Mathematical Modeling and Experimental Test of Manta-type UUV

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***Abstract*-This paper describes the mathematical modeling, control algorithm, system design, hardware implementation and experimental test of a Manta-type Unmanned Underwater Vehicle (MUUV). The vehicle has one thruster for longitudinal propulsion, one rudder for heading angle control and two elevators for depth control. It is equipped with a pressure sensor for measuring water depth and Doppler Velocity Log for measuring position and angle. The vehicle is controlled by an on-board PC, which runs with the Windows XP operating system. The dynamic model of 6DOF is derived including hydrodynamic forces and moments acting on the vehicle, while the hydrodynamic coefficients related to the forces and moments are obtained from experiments or estimated numerically. We also utilized the values obtained from PMM (Planar Motion Mechanism) tests found in the previous publications for numerical simulations. Various controllers such as PID, Sliding mode, Fuzzy and H_∞ controllers are designed for depth and heading angle control in order to compare the performance of each controller based on simulation. In addition, experimental tests are carried out in towing tank for depth keeping and heading angle tracking.**

I. INTRODUCTION

Recently, unmanned underwater vehicles have been developed in order to prepare the change of ocean environments and underwater battlefield. To reinforce the naval power, it is necessary to develop the underwater guidance weapon system. The research of underwater vehicles which are applied various guidance system is proceeding [1]. The NUWC (Naval Undersea Warfare Center) has been developing a new type underwater warfare vehicle for the future undersea battlefield, and it was named MTV (Manta Test Vehicle) [2]. The MTV is normally a part of submarine but it can be used as a tool of data acquisitions and carry out missions such as surveillance, tactical oceanography, mine warfare, and anti-submarine warfare payloads.

This paper deals with design, implementation and test of MUUV(Manta-type Unmanned Underwater Vehicle) based on the concept of MTV. We have tried dynamic performance analysis and controller design using mathematical model of MUUV and have made experimental tests for comparing with simulation results.

II. SYSTEM DESIGN OF MUUV

The operating concept of the MUUV is a part of submarine then it operates in tactical area as shown in Fig. 1. Fig. 2 shows the appearance of MUUV for free running test and Fig. 3 describes the general arrangement of MUUV. In addition, table 1 describes specifications of the vehicle. The vehicle has 1 thruster for longitudinal direction and rudder and elevator for depth and heading control.

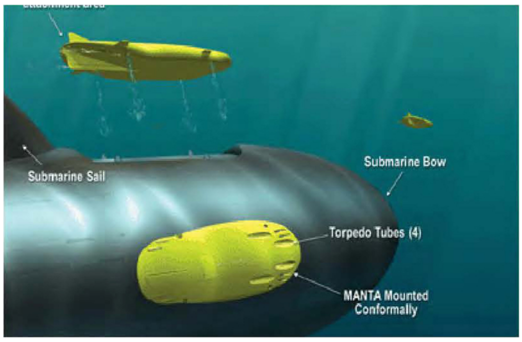

Figure 1. Operating concept of MUUV

Figure 2. Appearance of MUUV

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Figure 3. General arrangement of MUUV

TABLE 1
SPECIFICATIONS OF MUUV

Parameters	Specifications
Dimensions	1.5m × 0.55m × 0.26m
Weight	40kgf
Max. depth	10m
Max. speed	2m/s
Thruster	450watt x 1ea
Control mode	4DOF (Surge, Sway, Pitch, Yaw)
Computer	On-board PC (Intel Atom N450)
Sensors	Doppler velocity log Pressure sensor, Magnetic compass
Batteries	25.9V-6.6Ah Lithium polymer × 4ea
Communications	RS-232, Wireless LAN

A. *Thruster*

The vehicle's main thruster is mounted for longitudinal direction cruising. It has 450watts power consumption, 24volts input and 5.4kgf thrust force.

B. *Sensors*

To measure the vehicle's positions, depth and heading angle, DVL, pressure sensor and magnetic compass are implemented. Pressure sensor is manufactured by Measurement specialties and has 0.15% accuracy. It can measure 20 meters deep and its output is 1~5 analog voltage. Magnetic compass measure vehicle heading angle and its output is roll/pitch/yaw angle.

C. *Power*

The MUUV has 25.9V-6.6Ah lithium polymer battery for the thruster and the other system such as PC and sensors. This power system can operate the vehicle about 2 hours.

III. . MUUV MODELING

The mathematical model of underwater vehicle is comprised of vehicle body, thrusters and control surfaces. To simulate the 3-D motion, the mathematical model is presented with 6DOF equations of motion [3]. The hydrodynamic coefficients get from PMM (Planar Motion Mechanism) test and estimation[1, 4]. Abkowitz and Feldman presented equations of motion which are more close to a real situation [5, 6]. The motion of underwater vehicles is analyzed by considering two coordinate systems which are body-fixed frame and earth-fixed frame as shown in Fig. 4.

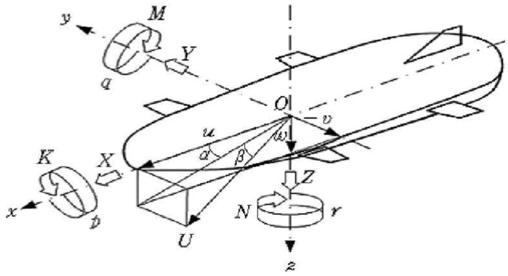

Figure 4. Coordinate system of MUUV

The proposed 6DOF mathematical model of MUUV is refered in [3] and the simulation program is developed using MATLAB/ SIMULINK as shown in Fig. 5. We analyzed the dynamic performances using the developed simulation program. Fig. 6 shows the 3-D underwater spiral descent trajectory.

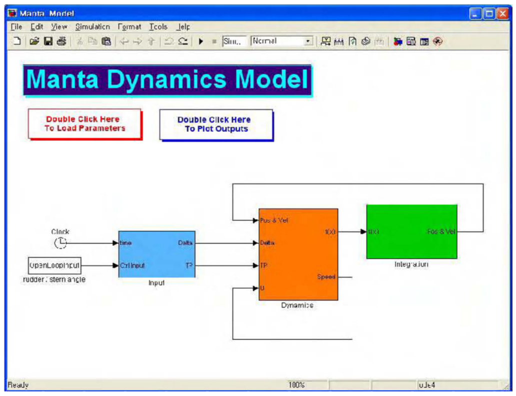

Figure 5. Simulation program of MUUV

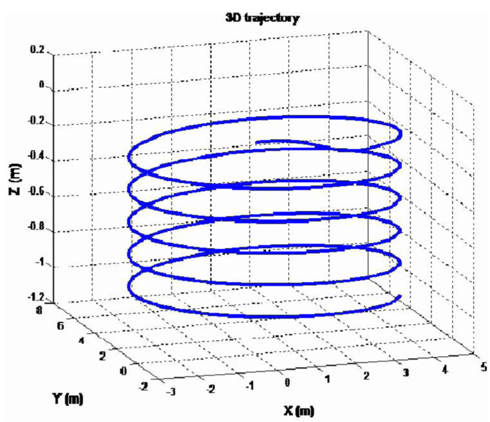

Figure 6. Dynamic performance of MUUV

IV. Controller Design

The MUUV needs a robust control system because the vehicle operates in rough environments of the ocean and the vehicle has to return to the submarine autonomously after the mission has completed. When using classical controller for underwater vehicle control, we have a good grasp of the vehicle's dynamic characteristics and all parameters of underwater vehicle is estimate by test and calculation. In this paper, modeling parameters were calculated and estimated from [1], and then PID, sliding mode, fuzzy and H_∞controller were designed by the mathematical model.

A. *Depth Control*

PID controller: Depth control by PID controller calculates elevator angle δs as follows. The desired depth is given 1m down from the initial depth during the 30 secs, and then returning back to the initial depth after 50 secs.

$$\delta_s(t) = K_p\left(z(t) - z_d\right) + K_\theta \theta(t) + K_q q(t) \tag{1}$$

Sliding mode controller: To design a controller in the vertical plane, the linearized diving system dynamics are developed. The sliding surface σ_s is defined as eq.(2) and the depth control law is determined as eq.(2).

$$\begin{aligned} \sigma_s &= 28.18\tilde{q} + 14.37\tilde{\theta} - \tilde{z} \\ \delta_s(t) &= 21.85q + 0.17\theta - 2.28\dot{z}_d + 5\tanh(\sigma_s/1.5) \end{aligned} \tag{2}$$

Fuzzy controller: Input parameters of fuzzy logic are depth error and time derivative of depth error. The control input(elevator angle) δs is calculated as follows.

$$\delta_s(t) = \textit{Depth Membership Function} \tag{3}$$

H_∞ controller: To design H_∞ controller for depth control. We have to decide weighting function about the linearized equation for overcome the model uncertainty and disturbance. The designed transfer function of depth control is as follows.

$$K(s) = \frac{0.004478s^4 + 44.79s^3 + 102s^2 + 112.2s + 67.68}{s^5 + 103.1s^4 + 309.6s^3 + 425s^2 + 356.9s + 109.9} \tag{4}$$

Fig. 7 shows the depth control simulation results using above 4 controllers.

B. *Heading Control*

PID controller: Heading control by PID controller calculates rudder angle δr as follows. The desired heading angle is 10° towards to starboard during the 30 seconds after first 20 seconds, after that returning to initial position with initial speed 1.0m/s.

$$\delta_r(t) = K_p\left(\psi(t) - \psi_d\right) + K_d r(t) \tag{5}$$

Sliding mode controller: To design a controller in the horizontal plane, the linearized steering system dynamics are developed. The sliding surface σ_r is defined as eq.(6) and the heading control law is determines as eq.(6). The δr is an input angle of horizontal plane for heading control.

$$\begin{aligned} \sigma_r &= 0.15\tilde{q} + 1.65\tilde{r} + \tilde{\psi} \\ \delta_r(t) &= 4.37v - 32.5r - 61.6\dot{\psi}_d + 1.8\tanh(\sigma_r/0.08) \end{aligned} \tag{6}$$

Fuzzy controller: Input parameters are heading angle error and time derivative of heading angle error. The rudder angle δr is calculated as follows.

$$\delta_r(t) = \textit{Heading Membership Function} \tag{7}$$

H_∞ controller: To design H_∞ controller for heading control. We have to decide weighting function about the linearized equation for overcome the model uncertainty and disturbance. The designed transfer function of heading control is as follows.

$$K(s) = \frac{-0.02449s^4 - 245s^3 - 613.1s^2 - 534.7s - 155.3}{s^5 + 104.5s^4 + 453.6s^3 + 855.4s^2 + 697.3s + 192} \tag{8}$$

Fig. 8 shows the heading control simulation results using above 4 controllers.

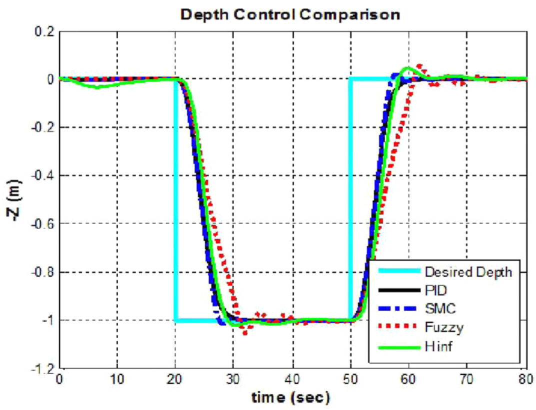

Figure 7. Depth control simulation results

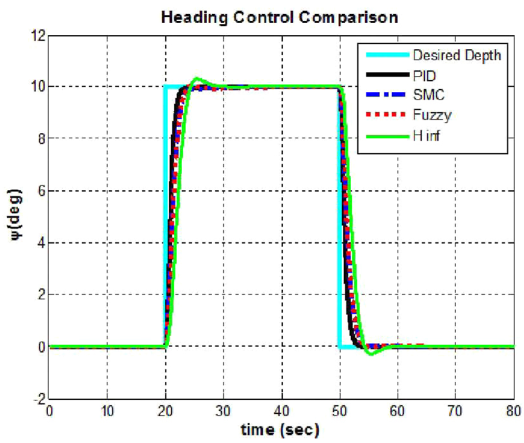

Figure 8. Heading control simulation results

V. FREE RUNNING TEST

To verify the depth and heading control simulation, free running tests were carried out in towing tank as shown in Fig. 9. The dimension of towing tank is 100m(L) x 8m(W) x 3.5m(D).

As the basic functions of MUUV test-bed, depth and heading control were tested using PID controller. The desired value is 50cm in depth control and 20° in heading control. Experimental result of depth control shows in Fig. 10 and heading control in Fig. 11. Depth control result has sensor noise of pressure sensor and heading control result has not good because magnetic compass is disturbed by magnetic field of the towing tank.

Figure 9. Free running test in towing tank

VI. CONCLUSIONS

This paper describes the design, implementation and test results of MUUV. The vehicle is test-bed for the comparison of the simulation results with free running test results. In simulation, we designed classical and modern controller such as PID, sliding mode, fuzzy and H_∞ controller. The free running tests were carried out in towing tank in order to compare with the simulation results for depth and heading control.

Experiment results are not good enough what we expect because of depth sensor noise and magnetic field of towing tank. Future work is that various controller will be adopt on the MUUV for free running test.

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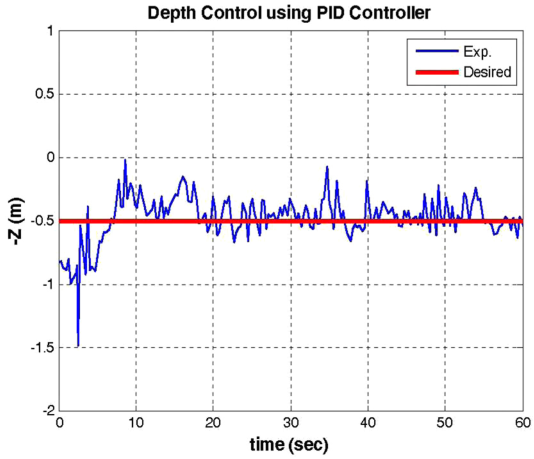

Figure 10. Depth control test using PID

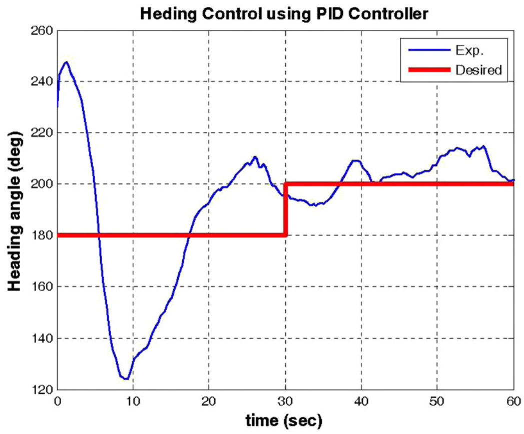

Figure 11. Heading control test using PID

REFERENCES

[1] Bae Jun-Young and Sohn Kyoung-Ho, "A Study on Maneuvring Motion Characteristics of Manta-type Unmanned Undersea Vehicle," *Journal of the Society of Naval Architects of Korea*, Vol. 46, No. 2, pp. 114-126, 2009

[2] Menozzi A., Gagliardi T.C. and Lyshevski S.E., "Dynamics and Control of MTV : a Multipurpose Unmanned Underwater Vehicle", *Proceedings of the American Control Conference Chicago*, Illinois, pp 70-74, 2000.

[3] Lee Seung-Keon, Sohn Kyoung-Ho, Byun Seung-Woo and Kim Joon-Young, "Modeling and controller design of manta-type unmanned underwater test vehicle", *Journal of Mechanical Science and Technology*, Vol.23 pp 987-990, 2009.

[4] Lee Seung-Keon, Sohn Kyoung-Ho, Lee Sang-Eui, Hwang Sung-Jun and Seo Jung-Ho, "A Study on the Oblique Towing Test of the Manta Type UUV," *Journal of Korean Navigation and Port Research*, Vol.29 No.8 pp.679-684, 2005.

[5] Abkowitz, Martin A., "Stability and Motion Control of Ocean Vehicles," *The MIT Press*, Cambridge, 1969.

[6] Feldman, J., "DTNSRDC Revised Standard Submarine Equation of Motion," *Report No. DTNSRDC/SPD-0393-09*, Washington, D.C., 1979.