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Study on the Control Algorithm for Autonomous Underwater Helicopter

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Abstract: The ocean resources are extremely plentiful and diverse but human being's capability is still limited to utilize these available natural resources and exploitations are being faced numerous challenges. Therefore, several types of research about underwater vehicles are developed, in particular, the Autonomous Underwater Vehicle (AUV). It is undeniable that AUV is the mainstream equipment for underwater scientific research and engineering. However, it remains a great challenge for AUVs to carry out near-seabed operations because of their poor maneuverability. For these reasons, a new design for a high-maneuverability disc-shaped AUV is proposed, namely, the Autonomous Underwater Helicopter (AUH). The current situation illustrates that the AUH's control is difficult in transmitting data due to the effects of external noise. In this study, AUH's control algorithm through dynamic analysis is given by using a PID controller to optimize AUH's maneuverability and velocity as well as tested the simulation results in MATLAB software.

INTRODUCTION

Recently, the autonomous underwater vehicle has received great attention because of its importance such as the mineral exploration programs for economic development, military, oceanographic, etc.[1-4]. Initially, the underwater vehicles were researched and developed in terms of manned underwater devices (Manned Underwater Submersible). In early 1957, the conceptual design of AUVs is first developed at the University of Washington by Murphy *et al*. Another early AUV was proposed by Myring that gives the shape of nose and tail with a minimal drag coefficient[5]. These devices satisfied the ambitiousnesses of human being in ocean discovery, but, unfortunately, there were several accidents occurred and lead to many people were injured or even killed. At the end of the 1960s, manned underwater devices reached the limitation and stopped developing because it was extremely dangerous for people to face numerous risks such as high pressure, losing signal, etc. As a consequence, a new type of Autonomous Underwater Vehicle (AUV) that uses the adjustments in buoyancy and mass center position is called the autonomous underwater Helicopter[6]. In deep-sea exploration, Autonomous Underwater Vehicles (AUVs) play an important role by their unique characteristics, which include their autonomous, long-time, and long-range operation capabilities. The research on them is booming all over the world and they have caused a revolution in the field of ocean research. On one hand, the demand for AUVs comes from the need for large-scale underwater observation and resource exploration in traditional scientific research[7]. The disc-shaped AUV has been developed in recent years and still met several challenges in controlling such as transmitting data, velocity limitation as well as lack of flexible motions due to the effects of external noises. Alyanak *et al*.[8] showed the optimum design of a torpedo with the conditions about overall size, shape and configuration. Their algorithm determined the optimal stiffener configuration in the torpedo shape. The optimum design problem is also studied by De Sousa *et al*.[9]. The numerical results indicated that the optimum hull geometry is obtained by the analysis of turbulent single fluid over various shapes of an AUV hull. The obtained geometry of AUV generated a lower drag force that reduces the energy consumption of the vehicle. Jeon *et al*.[10] analyzed the dynamic characteristic of an AUV to select the important hull form parameters. From this analysis, the required intercept time of mission competence of an AUV and turning rate are determined. Computational Fluid Dynamics (CFD) is known as a very useful tool to solve numerical problems that relate to fluid mechanics. CFD simulation methods used to determine the hydrodynamic characteristics of AUVs have been investigated by Singh *et al*.[11]. Their results showed the agreement between the experimental results of the glider trajectory and the hydrodynamic coefficients obtained from the CFD approach. Although, there are a lot of studies about the control algorithm for AUVs, it rarely has similar research in the subject related to an autonomous underwater helicopter. It is very interesting to use the Ziegler-Nichols approach to control the motion of an AUH. This is a promising idea to manipulate an unmanned underwater robot in the future. This study illustrates the AUH's control algorithm through dynamic analysis by using the PID controller. In addition, the Euler's equations and the momentum theorem coupled with the appropriate conditions are solved numerically by using MATLAB software and the PID parameters were chosen by applying the Ziegler Nichols method (ZN) to optimal AUH's maneuverability and velocity. Since, the obtained results show a good observation with the experiment works, the need and the practice of using PID controller in the disc-shaped design process is proven.

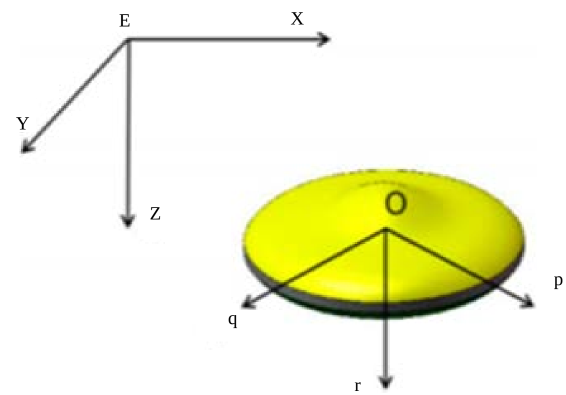

Fig. 1: Fixed coordinate system and moving coordinate system

MATERIALS AND METHODS

To measure the position of AUH, first, the relationship between the body-fixed coordinates and earth-fixed coordinates are expressed using the angle of the hull and the acceleration (Fig. 1). The coordinate conversion matrix is described as following:

$$\begin{bmatrix}\gamma\\ \beta\\ \alpha\end{bmatrix} = \begin{bmatrix}\cos\alpha\cos\beta \;\; \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma\\ \sin\alpha\sin\gamma + \cos\alpha\sin\beta\cos\gamma\\ \sin\alpha\cos\beta\cos\alpha\cos\gamma + \sin\alpha\sin\beta\sin\gamma\\ \sin\alpha\sin\beta\cos\gamma - \cos\alpha\sin\gamma\\ -\sin\beta \qquad \cos\beta\sin\gamma \qquad \cos\beta\cos\gamma\end{bmatrix} \tag{1}$$

Where:

α = An angle rotate around the z-axis (yaw)
β = An angle rotate around the y-axis
γ = An angle rotate around the x-axis (roll)

The linear motion description of AUH can easily be described as:

$$F = \frac{dH}{dt} = \frac{d(mV_{GE})}{dt} \tag{2}$$

Where:

F = The resultant external force vector (N)
H = The momentum of AUH (N.m)
V_{GE} = The velocity of AUH relative to fixed coordinate system E-xyz (m/s)

Through the transformation between coordinate systems, the equation of motion in moving coordinate system O-pqr can be described as:

$$F = m\frac{d(V + \omega\times R_{G_0})}{dt} = m\left[\frac{\partial V}{\partial t} + \omega\times V + \frac{\partial \omega}{\partial t}\times R_{G_0} + \omega\times(\omega\times R_{G_0})\right] \tag{3}$$

According to Euler's second law, the AUH rotational motion is described as:

$$T = \frac{dL}{dt} = J\frac{\partial\omega}{\partial t} + \omega\times(J\omega) + R_{Go}\times m\frac{\partial V_{Go}}{\partial t} + R_{Go}\times(\omega\times mV_{Go}) \quad (4)$$

Where:

T	=	The resultant external moment vector relative to the origin of the moving coordinate system (N.m)
L	=	The Momentum moment of AUH relative to fixed coordinate system E-pqr
R_{Go} (m) and V_{go} (m/s)	=	Distance and velocity of AUH's center of gravity relative to O-pqr, respectively
J	=	The moment of inertia (kg.m^2)

The equation of linear motion can be written as:

$$F_1 + F_2 - f_p = m\frac{du}{dt} \quad (5)$$

The rotation motion equation is describe as:

$$F_1R + F_2R - M_{fr} = J_r\frac{d\omega}{dt} \quad (6)$$

Where:

F_1 and F_2 (N)	=	The force of the horizontal thruster
f_p	=	The resistance of flow
M_{fr} (N.m)	=	The resistance moment of the z-axis
U (m/s)	=	The velocity of the p-axis
ω (rad)	=	The angular velocity about the r-axis
R(m)	=	The radius of AUH which is effectively the moment arm for each thruster

To reach the stability, AUH's center of gravity has to lower than the center of buoyancy. Furthermore, the motion description of the pitch axis is shown in Eq. 7:

$$-GR_{BG}\sin\theta + M_{fp} - M_{fq} = J_q\frac{d^2\theta}{dt^2} \quad (7)$$

$$M_{fq} = \int_0^R \rho C_d \frac{d\theta}{dt}\sqrt{R - x^2}\,x\,dx = \frac{1}{3}\rho C_d R^{\frac{3}{2}}\frac{d\theta}{dt} \quad (8)$$

Where:

G(N)	=	Gravity force
R_{BG} (m)	=	The distance between the center of gravity and the center of buoyancy
θ (rad)	=	The pitch angle
J_q (kg.m^2)	=	The AUH's rotating inertia of the pitch axis
M_{fq} (N.m)	=	The hydrodynamic resistance moment caused by the pitch
ρ (kg cm^{-3})	=	The water density
C_d	=	The resistance coefficient

The parameters of the fluid and an AUH selected in the simulations are R = 0.5 m; R_{BG} = 0.05 m; C_d = 0.02; $C_{u|u|}$ = 0.01; m = 42 kg; ρ = 9810 kg m^{-3}. So we have f_p = 0.08; M_{fp} = 0.08 N.m; J_p = 5.25 kg m^{-2}.

Regarding DC motor, the transfer function of DC motor will be developed for a linear approximation to an actual motor. We have the set of equation for DC motor

$$M_{FP}(s) = K_m I_f(s) \quad (9)$$

$$I_f(s) = \frac{V_f(s)}{R_f + L_f S} \quad (10)$$

where, K_m = 5 is the motor constant, R_f = 10Ω is the motor resistance, L_f = 0.4 H is the motor reactance. From these parameters, we have:

$$T_m(s) = K_m\frac{V_f(s)}{R_f + L_f s} = \frac{5V_f(s)}{10 + 0,4s} \quad (11)$$

According to equations (Eq. 10) and (Eq. 12), we find out the transfer function of system:

$$G(s) = \frac{\theta(s)}{V_f(s)} = \frac{2.4}{(s+25)(s+4.383)(s+0.02)} \quad (12)$$

RESULTS AND DISCUSSION

In the horizontal motion, we just use a pair of the horizontal propeller to force AUH in the horizontal plane. The experiment was carried out to determine the velocity and status of AUH in several different output forces with 0.7 N; 1.3 N; 2.2 N and 3.2 N, respectively. According to this experiment, the final results were demonstrated in Fig. 2. Figure 2 illustrates the relevant between the active force and velocity of AUH. The curved is seemed to be reasonable and the maximum active force of the propeller is 38 N to ensure the AUH's velocity reaches 1 m sec^{-1}.

Regarding the high maneuverability requirement, the settling time has to <2 sec and the overshoot is <20%. In addition, the steady-state error must be also approached to zero (Fig. 3).

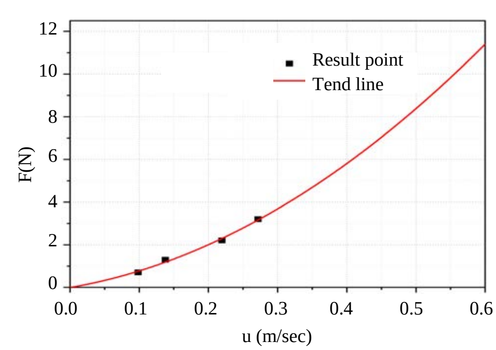

Fig. 2: The trend diagram of thrust force F and velocity u

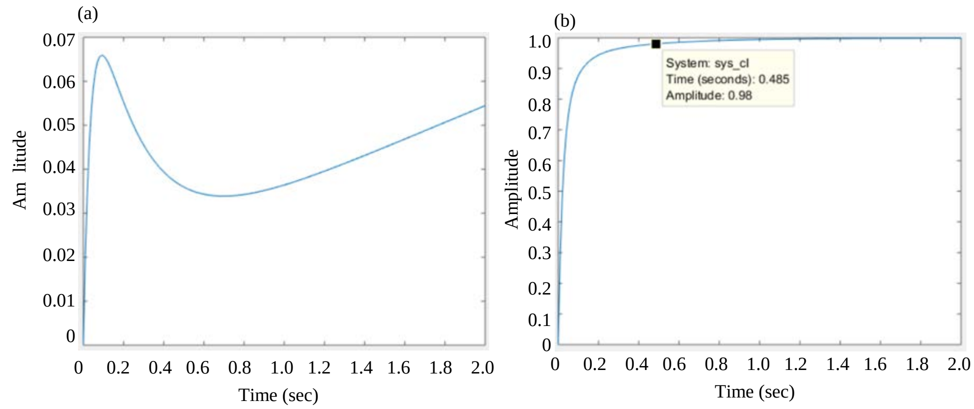

Fig. 3(a, b): The system response without and with the PID controller

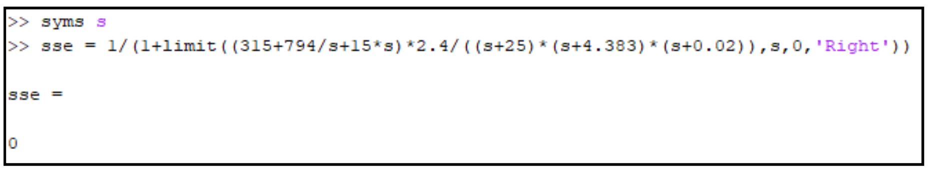

Fig. 4: The steady-state error of the system

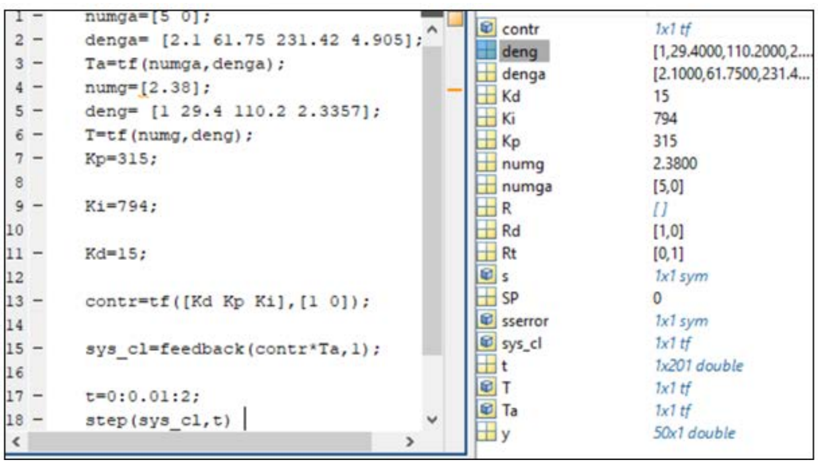

Fig. 5: The PID controller parameters

It is clear that the system response has good performance in comparison with the initial requirement with the settling is approximately 0.2 sec and the overshoot is <20%. Moreover, the steady-state error is also eliminated (Fig. 4).

By the Ziegler-Nichols method (ZN), the PID controller factors were calculated and tested in MATLAB software several times. As a result, the PID parameters (Fig. 5) were chosen as follows.

After determining the system characteristics, we need to test the system performance whether it was stable or not. In this study, we decided to use the Routh Criterion to check the system stability. It is obvious that the numbers in the first column of Table 1 are positive and have no significant changes. For this reason, the response of the system reaches a steady-state.

Table 1: The Routh criterion to check the system stability

s^4	1	146.2	1905.6
s^3	29.04	758.34	0
s^2	120	1905.6	0
s^1	712.21	0	0
s^0	1905.6	0	0

CONCLUSION

In the study, a new disc-shaped prototype namely AUH is proposed. It satisfies the characteristics of maneuverability and vertical motion stability. This study is based on general information from several research groups in the world. AUH is born to overcome the limit motions of AUV in the narrow space. This research gave the control algorithm of AUH with optimal speed and high maneuverability but there are just simple motions. By applying the PID controller, the system was controlled accurately and reached a stable state in a short time. These results were simulated on MATLAB to further demonstrate its performance.

RECOMMENDATIONS

In the future, we will carry out this model with a complex running path in comparison with the previous to evaluate its excellent maneuverability.

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