Field and Service Robotics Technical Project: Fish – like Underwater Robot

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1. INTRODUCTION

Underwater robots can replace or help humans to complete underwater missions in unknown and complex submerged environments efficiently, which have broad application prospects for scientific exploration, economic operations, and military fields.
Propulsion mode is the key factor to determine the underwater maneuverability, endurance, and concealment of the robot. Rotor and bionic propulsion are two mainstream propulsion modes. Multi-rotor propulsion has the advantages of high maneuverability and stability, which is particularly important for underwater robots to perform submarine salvage, sampling, pipeline maintenance, and other operations. In particular, quadrotor underwater vehicles can achieve flexible and stable motion with fewer thrusters.
In the field of marine search and rescue and marine exploration, the aim is to make marine robots able to move quietly and efficiently like fish and move in all directions like rotor robots to achieve complex tasks and avoid disturbing and damaging the marine ecosystem.
Since we wanted to better understand these technologies, in this technical project we re-implemented the studies based on the paper [1] that presents the development of a robot in which bionic propulsion and rotor propulsion are combined.
To achieve the former goals, the developed robot is based on hybrid propulsion of a quadrotor and a bionic undulating fin.
The robot works in the rotor propulsion mode when it needs to hover, such as when performing underwater pipes maintenance. Then, it will work mainly in the fin propulsion mode to achieve quiet and efficient movements.
In this report it is shown the model of the whole system and the simulations for yaw motion, heave motion and surge motion. Simulations and scripts were made by using MATLAB-Simulink R2023b.

2. STRUCTURE

The design model of the underwater robot is composed of one control cabin, four propellers, one undulating fin, one driving unit, one tilting unit and one sine wave generator. The four propellers are configured as an X-type and installed vertically at the diagonal of the control cabin. The undulating fin is placed under the control cabin linking with the sine wave generator. The whole structure is shown in Figure 1.

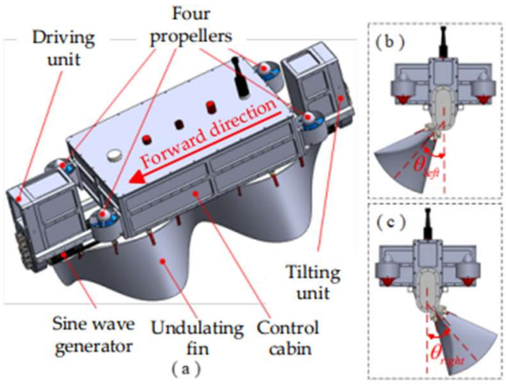

Figure 1. The overall design of the underwater robot.

The undulating fin can tilt left and right around the central axis in order to generate horizontal propulsion and yaw movement. It is composed of a tilting socket, a common shaft, cam mechanisms, fin ray units, and a flexible fin. The fin is clamped on the corresponding cam by 8 fin ray units. The phase interval between each cam is $\pi/2$ and is installed on the common shaft at an equal distance. The fin ray units swing back and forth according to the motion characteristics of the cam and drive the undulating fin to produce sinusoidal motion. The tilting angle of the fin around the central axis can be changed in order to obtain the steering motion.

3. MODELING

3.1 Kinematic model

In Figure 2 it is shown how the *inertial coordinate system E-XYZ* and the *robot coordinate system G-XYZ* are established to describe the motion of the robot. The point G represents the center of mass of the robot. The *NED configuration* has been used.

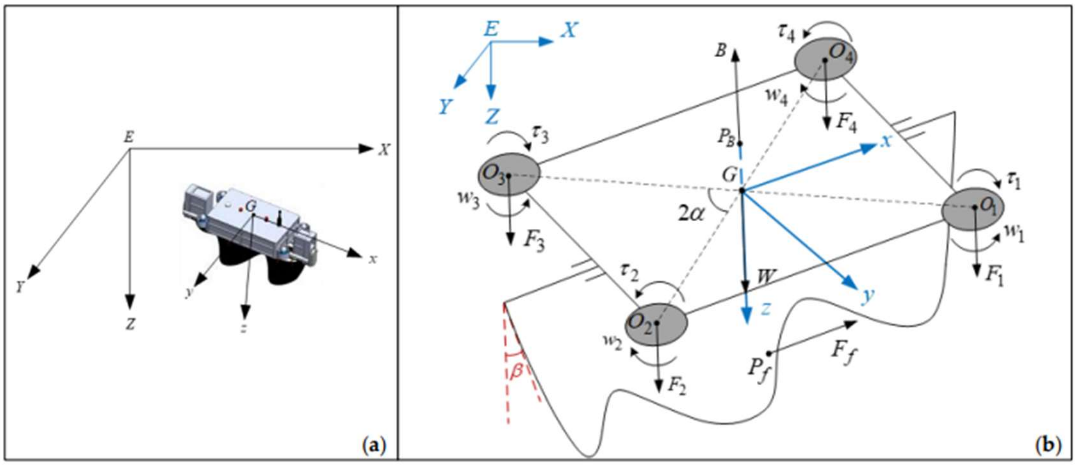

Figure 2. Kinematic and mechanical model of the robot. (a) Inertial coordinate system and robot coordinate system; (b) Dynamic model of the robot.

The pose of the robot, in E-XYZ, is $\eta = (\eta_1^T, \eta_2^T)^T$ where:

- $\eta_1 = (X, Y, Z)^T$ is the position of the robot;
- $\eta_2 = (\varphi, \phi, \psi)^T$ is the attitude angle of the robot;

The velocity of the robot, in G-XYZ, is $v = (v_b, w_b)^T$ where:

- $v_b = (u, v, w)^T$ is the linear velocity;
- $w_b = (p, q, r)^T$ is the angular velocity;

The kinematic model of the robot is given by:

$$\dot{\eta} = J(\eta) \cdot v$$

$J(\eta)$ is the velocity rotation matrix from *G-XYZ* to *E-XYZ* and it is defined as:

$$J(\boldsymbol{\eta}) = \begin{pmatrix} J_1(\boldsymbol{\eta}) & \mathbf{0} \\ \mathbf{0} & J_2(\boldsymbol{\eta}) \end{pmatrix}$$

$$J_1(\boldsymbol{\eta}) = \begin{pmatrix} c_\psi c_\theta & c_\psi s_\theta s_\phi - s_\psi c_\phi & c_\psi s_\theta c_\phi + s_\psi s_\phi \\ s_\psi c_\theta & s_\psi s_\theta s_\phi + c_\psi c_\phi & s_\psi s_\theta c_\phi - c_\psi s_\phi \\ -s_\theta & c_\theta s_\phi & c_\theta c_\phi \end{pmatrix}$$

$$J_2(\boldsymbol{\eta}) = \begin{pmatrix} 1 & s_\phi t_\theta & c_\phi t_\theta \\ 0 & c_\phi & -s_\phi \\ 0 & s_\phi / c_\theta & c_\phi / c_\theta \end{pmatrix}$$

where *c(), s(), t()* stand for *cos(), sin(), tan(),* respectively.

3.2 Dynamic model

The robot is subjected to the combined action of gravity, buoyancy, propulsion of propellers, and undulating fin and resistance. The weight force of the robot is F_W which acts on point G. The buoyancy F_B acts on the center of buoyancy that is P_B. The thrust of propellers and counter torque are F_i, τ_i $(i = 1,2,3,4)$ respectively, and act on O_i $(i = 1,2,3,4)$ which is the centroid of each propeller. The distance between the propellers and the center of the robot is $GO_i = L$ $(i = 1,2,3,4)$ and the angle between the diagonal is 2α. The equivalent force of the undulating fin is F_f and acts on $P_F(0,0,z_F)$.

3.2.1 Dynamic model of the propellers

The thrust and the reverse torque of each propeller can be given by:

$$F_i = sign(w_i) c_T w_i^2$$
$$\tau_i = \lambda_i \cdot sign(w_i) c_M w_i^2$$

- w_i is the rotation speed of the *i-th* propeller;
- c_T, c_M are respectively the thrust coefficient and the reverse torque coefficient;
- λ_i is the directional coefficient and it is determined by the installation direction.

In order to counteract the reverse torque in hover, the rotation directions of adjacent propellers are opposite, so it leads to $\lambda_1 = \lambda_3 = 1$, $\lambda_2 = \lambda_4 = -1$.

3.2.2 Dynamic model of the undulating fin

The undulating fin can generate forward or backward thrust through sinusoidal motion. It is denoted as F_f and it acts on the action point P_f whose position is $(0, -l\, c_\beta, l\, s_\beta)$.

β is the tilting angle of the fin and $GP_f = l$. The thrust of the fin is given by:

$$F_f = sign(w_f)c_f {w_f}^2$$

- w_f is the undulating frequence of the fin;
- c_f is the thrust coefficient of the undulating fin;

3.2.3 Equation of motion control

We define the control force matrix and the 6-DoF control force of the robot as:

$$u = (F_1, F_2, F_3, F_4, F_f)^T$$
$$\tau = (\tau_X \tau_Y \tau_Z \tau_K \tau_M \tau_N)^T$$

$k = {}^{c_M}/_{c_T}$ is the proportional coefficient of propellers thrust and reverse torque.

$$\boldsymbol{\tau} = \begin{pmatrix} \tau_X \\ \tau_Y \\ \tau_Z \\ \tau_K \\ \tau_M \\ \tau_N \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 \\ Ls_\alpha & Ls_\alpha & -Ls_\alpha & -Ls_\alpha & 0 \\ -Lc_\alpha & Lc_\alpha & Lc_\alpha & -Lc_\alpha & lc_\beta \\ k & -k & k & -k & ls_\beta \end{pmatrix} \cdot \begin{pmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_f \end{pmatrix}$$

Under the combined action of robot control force, resistance and resilience, the dynamic mathematical model of the robot is given by:

$$\begin{cases} \boldsymbol{\tau} = \boldsymbol{M}(\boldsymbol{v})\dot{\boldsymbol{v}} + \boldsymbol{C}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{D}(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{g}(\boldsymbol{\eta}) \\ \boldsymbol{\tau} = \boldsymbol{B}\boldsymbol{u} \end{cases}$$

- $M(v)$ is the 6x6 inertia matrix;
- $C(v)$ is the 6x6 centrifugal force and Coriolis force matrix;
- $D(v)$ is the 6x6 resistance matrix;
- $g(\eta)$ is the 6x6 resilience matrix;
- B is the 6x5 control matrix that represents the conversion relationship between the input force and the 6-DoF force of the robot;

Since the robot navigates at low speed, we can make the following assumptions:

- To ignore the additional mass force;
- To assume that Coriolis and centrifugal force have negligible influence on the motion, so $C(v) = 0$;
- The control component of the robot along the Y-axis direction is 0, so the sway motion is ignored.

The motion is decomposed into 6 independent channels, so the 6-DoF motion dynamic equation is:

$$\begin{cases} m\dot{u} = \tau_X - (X_u + X_{u|u|}\left|u\right|)u - (F_w - F_b)s_\theta \\ m\dot{v} = 0 \\ m\dot{w} = \tau_Z - (Z_w + Z_{w|w|}\left|w\right|)w - (F_b - F_w)c_\theta c_\phi \\ J_{xx}\dot{p} = \tau_K - (K_p + K_{p|p|}\left|p\right|)p + z_B F_b c_\theta s_\phi \\ J_{yy}\dot{q} = \tau_M - (M_q + M_{q|q|}\left|q\right|)q + z_B F_b s_\theta \\ J_{zz}\dot{r} = \tau_N - (N_r + N_{r|r|}\left|r\right|)r \end{cases}$$

Through the kinematic matrix conversion, the linear and angular acceleration of the robot in the geographical coordinate system can be given by:

$$\begin{pmatrix} \ddot{X} \\ \ddot{Y} \\ \ddot{Z} \end{pmatrix} = \begin{pmatrix} c_\theta c_\psi & s_\theta c_\psi s_\phi - s_\psi c_\phi & s_\theta c_\psi c_\phi + s_\psi s_\phi \\ c_\theta s_\psi & s_\theta s_\psi s_\phi + c_\psi c_\phi & s_\theta s_\psi c_\phi - c_\psi c_\phi \\ -s_\theta & c_\theta s_\phi & c_\theta c_\phi \end{pmatrix} \cdot \begin{pmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{pmatrix}$$

$$\begin{pmatrix} \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{pmatrix} = \begin{pmatrix} 1 & s_\phi t_\theta & c_\phi t_\theta \\ 0 & c_\phi & -s_\phi \\ 0 & s_\phi / c_\theta & c_\phi / c_\theta \end{pmatrix} \cdot \begin{pmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{pmatrix}$$

4. CONTROL MODEL AND STRATEGY

In order to handle the instability and the oscillations which the robot is prone to, due to the nonlinear and time-varying characteristics of the external water flow, it was proposed a 4-DoF cascade PID controller. The schematic diagram of the system is shown in Figure 3.

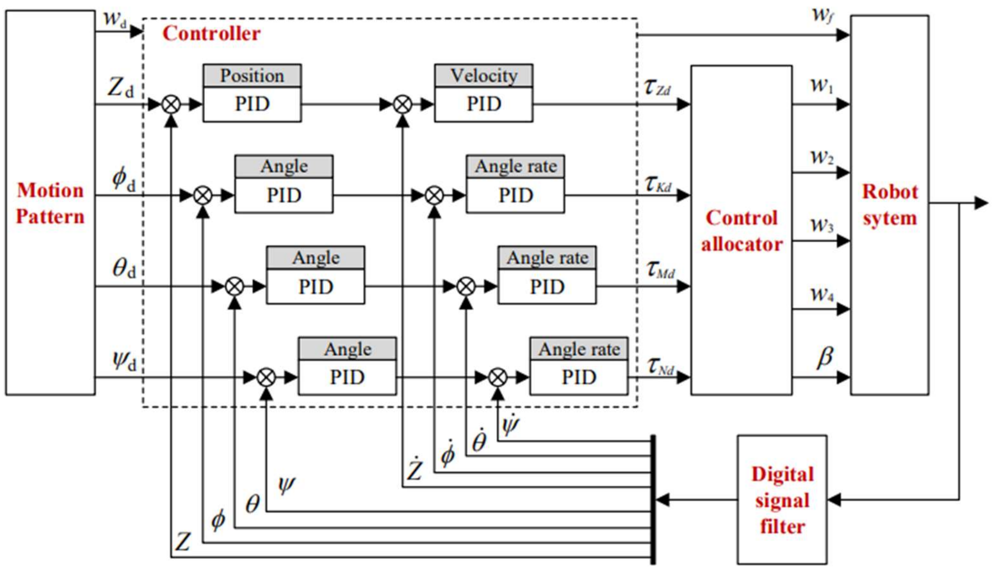

Figure 3. Cascade PID controller of depth and attitude.

It was designed an independent cascade PID closed-loop controller for the three-axis angle and the Z-axis position. It was introduced speed feedback to improve the response speed of the system. The reference input of the control system is $R = (Z_d, \varphi_d, \theta_d, \psi_d, w_d)^T$, whereas $U_d = (\tau_{Zd}, \tau_{Kd}, \tau_{Md}, \tau_{Nd})^T$ is the output. The components of R represent the expected value of depth and triaxial angle and the undulating frequency. The components of U represent the expected vertical force, rolling torque, pitch torque and yaw torque. $U_0 = (w_1, w_2, w_3, w_4, w_f, \beta)^T$ is the control parameters matrix. It is composed of the spinning velocities of the propellers, the undulating frequency and the tilting angle of the fin that are the final parameters directly controlled and the output through the motor.

It was introduced a control allocator in order to convert the expected torques computed by the controller into direct control parameters.

We can compute the propellers speed as:

$$\begin{pmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{pmatrix} = \frac{1}{4}\begin{pmatrix} 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \\ 1 & -1 & 1 & 1 \\ 1 & -1 & -1 & -1 \end{pmatrix} \cdot \begin{pmatrix} \tau_{Zd} \\ \tau_{Kd} \\ \tau_{Md} \\ \tau_{Nd} \end{pmatrix}$$

The undulating fin sub-system is expressed by:

$$\begin{pmatrix} \tau_Z \\ \tau_K \\ \tau_M \\ \tau_N \end{pmatrix} = \begin{pmatrix} 0 & \cos\beta \\ 0 & 0 \\ l\cos\beta & 0 \\ l\sin\beta & 0 \end{pmatrix} \cdot \begin{pmatrix} F_u \\ F_w \end{pmatrix}$$

To get the tilting angle of the fin it was adopted a proportional control distribution strategy:

$$\begin{cases} w_f = w_d \\ \beta = \lambda \tau_{Nd}, \beta \in [-60°, 60°] \end{cases}$$

λ determines the steering speed.

The control scheme that was implemented in Simulink is shown in Figure 4.

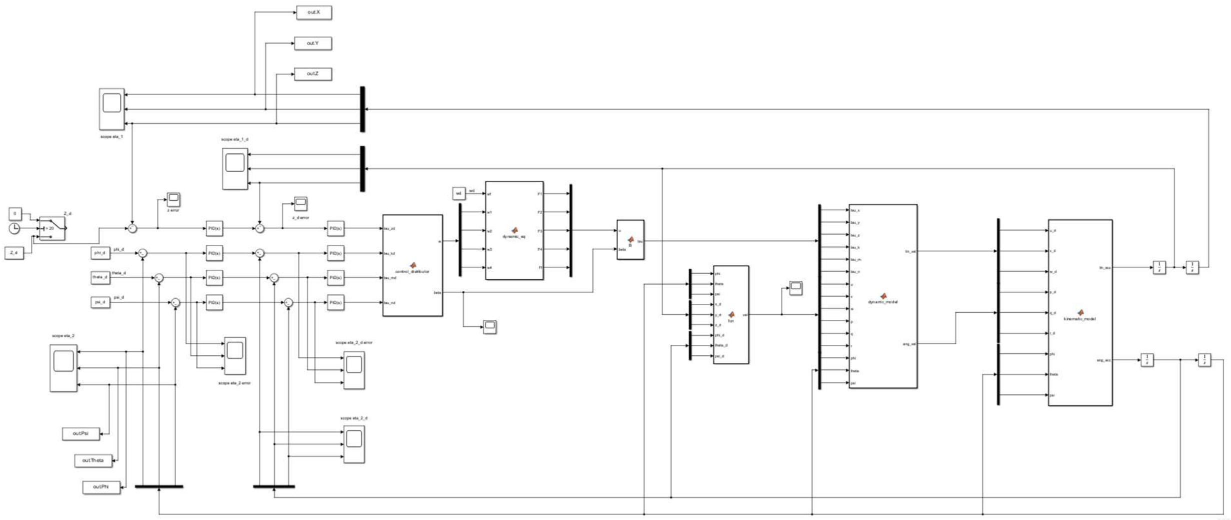

Figure 4. Control scheme in Matlab-Simulink.

It was also used a Matlab script, "fish_bot_init.m", to load the following system parameters in the workspace.

Mass parameter	**Mass** m	15.02 kg
	Y-axis inertia J_{xx}	$0.119\ \mathrm{kg} \cdot \mathrm{m}^2$
	Y-axis inertia J_{yy}	$0.592\ \mathrm{kg} \cdot \mathrm{m}^2$
	Z-axis inertia J_{zz}	$0.563\ \mathrm{kg} \cdot \mathrm{m}^2$
	No-load buoyancy B	160
	Buoyant center z_B	-0.04 m
Propeller parameter	**Distance between the propellers** L	0.281 m
	Angle between the diago-nal α	23.6°
	Maximum rotating speed $w_{\max}$	10,000 rpm
	Thrust coefficient c_T	2.188×10^{-7}
	Reverse torque coefficient c_M	1.944×10^{-9}
Fin parameter	**Fin width** d	0.143 m
	Flexible arc angle α	$\pi/3$
	Arc inner diameter R	0.8 m
	Wave length λ	0.419 m
	undulating amplitude λ	0.06 m
	Fin coefficient c_f	6.276×10^{-4}
	Fin center z_F	0.16 m
	Maximum undulating fre-quency $f_{\max}$	6 Hz

Tab 1. System parameters

5. SIMULATION

The objective of the simulations is to study the performances of the robot in three different cases of motion:

- Yaw motion, around the Z-axis;
- Heave motion, along the Z-axis;
- Surge motion, along the Z-axis and the X-axis;

The robot is meant to be submerged into a water tank for the experiments.

5.1 Yaw Motion

In this simulation we want to check if the robot is able to lead its orientation around the Z-axis to the desired one. The initial state is set to $s = (0,0,0,0,0)^T$ and the reference input is $R = (0,0,0,{}^{\pi}/_{2},0)^T$.
During this motion the undulating fin is not used, and the robot only uses the four propellers to adjust the yaw angle.
The results are shown in Figures 5-6-7.

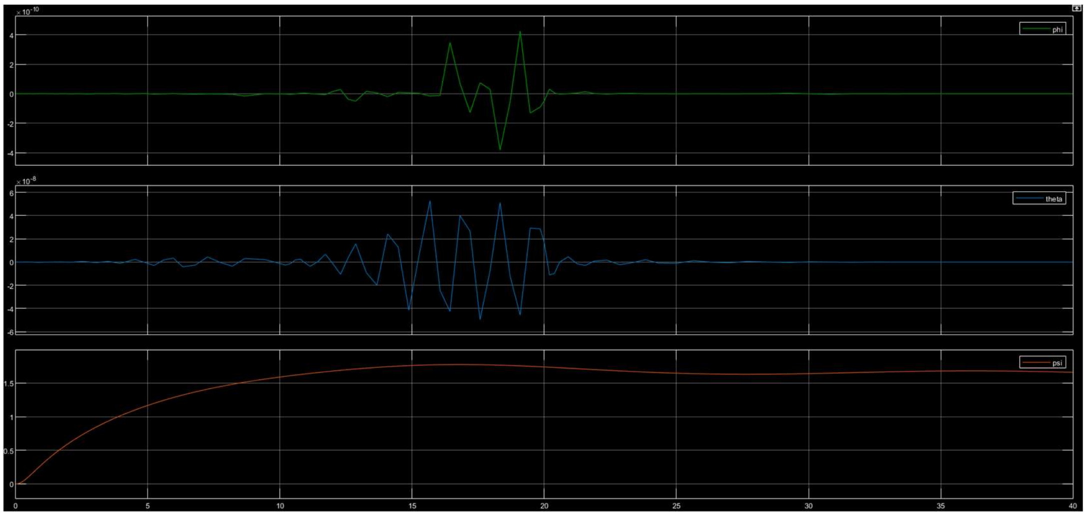

Figure 5. Simulation result of yaw motion attitude angles.

As we can see the yaw angle has a transient and sets to the desired value of $\frac{\pi}{2}$ in 25 seconds with a negligible error, which is less than $\pm 2°$. The roll and pitch angle suffer of very little oscillations in the order of 10^{-8} around the stable value of 0, that coincide with the settling time to the desired value of the yaw angle. These may be traceable to hydrodinamic effects.

The robot achieves the desired value of yaw angle with a maximum spinning velocity of *0.37 rad/s.*

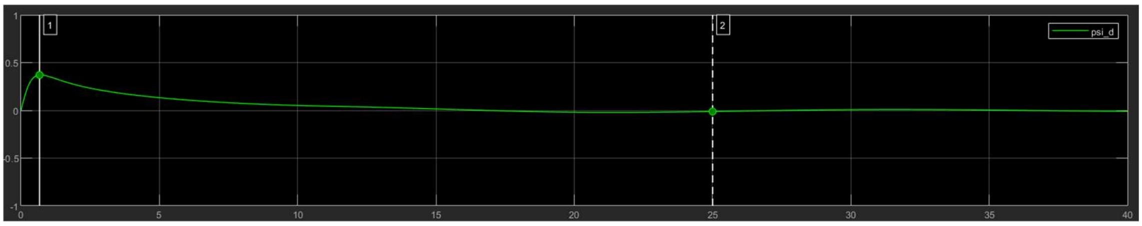

Figure 6. Simulation result of the yaw velocity.

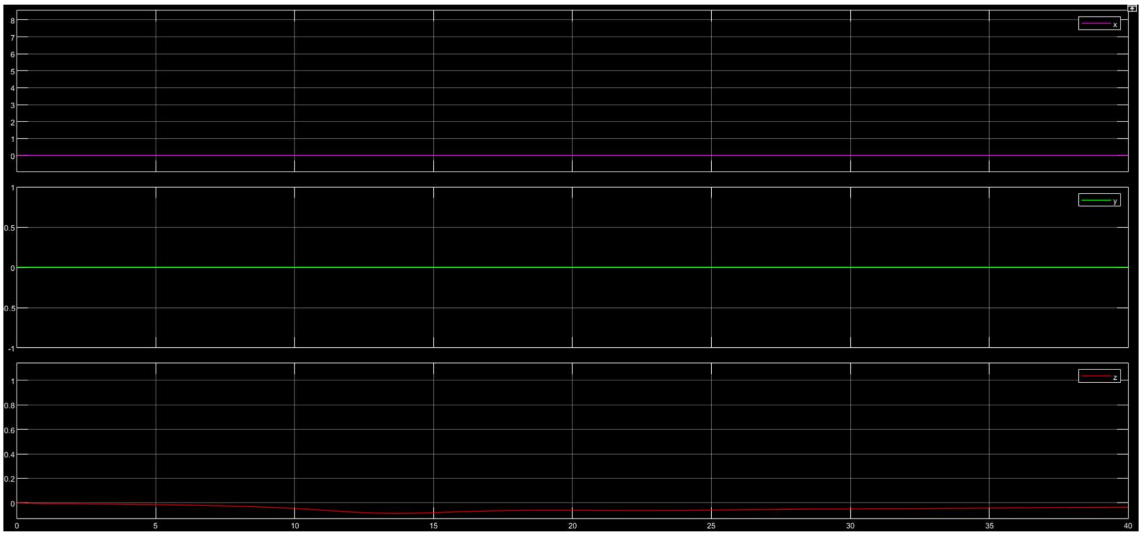
Figure 7. Simulation result of the position of the robot.

The Z position suffers of an error in the order of 10^{-2} near the 0 value that is traceable to buoyancy effects, whereas the X and Y positions are stable to 0.

In Figure 8 it is shown the 3D model of the robot during the yaw motion simulation.

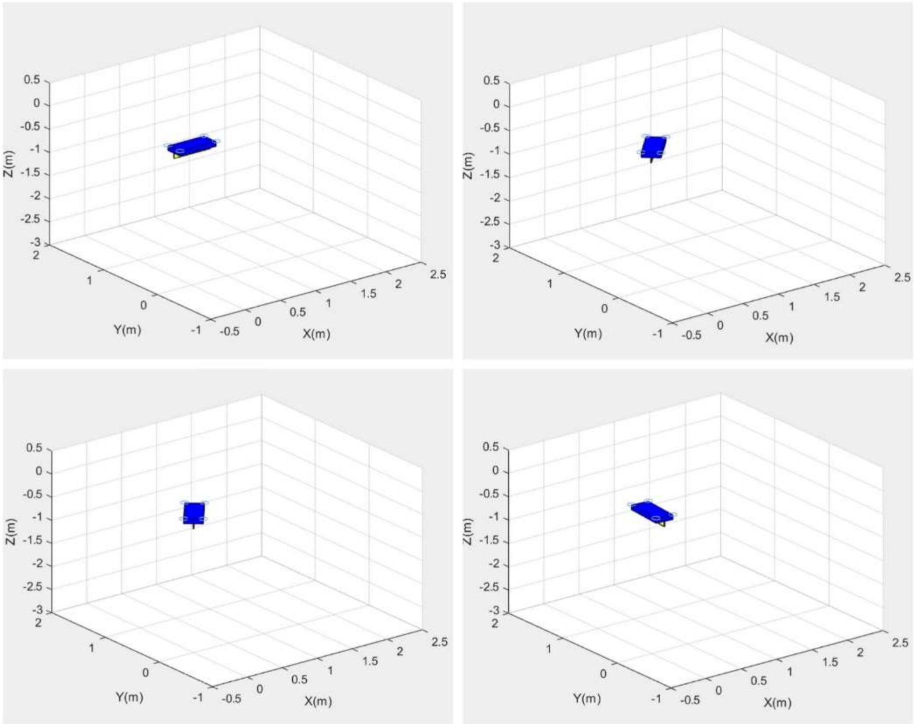

Figure 8. 3D model of the robot during the yaw motion simulation

5.2 Heave motion

The goal of this simulation is to check if the robot is able to hover and settle to a desired Z value. The initial state of the robot is set to $s = (0, 0, 0, 0, 0)^T$ and the reference input is $R = (1, 0, 0, 0, 0)^T$ when $(t < 20\ s)$ and $R = (0, 0, 0, 0, 0)^T$ for $(t > 20\ s)$. Neither in this case the undulating fin is used and the hovering is carried out only through the propellers.
The results are shown in Figures 9-10.

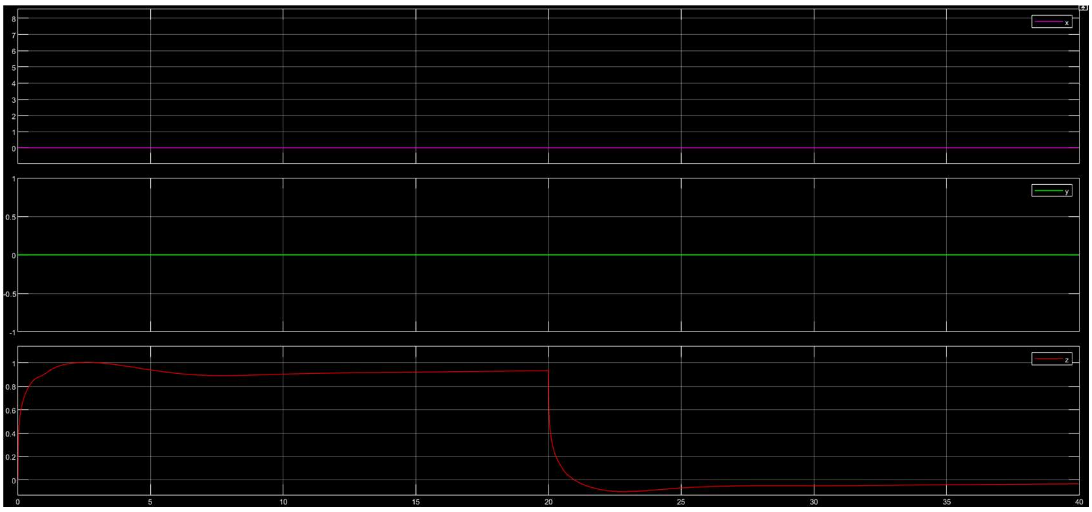

Figure 9. Simulation result of position of the robot.

As we can see the X and Y position are stable to 0 and the Z position reaches the desired value of 1 in 15 seconds after a transient and with a negligible error in the order of 10^{-2}. Then the Z value returns to 0 at the second 30 after a transient, still with an error in the order of 10^{-2}. These errors are traceable to buoyancy effects.

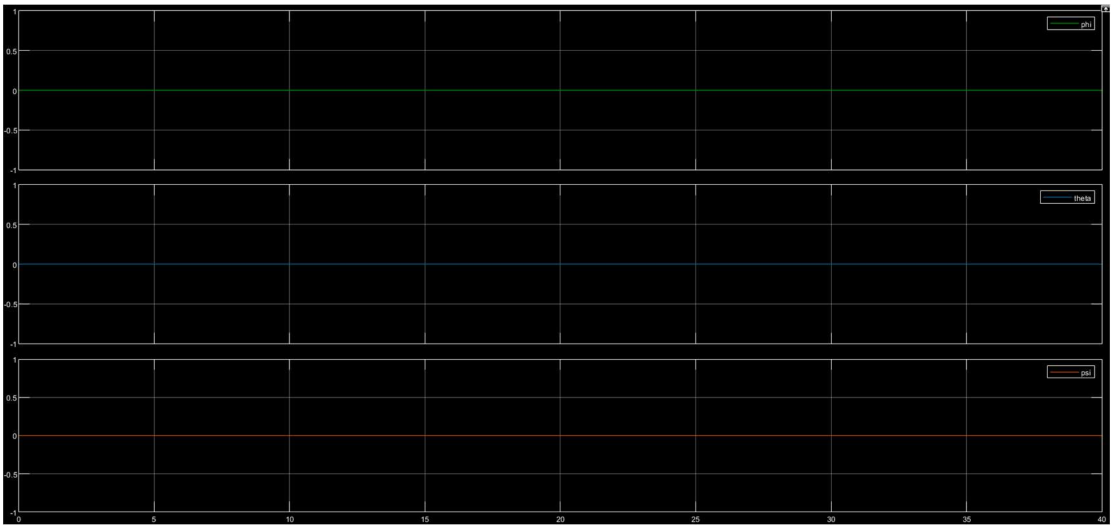

Figure 10. Simulation result of attitude angles.

The roll, pitch and yaw angle are stable to the value of 0.

Figure 11 shows how the robot manages to reach the desired depth with an initial velocity that is higher than 30 *m/s* and, after 20 *s*, with the same value into the opposite direction to return to the surface.

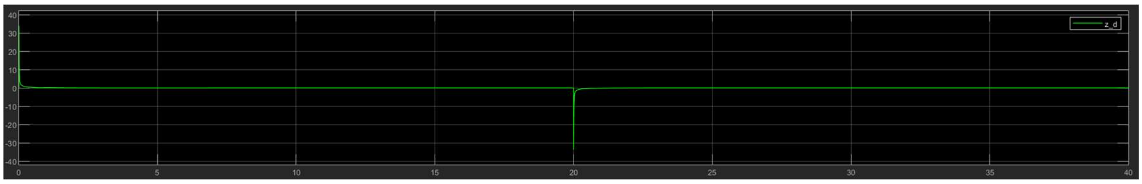

Figure 11. Simulation result of heave motion velocity.

In Figure 12 it is shown the 3D model of the robot during the heave motion simulation.

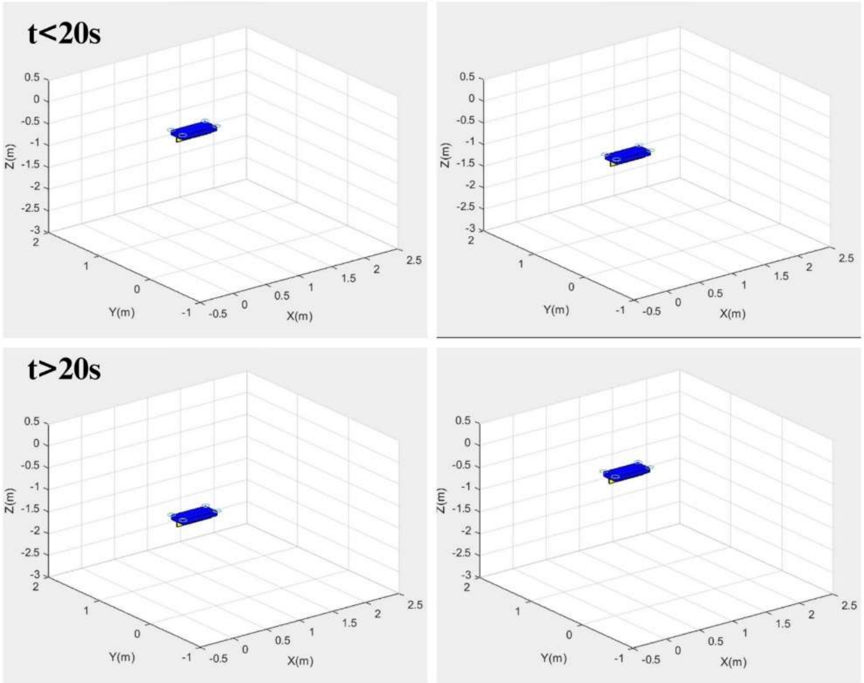

Figure 12. 3D model of the robot during the heave motion simulation

The robot has good motion stability, the roll, pitch, and yaw angle of the robot remain stable during the process of descent, hovering, and floating.

5.3 Surge motion

In this simulation the robot uses both the propellers, to hover, and the undulating fin to move along the X-axis and obtain the surge motion, that is the most important motion for an underwater robot. The initial state of the robot is set to $s = (0, 0, 0, 0, 0)^T$ and the reference input is $R = (1, 0, 0, 0, 10)^T$. The results are shown in Figures 13-14-15.

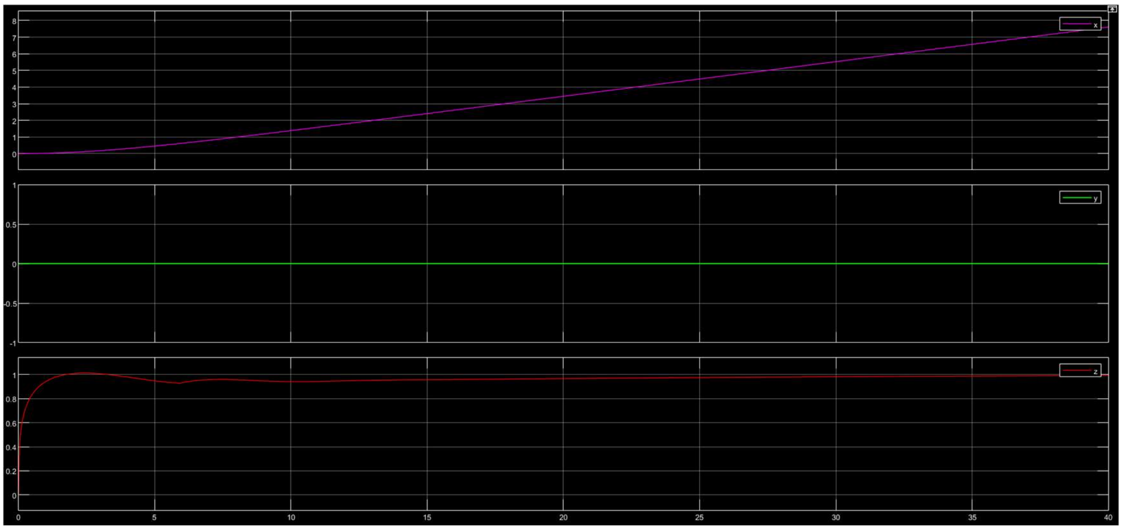

Figure 13. Simulation result of position of the robot.

As we can see, the robot moves from the surface to a depth of 1 *m* and at the same time it moves along the X-axis thanks to the undulating fin that undulates at the frequency of 2 *Hz*. The Y position is stable to 0 and the Z position reaches the desired value of 1 after a transient and with a negligible error in the order of 10^{-3}.
In Figure 14 it is shown how the robot manages to obtain the surge motion with the constant velocity of 0,2 *m/s* along the *x-axis* and a velocity along the *z-axis* with a peak of *25 m/s* only in the beginning.

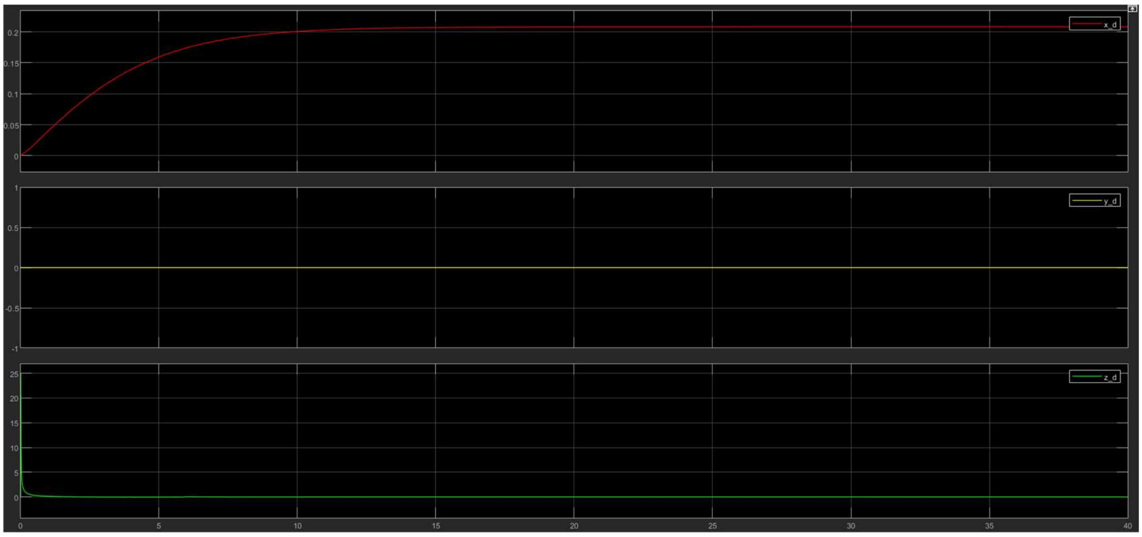

Figure 14. Simulation result of linear velocities.

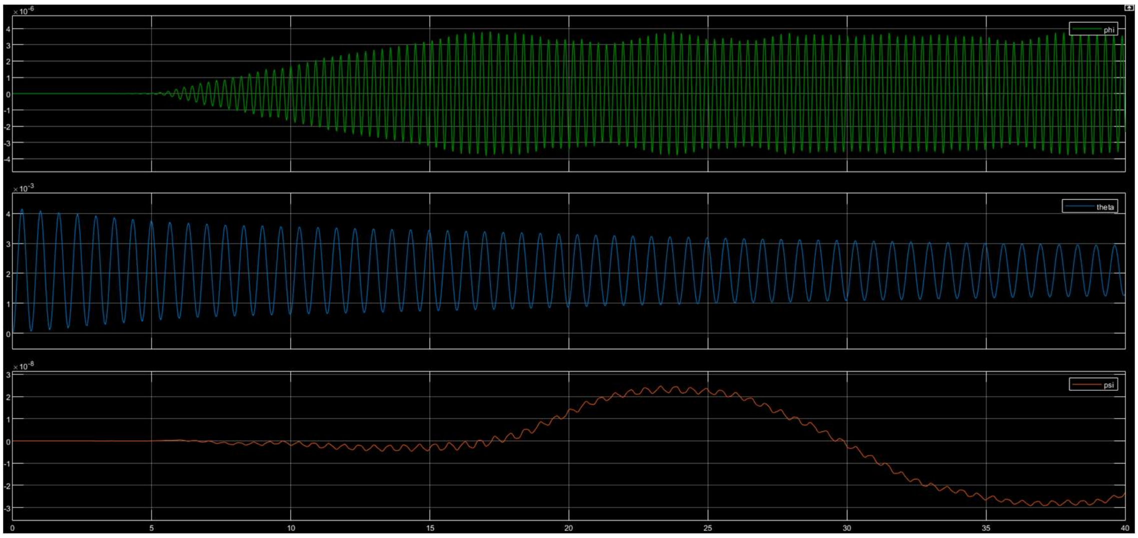

Figure 15. Simulation result of attitude angles.

The value of roll, pitch and yaw angle suffer of very little negligible oscillations around the value 0 that are, respectively, in the order of 10^{-6}, 10^{-3}, 10^{-8} and are traceable to hydrodynamic effects.
The value of the tilting angle β of the undulating fin is set before the beginning of the simulation and it is meant to be constant during all the motion. In this case it is set to 0. Figure 16 shows the oscillations which it is subject to that are due to hydrodynamic effects. Their amplitude is in the order of 10^{-7}so they are negligible.

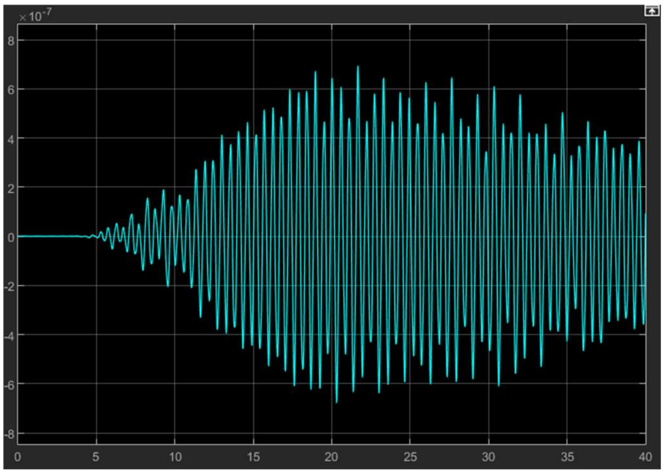

Figure 16. Oscillations of the tilting angle β of the undulating fin

In Figure 17 it is shown the 3D model of the robot during the surge motion simulation.

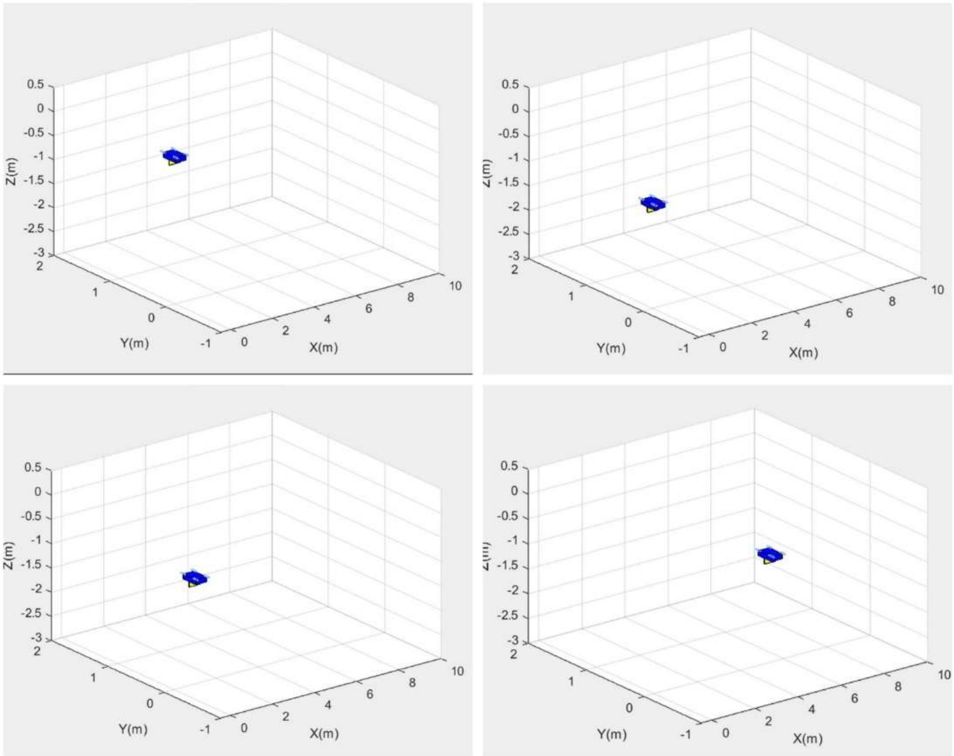

Figure 17. 3D model of the robot during the surge motion simulation

6. CONCLUSIONS

6.1 Discussion about performances

The undulating fin inspired by Gymnarchus niloticus plays an important role in enabling the underwater robot to realize the basic motion of heave, yaw and surge. The bionic fin, driven by the cam mechanism, can undulate at a high frequency, as shown in surge motion experiment.

The quadrotor is the other vital component of the underwater robot that hovers the robot and assists in maintaining its balance. The simulation and experiment results show that the attitude angle fluctuation range is less than ±2° in basic motion and hovering. This means that the robot can achieve attitude stability which fulfills the control strategy purpose.

The use of quadrotors sacrifices hydrodynamic performances in the direction of the robot's wave-fin propulsion, but also increases the robot's maneuverability in other directions. In addition, when the wave fin fails, the quadrotor can help the robot to complete the task.

6.2 Applicability

The present underwater robot prototype has successfully realized basic motion and high-frequency propulsion, which increase its suitability for a variety of tasks such as marine exploration, rescue, and operation. The most common example of such a task in the oil and gas industry is using the robot to make detailed maps of the seafloor before building a subsea infrastructure. However, compared to our design purpose and the simulation results, its swimming performances still have room for improvement. For example, the shape of the robot can be designed to be fish-like in order to improve the hydrodynamic performances of the robot in the directions of moving forward, rising, and sinking; then, the cam mechanism can be optimized by replacing the rigid shaft with a flexible shaft and improving the structure of the fin with soft material to generate an ideal sine wave; and, last but not least, the control strategy can be improved to enhance stability and maneuverability.

References

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