Design of a new high speed unmanned underwater glider and motion control

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***Abstract*—In this paper, the design and control of a new underwater glider having a high horizontal speed was studied. For this, the capacity of buoyancy engine which performs 2.5(knots) horizontal speed was designed. Especially, a controllable buoyancy engine to regulate the amount of buoyancy was designed and developed for control of the pitching angle of UG and the mass shifter carrying the battery was designed for controlling pitching and yawing motion of the UG. A mathematical modeling based on six degree-of-freedom dynamics equation including the buoyancy engine and mass shifter dynamics was performed to control the UG. Using the mathematical model, a simulation of the yaw motion control of the UG is presented. A number of sea experiments were performed to verify the navigation performance of the developed UG.**

Keywords—Underwater glider; Buoyancy Engine; Control system; Motion control

I. 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 [1]. Also, Seaglider built at the University of Washington, Slocum Battery manufactured by Webb Research Corp, succeeded in travelling 3,500km [2]. In 2011, WHOI and Scripps developed Spray[3] 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.

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 [4-6]. Leonard and Graver analyzed the stability of the sawtooth gliding motion based on the a model-based feedback control method [4].

So far, most of research papers presented simulation results based on the dynamic model. Also, the maximum horizontal speeds of all the developed commercial UGs are less than 1 knot such that they may be inappropriate for tracking the path or targeting desired 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.

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.

A. Strucure of UG system

The picture of the developed UG is shown in Figure 1. The total weight of the UG is about 58kg, the diameter of the hull is 200mm, and total length is 3100mm. The structure of the UG is composed of the stern, hull and bow as shown in Figure 2. The bow was designed to facilitate seawater to enter and go out of the buoyancy engine whose structure is shown in Figure 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 cylindrical shape to reduce the water resistance.

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The advantage 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.

Fig. 1. The picture of the developed of UG

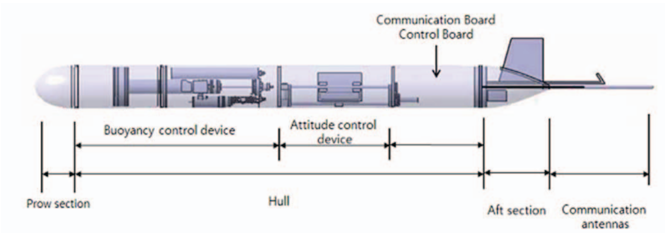

Fig. 2. Strucure of the UG

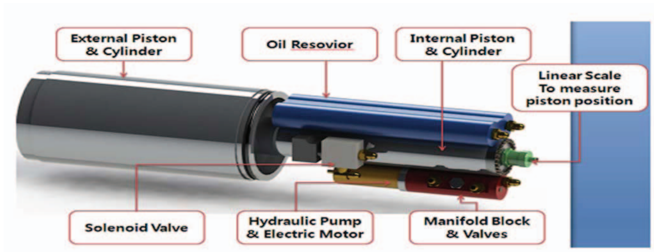

Fig. 3. Strucure of the developed buoyance engine

B. 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 degree-of-freedom motion equations of the UG can be described as Figure 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 (1) according to Newton's second law [7].

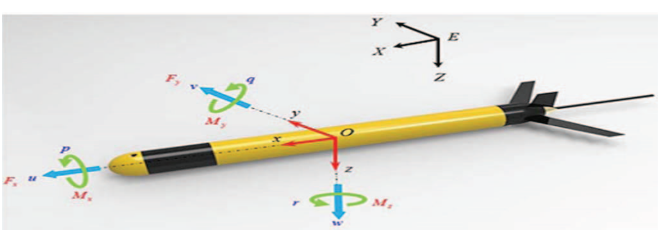

Fig. 4. Definition of the coordinate system

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

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

At Equation (1) $\mathrm{u,v,w}$, and $\mathrm{p,q,r}$ represent the glider's angular speed of translational and rotational motion for the axes $\mathrm{x,y,z}$ 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. $\mathrm{X}, Y, Z, K, M, N$ 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.

1) 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 Figure 5, then the buoyancy center r_{cb} can be expressed as (2).

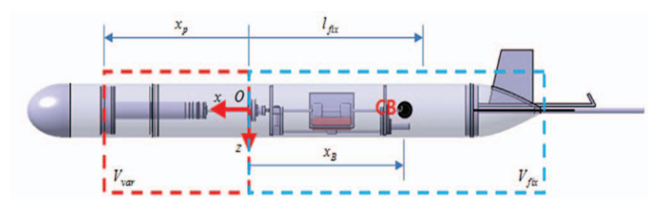

Fig. 5. Configureation of mass center and buoyancy center of UG

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

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.

2) 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 Figure 6 and (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

$$m_{total} = m_h + m_s + m_m \tag{3}$$

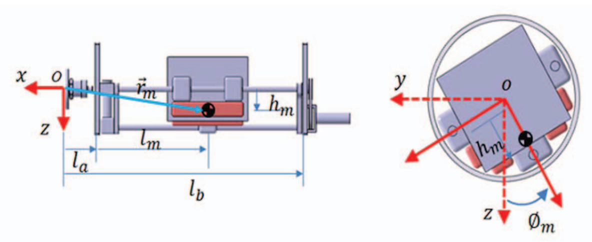

Fig. 6. Positioning system of internal moving mass

$$\overrightarrow{r_{cg}} = \left[x_{G,}\, y_G, z_G\right]^T = \frac{m_h\overrightarrow{r_h}+m_s\overrightarrow{r_s}+m_m\overrightarrow{r_m}}{m_{total}} \tag{4}$$

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

$$\overrightarrow{r_m} = \left[x_{m,}\, y_m, z_m\right]^T = \begin{bmatrix} l_a + l_m \\ -h_m sinØ_m \\ h_m cosØ_m \end{bmatrix} \tag{5}$$

According to the rotating angle Ø 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 (6) related with the mass changes of the UG.

$$\mathrm{I_o} = (\mathrm{I_h} - \mathrm{m_h}\widehat{\mathrm{r_h}}\widehat{\mathrm{r_h}}) + (\mathrm{I_s} - \mathrm{m_s}\widehat{\mathrm{r_s}}\widehat{\mathrm{r_s}}) + (\mathrm{I_m} - \mathrm{m_m}\widehat{\mathrm{r_m}}\widehat{\mathrm{r_m}}) \tag{6}$$

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, $\widehat{r_h}$, $\widehat{r_s}$ and $\widehat{r_m}$ 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 Figure 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

$$\dot{\mathrm{x}_\mathrm{p}} = \frac{\mathrm{Dw} - \mathrm{Dw_{nom}}(1-\eta_\mathrm{v})}{\mathrm{A}} \tag{7}$$

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 Equations (1) ~ (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.

C. *Motion analysis of the UG*

In this paper, to validate the horizontal motion of the developed UG, the external forces of X, Y, and N are considered only. The external forces due to buoyancy change are expressed as the following equations

$$\begin{aligned}
\mathrm{X} &= X_{u|u|}u|u| + X_{\dot{u}}\dot{u} + X_{qq}qq + X_{vr}vr + X_{rr}rr - (W - B)sin\theta \\
\mathrm{Y} &= Y_{v|v}v|v| + Y_{r|r}r|r| + Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_{ur}ur + Y_{wp}wp + Y_{pq}pq \\
&\quad + Y_{uv}uv + (W - B)\cos\theta sin\phi \qquad (8) \\
\mathrm{N} &= N_{v|v|}v|v| + N_{r|r|}r|r| + N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + N_{ur}ur + N_{wp}wp \\
&\quad + N_{pq}pq + N_{uv}uv + \left(W_{x_G} - B_{x_B}\right)\cos\theta\sin\phi + \left(W_{y_G} - B_{y_B}\right)\sin\theta
\end{aligned}$$

Figure 7 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 5% buoyancy of the total volume of the UG which is equivalent to 2.2 litter, and which maintains about 35° underwater downhill angle and has speed of more than 2.5 knot at the depth of 100m as shown in the right side of Figure 7.

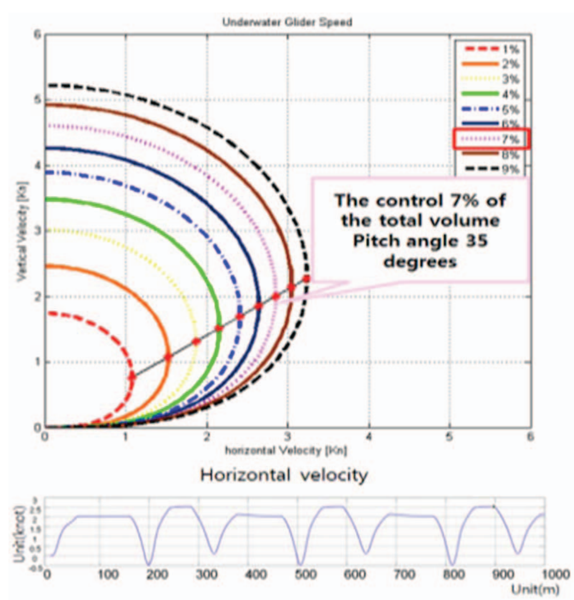

Fig. 7. Simulation graph relating the speed with buoyancy control amount of UG

II. DESIGNING CONTROL SYSTEM OF THE UG

The control system of the UG is composed of the motion and the system control boards. The motion control board controls propelling buoyancy and attitude of the attack angle and moving direction of the body by moving the internal mass. The system control board is for communication and positioning and processed sensor data.

The system control board is made up of ARM cortex-A8 as its CPU. To link the embedded PC used for system control to many sensors and control systems, system control board is made like Figure 8. It comprises the embedded PC, AHRS, GPS, depth sensor and internal pressure sensor with RF modem and CDMA modem as the communication module.

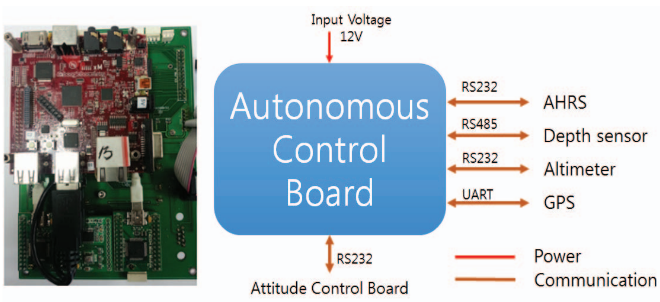

Fig. 8. System control board of UG

The motion control board is designed for motion control of the UG based on the data that go through computation at the system control board. 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.

This board consisted of ATmega128 that is an 8bit controller, two-channel DC motor driver, FET controlling the buoyancy controller and communication converter as in Figure 9.

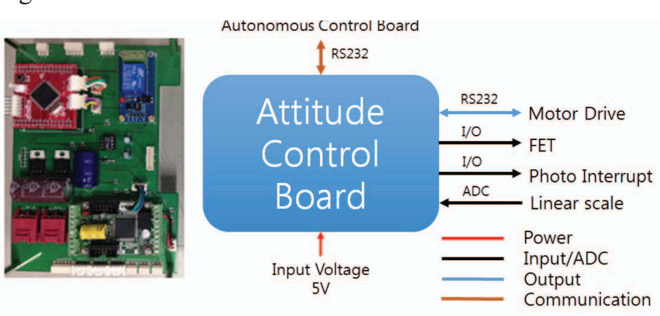

Fig. 9. Motion control board Composition control Diagrams of UG

The software of the designed UG is composed of 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. The navigation control part controlled heading angle so that peak can be tracked down in the line of sight style. Figure 10 shows the block diagram of sequential control structure.

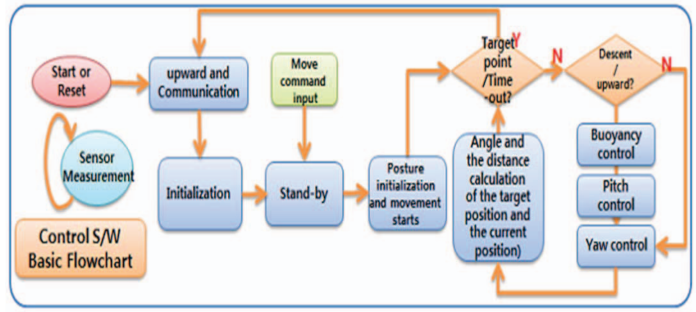

Fig. 10. Block diagram of sequential control structure of UG

III. PERFORMANCE TEST

A. UG test in the water tank

Before seawater test of the designed UG, 50m(L)x 25m(W)x3m(D) indoor swimming pool is used to test yaw motion performance through sinusoidal motion. Yaw motion performance of the UG was tested with 50m sailing at a 2.7m-deep pool with ascending limit of 0.5m and descending limit of 2.5m.

To control the yaw motion of the UG, a rotation control test for moving mass was carried out. The PD controller was used as a controller, and Figure 11 shows test results. Red lines on graph represent the desired angles of rotation position of mass and blue line represents real position angles of mass. The figure on the right side represents the rotation angle of UG according to the control of the roll angle of mass.

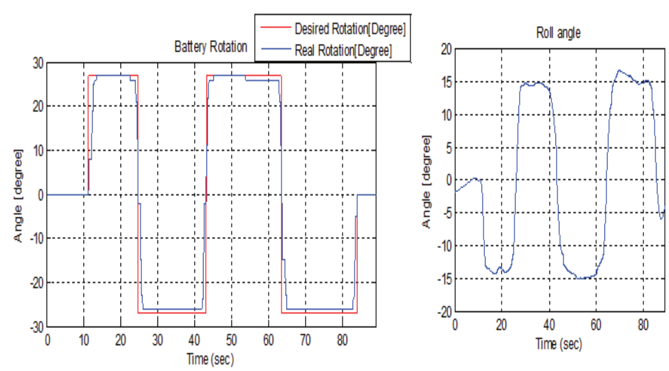

Fig. 11. Mass movement test results

A test of turn radius performance according to direction-steering control of a developed UG was carried out, and the process is shown in Figure 12. The test was carried out in two-dimensional wave tank of 100m(L)x3.5m(W)x2.5m(D). In consideration of a low depth of wave tank, the test was carried out with 1-meter upper limit and 2-meter lower limit for diving. In the time of rise and fall, a battery was rotated +/- 27 degrees clockwise. The vertical distance and horizontal distance of underwater glider traveled during the test were measured, and based on the results, the turning angle was estimated. Figure 13 represents the sensor data of the IMU over indoor swimming test.

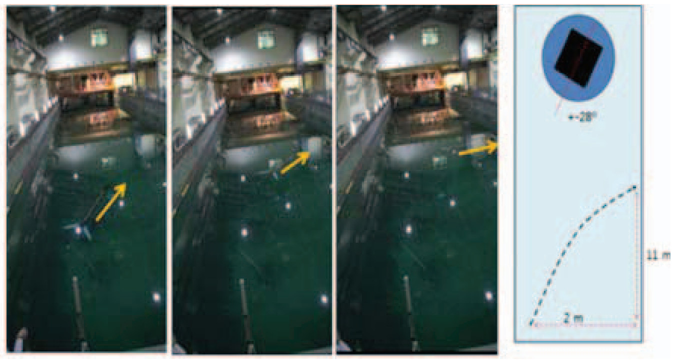

Fig. 12. Indoor swimming pool test

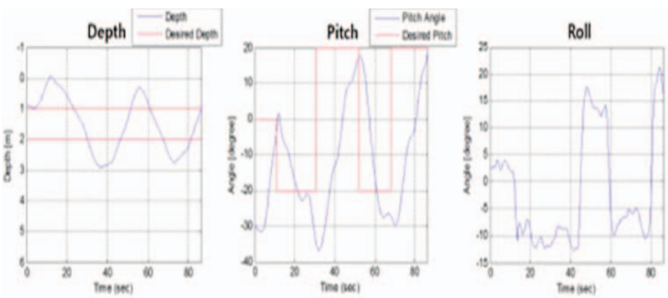

Fig. 13. Sensor data of the IMU overpool test

A distance traveled during rotation was calculated using a camera installed beside wave tank and the turn radius was estimated using Figure 14 and the calculation of the radius is 9.8m, which comes from $\frac{\sqrt{(11^2+2^2)/2}}{\sin(70/2)} = 9.8m$.

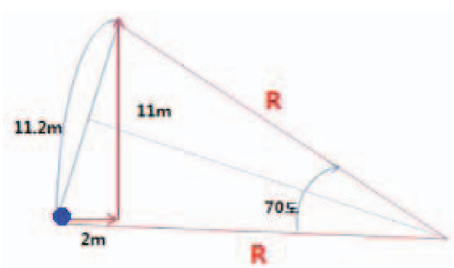

Fig. 14. Turn radius estimated of Underwater Glider

B. UG test in the sea

Tests of tracking the aiming point at a short distance of a developed UG, path tracking and seabed detection were carried out in the sea. The test was carried out in sea trial testing place (1km x 1km, 5 to 7m deep) of Korea Maritime and Ocean University. At the time of the test, air temperature was 15.2℃, wind speed was 2.3m/s, and wave height was 0.5 to 1.0m.In the first place, a path tracking test was designed to track three vertices at 100m intervals. The aiming point was designed to get within a distance of 30m radius from the aiming point by GPS. As the results of the test of avoiding collision with seabed, the fact that collision does not occur was identified by extracting sensor information about the distance between the water depth collected after a path tracking test according to an established collision avoidance program and the seabed measured using a depth sounder.

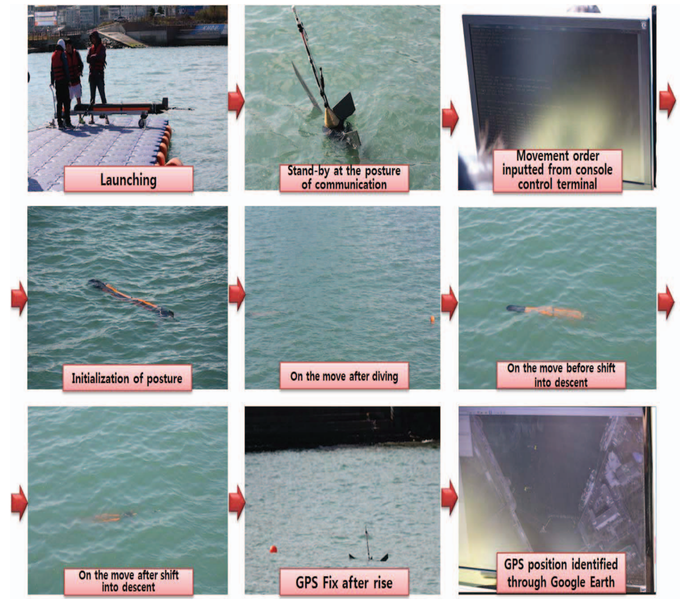

Fig. 15. Sea trial test procedures

The sea trial test procedures are shown at Figure 15. The first process is launching. The next process is standing-by at the posture of communication and inputting movement order from console control terminal. The next process shows initialization of posture, move after diving, move before shift into descent and move after shift into descent. The last process is GPS Fix after rise and identified the GPS position through Google Earth.

C. Path routing

As shown in Figure 16, path coordinates were established using Google Earth and these were stored in path routing file (/glider/wp/seatest.config) of underwater glider. Path was routed to be tracked in the order of WP00 -> WP01 -> WP03. As the results of moving, WP00 approached within 29m radius, and WP01 and WP02 entered within 17m and 20m radius successfully respectively.

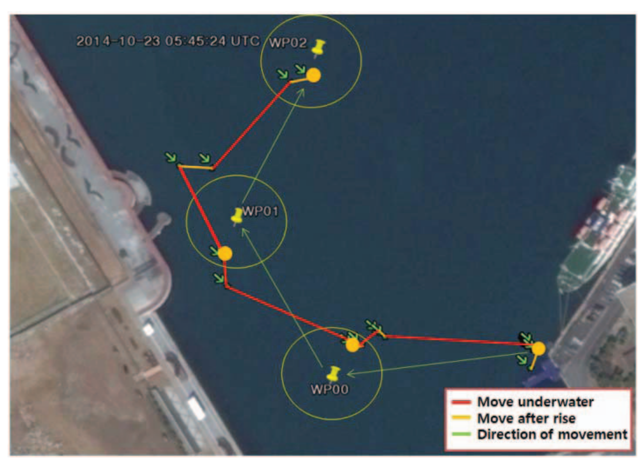

Fig. 16. Results of path tracking and moving

D. Test of avoiding collision with seabed

Results of investigating the information about water depth on the move and its distance with seabed measured through a depth sounder is shown in Figure 17. The red line represents the depth information of the depth sensor of the glider and the blue line represents the measured distance to seabed. It was found that a collision with seabed did not occur.

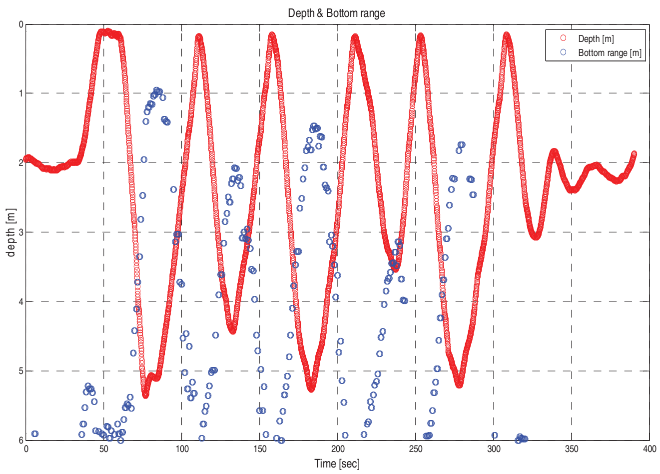

Fig. 17. Results of avoiding collision with seabed

IV. Conclusions

A control of new underwater glider having a high horizontal speed of the maximum 2.5(Knots) was studied. 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 horizontal motion of the UG was developed.

Through a wave tank test, the performance of a steering controller was tested, and it showed a successful result. A sea trial test was carried out. The test of the aiming point tracking and path tracking successfully entered within a certain radius. The performance of avoiding collision with seabed was identified based on the measurement of the distance with seabed by a depth sounder.

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