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Design and Control of High Speed Unmanned Underwater Glider

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KEYWORDS: Under water glider, Buoyancy engine, Control system, Motion control

In this paper, an underwater glider (UG) has been studied and developed for observing the ocean environment. The design and control of a new underwater glider (UG) having a high horizontal speed of the maximum 2.5 (Knots) was studied. For this, the capacity of buoyancy engine which performs 2.5 (Knots) horizontal speed was designed. Also, a controllable buoyancy engine to regulate the amount of buoyancy was developed for control of the pitching angle of UG. The mass shifter carrying the battery was designed for controlling pitching and yawing motion of the UG and the control system to control them was constructed. A mathematical modeling based on six degree-of-freedom dynamics equation including the buoyancy engine and mass shifter dynamics was performed to find the optimal pitching angle of the UG for maximum speed. Using the mathematical model, a simulation representing the vertical and horizontal speed of the UG with respect to pitching angles is developed and is presented. A number of experiments was performed to verify the accuracy of the simulation and the performance of the developed UG.

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1. Introduction

The underwater glider is a green autonomous underwater vehicle which uses much smaller energy than any other underwater vehicles such that it has been widely utilized as important platforms in ocean exploration. It offers a number of advantages such as superior spatial and temporal measurement density, longer duration missions, and greater operational flexibility.

In 1989, an underwater glider Slocum was built with the speed of 0.5 knots which can collect ocean information. Also, Seaglider built at the University of Washington, Slocum Battery manufactured by Webb Research Corp, succeeded in travelling 3,500 km. In 2011, WHOI and Scripps developed Spray' equipped with many sensors such as CTD, ADCP, etc. Alsin France, ACSA developed an UG, SeaExplorer which does not have wings. Specifications for the Spray, Slocum, and Seaglider are described and are compared.[1-3]

For research related with the sawtooth motion of UG, a number of researchers have worked on the dynamic modeling and analysis. The dynamic models of gliders including the mass shifter motion were set up by a number of researchers such as Graver and Leonard, Bhatta and Leonard, and Isa and Arshad. Leonard and Graver analyzed the stability of the sawtooth gliding motion based on the a model-based feedback control method. Isa and Arshad also proposed a dynamic model of USM' sunderwater glider for the sawtooth gliding motion. Also, for research related with the spiral motion of the UG, a number of researchers have worked on the dynamic modeling and analysis such as Kan, Mahmoudian and Woolsey, and Zhang, Mahmoudian and Woolsey analyzed the spiraling motion based on the dynamic model of UG and performed simulations for the spiraling motion. A dynamic equations for spiraling motions of seawing UG are derived and then solved by a recursive algorithm, and experiments were performed to show the consistent of theoretical glider model with experimental results by Zhang.[4-9]

So far, most of research papers presented simulation results based on the dynamic model. Also, the maximum horizontal speeds of all the developed commertial UGs are less than 1 knot such that they may be inappropriate for tracking the path or targeting disired goals in the regions of fast currents. So, a high speed UG is needed for tracking the path under fast currents and experimental researches are required for real application.

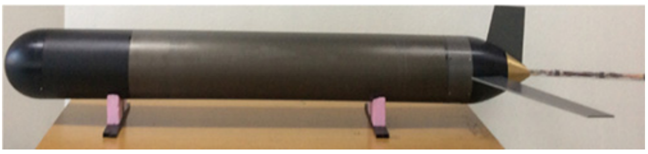


Fig. 1 The picture of the developed of UG

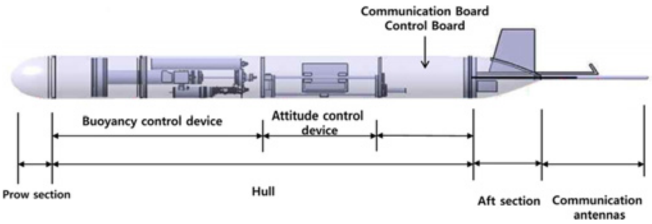


Fig. 2 Structure of the UG

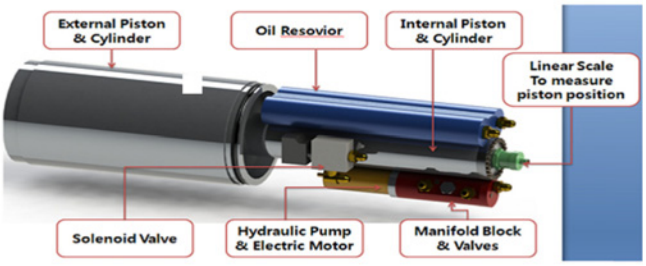


Fig. 3 Structure of developed buoyance engine

In this paper, a design and control of an unmanned underwater glider (UG) with maximum speed of 2.5 knots are studied and presented. Also, a study on buoyancy controller capacity design of the glider for 2.5 knots speed was performed. It also covers the design of the mass shifter using battery control to control glider pitching and yawing and a control system for them.

In the paper, a simulator was developed showing relations between buoyancy control amount and speed of the UG developed with mathematical modeling based on six DOF equations of motion to find the optimal pitching angle for high speed control. The similarity of the simulator and developed UG was verified with basic experiments. It conducted performance test on the developed UG at an indoor tank and in the sea to verify the high speed and control performance. Through this, maximum horizontal speed of 2.5 knots is estimated.

2. Mathematical Model and Motion Simulation of the UG

2.1 Structure of UG System

The picture of the developed UG is shown in Fig. 1. The total weight of the UG is about 58 kg, the diameter of the hull is 200 mm, and total length is 3100 mm. The structure of the UG is composed of the stern, hull and bow as shown in Fig. 2. The bow was designed to facilitate seawater to enter and go out of the buoyancy engine whose structure is shown in Fig. 3 where the stern along with the communication antenna is to transmit communication data and GPS data. The hull has buoyancy engine, mass shifter moving the internal battery, control board and communication device and was designed as a cylinderical shape to reduce the water resistance.

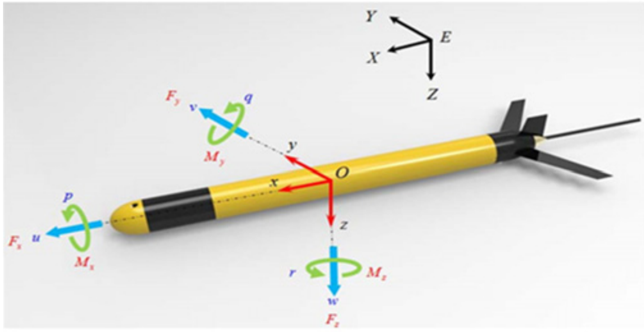


Fig. 4 Definition of the coordinate system

The advantages of the developed UG is to control the amount of buoyancy amount using the linear scale sensor such that it can control the pitching angle of UG.

2.2 Mathematical Model of UG

A mathematical model for the UG is needed to design the controller for identifying of dynamic characteristics of the UG that includes the motion of the internal mass shifter and buoyancy engine. First of all, the coordinates of six defree-of-freedom motion equations of the UG can be described as Fig. 4 in general. For the motion equations of the underwater vehicle, earth-fixed coordinate system EXYZ and body-fixed coordinate system Oxyz are set up. For the body-fixed coordinate system, moving direction of UG is put at axis x, starboard direction at axis y and depth direction at axis z. With the defined coordinates, translational motion and rotational motion of the UG is expressed as Eq. (1) according to Newton's second law.[11]

The hydrodynamic coefficients in the right hand side can be determined through the CFD analysis and PMM test or empirical formula.

$$\begin{gathered}
m[\dot{u}-vr+wq-x_G(q^2+r^2)+y_G(pq+\dot{r})+z_G(pr+\dot{q})]=X \\
m[\dot{v}-wq+ur-y_G(r^2+p^2)+z_G(qr+\dot{p})+x_G(pq+\dot{r})]=Y \\
m[\dot{w}-uq+vp-z_G(p^2+q^2)+x_G(pr+\dot{q})+z_G(pq+\dot{p})]=Z \\
I_{xx}\dot{p}+(I_{zz}-I_{yy})qr-I_{yz}(q^2-r^2)+I_{xy}(pr-\dot{q}) \\
-I_{zx}(pq+\dot{r})+m[y_G(\dot{w}-uq+vp)-z_G(\dot{v}-wp+ur)]=K \\
I_{yy}\dot{q}+(I_{xx}-I_{zz})pr-I_{zx}(r^2-p^2)+I_{yz}(pq-\dot{r}) \\
-I_{xy}(qr+\dot{p})+m[z_G(\dot{u}-vr+wq)-x_G(\dot{w}-uq+vp)]=M \\
I_{zz}\dot{r}+(I_{yy}-I_{xx})pq-I_{xy}(p^2-q^2)+I_{zy}(qr-\dot{p}) \\
-I_{yz}(pr+\dot{q})+m[x_G(\dot{v}-wp+ur)-y_G(\dot{u}-vr+wq)]=N
\end{gathered} \tag{1}$$

At Eq. (1) u, v, w, and p, q, r represent the glider's angular speed of translational and rotational motion for the axes x, y, z respectively. I_{ij} represents the mass moment of inertia of the UG for the axis of each subscript where x_G, y_G, z_G represent the location of the glider's mass center. X, Y, Z, K, M, N represent the external forces and moment working on the UG for each motion direction such as thrust, buoyancy, gravity, and hydrodynamic force.

The buoyancy engine changes the mass center and buoyancy center of the UG and the mass shifter changes the mass moment of inertia by control. The equations of the mass shifter for AUV is previously analyzed and similarly related equations of the buoyancy engine and mass shifter of the glider are modeled as below.[10]

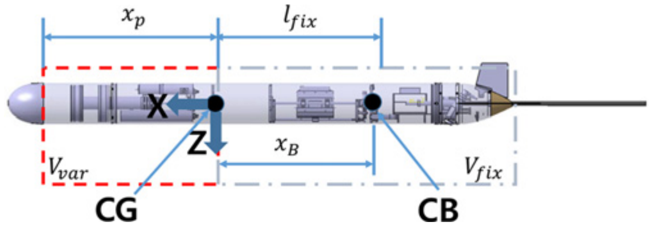


Fig. 5 Configuration of mass center and buoyancy center of UG

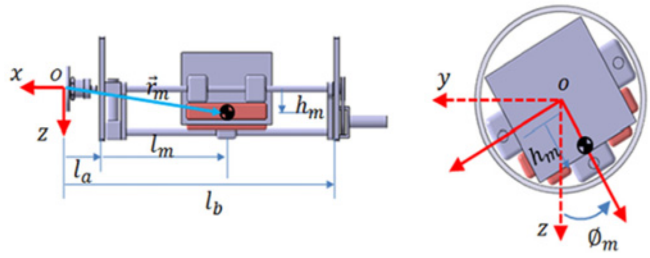


Fig. 6 Positioning system of internal moving mass

a. Relationship between hull mass and buoyancy center

When O is the mass center, V_{fix} is fixed volume of body-fixed coordinate system, and V_{var} is the changing volume by the buoyancy controller at Fig. 5, then the buoyancy center r_{cb} can be expressed as Eq. (2).

$$\overrightarrow{r_{cb}} = [x_B, 0, 0]^T = \left[\frac{V_{var}\frac{x_p}{2} + V_{fix} l_{fix}}{V_{var} + V_{fix}}, 0, 0\right]^T \quad (2)$$

where x_B is the distance between the mass center and buoyancy center and is that between the terminal of the buoyancy engine piston to mass center.

b. Analysis of attitude controller dynamics

Vector $\overrightarrow{r_m}$ from the origin of the body-fixed coordinate system O to the mass center of the battery pack changing in real time with the moving internal battery pack. This change caused movement of the hull mass center $\overrightarrow{r_{CG}}$ and the mass moment of inertia I_O which could be described as Fig. 6 and Eq. (3). The total mass of the UG m_{total} is composed of hull mass m_h intrnal system mass m_s, and the internal moving mass m_m, m_{total} is expressed as

$$m_{total} = m_h + m_s + m_m \quad (3)$$

$$\overrightarrow{r_{cg}} = [x_G, y_G, z_G]^T = \frac{m_h\overrightarrow{r_h} + m_s\overrightarrow{r_s} + m_m\overrightarrow{r_m}}{m_{total}} \quad (4)$$

In Eq. (4), $\overrightarrow{r_m}$ is a variable, which is obtained through the designed parameters and Eq. (5)

$$\overrightarrow{r_m} = [x_m, y_m, z_m]^T = \begin{bmatrix} l_a + l_m \\ -h_m \sin\varnothing_m \\ h_m \cos\varnothing_m \end{bmatrix} \quad (5)$$

According to the rotating angle $\varnothing$ of the moving mass, the mass center y_m and z_m change, and x_m changes according to the changes of translational movement of the moving mass l_m The changing moment of inertia is expressed as Eq. (6) related with the mass changes of the UG.

$$I_o = (I_h - m_h\hat{r}_h\hat{r}_h) + (I_s - m_s\hat{r}_s\hat{r}_s) + (I_m - m_m\hat{r}_m\hat{r}_m) \quad (6)$$

where I_h, I_s and I_m are the constant mass moment of inertia of hull, internal constant device, and internal moving mass, respectively and m_h, m_s and m_m are the related masses. Also, $\hat{r}_h$, $\hat{r}_s$ and $\hat{r}_m$ are the vector to the mass center of the related masses.

The buoyancy engine of the UG is designed in side of the hull as Fig. 3 in the way to control buoyancy by controlling the seawater volume in the cylinder with piston moving back and forth.

The relationship between the pump and motor of the buoyancy controller to control seawater discharge with control of the buoyancy engine piston position is described as

$$\dot{x}_p = \frac{Dw - Dw_{nom}(1-\eta_v)}{A} \quad (7)$$

where A is the cross section of the buoyancy engine, q is discharge per unit hour, was discharge per pump rotation, D is rotational angular speed of the motor connected the pump, w_{nom} is nominal angular speed of the motor, and η_v is volume efficiency of the pump.

Based on Eqs. (1) to (7), a simulator is developed showing the vertical and horizontal with respect to the pitching angle and the volume of buoyancy of the developed UG using the Matlab /Simulink.

2.3 Motion Analysis of the UG

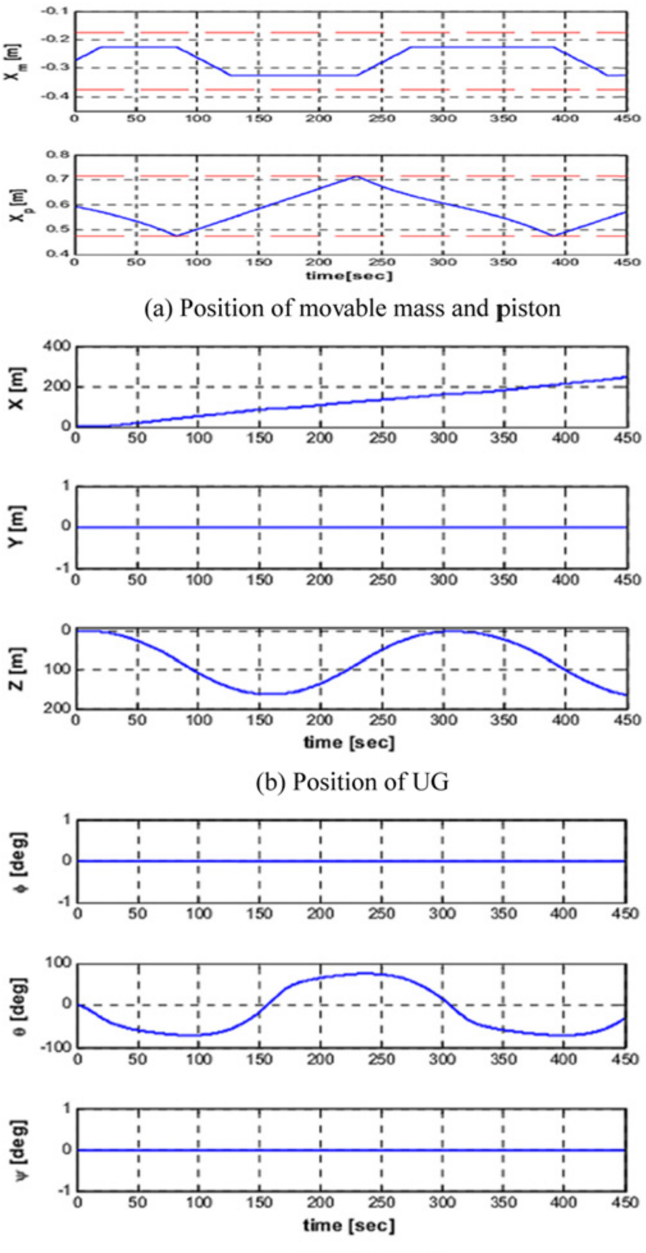
In this study, motion simulation is performed using Matlab/ Simulink to verify effectiveness of the UG modeling. In the simulation, the nonlinear six DOF equations of motion is analyzed for the piston speed of the buoyancy engine and moving speed of mass shifter. It is assumed that ideal fluid was used for the simulation with no disturbance. Hydrodynamic parameters for the simulation are obtained from the PMM test result.

To find out the motion behavior of the UG pitching direction, forward and backward movement and piston movement was applied except for rotational movement of the internal mass shifter. The target of the buoyancy engine was set at piston position x_p the position and direction of the attitude controller battery pack x_o and rotational angle ϕ_m.

Simulation results are presented in Figs. 7 and 8. Fig. 7(a) demonstrates the forward movement of the attitude controller by piston movement of the buoyancy engine and by the translational motion of the mass shifter without rotation motion of the internal mass. In Fig. 7(a), the sinusoidal motion of UG to z direction is shown by the motion of the buoyancy engine and the translational motion of the mass shifter. Also, according to the sinusoidal motion, the UG motion along x-axis is shown in Fig. 7(b). The pitching angle of UG is presented for the UG motion in Fig. 7(c). It was also found from Figs. 7(b) and (c) that the UG motion occurred depending on the result of Fig. 7(a).

In this paper, to validate the horizontal and vertical speed of the developed UG, the external forces of X, Z, and M are considered only. The external forces due to buoyancy change are expressed as the following Eq. (8).[12]

$$\begin{aligned} X &= X_{u|u|}u|u| + X_{\dot{u}}\dot{u} + X_{wq}wq + X_{qq}qq + X_{vr}vr + X_{rr}rr - (W-B)\sin\theta \\ Z &= Z_{w|w|}w|w| + Z_{q|q|}q|q| + Z_{\dot{w}}\dot{w} + Z_{\dot{q}}\dot{q} + Z_{uq}uq + Z_{vp}vp \\ &\quad + Z_{rp}rp + Z_{uw}uw + (W-B)\cos\theta\cos\phi \\ M &= M_{w|w|}w|w| + M_{q|q|}q|q| + M_{\dot{w}}\dot{w} + M_{\dot{q}}\dot{q} + M_{uq}uq + M_{vp}vp \\ &\quad + M_{rp}rp + M_{uw}uw + (W_{Z_G} - B_{Z_B})\sin\theta - (W_{X_G} - B_{X_B})\cos\theta\cos\phi \end{aligned} \quad (8)$$



(a) Position of movable mass and piston

(b) Position of UG

(c) Attitude of UG

Fig. 7 Simulation results of UG motion

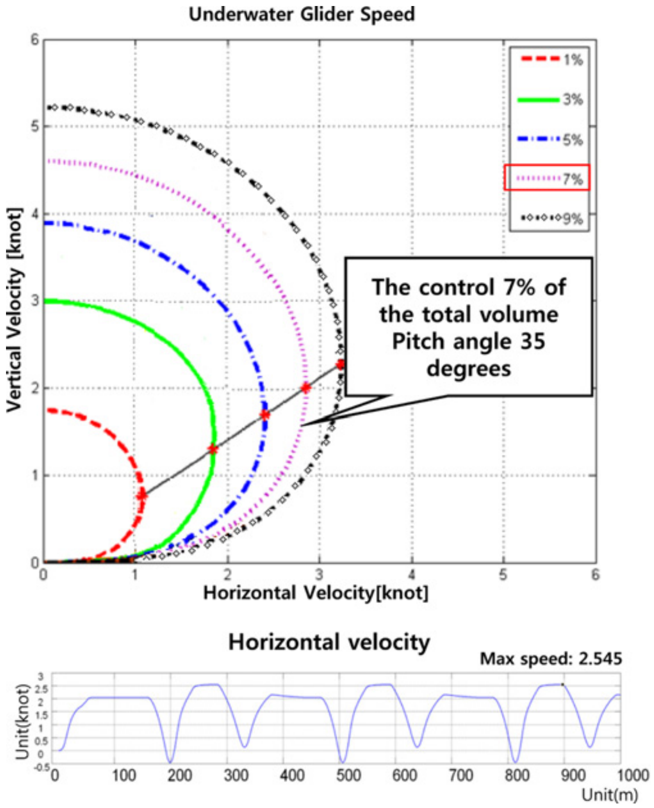


Fig. 8 Simulation graph relating the speed with buoyancy control amount of UG

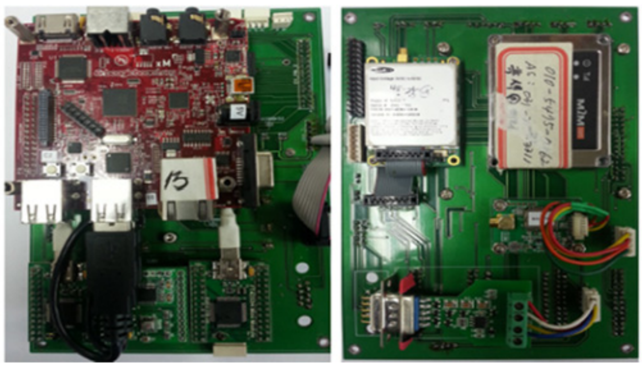


Fig. 9 System control board of UG

Fig. 8 is the simulation graph showing horizontal velocity and vertical velocity due to the external forces and moment working on the UG. The velocity result comes from changing buoyancy of UG volume by 1% to 7%.

It was found here that the maximum speed of the developed UG comes from 7% buoyancy of the total volume of the UG which is equivalent to 3 litter, and which maintains about 35^o underwater downhill angle and has speed of more than 2.5 knot at the depth of 100m as shown in the right side of Fig. 8.

3. Designing Control System of the UG

The control system of the UG is composed of two major boards. One is motion control board that controlled propelling buoyancy controller and attitude controller that controlled attack angle and moving direction of the body by moving the internal mass and the other is system control board that tracked communication and positioning and processed sensor data.

The system control board is made up of an embedded PC that uses ARM cortex-A8 as its CPU. Embedded Linux is used as the OS to run the overall UG system and create control algorithm based on the embedded Linux scalability and real time.

To link the embedded PC used for system control to many sensors and control systems, system control board is made like Fig. 9. It comprises the embedded PC, AHRS, GPS, depth sensor and internal pressure sensor with RF modem and CDMA modem as the communication module.

The motion control board is designed to directly control motion of

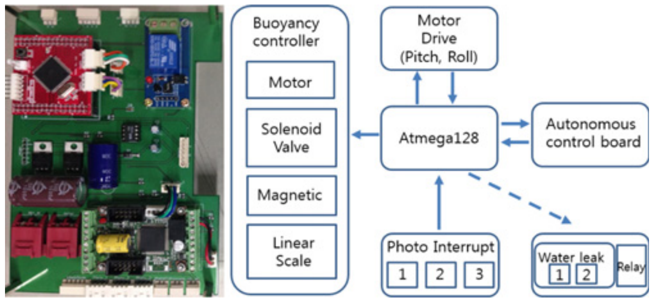


Fig. 10 Motion control board composition control diagrams of UG

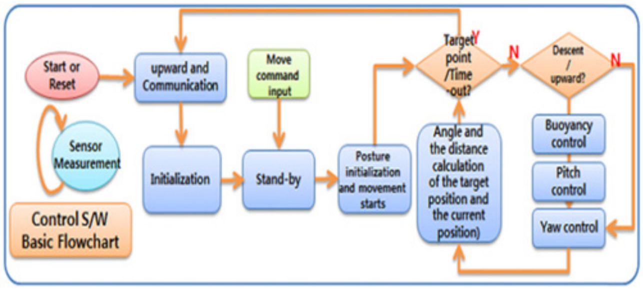


Fig. 11 block diagram of sequential control structure of UG

the UG based on the data that go through computation at the system control board. As mentioned above, it controls propulsion by controlling the position of the buoyancy controller pump and piston that the system control board cannot handle as well as the moving direction and incidence angle of the UG by changing the battery position of the attitude controller.

This board consisted of ATmega128 that is an 8bit controller, two-channel DC motor driver, FET controlling the buoyancy controller and communication converter. Fig. 10 shows the developed board with composition control diagram.

The software of the designed UG was designed in two parts: motion control and navigation control. The motion control part controlled buoyancy and attitude so that optimal descending angle is kept when the UG moved vertically. On the other hand, navigation control part controlled heading angle so that peak can be tracked down in the line of sight style. Fig. 11 shows the block diagram of sequential control structure.

4. Performance Test

4.1 UG Test in the Water Tank

Before seawater test of the designed UG, 50 m (L) × 25 m (W) × 3 m (D) indoor swimming pool is used to test straight motion performance through sinusoidal motion and the process is illustrated at Fig. 12. Straight motion performance of the UG was tested with 50 m sailing at a 2.7 m-deep pool with ascending limit of 0.5 m and descending limit of 1.5 m.

Good underwater motion performance was observed at the up and down motion test of one cycle. The test data were sampled and saved for every 0.1 second with the result shown at Fig. 13.

The four graphs at Fig. 13 used data from descending and ascending

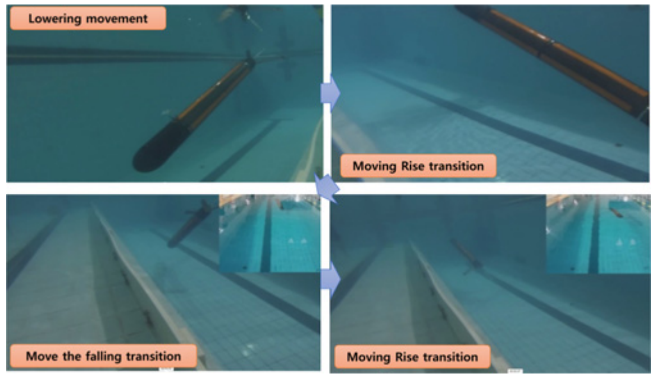


Fig. 12 Indoor swimming pool test

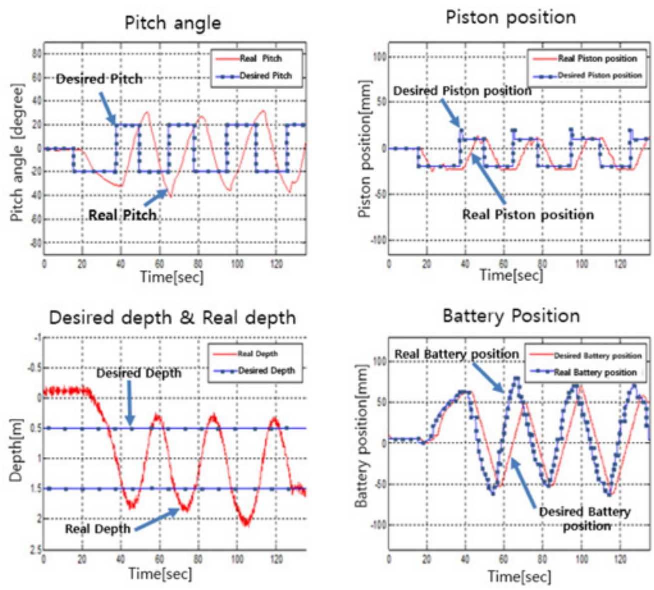


Fig. 13 Result graph of Indoor swimming pool test

angle of the glider (Top Left), depth control value during ascent and descent (Bottom Left), position of the buoyancy controller piston of the UG in motion (Top Right) and changing position of the attitude controller separate from the straight motion test (Bottom Right). The top left graph presented actual tracking angle depending on desired pitching angle while the top right graph showing controlling of piston position depending on the desired pitching angle. The red line here displayed the desired piston position and triangular line did the actual piston position. The bottom left was the result of elaborately controlling the pitching motion by moving the battery and the bottom right explained the motion of the UG within ascending limit of 0.5m and desc ending limit of 1.5 m because o f the motions. The desired pitching angle was set to be decided by the desired piston position based on the simulation before the test. However, the piston had delay of eight seconds because of delay in actual piston motion and triangular motion occurred. Subsequently, the pitching angle also went through triangular pitching motion.

The top left graph limited the ascending and descending angle to 20° when the UG went up and down. According to the result of bottom left, it advanced with sinusoidal up and down motion within descending angle of -30° to -35° and ascending angle of 34° to 35°,

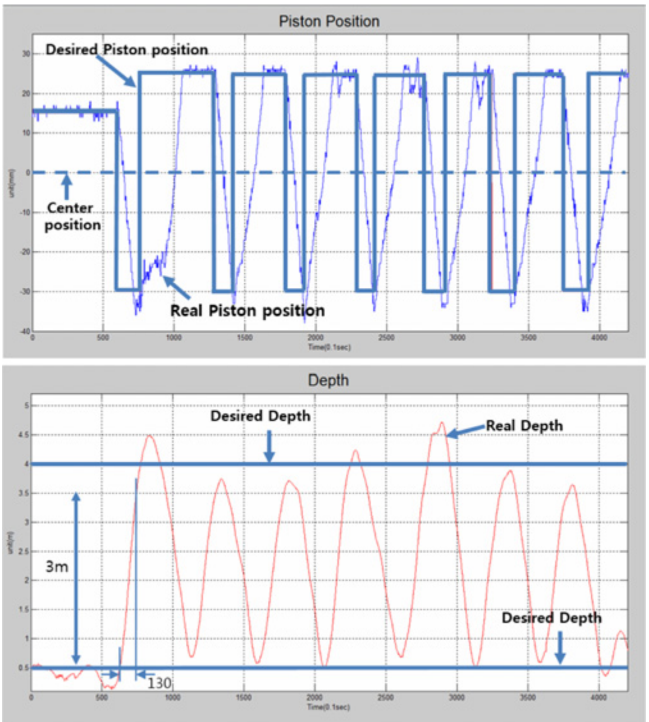


Fig. 14 Result of sea test data (Piston position and trajectory of UG)

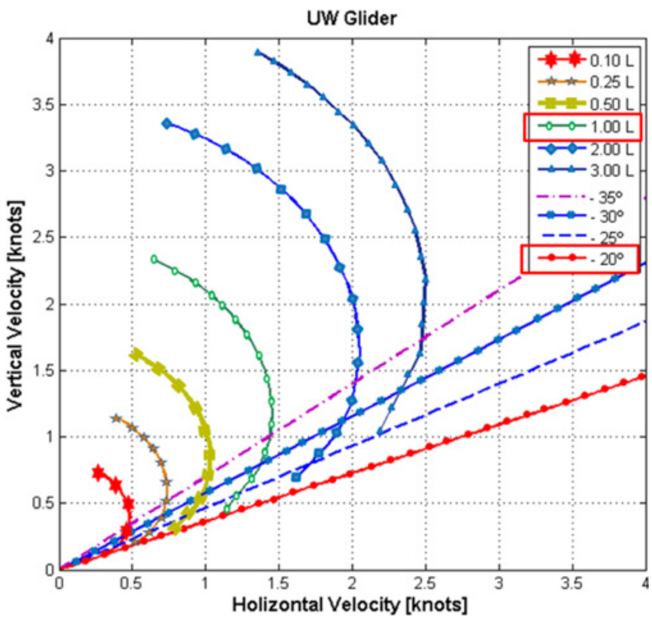


Fig. 15 Simulation graph relating the speed with buoyancy control amount of UG

which represents the over and under shoot due to the difficulty of the control pitching angle. The graph data that explained up and down motion were largely different from the actual control angle. However, the glider is over 3 m long including the rear antenna and the testing water is shallow, making it impossible for the glider to reach actual steady state and descend at an optimal angle to the water floor. Considering this, the straight motion of the UG was found satisfactory like the simulation result. Besides, overshoot of 12 to 25% occurred at the bottom left with 0.3 m during ascent and 1.7 to 1.9 m during descent through the depth control graph. The indoor pool was not deep enough for the test unlike the actual sailing environment. Despite of the circumstance, it is shown that the glider motion was well controlled according to the test results as shown in Fig. 13.

To validate maximum 2.5 knots speed of the developed UG, a sea test was performed and its result is shown in Fig. 14 where the upper figure represents the piston position of the buoyancy engine through control and the lower figure represents the trajectory of the UG. The test was performed in the about 7 meter shallow water such that the UG motion was confined within 5 m. It is shown that the actual position of the piston is delayed compared with the desired command. Also, the moving distance of the piston is about 25 mm which is equivalent to about 1000 mL of the buoyancy engine capacity. With this buoyancy control, The UG travelled under the sea and its trajectory is presented in Fig. 14. In the first diving trajectory as marked in Fig. 14, the fastest traveled depth of the UG is 3 m during 13seconds such that the vertical velocity is 0.23 m/sec which is equivalent to 0.44 knots. Also, for the traveling motion, the pitching angle is 20^o. With this condition, according to the simulation graph of the developed UG in Fig. 15, the intersection point of the green line (the Fourth Line from the Bottom) with the red straight line (the Bottom Line) coincides the vertical speed of about 0.44 knots, which validates the credibility of the simulation. Also, according to the simulation graph, the maximum speed of the UG occurs at the pitching angle of 35^o. Hence, for the pitching angle of the UG is 35^o (Red Dashed Dot Line) and the buoyancy control of 3liter, the maximum horizontal speed is estimated to be 2.5 knots using the simulation graph.

5. Conclusions

A new underwater glider having a high horizontal speed of the maximum 2.5 (Knots) was studied. For this, the capacity of buoyancy engine which performs 2.5 (Knots) horizontal speed was designed. Also, a controllable buoyancy engine to regulate the amount of buoyancy was developed for control of the pitching angle of UG. The mass shifter carrying the battery was designed for controlling pitching and yawing motion of the underwater glider and the control system to control them was built. The performance of the moving mass and buoyancy engine was tested. According to the test results, the actual piston position was delayed to the desired command, which causes the delay of the pitching motion of the UG. Despite of this, the motion of the UG was controlled well with a little overshoot.

A mathematical modeling based on six degree-of-freedom dynamics equation including the buoyancy engine and mass shifter dynamics was performed to find the optimal pitching angle of the UG for maximum speed. Using the mathematical model related with the pitching motion, a simulation graph representing the vertical and horizontal speed of the UG with respect to pitching angles was developed. Through simulation, it was shown that the optimal pitching angle for the developed UG is 35^o. To validate the credibility of the simulation, water tank and sea experiments were performed. The experiments showed the credibility of the simulation, and using the simulation graph, the maximum speed of 2.5 knots of the developed UG could be estimated.

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