SIMULATION OF A SIMPLE ROV SYSTEM

RAMAHANDRISOA Fetraharijaona[1], RAKOTOMIRAHO Soloniaina[2],
RANDRIAMAROSON Rivo Mahandrisoa[3]

[1] *Phd Student, SE-I-MSDE, ED-STII, Antananarivo, Madagascar*
[2] *Thesis director and Laboratory Manager, SE-I-MSDE, ED-STII, Antananarivo, Madagascar*
[3] *Thesis co-director, SE-I-MSDE, ED-STII, Antananarivo, Madagascar*

ABSTRACT

In order to discover the seabed, remotely operated vehicles, commonly referred to as ROVs, found limits in their operation related to underwater operation. This category of gear is confronted with several major classes of scientific problems, namely: energy autonomy, navigation coupled with the problem of positioning. Today, underwater robots are an integral part of scientific equipment to explore the seas and oceans. The modeling and simulation of the operation of these machines are part of the steps to solve these problems.

Keyword: - *ROV, DOF, Simulation, Model*

1. INTRODUCTION

Modeling and simulation are an important step in understanding the behavior of the system before it is implemented. It is at the heart of most current technological innovations and has become a fundamental tool in many areas of engineering. Essentially multidisciplinary in its applications, modeling and simulation alone constitute a key technology that can only strengthen its presence in industries and even institutions.

Models used to simulate ROV dynamics, including mass of inertia and mass-added model, Coriolis and centripetal forces, Euler's transformation model, gravitational and buoyant forces, forces of damping and propeller model are presented. Accurate dynamic models are essential for the realization of ROV simulators.

2. FORCES ACTING ON MOVING AN ROV

The generalized forces acting on the ROV come mainly from the ocean current, thrusters and gravity. Ocean current forces are included in the equations of motion through relative velocity.

2.1 Current forces

Ocean current forces are included in the Process Plant Model through the velocity of the ocean current in the body. This is generated using a model of the speed and direction of the ocean current in the geographic reference, e.g. the NED frame. The velocity of the ocean current is V_c and it has a vertical and horizontal direction α_c and β_c in the frame {n}. The velocity vector of the ocean current in {n} is

$$v_c^n = R_{y,\alpha_c}^T R_{z,-\beta_c}^T \begin{bmatrix} V_c \\ 0 \\ 0 \end{bmatrix} \qquad (1)$$

With α_c and β_c as arguments.

The dynamics for V_c, α_c and β_c can be added to obtain a slowly varying ocean current. A model suggested in [1] is to use a first order Gauss-Markov process given by

$$\dot{V}_c + \mu V_c = w, \qquad (2)$$

$$\dot{\alpha}_c + \mu_\alpha \alpha_c = w_\alpha, \qquad (3)$$

$$\dot{\beta}_c + \mu_\beta \beta_c = w_\beta, \tag{4}$$

Where $\mu_i \geq 0$ is a constant and w_α is a white Gaussian noise.

The ocean current is transformed into a body before use in the Process Plant Model as

$$v_c = J^T(\eta) v_c^n \tag{5}$$

2.2 Propulsive forces

Most ROVs are fully powered and can produce force in any DOF (Degrees of Freedoms) using propellers. Each thruster unit, with propeller and duct, is called a thruster. The thrusters used on the Minerva ROV are shown in **Fig -1 and 2** which show single- and double-sided thrusters.

The forces produced by each thruster constitute the total control force. However, the actual thrust is not easy to measure and must be estimated from a propeller model.

Fig -1: Simple thruster of Minerva

Fig - 2: Double-sided thruster of Minerva

A basic model of the thrust production of a single propeller is given by (6) as

$$f = K_T(J)\rho D^4 n^2 \tag{6}$$

Where f is the thrust, $K_T(J)$ is the thrust coefficient, ρ is the density of water, D is the diameter of the propeller and n is the speed of rotation of the propeller in revolutions per second (*r/s*).

The thrust coefficient depends on the number of J advance that is given by

$$J = \frac{V_a}{nD} \tag{7}$$

Where V_a is the speed of the flow water of the propeller.

a. The thrust vector

The thrust produced by the thruster no. i is f and is given by (6). The vector with thrust for the r-propellers is

$$f = [f_1 f_2 \cdots f_r]^T \tag{8}$$

The total force of the thruster, in p DOF, acting on the vehicle is

$$\tau = Tf \tag{9}$$

Where $T \in \mathbb{R}^{p \times r}$ is the configuration matrix of the thruster which is a function of the position of the thrusters $r_{t_i/b}^b$ bet of the azimuth and elevation angles, respectively α and β. While respecting the mark of the vehicle. The thruster configuration matrix is

$$T = [t_1, t_2, \ldots, t_r], \tag{10}$$

Where the column vectors corresponding to propeller i, are calculated by

$$t_i = \begin{bmatrix} I_{3\times3} \\ -S^T(r_{t_i/b}^b) \end{bmatrix} R(\alpha, \beta) \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} f_i \tag{11}$$

The rotation matrix of the thruster axes to the chassis of the vehicle is

$$R(\alpha, \beta) = R_{z,\alpha} R_{y,\beta} \tag{12}$$

Where the rotation matrices from the elevation and azimuth angles are

$$R_{y,\beta} = \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix}, R_{z,\alpha} = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{13}$$

The azimuth and elevation angles are constant for fixed thrusters. This simplifies the thruster allocation problem as described below.

b. Thrust allowance

The thrust vector τ, as in (9), is controlled by the control system and must be distributed to the individual thrusters. More precisely, the input of each thruster must be calculated. Here, the final input is the rotational speed of each thruster. Equation (9) is rewritten in

$$\tau = TKu \tag{14}$$

Where $K \in \mathbb{R}^{r \times r}$ is a diagonal matrix with coefficients of thrusters. $K_i = K_T(J)\rho D^4$ and the elements of $u \in \mathbb{R}^r$ are $u_i = |n|n$, where n is the speed of rotation of the propeller.

The problem of allocation of thrusters is to solve (14) for u if

$$u = K^{-1}T^{-1} \tag{15}$$

However, T may not be invertible. A common solution if $r > p$ is to use the Moore-Penrose pseudo-inverse as

$$T^\dagger = T^T(TT^T)^{-1} \tag{16}$$

$$u = K^{-1}T^\dagger\tau \tag{17}$$

Where the rotational speed of each propeller is calculated from

$$n_i = sgn(u_i)\sqrt{|u_i|} \tag{18}$$

It should be noted that saturation of the thruster can cause problems. Thus, a method of allocation of thrusters where DOFs can be prioritized is interesting. Management is usually the most important DOF to control. The work on the allocation of thrusters with DOF prioritization is in [2]. A weighting function can be used in the allocation if some thrusters must be prioritized [1]. The methods of reassigning the thrusters are useful in case of defective thruster.

3. DEFINING FRAMES

Modeling and simulation require the step of defining reference points with respect to which the evolution of the machine will be described. To establish the equations describing the motion of an underwater robot in three-dimensional Euclidean space, two markers are used. The first is the global inertial reference frame R0 = (O, X0, Y0, Z0). This global coordinate system R0 being linked to the earth, will be considered as Galilean and it is oriented as follows (see **Fig -3**): X0: directed towards the north, Y0: directed towards the East, Z0: directed towards the bottom. Its origin O will be chosen arbitrarily and may be for example the initial position of the ROV. Then a local landmark, having as origin the center of buoyancy of the ROV to know

- The frame linked to the ROV, $R_v = (C, X_v, Y_v, Z_v)$ also called moving frame (See **Fig. 3**), whose axes are chosen as follows: X_v the longitudinal axis, Y_v the transverse axis, Z_v the normal axis to the plane (X_v, Y_v).

The configuration of the machine is described by means of three elementary rotations defined by three angles of orientation namely the yaw ψ, the pitch θ and the roll φ:

$$B(X_0, Y_0, Z_0) \rightarrow H_\psi B(X_1, Y_1, Z_0) \rightarrow H_\theta B(X_v, Y_1, Z_1) \rightarrow H_\varphi B(X_v, Y_v, Z_v)$$

Where $B(X_0, Y_0, Z_0)$ is the basis of the global frame R_0, $B(X_v, Y_v, Z_v)$ is the base of the local frame R_v, $B(X_1, Y_1, Z_0)$ and $B(X_v, Y_1, Z_1)$ are the intermediate bases and H_ψ, H_θ and H_φ the orthogonal rotation matrices. The first yaw angle rotation ψ is counted positively in the forward direction with respect to Z_0 (See **Fig - 4**).
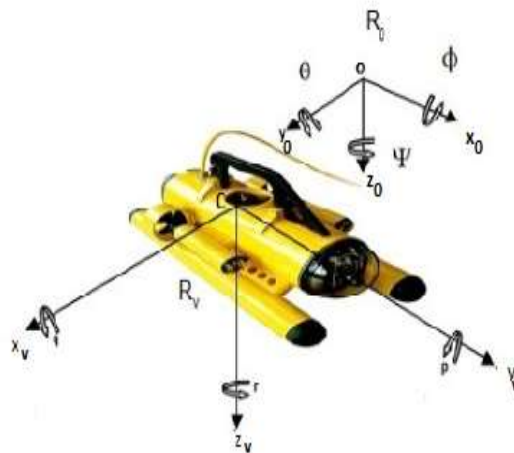

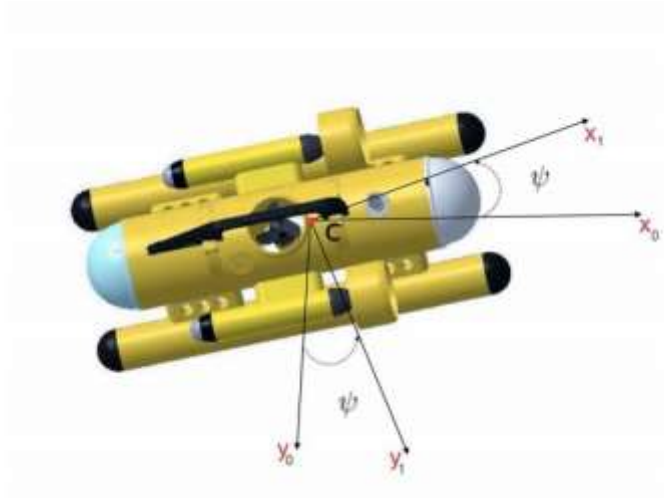**Fig -3**: Definition of frames used for modeling and simulation

Fig -4: Yaw motion

The second angle rotation θ describes the pitch around the Y1 axis (see **Fig -5**) and gives the transition matrix H_θ between the given bases $B(X_1, Z_1, Z_0)$ and $B(X_v, Y_1, Z_1)$ by:
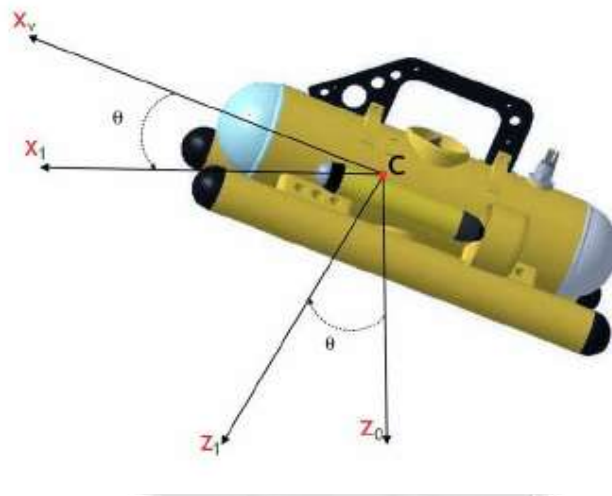

Fig -5: Pitching motion

The third roll angle rotation φ is made around the axis X_v of the new base (see Fig -6)

Fig -6: Roll motio*n*

4. PRESENTATION OF THE BLOCKS USED IN THE SIMULATION

The first simulation is that of an ROV, having a simple model presented in **Fig -7**. The model is composed of the following elements:

- A "uuv_dynamics" block describing the motion in six degrees of freedom (DOF), designed with a system function (S-function, including the added mass matrix, the restoring force, the Coriolis matrix).
- A "current velocity" block with the external current force
- A "thrust vector" or thruster block, which presents the propulsion force of the ROV
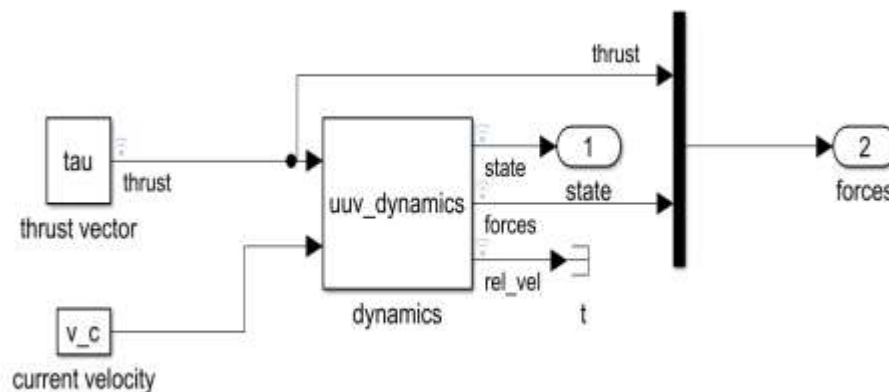

Fig -7: Simple ROV model

4.1 Uuv_dynamic block

The dynamic model of the ROV is shown in **Fig -8**, having as inputs the thrust vector and the current velocity vector, and as outputs the state, the forces and the relative velocity

The model inputs for the ROV are:

- The vector force thrust, it is a vector which corresponds to the six DOFs, presented by tau = $[\tau_x; \tau_y; \tau_z; \tau_\phi; \tau_\theta; \tau_\psi]$ in the simulation.

- The current velocity vector: vc is the velocity corresponding to the six DOFs

On the other hand, the outputs of the model are

- The state, having a dimension 12, corresponding to the indices $x, y, z, \varphi, \theta, \psi$ and u, v, w, p, q, r (units: m and m/s)
- Forces: Restoration, damping and Coriolis forces
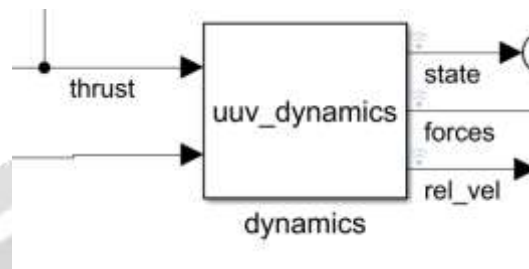- The relative velocity (unit m/s).

Fig -8: Model representing the dynamics of the ROV

The parameters used by the ROV for the simulation are given in the following table:

Table -1: ROV's Parameters

Parameter's name	Description
P_W	Weight (N)
P_B	Buoyancy
P_CG	Center of gravity
P_CB	Buoyancy Center
P_IC	Initial conditions
P_M	Inverse of the mass matrix
P_MA	Matrix added mass

In order to calculate the values of the output states, let us remember that the dynamics of a UUV can be expressed by the following system of ordinary differential equations:

$$\dot{\eta}\dot{v} = J(\eta)v_r(MRB + MA)^{-1}(-f_h - f_d - f_c + f_e + \tau) \tag{5.76}$$

Where

$$J$$

is the transformation matrix for the generalized coordinates,

$$MRB$$

the inertia matrix of the rigid body,

$$MA$$

the added mass inertia matrix,

$$f_h$$

the force vector of restoration,

$$f_d$$

the damping force vector,

$$f_c$$

the Coriolis force vector,

$$f_e$$

the environmental force vector (which includes the attachment effects, if any, for example on an ROV) and τ the thrust force vector.

4. DEFINITION OF THE PARAMETERS USED FOR THE SIMULATION
The simulation first uses default settings set to 0 (**Tableau 5.02 et Tableau 5.03**)

Table -2: First vector values of thruster

τ_x	0
τ_y	0
τ_z	0
τ_ϕ	0
τ_θ	0
τ_ψ	0

Table -3: First values of current velocity vector

vc_x	0
vc_y	0
vc_z	0
vc_ϕ	0
vc_θ	0
vc_ψ	0

Taking the $\tau_x = \tau_y = \tau_z = \tau_\phi = \tau_\theta = \tau_\psi = 0$, we see that the ROV undergoes no movement on the horizontal plane but only along the vertical axis. (**Fig -9**). Likewise, for the rotational movement, the ROV does not undergo any rotation.

The vertical movement is the result of the weight applied to the ROV.

From this result we deduce that the velocity along the horizontal translation is also zero, but only along the vertical axis we observe a variation. The rotational speed also remains zero (**Fig -10**).
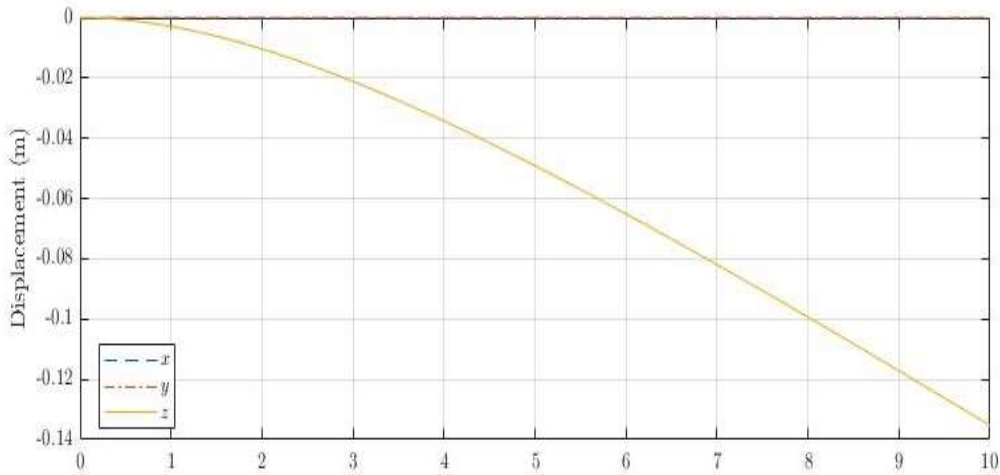

Fig -9: Presentation of the translation movement of the ROV if tau and vc are zero
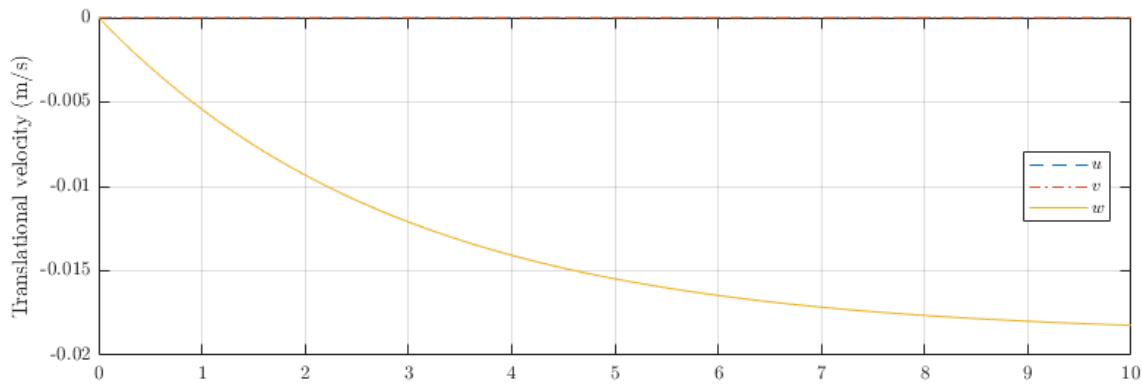
Fig -10: Presentation of the velocity of the ROV if tau and vc are zero

Now, if we vary tau along the x-axis (See **Table -4**), we obtain a translational movement of the ROV along the x-axis and the z-axis (keeping the speed of the current at zero). (**Fig -11**)

Table -4: Positive value along the x-axis on the thrust vector

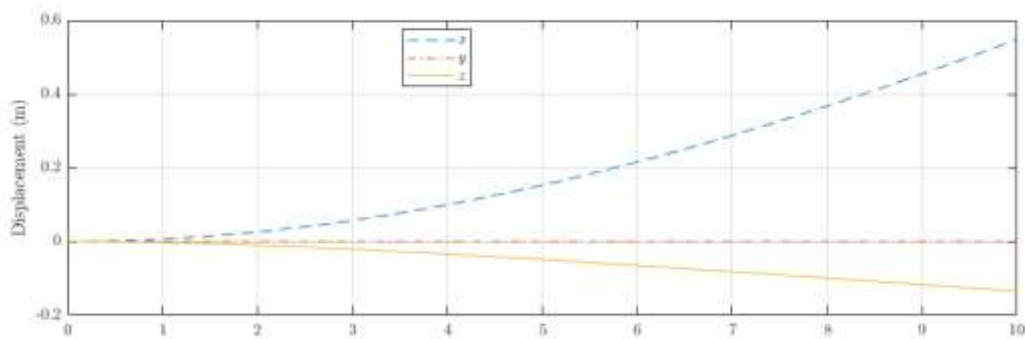|	
τ_x	10
τ_y	0
τ_z	0
τ_ϕ	0
τ_θ	0
τ_ψ	0

Fig -11: Presentation of the translational motion of the ROV if tau = [10,0,0,0,0,0]

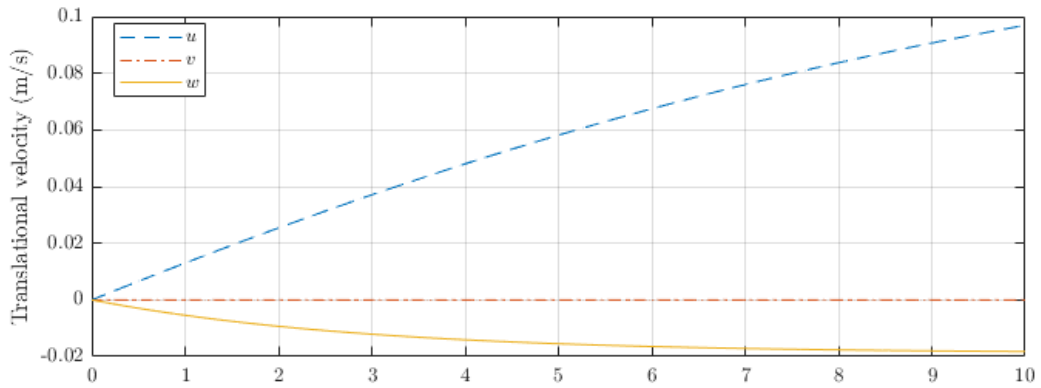We also obtain a variation of velocity according to **fig -12**

Fig -12: ROV translation velocity if tau = [10,0,0,0,0,0]

Increasing the value to 100 and then to 1000 (**Table -5**) results in a translational movement variation as well as a variation in the translational speed.

Table -5: Values of τ_x equal to 100, then to 1000, keeping the other values at 0

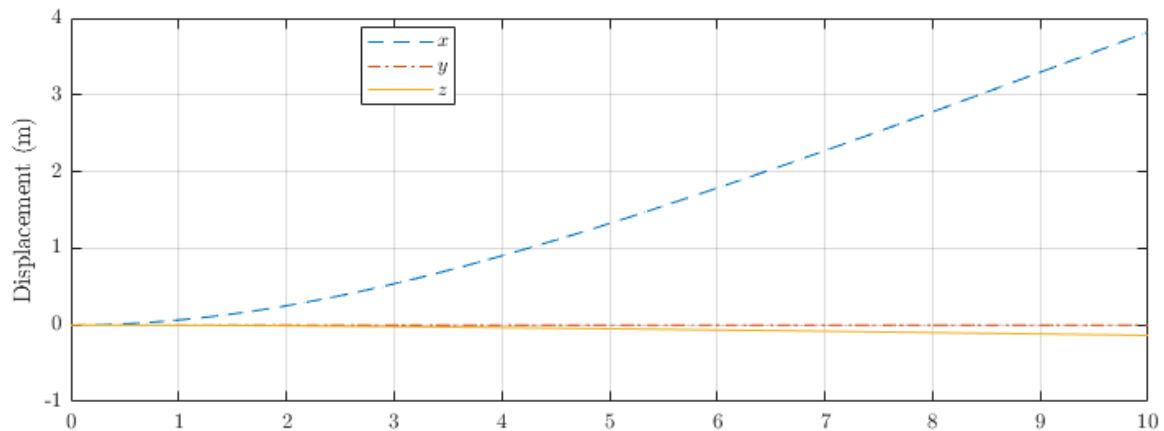|	100	1000
τ_x		
τ_y	0	0
τ_z	0	0
τ_ϕ	0	0
τ_θ	0	0
τ_ψ	0	0

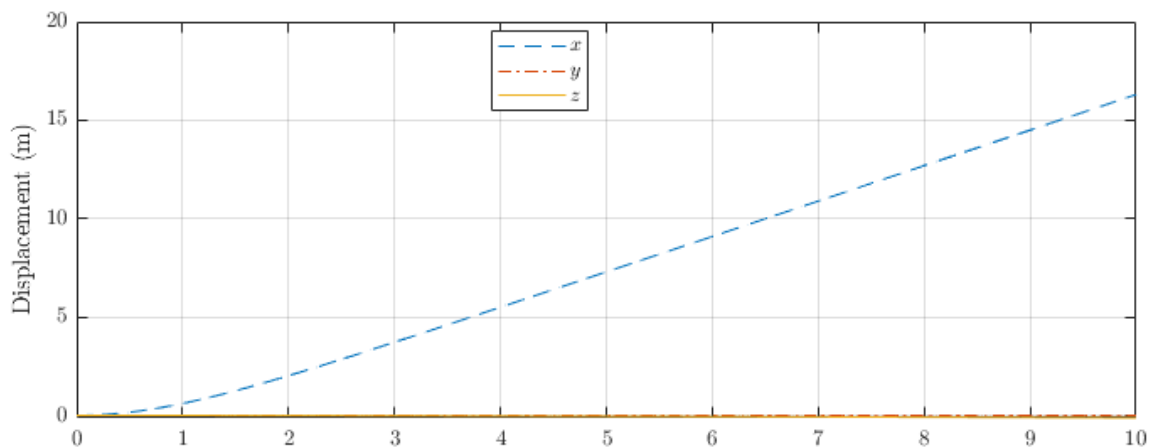**Fig -13**: ROV translational motion if tau = [100,0,0,0,0,0]

Fig -14: ROV translational motion if tau = [1000,0,0,0,0,0]

We note that, the more we increase the value of τ_x, the more the motion of the ROV along the x-axis becomes more stable (the vertical motion decreases less and less).

5. CONCLUSIONS

By implementing each subsystem of the UUV developed in MATLAB-SIMULINK, notably using system functions, and applying various mathematical models and algorithms, simulation of the results of each subsystem can be produced. The behavior of the vehicle changes well according to the values given to the parameters used in the mathematical equations that govern the ROV. The simulation was based on algorithms used in order to have a good implementation of the model in SIMULINK and it shows above all the behavior according to the displacements and the speed of the ROV, as well as the forces applied to the ROV.

6. REFERENCES

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