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Modeling the Auv Autonomous Underground Vehicles by Lacking of Actuators Method

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ABSTRACT: The Nonlinear Controller has to use much effort in modeling objects, underground vehicles in particular and ships in general, which Fossen estimates in most of the work. Therefore, Fossen encourages readers to continue to study many advanced control models and how to make the most effective and straightforward control model. This paper presents a mathematical model of Autonomous Diving Equipment (AUV) with 4 Degrees Of Freedom (DOF) lacking an actuator. Therefore, the authors have used Matlab software to declare the parameters of the object model to simulate the motion in a circular orbit to verify the stability, which is the premise for the study of controllers later.

KEYWORDS:AUV; Controller of Autonomous Diving Equipment; 4 DOF; Lack a UMS Actuator.

I. INTRODUCTION

An underactuated mechanical system is a control system with fewer actuators than the number of degrees of freedom or model variables, which means several output variables of the system are jointly dependent on the same input variable [1]. In recent years, the underactuated mechanical system have been studied more and more. Systems such as ships, submarines, aircraft, spacecraft, and robots are designed to lack actuator mechanics to reduce cost or weight and reduce energy consumption [2] and [3]. In some cases, the system becomes a system lacking an actuator mechanic because the system has a faulty actuator. When the number of actuator mechanic is reduced, developing control techniques is more necessary and complex than for systems with whole actuator mechanic. The studies in recent decades on underactuated mechanical systems (UMS) have focused a lot on designing control algorithms for nonlinear UMS systems, especially when they have considered the uncertain factors, inaccurate models, and noise affecting the system [4]. The objects that lacked actuator mechanics are diverse with different dynamic systems, so the controlling method is also very diverse. Therefore, it is necessary to have in-depth studies for each specific object to give an appropriate control solution [5].

Autonomous underwater vehicles are modeled mainly by the 6 DOF equation of motion [6] and [7]; the 4 DOF equation of motion applied to small AUVs is being studied. For each controlling method, we will need a different understanding of the controller object [8]. However, the more fully the object is described, the better the control quality [9]. In this article, the authors focus on modeling a 4 DOF AUV with an underactuated mechanical system to be a premise for controller design studies in the future, in which the obtained results will prove the practicality and stability of the algorithm model. With such content, the rest of the article is drafted as follows. The model of a 6 DOF AUV is introduced in Section 2. Section 3 presents a 3D model of 4 DOF AUV, where the underactuated mechanical system AUV is discussed. Transforming the model presented in Section 4 and Section 5 presents the object model simulation on Matblap Simulink before the conclusions are drawn in Section 6.

II. EQUATION OF MOTION OF THE 6 DOF AUTONOMOUS UNDERWATER VEHICLE (AUV)

The kinematic model of the AUV is made based on mechanical theory, the principles of kinematics, and statics. Dynamic modeling of the

AUV is used to design control systems for this vehicle to meet specific goals. In general, the motion of the AUV can be represented by the equation of motion with six degrees of freedom (6 DOF) [1]. The components, such as direction of motion, impact force and torque, speed, and position of the AUV, are shown in Table 1.

Table 1: Parameters in the 6 DOF underground moving vehicle model

DOF	PARAMETERS	FORCE AND MOMENTS	VELOCITIES	POSITIONS AND ANGLES
1	Motion in x direction (surge)	X	u	x
2	Motion in y direction (sway)	Y	v	y
3	Motion in z direction (heave)	Z	w	z
4	Rotation about x axis (roll)	K	p	ϕ
5	Rotation about y axis (pitch)	M	q	θ
6	Rotation about z axis (yaw)	N	r	ψ

AUV is considered as a solid body, so a set of vectors represents the equation of motion of AUV (Eq.1):

$$M_{RB}\dot{v} + C_{RB}(v)v = \tau_{RB}$$

In which:
$v = [u,v,w,p,q,r]^T$ are the linear and angular velocity vectors in the Oxyzcoordinate system
$\tau_{RB} = [X,Y,Z,K,M,N]^T$is the control force and torque vector in the Oxyz dynamic coordinate system
M_{RB} is the systematic inertia matrix of AUV
$C_{RB}(v)$is the Coriolis matrix and the centripetal force of AUV
The equation of motion of the 6 DOF AUV is represented through the force and torque quantities as the following (Eq.2):

$$m\left[\dot{u} - vr + wq - x_g(q^2 + r^2) + y_g(pq - \dot{r}) + z_g(pr + \dot{q})\right] = X$$
$$m\left[\dot{v} - wp + \mathrm{ur} - y_g(r^2 + p^2) + z_g(pr - \dot{p}) + x_g(qp + \dot{r})\right] = Y$$
$$m\left[\dot{w} - uq + vp - z_g(q^2 + p^2) + x_g(rp - q) + y_g(rq + \dot{p})\right] = Z$$
$$I_{xx}\dot{p} + (I_{zz} - I_{yy})qr + m\left[y_g(\dot{w} - uq + vp) - z_g(\dot{v} - wp + \mathrm{ur})\right] = K$$
$$I_{yy}\dot{q} + (I_{xx} - I_{zz})rp + m\left[z_g(\dot{u} - vr + wq) - x_g(\dot{w} - uq + vp)\right] = M$$
$$I_{zz}\dot{r} + (I_{yy} - I_{xx})qp + m\left[x_g(\dot{v} - wq + \mathrm{ur}) - y_g(\dot{u} - vr + wq)\right] = N$$

III. DYNAMIC MODEL OF A 4 DOF AUV ON 3D SPACE COORDINATES

Depending on the specific application that we choose the appropriate number of degrees of freedom, the smaller the number of degrees of freedom, the less complicated the control will be. For a device operating in the water environment, precise control of the positions and coordinates of all six steps is highly complicated. Small and diamond-shaped autonomous underwater vehicles it is to simplify and less affected by longitudinal waves.

AUV can remove two parts of force and moment acting on Θ angle (rotation motion) and Ø angle (swinging motion) of K, M. The purpose is to simplify the control process while still ensuring the required task requirements. Coordinate position (x, y), the direction of AUV motion (ψ), and z-axis position (dive depth). Now, p=const and q=const, so the derivative is$\dot{p} = 0; \dot{q} = 0$; Solve the system of equations to find p, q are the values to replace the remaining four force and torque equations of X, Y, Z, and N.
The system of equations in terms of K, and M is rewritten as follows (Eq.3):

$$I_{xx}\dot{p} + (I_{zz} - I_{yy})qr + m\left[y_g(\dot{w} - uq + vp) - z_g(\dot{v} - wp + \mathrm{ur})\right] = 0$$

$$I_{yy}\dot{q} + (I_{xx} - I_{zz})rp + m\left[z_g(\dot{u} - vr + wq) - x_g(\dot{w} - uq + vp)\right] = 0$$

Since, p=const and q=const, so $\dot{p} = 0; \dot{q} = 0$; (Eq.4)

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$$\begin{cases}(I_{zz}-I_{yy})qr+my_g(\dot{w}-uq+\mathrm{vp}) \\ \quad -mz_g(\dot{v}-wp+\mathrm{ur})=0 \\ (I_{xx}-I_{zz})rp+mz_g(\dot{u}-vr+wq) \\ \quad -mx_g(\dot{w}-uq+vp)=0\end{cases}$$

Derived the following system of equations (Eq.5):

$$\begin{cases}[(I_{zz}-I_{yy})r-my_gu]q+m(y_gv+z_gw)p \\ \quad =m[z_g(\mathrm{ur}+\dot{v})-y_g\dot{w}] \\ m(z_gw+x_gu)q+[(I_{xx}-I_{zz})r-mx_gv]p \\ \quad =m[x_g\dot{w}+z_g(vr-\dot{u})]\end{cases}$$

Set the values of the variables as follows (Eq.6):

$$\Rightarrow\begin{cases}t_1=(I_{zz}-I_{yy})r-my_gu;,h_1=m(y_gv+z_g\mathrm{w});,\mathrm{i}_1=m[z_g(\mathrm{ur}+\dot{v})\text{-}y_g\dot{\mathrm{w}}] \\ t_2=m(z_g\mathrm{w}+x_gu);,h_2=[(I_{xx}-I_{zz})r-mx_gv];,\mathrm{i}_2=m[x_g\dot{\mathrm{w}}+z_g(vr-\dot{u})]\end{cases}$$

Solved a system of equations using the determinant method (Eq.7):

$$\begin{cases}t_1q+h_1p=i_1 \\ t_2q+h_2p=i_2\end{cases}$$

$$\Rightarrow \Delta=\begin{vmatrix}t_1 & h_1 \\ t_2 & h_2\end{vmatrix};\Delta_q=\begin{vmatrix}i_1 & h_1 \\ i_2 & h_2\end{vmatrix};\Delta_p=\begin{vmatrix}t_1 & i_1 \\ t_2 & i_2\end{vmatrix}$$

It is derived (Eq.8):

$$\begin{cases}q=\dfrac{\Delta_q}{\Delta}=\dfrac{\begin{vmatrix}i_1 & h_1 \\ t_2 & h_2\end{vmatrix}}{\begin{vmatrix}t_1 & h_1 \\ t_2 & h_2\end{vmatrix}}=\dfrac{i_1h_2-h_1i_2}{t_1h_2-h_1t_2}=\mathrm{k}_1\end{cases}$$

$$\begin{cases}p=\dfrac{\Delta_p}{\Delta}=\dfrac{\begin{vmatrix}t_1 & i_1 \\ t_2 & i_2\end{vmatrix}}{\begin{vmatrix}i_1 & h_1 \\ t_2 & h_2\end{vmatrix}}=\dfrac{t_1i_2-i_1t_2}{t_1h_2-h_1t_2}=k_2\end{cases}$$

It is assumed that the origin attached to the AUV coincides with the center of gravity of the AUV. Equation (2) after removing 2 DOF is written as (Eq.9):

$$m[\dot{u}-vr+\mathrm{wk}_1-x_g({k_1}^2+r^2)+y_g(k_1k_2-\dot{r})+z_gk_2r]=X$$
$$m[\dot{v}-\mathrm{wk}_2+\mathrm{ur}-y_g(r^2+{k_2}^2)+z_gk_2r+x_g(k_1k_2+\dot{r})]=\mathrm{Y}$$
$$m[\dot{w}-uk_1+vk_2-z_g({k_1}^2+{k_2}^2)+x_g(rk_2-k_1)+y_grk_1]=Z$$
$$I_{zz}\dot{r}+(I_{yy}-I_{xx})k_1k_2+m[x_g(\dot{v}-\mathrm{wk}_1+\mathrm{ur})-y_g(\dot{u}-vr+\mathrm{wk}_1)]=N$$

The AUV 4 DOF motion model includes: $\eta=[x,y,z,\psi]^T$ is the position vector of the ship along the axes of Ox,Oy,Oz and the ship's navigation angle around the axis of Oz; $v=[u,v,w,r]^T$ is the long velocity vector in the directions of Ox,Oy,Oz and the rotational speed around the Oz axis.

According to Equation (1), we rewrite the kinematic equation of AUV as follows (Eq.10):

$$\begin{cases}\dot{\eta}=J(\eta)v \\ M\dot{v}+C(v)v+D(v)v=\tau\end{cases}$$

The rotation matrix on the Oz axis is shown as follows (Eq.11):

$$J(\eta)=\begin{bmatrix}cos(\psi) & -sin(\psi) & 0 & 0 \\ sin(\psi) & cos(\psi) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1\end{bmatrix}=\begin{bmatrix}J_{11}J_{12} \\ J_{21}J_{22}\end{bmatrix}$$

Systemic inertia matrix is shown as follows (Eq.12):

$$M=\begin{bmatrix}m+X_{\dot{u}} & 0 & X_{\dot{w}} & -my_g \\ 0 & m+Y_{\dot{v}} & 0 & Y_{\dot{r}}+mx_g \\ Z_{\dot{u}} & 0 & m+Z_{\dot{w}} & 0 \\ -my_g & mx_g+N_{\dot{v}} & 0 & I_z+N_{\dot{r}}\end{bmatrix}=\begin{bmatrix}M_{11}M_{12} \\ M_{21}M_{22}\end{bmatrix}$$

Coriolis matrix and systemic centripetal force are shown as follows (Eq.13):

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$$C = \begin{bmatrix} 0 & -mr & 0 & -mx_g r - a_2 \\ mr & 0 & 0 & -my_g r + a_1 \\ 0 & 0 & 0 & 0 \\ mx_g r + a_2 & my_g r - a_1 & 0 & 0 \end{bmatrix} = \begin{bmatrix} C_{11} C_{12} \\ C_{21} C_{22} \end{bmatrix}$$

Hydrodynamic attenuation matrix is shown as follows (Eq.14):
With matrices of $M, J(\eta), C(v), D(v)$ to satisfy the following properties:
$M = M^T > 0$; $C(v) = C^T$(v); $D(v) > 0$
$J(\eta)$is the matrix rotating about the axis Ozand is the orthogonal matrix$J^{-1}(\eta) = J^T(\eta)$

$$D(v) = \begin{bmatrix} X_u + X_{u|u|}|u| & 0 & 0 & 0 \\ 0 & Y_v + Y_{v|v|}|v| & 0 & 0 \\ Z_0|u| & 0 & Z_w + Z_{w|w|}|w| & 0 \\ 0 & 0 & 0 & K_p + K_{p|p|}|p| \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix}$$

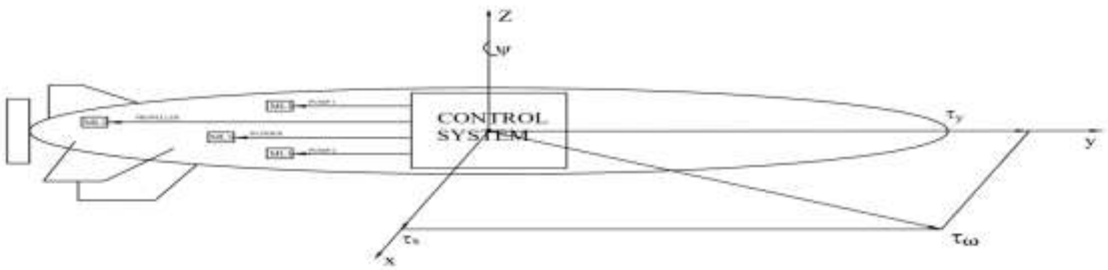
IV. DYNAMIC MODEL OF AUV 4 DOF UNDERACTUATED MECHANICAL SYSTEM

AUV submarine's 4 DOF motion model includes: $\eta = [x, y, z, \psi]^T$is the position vector of the ship along the axes of $Ox, Oy, Oz$and the ship's navigation angle around the axis Oz; $v = [u, v, w, r]^T$ is the long velocity vector in the directions of$Ox, Oy, Oz$and rotational speed around the axis Oz.

The applied force $\tau_1$to AUV can be analyzed into two types: Perpendicular force and parallel force. The analysis of perpendicular and parallel forces helps us better understand how forces act on an object and how they affect factors such as thrust, lift, reflection, friction, and AUV's motion performance.

The perpendicular force (also known as the reflection force or support force) is the component of the force acting perpendicularly to the AUV. It controls the AUV in the Z direction so that underground vehicles can dive deep.

Parallel force (also known as shear force) is the component of the force acting parallel to the AUV's surface. When projected onto the horizontal plane, this force is decomposed into two components as $\tau_x$controlling the AUV in the X-direction and $\tau_y$controlling the AUV in the Y-direction.



AUV FORCE ANALYSIS 4 DOF

$\tau_x$and$\tau_y$is the force component in the x direction and in the y direction that will form a combined force that creates a torque with angle ψ , whose value is in the range (-90^{0}to 90^0). Thus, with 3 force components such asτ_x,$\tau_y$and $\tau_z$can control 4 DOF of the AUVunderground moving vehicle with$v = [u, v, w, r]^T$ is the long velocity vector in the directions of$Ox, Oy, Oz$and the rotational speed around the Oz axis. The AUV underground vehicle model has 3 input signals and 4 output signals, so it is an underactuated mechanical system.

The kinematic equation of AUV is rewritten as (Eq.15):

$$\begin{cases} \dot{\eta}_1 = J_{11}v_1 + J_{12}v_2 \\ \dot{\eta}_2 = J_{21}v_1 + J_{22}v_2 \\ M_{11}\dot{v}_1 + (C_{11} + D_{11})v_1 + M_{12}\dot{v}_2 + (C_{12} + D_{12})v_2 = \tau \\ M_{21}\dot{v}_1 + (C_{21} + D_{21})v_1 + M_{22}\dot{v}_2 + (C_{22} + D_{22})v_2 = 0 \end{cases}$$

Since M_{22} is a positive definite matrix, so from the fourth equation in (15), we get (Eq.16):

$$\dot{v}_2 = -M^{-1}{}_{22}[M_{21}\dot{v}_1 + (C_{21} + D_{21})v_1 + (C_{22} + D_{22})v_2]$$

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Substituting (Eq.16) into the third equation in (Eq.15), we get (Eq.17):

$$M_{11}\dot{v}_1 + (C_{11} + D_{11})v_1 + (C_{12} + D_{12})v_2 - M_{12}M^{-1}{}_{22}[M_{21}\dot{v}_1 + (C_{21} + D_{21})v_1 + (C_{22} + D_{22})v_2] = \tau$$

Simplifying the equation (Eq.17) , we get (Eq.18):

$$\bar{M}\dot{v}_1 + \bar{C}_1 v_1 + \bar{C}_2 v_2 = \tau$$

With: $\bar{M} = M_{11} - M_{12}M^{-1}{}_{22}M_{21}$

$$\bar{C}_1 = (C_{11} + D_{11}) - M_{12}M^{-1}{}_{22}(C_{21} + D_{21})$$
$$\bar{C}_2 = (C_{12} + D_{12}) - M_{12}M^{-1}{}_{22}(C_{22} + D_{22})$$

Since the $\bar{M}$matrix is a positive definite matrix, so from equation (18), we get (Eq.19):

$$\dot{v}_1 = \bar{M}^{-1}(-\bar{C}_1 v_1 - \bar{C}_2 v_2) + \bar{M}^{-1}\tau \qquad \to (19)$$

Substituting equation (19) into equation (18):

$$\dot{v}_2 = -M^{-1}{}_{22}[M_{21}\bar{M}^{-1}(\tau - \bar{C}_1 v_1 - \bar{C}_2 v_2) + (C_{21} + D_{21})v_1 + (C_{22} + D_{22})v_2]$$
$$\Leftrightarrow \dot{v}_2 = -M^{-1}{}_{22}[M_{21}\bar{M}^{-1}(-\bar{C}_1 v_1 - \bar{C}_2 v_2) + (C_{21} + D_{21})v_1 + (C_{22} + D_{22})v_2] - M^{-1}{}_{22}M_{21}\bar{M}^{-1}\tau$$

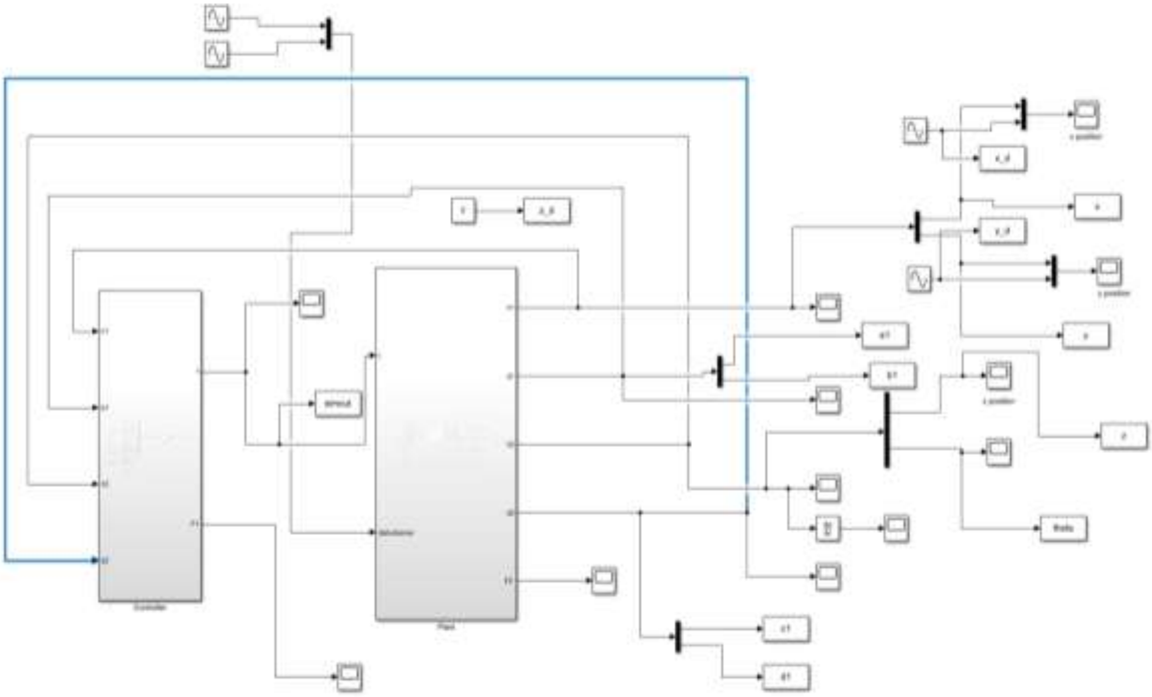
Substituting equation (19) and equation (20) into the system of equations (15), the system of dynamic equations of AUV is calculated as follows (Eq.21):

$$\begin{cases} \dot{\eta}_1 = J_{11}v_1 \\ \dot{v}_1 = \bar{M}^{-1}(-\bar{C}_1 v_1 - \bar{C}_2 v_2) + \bar{M}^{-1}\tau \\ \dot{\eta}_2 = J_{22}v_2 \\ \dot{v}_2 = -M^{-1}{}_{22}[M_{21}\bar{M}^{-1}(-\bar{C}_1 v_1 - \bar{C}_2 v_2) + (C_{21} + D_{21})v_1 + (C_{22} + D_{22})v_2] - M^{-1}{}_{22}M_{21}\bar{M}^{-1}\tau \end{cases}$$

With: $J_{12}(v) = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$and $J_{21}(v) = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$

This is the system of kinematic equations after being transformed by the method of actuator mechanical lacking, the system of equations is important for control algorithms that can be applied later. It is able to apply in the simulation, we must build a model of the objectfirst.

V. BUILDING THE OBJECT MODEL



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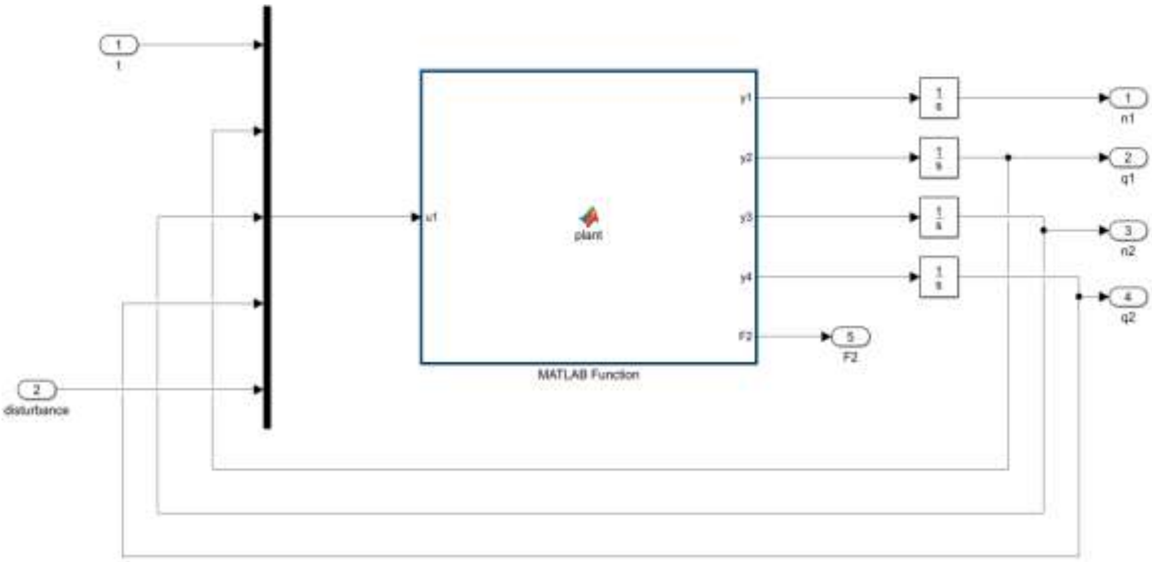
FUNCTION BLOCK IN MATLAB SIMULINK



OBJECT MODEL BLOCK IN MATLAB SIMULINK

AUV modeling is performed with the following parameter sets:

Parameters	Values	Parameters	Values	Parameters	Values
m	18.5kg	Y_r	-1.03kg.m/rad/s	N_r	-12.32 kg.m2/rad/s
x_g	0.15 m	$\dot{Y}_v$	-0.85 kg	$\dot{N}_v$	0.32kg.m2/rad
y_g	0.15 m	$\dot{Y}_{v\|v\|}$	-0.62 kg/m	I_z	1.57 kg.m2
z_g	0 m	Z_w	4.57 kg/s	$N_{r\|r\|}$	0.5×10^{-3} kg/m
$\dot{X}_u$	6.83×10^{-6}kg/s	$\dot{Z}_u$	0.32 kg	$N_{r\|r\|}$	0.5×10^{-6}
$X_{u\|u\|}$	-0.58 kg/m	Z_0	0	$Z_{w\|w\|}$	1.15×10^{-6}kg/m
Y_v	0.08 kg/s	$\dot{X}_w$	-1.13×10^{-6} kg		

Declare part of model parameters

```
function [y1,y2,y3,y4,F2] = plant(u1)
t = u1(1:2);
q1 = u1(3:4);
n2 = u1(5:6);
q2 = u1(7:8);
dis = u1(9:10);
u = q1(1);
v = q1(2);
w = q2(1);
r = q2(2);
cosi = n2(2);
 m = 18.5;
xg = 0.15;
yg = 0.15;
lz = 1.57;
Xu = 6.83e-6;
Xu1 = 6.53;
Xuu = -0.58;
Xw = -1.13e-6;
m11 = m + Xu; m12 = 0; m13 = Xw; m16 = -m*yg;
m21 = 0; m22 = m + Yv; m23 = 0; m26 = Yr + m*xg;
m31 = Zu; m32 = 0; m33 = m + Zw; m36 = 0;
m61 = -m*yg; m62 = m*xg + Nv; m63 = 0; m66 = lz + Nr;
M11 = [m11 m12;m21 m22];
M12 = [m13 m16;m23 m26];
M21 = [m31 m32;m61 m62];
M22 = [m33 m36;m63 m66];
a1 = Xu*u + Xw*w;
a2 = Yv*v + Yr*r;
c11 = 0; c12 = -m*r; c13 = 0; c16 = -m*xg*r - a2;
c21 = m*r; c22 = 0; c23 = 0; c26 = -m*yg*r + a1;
c31 = 0; c32 = 0; c33 = 0; c36 = 0;
c61 = m*xg*r + a2; c62 = m*yg*r - a1; c63 = 0; c66 = 0;
d11 = Xu1 + Xuu*abs(u);
d22 = Yv1 + Yvv*abs(v);
d31 = Zou; d33 = Zw1 + Zww*abs(w);
d66 = Nr1 + Nrr*abs(r);
C11 = [(c11+d11) c12;c21 (c22+d22)];
```

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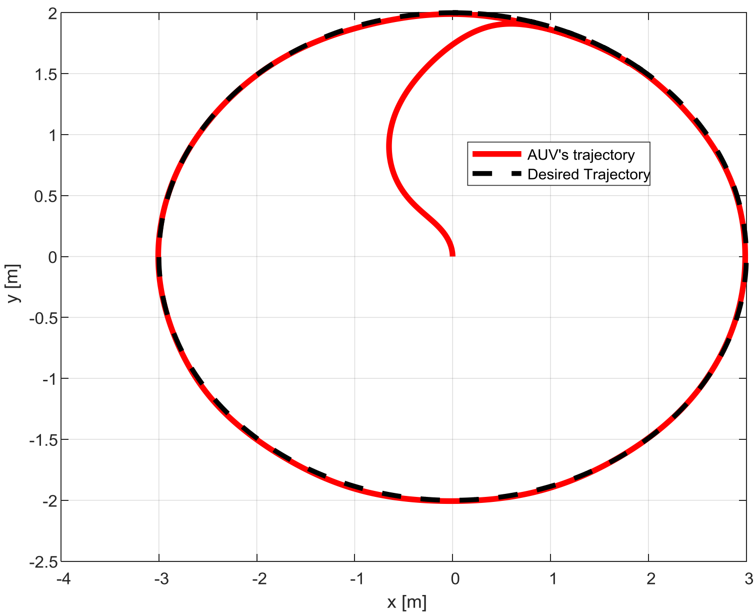
```
Yv1 = 0.08;
Yv = -0.85;
Yr = -1.03;
Yvv = -0.62;
Zw1 = 4.57;
Zu = 0.32;
Zw = -0.32e-6;
Zou = 0;
Zww = 1.15e-6;
Nv = 0.32;
Nr = -2.15;
Nr1 = -12.32;
Nrr = 0.5e-6;
```

```
C12 = [c13 c16;c23 c26];
C21 = [(c31+d31) c32;c61 c62];
C22 = [(c33+d33) c36;c63 (c66+d66)];
j11 = cos(cosi); j12 = -sin(cosi);
j21 = sin(cosi); j22 = cos(cosi);
J11 = [j11 j12;   j21 j22];
J22 = [1 0;0 1];
M = M11 - M12*(M22^(-1))*M21;
C1 = C11 - M12*(M22^(-1))*C21;
C2 = C12 - M12*(M22^(-1))*C22;
```

Declare AUV moving in space with circular orbit in 2D space (x, y)

```
plot3(x.Data,y.Data,'red','linewidth',3.5); hold on; grid on;
plot3(x_d.Data,y_d.Data,'black--','linewidth',3);
xlabel('x [m]'); ylabel('y [m]')');
legend("AUV's trajectory","Desired Trajectory");
```



SIMULATION OF AUV TRAJECTORY IN 2D SPACE (X, Y)

Declare AUV moving in space with circular orbit in 3D space (x, y, z)

```
plot3(x.Data,y.Data,z.Data,'red','linewidth',3.5);
hold on; grid on;
plot3(x_d.Data,y_d.Data,z_d.Data,'black--','linewidth',3);
xlabel('x [m]'); ylabel('y [m]'); zlabel('z [m]');
legend("AUV's trajectory","Desired Trajectory");
```

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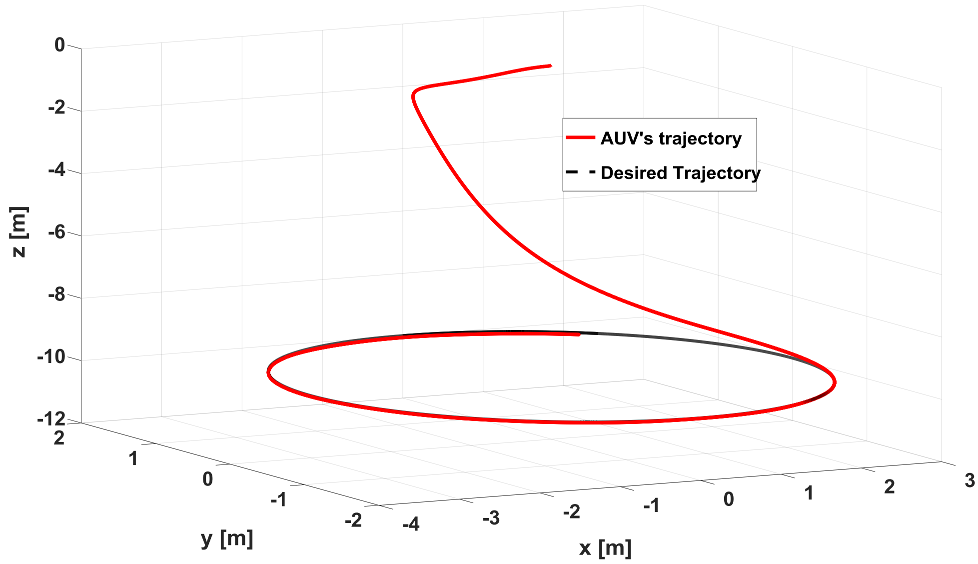

SIMULATION OF THE AUV TRAJECTORY IN 3D

VI. CONCLUSIONS

The article proposed to model the controlling object of the AUV 4DOF underactuated mechanical system and transformed the model according to the typical actuator mechanical, lacking method. Therefore, the authors have used Matlab software to declare the parameters of the object model and simulate the motion in a circular orbit to verify the stability. In the coming time, the authors will also combine intelligent controllers to optimize the control algorithm further to bring high efficiency in controlling the AUV model we have made.

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