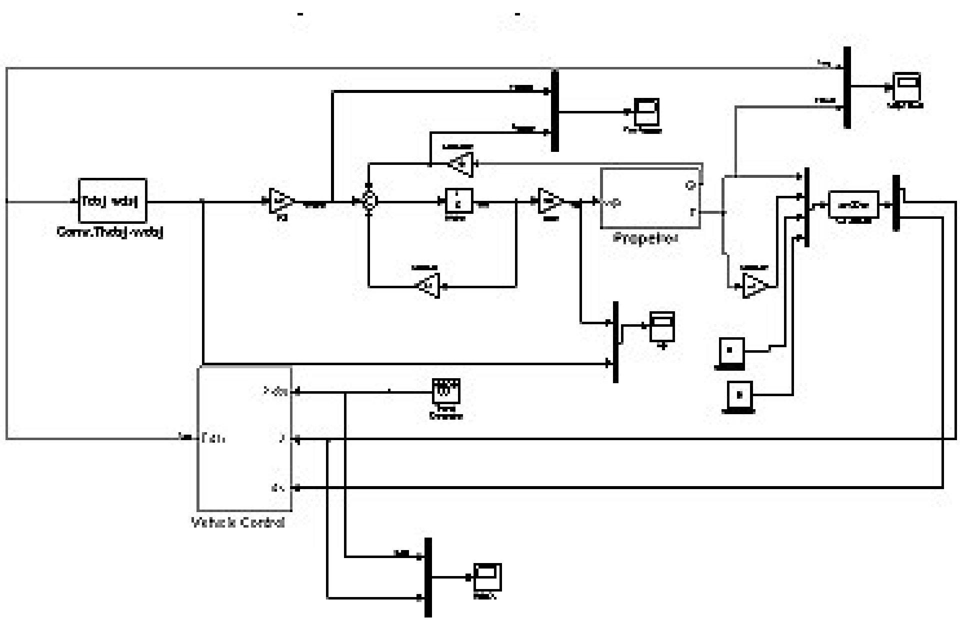


Figure 10 Simulink diagram blocks model.

Main propellers functioning in differential ways stimulate the vehicle. A model of a *DC* servomotor was used and acts as an ideal integrator in steady state, the electric torque of the motor is controlled by PI controller, syntonized through allocation polar regions procedure, where the denominator terms of the transference function closed are equaled to the coefficients of the desired polynomial characteristic, that, in turn, are determined by the coefficient of damping ξ, the natural frequency of damping ω_n and by a constant real α. These parameters had been calculated so that the dynamic behavior of the system was characterized by two dominant complex conjugated polar regions "(Ogata, 2004)". A controller in sliding mode with a landslide surface $s = 0$ that the vehicle must follow, such way the vehicle dynamics is remained contained in the region delimited for the boundary layer $\phi\ (\phi > 0)$ around of the surface $s=0$, assuring that the keying (chattering) does not happen "(Slotine, 1998)". The input command signal are the trajectory desired and its orientation in *yaw* and, also, the behavior of the drag torque produced for the propulsion system in relation to an applied quadratic signal as reference signal, with frequency of 0.02 *Hz* and amplitude 1,0. These simulations was carried throughout considering a map of symmetrical operation, where the flow of the water always remains a constant direction and the propulsion system suffers inversion throughout the applied quadratic signal to the system, what it is equivalent to consider an operation in 1st and 3rd quadrants diagram operation presented in Fig. 4. The results of the simulations are presented in Figs.10 and 11.

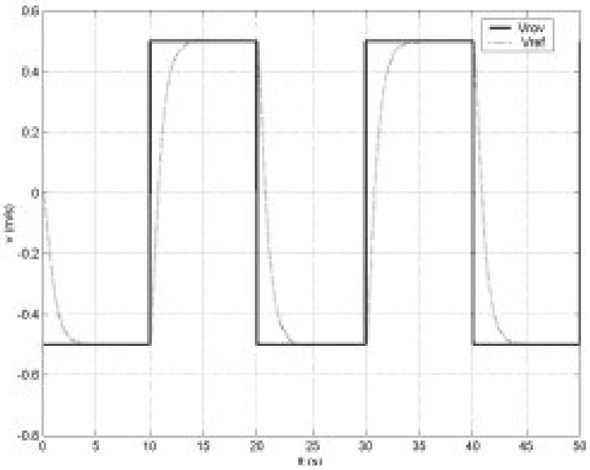


Figure 10 Position Control.

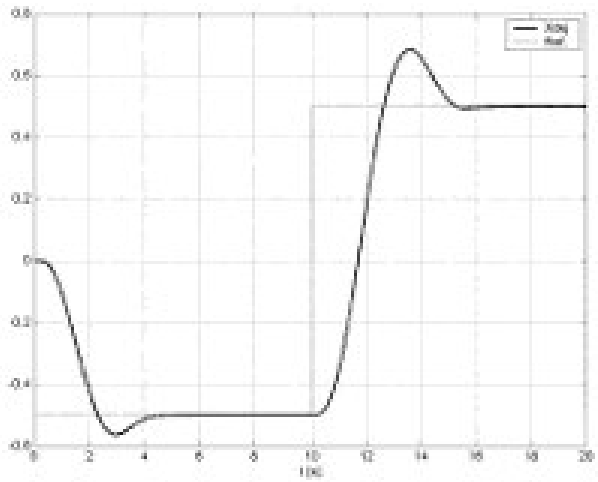


Figure 11 Thrust Control.

8. Conclusions

The results shown that the adopted model presents satisfactory result that assure its trustworthiness for use in ROVs, as established in "Healey *et al.* (1994)". A small overshoot in the propulsion torque is observed (error < 5%) in function of the inertial effect of the fluid as well as the fast action of the propulsion system response due to the thrust command, indicating a satisfactory performance in the attainment of the necessary torque to the vehicle propulsion. The same may be observed in relation to the trajectory tracking. Moreover, the control kept the vehicle in the steady state trajectory despite the insertion of the dynamics of the involving fluid in the propulsion system. One intends that the developed and implemented model in SIMULINK is a useful and very versatile platform to evaluate the performance of all types of controllers to be implemented, and will allow the analysis and simulation of the vehicle behavior in function of its physical properties and its kinematics and dynamics behavior.

9. Acknowledgments

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