Four Propellers Submarine Drone Modelling

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Abstract – *Modelling and simulation cover a very wide field for studies relating to scientific and technological research and they have even become an indispensable tool for several decades[1].*

Computers nowadays offer extraordinary and unequalled computing power, thus allowing the processing of huge flows of collected data in record time, thus allowing ease of readability and staging of results.

The inseparable whole theory, modelling, simulation and experimentation is omnipresent in many contemporary scientific and technological activities, so that the word research and almost linked to this aforementioned quartet[2].

The aim of the present study is to simulate via Matlab Graphic User Interface the submarine behavior in multiple thruster's power's configurations to approve this technological architecture solution.

These developments are part of the overall project initiated by the EAS team of the Computer Laboratory, systems and renewable energy (LISER) of the National School of Electrical and Mechanical (ENSEM)

Key Words: Mobile robot ROV, Underwater vehicle, Kinematic, Cinematic, Modelling, Simulation, Command Thrusters, Hydrodynamic, Forces, Couples.

1. INTRODUCTION

In the last study we presented our ROV model (figure 1) which has a propulsion and guidance system consisting only of four propellers at the rear of the machine, we also justify our choice of the configuration of the propellers with the advantages that 'she presents. In this study we will treat the modeling and simulation part of this ROV [3].

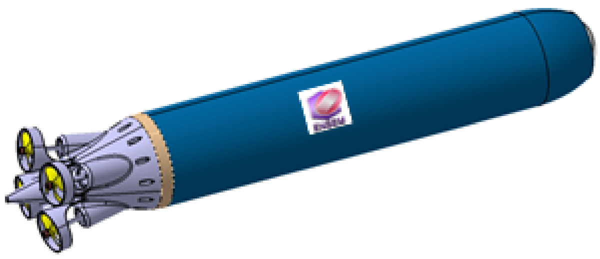

Figure 1: ROV's Isometric view

The equations of states that constitute the mathematical model are used to describe the kinematics and the dynamic and hydrodynamic behavior of underwater vehicles and especially the interactivity between this machine and the fluid that surrounds it. Once this model is established, it will be the subject of several simulations to describe the general behavior of the ROV.

2. UNDERWATER VEHICLE MODELLING

ROV modeling consists of two main parts: kinematics and dynamics. The kinematic part will be interested in the movement and the geometrical relations of the submarine vehicle. While the dynamic part deals with the forces and couples acting on this craft.

2.1 Denomination of the variables:

The evolution of the vehicle will be described in coordinate systems according to the notation (table 1) of the Society of Naval Architects and Marine Engineers (SNAME, 1950):

		Forces and moments	$\boldsymbol{\nu}_1, \boldsymbol{\nu}_2$	$\boldsymbol{\eta}_1, \boldsymbol{\eta}_2$
Motion in the x-direction	Surge	X	u	x
Motion in the y-direction	Sway	Y	v	y
Motion in the z-direction	Heave	Z	w	z
Rotation about the x-axis	Roll	K	p	ϕ
Rotation about the y-axis	Pitch	M	q	θ
Rotation about the z-axis	Yaw	N	r	ψ

Table 2: Common notation for the motion of a marine vehicle [4].

The center of gravity of the vehicle C is coincident with the origin of the reference R_v linked to the vehicle [5].

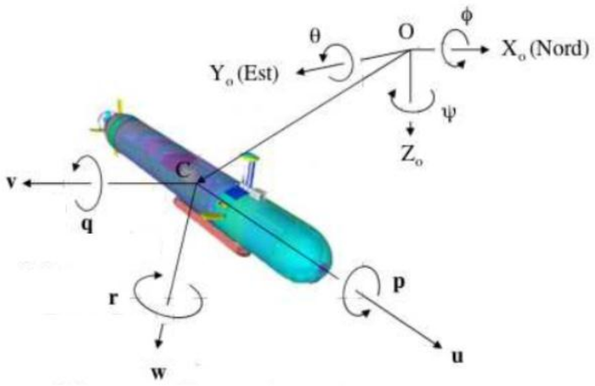

Figure 3: Euler's angles representation [6]

The Cartesian coordinates of the point C in the absolute coordinate system R_0 are:

$$\eta_1 = (x, y, z)^T \qquad (1)$$

The angles (φ, θ and ψ) represent in the order the angles of roll, pitch and yaw (figure 2), Which define the orientation of the vehicle in the frame R_0:

$$\eta_2 = (\varphi, \theta, \psi)^T \qquad (2)$$

We can then express the global position vector:

$$\eta = (\eta_1, \eta_2)^T \qquad (3)$$

Similarly, the linear speeds of advance, sliding and lowering in the reference R_v can be combined:

$$\nu_1 = (u, v, w)^T \qquad (4)$$

And also, the angular velocities of roll, pitch and yaw in the form:

$$\nu_2 = (p, q, r)^T \qquad (5)$$

Thus, the global speed vector in the reference R_v:

$$\nu = (\nu_1, \nu_2)^T \qquad (6)$$

6.2 kinematic model

The angles of Euler correspond in robotics to the system commonly called R.T.L which designates the (Roulis, Tangage and Lace) roll, pitch and yaw (φ, θ and ψ), figure(2).

This system can be adopted for this study, because the singularity for a pitch angle: $\theta = \pi / 2 \pm k\pi$ cannot take place, since the vehicle is supposed to be evolved at pitch $\theta = 0$.

The trajectory of the machine in the reference frame R_0 is described by the relation:

$$\dot{\eta}_1 = J_{C_1}(\eta_2)\nu_1 \qquad (7)$$

With:

$$J_{C_1}(\eta_2) = \begin{bmatrix} \cos\psi\cos\theta & -\sin\psi\cos\varphi + \cos\psi\sin\theta\sin\varphi & \sin\psi\sin\varphi + \cos\psi\sin\theta\cos\varphi \\ \sin\psi\cos\theta & \cos\psi\cos\varphi + \sin\psi\sin\theta\sin\varphi & -\cos\psi\sin\varphi + \sin\psi\sin\theta\cos\varphi \\ -\sin\theta & \cos\theta\sin\varphi & \cos\theta\cos\varphi \end{bmatrix} \qquad (8)$$

This matrix is the rotation matrix of R_0 to R_v [7].

In the same way the relation which links the angular velocities:

$$\dot{\eta}_2 = J_{C_2}(\eta_2)\nu_2 \qquad (9)$$

Whither:

$$J_{C_2}(\eta_2) = \begin{bmatrix} 1 & \sin\varphi\tan\theta & \cos\varphi\tan\theta \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi/\cos\theta & \cos\varphi/\cos\theta \end{bmatrix}, \theta \neq {}^{\pi}/_{2} \pm k\pi \qquad (10)$$

6.3 dynamic model

In a general way we can consider that the R_0 is a Galilean coordinate system, except that it is fixed on the surface of the earth. Thus, the forces generated by the rotation of the earth on the vehicle can be neglected compared to the hydrodynamics forces.

The expression of the dynamic equation in the fixed frame R_0 is as a function of the state vector: $\eta = [x, y, z, \varphi, \theta, \psi]^T$ which represents the position and the orientation of the vehicle in this coordinate system.

The fundamental principle of the dynamics applied to the mobile [8].in this system gives:

$$M\dot{\nu} = f_c + f_g + f_h + \tau + w \qquad (11)$$

Whither the vectors:

- $\dot{\nu} = [\dot{u}, \dot{v}, \dot{w}, \dot{p}, \dot{q}, \dot{r}]^T$: accelerations of the vehicle,
- f_c: forces and moments of training inertia and Coriolis,
- f_g: forces and torque induced by the weight and thrust of Archimedes,
- f_h: hydrodynamic forces and couples,
- τ: forces and torques produced by the actuators,
- w: external disturbances (waves ...).

And $M \in \mathbb{R}^{6X6}$ is the inertial matrix of the vehicle and has for expression [9]:

$$\begin{bmatrix} m & 0 & 0 & 0 & mz_g & -my_g \\ 0 & m & 0 & -mz_g & 0 & mx_g \\ 0 & 0 & m & my_g & mx_g & 0 \\ 0 & -mz_g & my_g & I_{xx} & -I_{xy} & I_{xz} \\ mz_g & 0 & mx_g & -I_{yx} & I_{yy} & I_{yz} \\ -my_g & mx_g & 0 & -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix} + M_{added\ masses} \qquad (12)$$

With:

- m: mass of the vehicle (kg);
- (x_g, y_g, z_g): the position of the center of gravity of the vehicle in R_v coordinate system (m).
- I_x, I_y, I_z: body's moments of inertia of the vehicle according to the x, y and z axes(kg.m²).
- $I_{ij} = \oiiint_V ij\ \rho_m\, dV$: Inertial products(kg.m²).
- $M_{added\ masses}$ estimated by simulation or determined experimentally, can be neglected with robust mobile control (kg).

a. Inertia and Coriolis

As the robot moves with low speeds, the forces and the drive torques and Coriolis can be neglected.

b. Weight and Archimedes thrust

The submarine's forces in the water are Archimedes thrust and its own weight and are written:

$$W = m\,.\,g \quad and \quad B = \rho \nabla g \tag{13}$$

with:

- m : mass of the vehicle (kg).
- g : Earth acceleration (m.s^{-2}).
- ρ : water density(kg.m^{-3})
- ∇ : displaced water volume (m³).

Thus, the vector of hydrostatic forces is written:

$$f_g = \begin{bmatrix} -(W-B)\sin\theta \\ (W-B)\cos\theta\sin\varphi \\ (W-B)\cos\theta\cos\varphi \\ (y_gW - y_bB)\cos\theta\cos\varphi - (z_gW - z_bB)\cos\theta\sin\varphi \\ -(x_gW - x_bB)\cos\theta\cos\varphi - (z_gW - z_bB)\sin\theta \\ (x_gW - x_bB)\cos\theta\cos\varphi - (y_gW - y_bB)\sin\theta \end{bmatrix} \tag{14}$$

- B: norm of Archimedes' thrust (Buoyancy)(N).
- W: weight (N).
- (x_g, x_g, x_g): the position of the gravity center in R_v(m).
- (x_b, x_b, x_b): the position of the thrust center in R_v (m).

If we consider [10] : the center of thrust is the center of the reference R_v, then $x_b = 0$, $y_b = 0$ *and* $z_b = 0$, and that the submarine's masse is symmetrically distributed with respect to the three planes $(xz), (xy)$ *and* (yz), then $x_g = 0, x_g = 0$ *et* $x_g = 0$, similarly to the equilibrium *W=B*, hence the relation (14) becomes :

$$f_g = [0,0,0,0,0,0]^T \tag{15}$$

c. Hydrodynamic forces and couples

In this first study we will momentarily begin the simulation without taking into consideration the hydrodynamic forces and couples, these will be presented in details in the next study.

d. External disturbances

Considering that the submarine will evolve in calm waters without the presence of waves or currents, these disturbances can be neglected.

e. Actuators effects

They generally designate any source of thrust that is exerted on the machine. We will limit ourselves in this study on the propellers that are installed on the machine and will be driven by electric motors.

The modeling of the thrust of a thruster is relatively delicate because it depends on several parameters and it is more complicated by the coupling of many thrusters.

In our case, the four thrusters are directed along the axis Ox, according to the following configuration seen back:

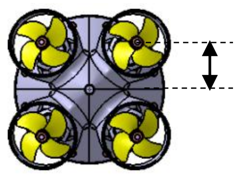

Figure 4: Back view "x" configuration.

The vector of the forces and torques applied to the vehicle by the actuators is generally defined as follows:

$$\tau = (f_x, f_y, f_z, \Gamma_x, \Gamma_y, \Gamma_z)^T \tag{16}$$

In our case, as we have four thrusters directed along the Ox axis, then:

$$\tau = (f_x, 0,0,0, \Gamma_y, \Gamma_z)^T \tag{17}$$

Hence the matrix of actuators [11]:

$$\tau = T.f_i \tag{18}$$

Who becomes:

$$\tau = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -d & -d & +d & +d \\ +d & -d & -d & +d \end{bmatrix} . \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} \tag{19}$$

With:

d: the distance between the origin of the axes (oy) and (oz) and the projection of the centers of the axis of the propeller (figure 3).

The resultant (in N) following Ox:

$$f_x = f_1 + f_2 + f_3 + f_4 \qquad (20)$$

With:

$$\sum_x f_i = m.\gamma_r \qquad (21)$$

And:

$$\gamma = \frac{f_1 + f_2 + f_3 + f_4}{m} \qquad (22)$$

The torque (in N.m) according to Oy:

$$\Gamma_y = d.(-f_1 - f_2 + f_3 + f_4) \qquad (23)$$

With:

$$\Gamma_y = J_{\Delta y}.\ddot{\varphi} \qquad (24)$$

And:

$$\ddot{\varphi} = d.\frac{(-f_1 - f_2 + f_3 + f_4)}{J_{\Delta y}} \qquad (25)$$

In the same way, the torque (in N.m) according to Oz:

$$\Gamma_z = d.(f_1 - f_2 - f_3 + f_4) \qquad (26)$$

With:

$$\Gamma_z = J_{\Delta z}.\ddot{\psi} \qquad (27)$$

And:

$$\ddot{\psi} = d.\frac{(f_1 - f_2 - f_3 + f_4)}{J_{\Delta z}} \qquad (28)$$

3. SIMULATION

The plot of the trajectory will be visualized on a 3D MATLAB interface. The core of the program is already treated [12]. However, the parameters specifics to this ROV as well as the equations governing its movement are already defined and will be implemented in the final program of the vehicle simulation.

The principle of the simulation is based on the use of homogeneous coordinates, so any equation: $y = Ax + b$ can be written in the form:

$$\begin{pmatrix} y \\ 1 \end{pmatrix} = \begin{pmatrix} A & b \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ 1 \end{pmatrix} \qquad (29)$$

If by definition:

$$x \mapsto x_h = \begin{pmatrix} x \\ 1 \end{pmatrix} \qquad (30)$$

So any affine equation:

$$y = A_3(A_2(A_1 x + b_1) + b_2) + b_3 \qquad (31)$$

Will write in this way:

$$y_h = \begin{pmatrix} A_3 & b_3 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} A_2 & b_2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} A_1 & b_1 \\ 0 & 1 \end{pmatrix} x_h \qquad (32)$$

The dynamic simulation will be inspired by the work of Fossen [13]. The kinematic equations that appear in this book will be used to establish the dynamic model. By applying the fundamental principle of mechanics (Newton's second law), the forces and torques acting on the ROV will generate tangentials and angulars accelerations. These magnitudes, in their turn, will become the entries of the system considered.

So, to deduce the state equations, the system can be defined as (figure 4):

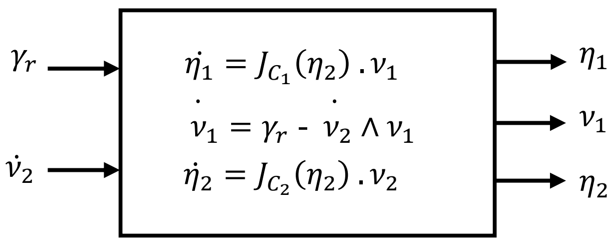

Figure 5: ROV's state equations.

By performing the matrix calculation of the vectors and matrices of the rotations, we can then write the state vector in form:

$$X = (x, y, z, v, \psi, \theta, \varphi)^T \qquad (33)$$

With:

$$\begin{cases} \dot{x} = v\cos\theta \; cos\psi \\ \dot{y} = v\cos\theta \; sin\psi \\ \dot{z} = -\,v\sin\theta \\ \dot{v} = u_1 \\ \dot{\psi} = \dfrac{sin\varphi}{cos\theta}.v.u_2 + \dfrac{cos\varphi}{cos\theta}.v.u_3 \\ \dot{\theta} = cos.v.u_2 - sin\varphi\,.v.u_3 \\ \dot{\varphi} = tan\theta.v.(sin\varphi.u_2 + cos\varphi.u_3) \end{cases} \qquad (34)$$

Where the system (figure5): inputs are tangential acceleration u_1, pitch u_2 and yaw u_3 :

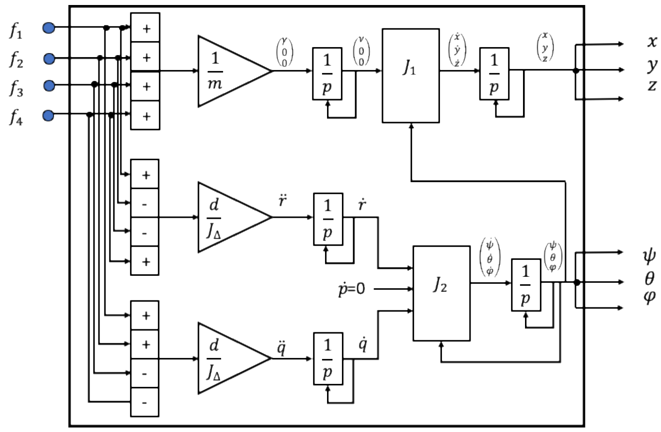

Figure 6: ROV's system input & output.

The simulation will be done by the Euler method which uses the numerical integration, thus a differential equation of type:

$$\dot{x} = f(x, u) \qquad (35)$$

can be replaced by the recurrence:

$$x(t + dt) = x(t) + dt.f(\,x(t), u(t)\,) \qquad (36)$$

According to the formula of Rodriguez [12], the rotation matrix of an angle and around a vector is:

$$R_\omega = expm\begin{pmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{pmatrix} \qquad (37)$$

With "$expm$" exponential of a matrix.

In a general way to deduce the matrix of rotation from the three angles of Euler:

$$R = expm\left[\psi.\begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}\right].expm\left[\theta.\begin{pmatrix} 0 & 0 & -1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}\right].expm\left[\psi.\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix}\right] \qquad (38)$$

4. RESULTS

In this part, several thrusters power configurations will be simulated to see the general dynamic behavior of the submarine robot.

Some numerical data specific to the ROV:

$$J_{\Delta y} = J_{\Delta z} = {}^1/_2\, m.r^2 = 3{,}504\ Kg.m^2$$

$$J_{\Delta x} = 0{,}143\ Kg.m^2$$

$$r_1 = 60\ mm$$

$$r_2 = 60\ mm$$

$$l = 1{,}2\ m$$

$$m = 28{,}6\ Kg$$

$$d = 90\ mm$$

a. Interface Presentation

The interface consists of graphs, input and display fields, and command buttons:

- The graphs: gives the position of the submarine in the absolute coordinate system and the other three trace the three Euler angles.
- Input fields: used to enter the thrusters' power and the duration of simulation.
- Display fields: informs about the positions (x, y, z), Euler angles, speed and acceleration in absolute reference.
- Command buttons: group together the buttons needed to control the simulation as a whole.

b. Case N°1:

The thrusters have the same power (figure 6):

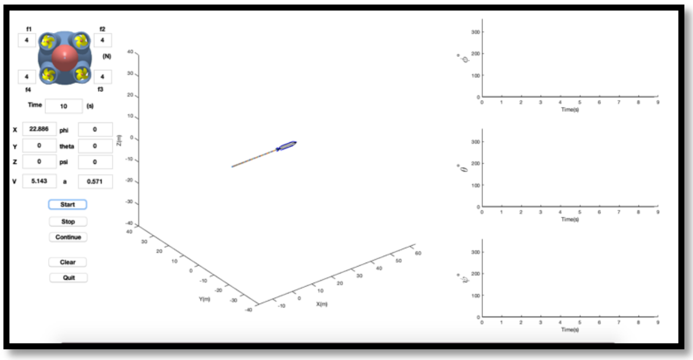

Figure 7: The thrusters have the same power.

In this case the robot keeps a rectilinear trajectory with constant acceleration. Only the position x changes, the other five parameters remain nulls.

c. Case N°2:

The diagonal thrusters have the same power (figure 7):

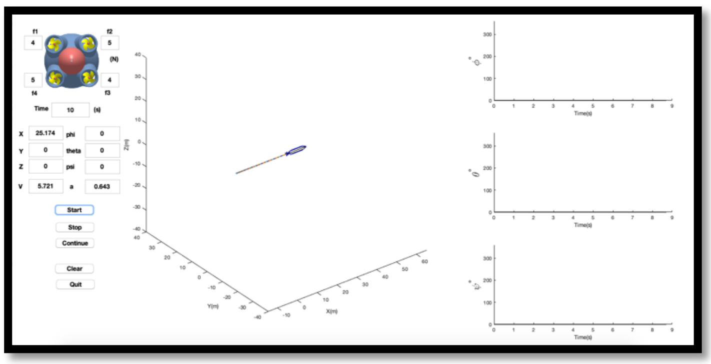

Figure 8: The diagonal thrusters have the same power.

Same case as before, the robot keeps a rectilinear trajectory with a constant acceleration. Only the position x changes, the other five parameters remain nulls.

d. Case N°3

The vertical thrusters have the same power (figure 8):

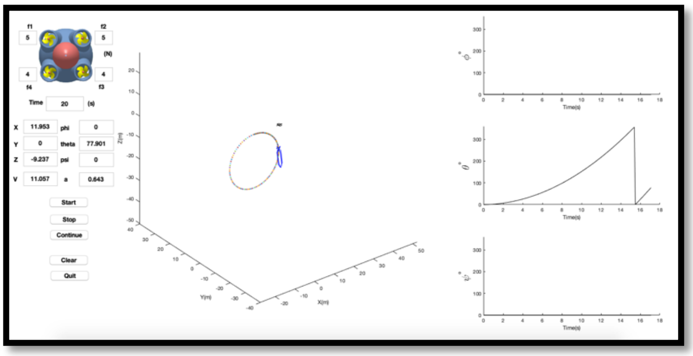

Figure 9: The vertical thrusters have the same power.

With this configuration the ROV describes a circle in the plane *(y=0)*, the radius depends on the power deference of the thrusters and only the theta angle varies.

e. Case N°4

The horizontal thrusters have the same power (figure 9):

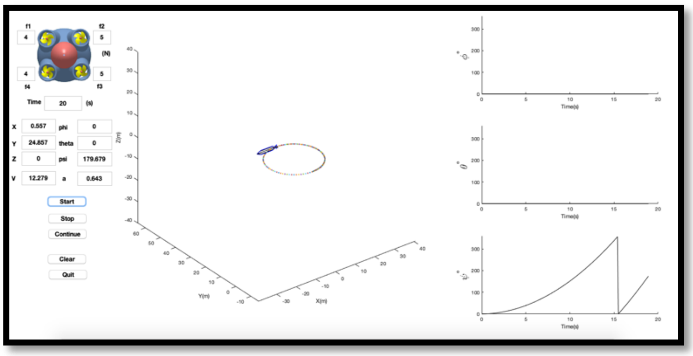

Figure 10: The vertical thrusters have the same power.

Results similar to the previous configuration, the ROV describes a circle in the plane *(z=0)*, the radius also depends on the power deference of the thrusters and only the angle *psi* varies.

f. Case N°5

One of the four propellers is different of the others (figure 10):

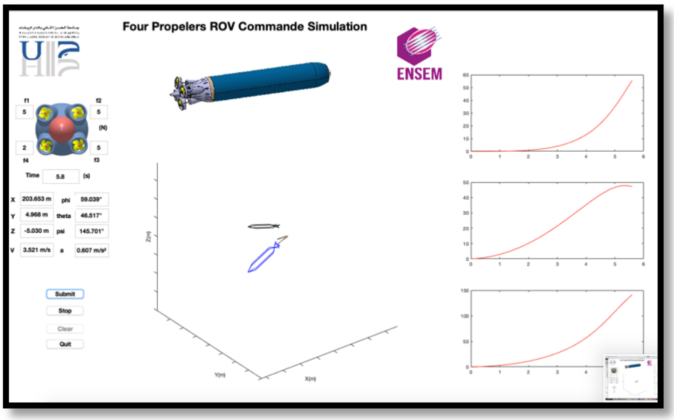

Figure 11: One of the four propulsors is different of the others.

In this combination the ROV will move in the lowest power direction and can describe a spiral whose radius and pitch will depend on the power deference this propeller with the others.

g. Case N°6

Propellers are different powers (figure 11).

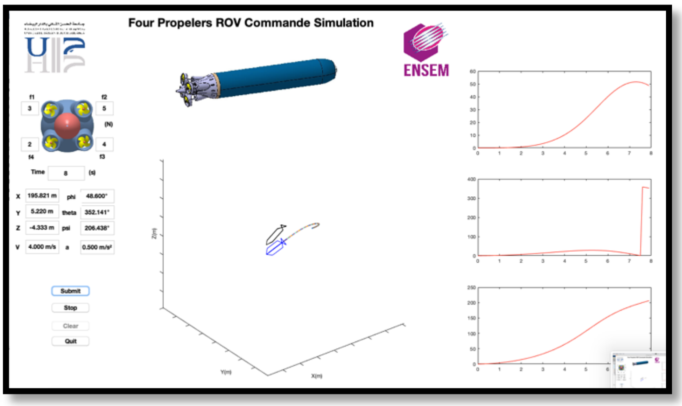

Figure 12: Propellers are different powers.

In this case, the trajectory will mainly respond to the deference of the horizontal and vertical powers.

5. CONCLUSION AND PERSPECTIVES

In this study we were able to show theoretically that a marine robot with four propellers can move in the marine environment without using rudders or dive bars.

in the next study we will add the dynamic dampers in the equations of the model to have a more realistic simulation.

REFERENCES

[1] A. Giordan & J-L. Martinand. (Éd.), Modèles et Simulation. Actes, IXe Journées Internationales sur l'Éducation Scientifique: UER de didactique des disciplines, Université Denis-Diderot-Paris France 1987.

[2] M. Coquidé & J-F. Le Maréchal, Institut de l'information scientifique et technique INIST. ASTER | 43| France 2006.

[3] M. Moustanir, K. Benkirane, A. Sayouti, H. Medromi, Submarine Drone, First Edition of the Doctoral Days on Engineering Science ENSEM, Hassan II University of Casablanca May 2018.

[4] B.Siciliano, O. Khatib, Springer Handbook of Robotics, Springer-Verlag Berlin Heidelberg Deutschland 2008

[5] M. Moustanir, K. Benkirane, A. Sayouti, H. Medromi, Four Propellers Architecture Proposed for the Submarine Drone, International Research Journal of Engineering and Technology (IRJET) Volume 6, Issue 11, November 2019.

[6] J-M. Spiewak, Contribution à la coordination de flottille de véhicules sous-marins autonomes, Automatique / Robotique, Université Montpellier II - Sciences et Techniques du Languedoc, France, 2007.

[7] A. KHADHRAOUI, ''Modélisation et simulation interactive pour la navigation d'un robot sous-marin de type ROV Observer'' Ph.D. Thesis, Dept. Sciences et technologies de l'information et de la communication, Université Paris-Saclay, Paris, France, 2015.

[8] E. Roche, D. SIMON et O. SENAME, Commande robuste d'un véhicule sous-marin autonome, INRIA Rhône Alpes Département d'Automatique de Gipsa-lab, France juin 2008.

[9] R. Yang, Modeling and robust control approach for autonomous underwater vehicles, Automatic, Université de Bretagne occidentale - Brest, France, 2016.

[10] N. BOËLY, Modélisation non linéaire et contrôle linéaire par retour entrée-sortie linéarisant d'un drone sous-marin quadri hélices à poussée vectorielle, école de technologie supérieure, university of Québec, Montreal, MAI 2010.

[11] V. CREUZE, Robots marins et sous-marins - Perception, modélisation, commande, Techniques de l'Ingénieur, 2014.

[12] L. Jaulin, La robotique mobile, ISTE editions Ltd, Great London Britain, 2015.

[13] T.I. Fossen, Guidance and Control of Ocean Vehicles, John Wiley and Sons, Inc., New York (1994).

BIOGRAPHIES

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