International Journal of Ocean System Engineering 1(4) (2011) 192-197
http://dx.doi.org/10.5574/IJOSE.2011.1.4.192

Design, Implementation and Navigation Test of Manta-type Unmanned Underwater Vehicle†

Joon-Young Kim[1], Sung-Hyub Ko[2], Sohyung Cho[3], Seung-Keon Lee[4] and Kyoung-Ho Sohn[5]*

[1]*Division of Marine Equipment Engineering, Korea Maritime University, Busan 606-791, Korea*

[2] *Department of Ocean System Engineering, Jeju National University, Jeju 690-756, Korea*

[3] *Department of Industrial and Manufacturing Engineering, Southern Illinois University, Edwardsville, IL 62026-1805, USA*

[4] *Department of Naval Architecture & Ocean Engineering, Pusan National University, Busan 609-735, Korea*

[5]*Department of Naval Architecture & Ocean Engineering, Korea Maritime University, Busan 606-791, Korea*

(Manuscript Received October 2, 2011; Revised October 30, 2011; Accepted November 16, 2011)

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 the 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 $H\infty$ 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 a towing tank for depth keeping and heading angle tracking.

Keywords: Manta-type unmanned underwater vehicle, Mathematical model, Planar Motion Mechanism, Controller design

1. Introduction

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

This paper deals with the design, implementation and test of the MUUV (Manta-type Unmanned Underwater Vehicle) based on the concept of MTV. We have attempted dynamic performance analysis and controller design using a mathematical model

†This paper was presented at the ISOPE 2011 conference, Maui, Hawaii, USA, June 19-24, 2011.

*Corresponding author. Tel.: +82-51-410-4303, Fax.: +82-51-405-8305
E-mail address: sohnkh@hhu.ac.kr

of the MUUV and have made experimental tests for comparison with simulation results.

2. System Design of MUUV

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

To verify the performance of the rotor, various currents were generated and the rpm was measured as charted in Fig. 1.

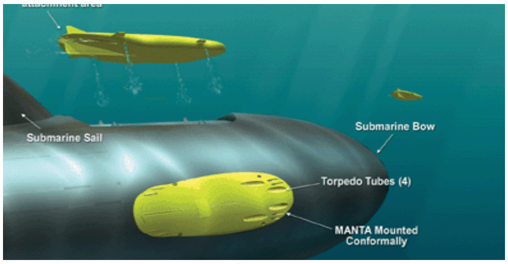

Fig. 1. Operating concept of MUUV

Fig. 2. Appearance of MUUV

Fig. 3. General arrangement of MUUV

Table 1. Specifications of MUUV

Parameters	Specification
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

2.1 Thruster

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

2.2 Sensors

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

2.3 Power

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

3. MUUV Modeling

The mathematical model of the underwater vehicle is comprised of a 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 are obtained 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 a body-fixed frame and earth-fixed frame as shown in Fig. 4.

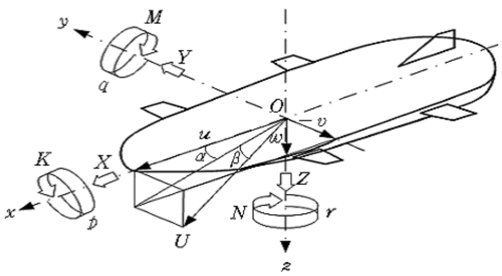

Fig. 4. Coordinate system of MUUV

The proposed 6DOF mathematical model of the MUUV is referred 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.

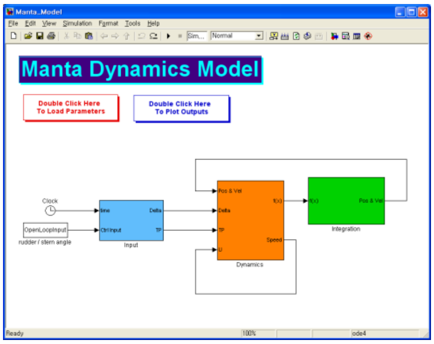

Fig. 5. Simulation program of MUUV

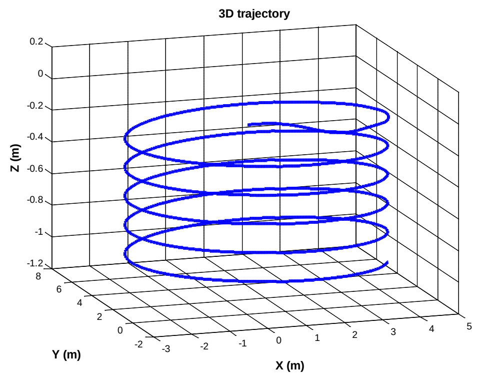

Fig. 6. Dynamic performance of MUUV

4. Controller Design

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

4.1 Depth Control

4.1.1 PID Controller

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

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

4.1.2 Sliding mode Controller

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

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

4.1.3 Fuzzy Controller

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

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

4.1.4 H_∞ Controller

To design the H_∞ controller for depth control, we need to decide the weighting function of the linearized equation to 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 the above 4 controllers.

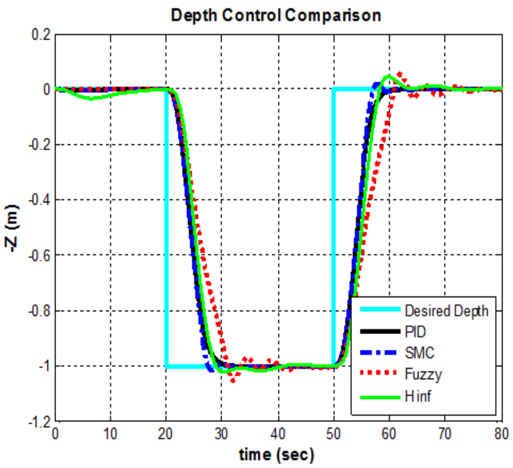

Fig. 7. Depth control simulation results

4.2 Depth Control

4.2.1 PID Controller

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

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

4.2.2 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 eg.(6) and the heading control law is determined as eq.(6). The δr is an input angle of the horizontal plane for heading control.

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

4.2.3 Fuzzy Controller

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

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

4.2.4 H_∞ Controller

To design the H_∞ controller for heading control, we need to decide the weighting function for the linearized equation to overcome the model uncertainty and disturbance. The designed transfer function of the 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 the above 4 controllers.

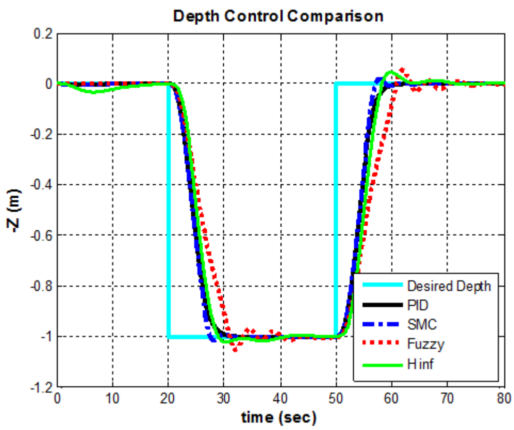

Fig. 8. Heading control simulation results

5. Free Running Test

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

As the basic functions of the MUUV test-bed, the depth and heading control were tested using the PID controller. The desired value is 50cm in depth control and 20˚ in heading control. The experimental result of the depth control is shown in Fig. 10 and the heading control is shown in Fig. 11. The depth control result shows the sensor noise of the pressure sensor and the heading control result is poor because the magnetic compass is disturbed by the magnetic field of the towing tank.

Fig. 9. Free running test in towing tank

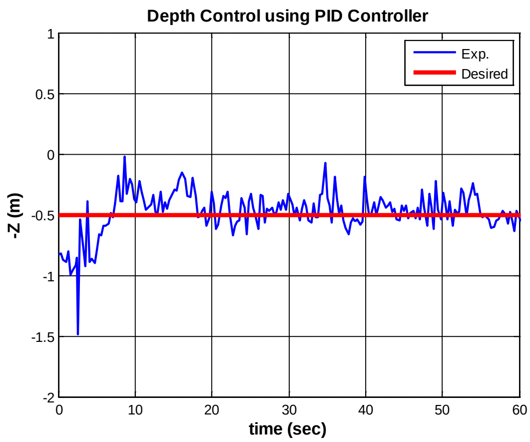

Fig. 10. Depth control test using PID

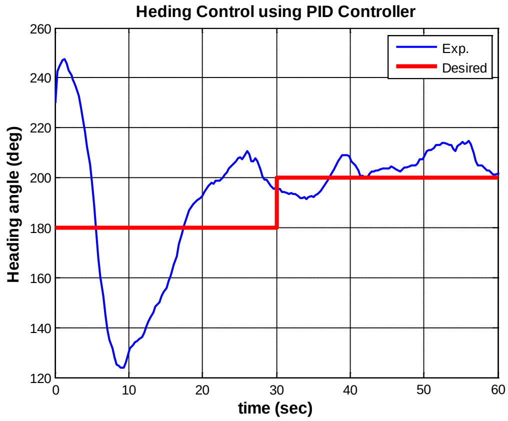

Fig. 11. Heading control test using PID

5. Conclusions

This paper describes the design, implementation and test results of the MUUV. The vehicle is tested for a comparison of the simulation results with the free running test results. In simulation, we designed classical and modern controllers such as PID, sliding mode, fuzzy and $H\infty$. The free running tests were carried out in a towing tank in order to compare with the simulation results for depth and heading control.

The experiment results are insufficient and not what we expected because of the depth sensor noise and magnetic field of towing tank. In future work, various controllers will be adopted on the MUUV for a free running test.

Acknowledgements

This research was supported by UVRC (Underwater Vehicle Research Center) and UTRC (Unmanned Technology Research Center) of ADD (Agency for Defense Development).

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, (2009) pp. 114-126.

[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, (2000) pp 70-74.

[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, (2009) pp 987-990.

[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, (2005) pp.679-684.

[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).