



# Dynamics Modeling and Behavior Analysis of Underwater Glider System

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(Manuscript Received December 1 2016; Revised January 3, 2017; Accepted February 8, 2017)

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## Abstract

Generally, underwater gliders do not have separate propellers for their forward movement. They derive a propulsive force due to the difference between their buoyancy and gravity. The attitude of an underwater glider is controlled by changing the relative position of the buoyancy center and mass center. In this study, we derived nonlinear 6-DOF dynamic and mathematical models for the motion controller and buoyancy controller. Using these equations, we performed dynamic underwater glider simulations and verified the suitability of the design and dynamic performance of the proposed underwater glider.

**Keywords:** Underwater glider, Buoyancy controller, Motion controller, Nonlinear 6-DOF equation

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## 1. Introduction

Owing to limited ground and coastal resources, exploration of oceans and deep seas is increasing. In the exploration of oceans and deep seas, there are many restrictions in approaching and observing the extreme ocean environment for a long duration of time. Therefore, ocean exploration equipment is being developed to overcome these restrictions, including Autonomous Underwater Vehicles (AUVs) that can execute missions by themselves. The operating range of AUVs is larger than Remotely Operated Underwater Vehicles (ROVs). However, AUVs cannot run for a long time. Therefore, missions using AUVs run for short durations of time. The need to overcome the drawbacks of AUVs and ROVs has led to the development of underwater gliders that can probe the ocean for a long time [1].

There is a difference between the buoyancy and gravity of the underwater glider when it moves continuously downward or upward. When the underwater glider moves upward or downward, it has a particular angle. This particular angle can be obtained based on the changes in the center of gravity of the underwater glider. The center of gravity can be calculated using the inner moving mass [2]-[4].

In this study, we designed a glider by applying the Myring equation to minimize fluid drag force while moving through a fluid. We derived the dynamic equation of the underwater glider based on the characteristics of the

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motion controller and buoyancy engine. The behavior of the underwater glider was analyzed through simulation using a dynamic equation. Using the simulation, we verified the validity of the underwater glider design and the behavior of the underwater glider through a field test.

## 2. Configuration of the Underwater Glider

### 2.1 External Configuration

The shape of the underwater glider in this work is a torpedo, as shown in Fig. 1. The underwater glider can be divided into bow, hull, and stern sections. In the bow section, there is a nose cone connected with the hull section, where fluid inflow is free. The horizontal and vertical wings are attached to the cowling in the stern section. There are also antennae for communication and a pintle.

### 2.2 Internal configuration

The internal configuration of the glider is shown in Fig. 2. The buoyancy engine, for controlling the volume of the ballast tank of the glider, is located in the bow section inside the glider. The hull section contains the motion controller to control the angle of the glider. It also includes a control board and a communication board to control the buoyancy engine and the motion controller.

## 3. Dynamics Modeling

### 3.1 Nonlinear 6-DOF dynamics equation

We used kinematic characteristics to derive the 6-DOF equation of the glider. In order to study the motion of the glider, the coordinate system was set as shown in Fig. 3. The origin  $O$  of the body fixed coordinate frame is located at the geometric center of the glider. The Earth fixed coordinate frame is defined as  $EX_EY_EZ_E$ . The glider

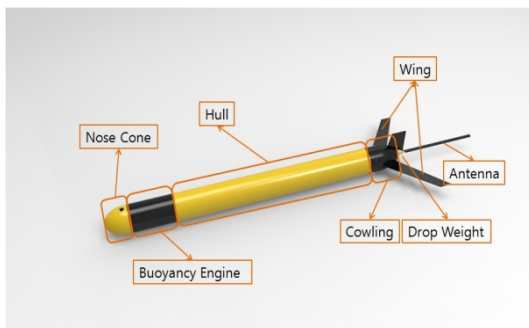


Fig. 1. External shape of the underwater glider

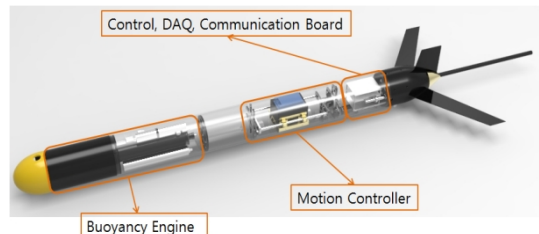


Fig. 2. Internal configuration of the underwater glider

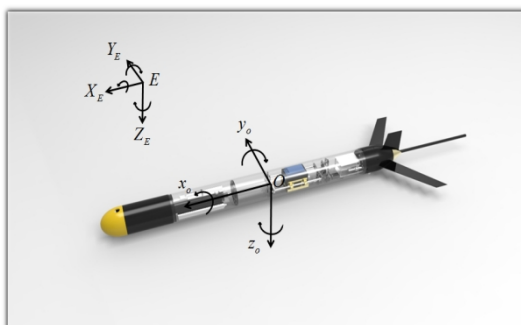


Fig. 3. Coordinate system of the underwater glider

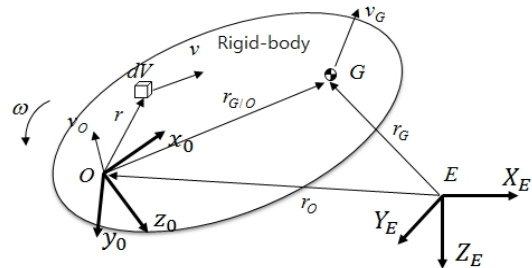


Fig. 4. Rigid body position vector

was assumed to have a rigid body. The coordinate frame was set as shown in Fig. 4. The derivation of the 6-DOF equation of general rigid body motion was performed using an existing method [5]. The translational motion equation (1) and the rotational motion (2) of a rigid body is as follows:

$$\begin{aligned} M[\dot{u} - vr + wq - x_G(q^2 + r^2) + y_G(pq - \dot{r}) + z_G(pr + \dot{q})] &= X \\ m[\dot{v} - wp + ur - y_G(r^2 + p^2) + z_G(qr - \dot{p}) + x_G(pq + \dot{r})] &= Y \\ m[\dot{w} - uq + vp - z_G(p^2 + q^2) + x_G(pr - \dot{q}) + y_G(qr + \dot{p})] &= Z \end{aligned} \quad (1)$$

where  $u, v, w$  and  $p, q, r$  in the left-hand side of the equation represent the translational velocity and angular velocity, respectively. They are expressed with respect to the body fixed frame.  $x_G, y_G, z_G$  is the position of the center of gravity.

$$\begin{aligned} I_{xx}\dot{p} + (I_{zz} - I_{yy})qr - I_{yz}(q^2 - r^2) + I_{xy}(pr - \dot{q}) - I_{zx}(pq + \dot{r}) \\ + m[y_G(\dot{w} - uq + vp) - z_G(\dot{v} - wp + ur)] &= K \\ I_{yy}\dot{q} + (I_{xx} - I_{zz})pr - I_{zx}(r^2 - p^2) + I_{yz}(pq - \dot{r}) - I_{xy}(qr + \dot{p}) \\ + m[z_G(\dot{u} - vr + wq) - x_G(\dot{w} - uq + vp)] &= M \\ I_{zz}\dot{r} + (I_{yy} - I_{xx})pq - I_{xy}(p^2 - q^2) + I_{zx}(qr - \dot{p}) - I_{yz}(pr + \dot{q}) \\ + m[x_G(\dot{v} - wp + ur) - y_G(\dot{u} - vr + wq)] &= N \end{aligned} \quad (2)$$

where  $I$  is the moment of inertia. The total mass of the underwater glider is

$$m_t = m_h + m_s + m_m. \quad (3)$$

$m_h$  is a fixed mass that is uniformly distributed throughout the hull,  $m_s$  is a fixed point mass, and  $m_m$  is the inner movable mass of the motion controller.

Using rigid body dynamics, the glider dynamics were derived after considering several variables. In the glider, the center of gravity, the center of buoyancy, and the moment of inertia change over time. The changes in these variables are shown in Fig. 5 and Fig. 6.

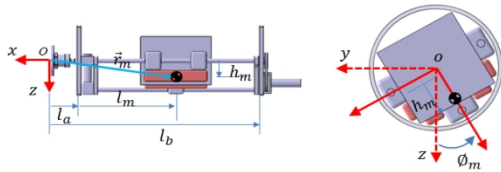


Fig. 5. Center of gravity of the movable mass

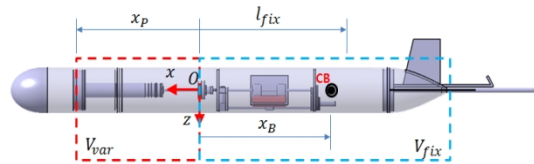


Fig. 6. Center of buoyancy

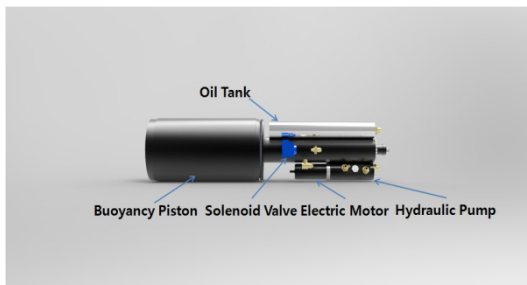


Fig. 7. 3D illustration of the buoyancy engine

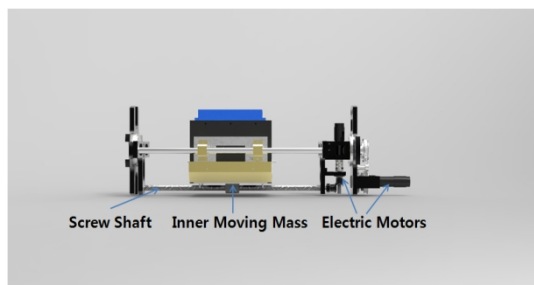


Fig. 8. 3D illustration of the motion controller

The center of gravity of the glider changes when the movable mass moves translationally and rotationally.

Therefore, the position of the center of gravity is expressed as follows:

$$\vec{r}_m = [x_m, y_m, z_m]^T = \begin{bmatrix} l_a + l_m \\ -\frac{h}{m} \sin \Phi_m \\ \frac{h}{m} \cos \Phi_m \end{bmatrix} \quad (4)$$

$$\vec{r}_{CG} = \begin{bmatrix} x_G \\ y_G \\ z_G \end{bmatrix} = \frac{m_{null} \vec{r}_h + m_{stat} \vec{r}_s + m_m \vec{r}_m}{m_t} \quad (5)$$

According to change of piston position, the volume of the buoyancy engine is changed. It is mean that the center of buoyancy is also changed.

The center of buoyancy of the glider is

$$\vec{r}_{cb} = [x_B, 0, 0]^T = \begin{bmatrix} \frac{V_{var} \frac{x_B}{2} + V_{fix} l_{fix}}{V_{var} + V_{fix}} \\ 0 \\ 0 \end{bmatrix}. \quad (6)$$

The mass moment of inertia of the underwater glider is defined as follows:

$$I_0 = (I_{null} - m_{null} \hat{r}_h \hat{r}_h) + (I_s - m_s \hat{r}_s \hat{r}_s) + (I_m - I_m \hat{r}_m \hat{r}_m) \quad (7)$$

Where,  $\hat{\quad}$  represent skew symmetric matrix.

The dynamics of the underwater glider are derived by the substitution of Eqs. (3) ~ (7) into Eqs. (1) and (2).

### 3.2 Mathematical Modeling of Buoyancy Engine and Motion Controller

We developed a mathematical model of the buoyancy engine and motion controller to simulate the dynamic behavior of the system.

Fig. 7. is the 3D illustration of the buoyancy engine. The hydraulic pump is used when the piston of the buoyancy engine is moved forward. When the solenoid valve is open, the piston in the buoyancy engine is moved backward. We used the pressure difference between inside and outside of the buoyancy engine to reduce energy consumption. To determine the forward velocity of the piston, we used the following equation:

$$q = Av_f \quad (8)$$

The forward moving velocity is determined by flow rate and area of the piston;  $q$  is the flow rate of the fluid in the hydraulic pump,  $A$  is the area of piston, and  $v_f$  is the velocity of the piston. In this equation, we neglected the frictional force between the piston and piston housing. The forward moving velocity of piston can be determined by the flow rate of the fluid in the hydraulic pump, which is expressed as

$$q = D\omega - K_{\leq ak}P, \quad (9)$$

where  $D$  is the flow displacement while the hydraulic pump makes one rotation,  $w$  is the angular velocity of the motor,  $K_{\leq ak}$  is the coefficient of leak flow rate, and  $P$  is the discharge pressure of the hydraulic pump.

The external pressure affects the velocity of the piston moving backward. The velocity of the piston moving backward could be obtained by measuring the velocity during the backward movement; then, pressure is applied to the piston housing of the designed buoyancy engine and approximated to the following quartic equation:

$$v_b = a_1 z^4 + a_2 z^3 + a_3 z^2 + a_4 z + a_5, \quad (10)$$

where  $v_b$  is the velocity of the piston moving backward,  $a_1, a_2, a_3, a_4$  and  $a_5$  are the coefficients of quartic, and  $z$  is the water depth.

The motion controller is shown in Fig. 8. The velocity of the inner moving mass is determined by the angular velocity of motor, the lead of the screw shaft, and the gear ratio of the reducer. It can be expressed by the following equation:

$$v_{tmov} = \omega \eta_n L_{s\&ad}, \quad (11)$$

where  $v_{tmov}$  is the velocity of inner moving mass,  $\omega$  is the angular velocity of motor,  $\eta_n$  is the gear ratio of the reducer, and  $L_{s\&ad}$  is the lead of the screw shaft.

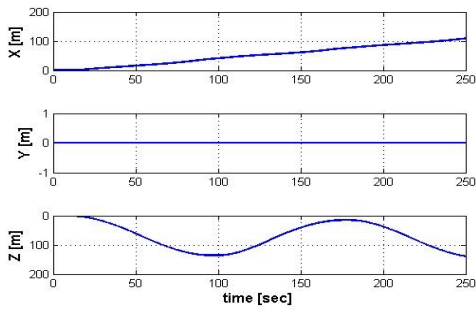


Fig. 9. The position of the underwater glider

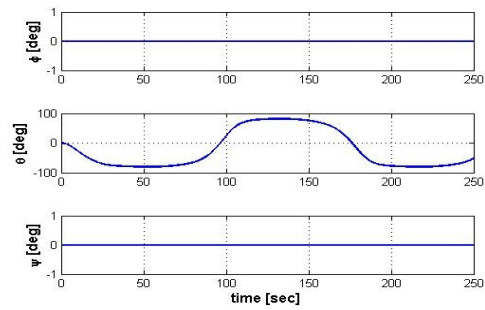


Fig. 10. The angle of the underwater glider

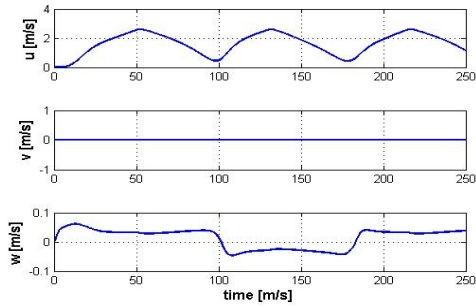


Fig. 11. The velocity of the underwater glider

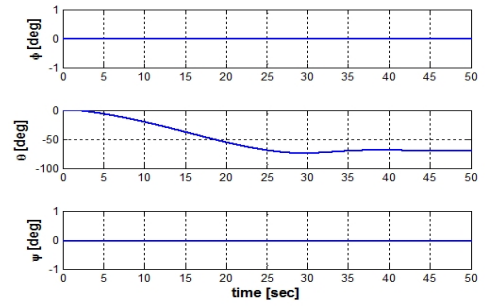


Fig. 12. The angle of the underwater glider position in communication mode

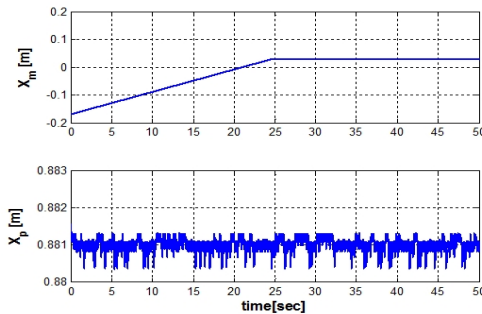
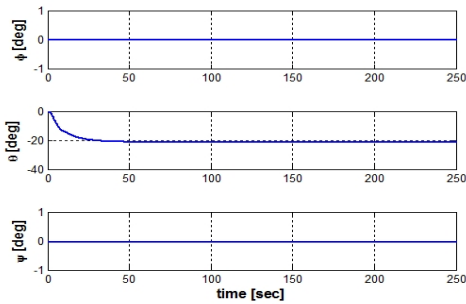
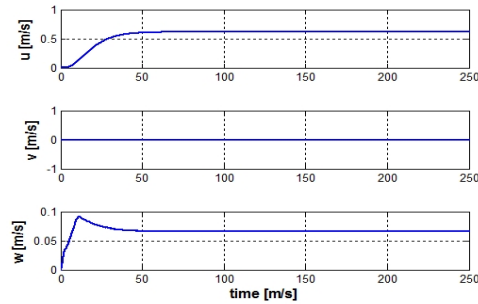
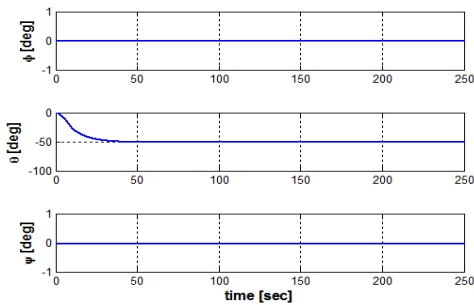
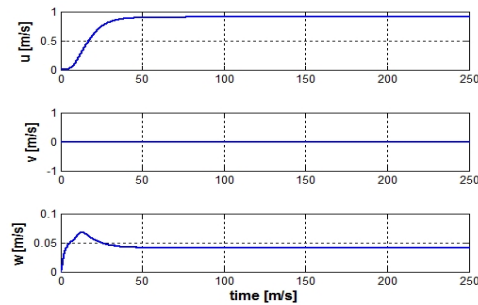


Fig. 13. The position of the inner moving mass & piston

Fig. 14. The  $-20^\circ$  pitch angle control simulationFig. 15. The velocity of the underwater glider in  $-20^\circ$  pitch angle control simulationFig. 16. The  $-50^\circ$  pitch angle control simulationFig. 17. The velocity of the underwater glider in  $-50^\circ$  pitch angle control simulation

## 4. Simulation & Analysis

We analyzed the behavior of the underwater glider by considering the characteristics of the motor of the buoyancy engine and the motion controller. We performed simulation using MATLAB/SIMULINK [6]. The velocity, pitch angle, and roll angle could be changed by the position of the inner movable mass and the piston in the buoyancy engine. Thus, the control inputs in the simulation were the position of the piston in the buoyancy engine and the position of the inner movable mass.

### 4.1 Open-Loop Control Simulation

The vertical motion of the underwater glider is shown in Fig. 9. By changing the position of the inner movable mass and the piston position in the buoyancy engine without using the control law, the motion characteristics of the underwater glider were confirmed. The piston of the buoyancy engine moved backward, and the inner movable mass moved forward when the underwater glider was in a downward motion. In this case, the pitch angle of the glider is around  $-80^\circ$ , as shown in Fig. 10. The maximum velocity of the body fixed frame wis around 3.5 m/s, as shown in Fig. 11.

### 4.2 Motion Controller Control Simulation

An antenna should be exposed to air while communicating with a command ship after floating an underwater glider near the surface of the water. The antenna should be inclined at a specific pitch angle under the neutral buoyancy condition.

The pitch angle for exposing the antenna of the underwater glider in this simulation was less than  $-40^\circ$ . When the inner moving mass in the motion controller moved forward to the maximum extent possible, with the neutral state of the buoyancy engine in the simulation, the pitch angle is approximately  $-70^\circ$ , as shown in Fig. 12. The

position of the piston and the inner moving mass are shown in Fig. 13.

#### 4.3 Pitch Angle Control Simulation

The velocity  $u$  is in the  $x_0$  direction of the body fixed frame. It can be determined by the buoyancy and pitch angle. When the volume of the buoyancy engine is controlled constantly, the velocity  $u$  is changed by varying the pitch angle. In the simulation, the pitch angle was controlled using the PID controller. During the simulation, the piston moved back by 20 mm.

As shown in Fig. 14, the pitch angle is controlled at  $-20^\circ$ , and the velocity  $u$  is approximately 0.6 m/s. This is confirmed from Fig. 15. As shown in Fig. 16, the pitch angle is controlled at  $-50^\circ$ . The velocity  $u$  is approximately 0.8 m/s, as shown in Fig. 17.

### 6. Conclusions

The simulation results confirmed that when the underwater glider moved downward or upward, the pitch angle of the underwater glider converged to a particular value. To control the pitch angle, it is effective to change the position of the center of gravity and the center of buoyancy at the same time. However, this approach cannot be used in operating an underwater glider. Limiting the volume of the buoyancy engine and using the motion controller for convergence to the desired pitch angle will be more effective than continuous control of the buoyancy engine, when operating an underwater glider. Therefore, we performed the simulation using a limited volume of the buoyancy engine.

Through simulations, we confirmed that communication was possible using only the motion controller. The pitch angle could be controlled using the motion controller. The volume of the buoyancy engine could be controlled by the ON/OFF controller.

In our future work, we intend to design an optimal controller for underwater gliders.

### Acknowledgements

This research was supported by Research on Automatic Control Technologies of Underwater Glider, which is supported by ADD (Agency for Defence Development).

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