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DYNAMIC MODELING AND STRUCTURAL ANALYSIS OF MANTA-TYPE UUV

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This paper describes the dynamic modeling, structural analysis, implementation and experimental test of a Manta-type Unmanned Underwater Vehicle (MUUV). Various controllers such as PID, Sliding mode, and Fuzzy and H_∞ controllers are designed for depth and heading 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: Unmanned underwater vehicle; Mathematical model; Controller design.

1. Introduction

Recently, unmanned underwater vehicles have been developed in order to prepare for the change in ocean environments and underwater battlefield. To reinforce naval power, it is necessary to develop an underwater guidance weapon system. The NUWC (Naval Undersea Warfare Center) has been developing a new type of underwater warfare vehicle for future undersea battlefields, named MTV (Manta Test Vehicle).[1] The MTV is normally part of a submarine but it can be used as a tool of data acquisitions and can carry out missions such as surveillance, tactical oceanography, mine warfare, and anti-submarine warfare payloads. This paper deals with the dynamic modeling, structural analysis, implementation and testing of the MUUV (Manta-type Unmanned Underwater Vehicle) based on the concept of MTV. We have attempted a dynamic performance analysis and controller design using a mathematical model of the MUUV and have made experimental tests for comparison with simulation results.

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2. System Design of MUUV

The operating concept of the MUUV is part of a submarine when 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. The vehicle has 1 thruster for longitudinal direction and a rudder and elevator for depth and heading control.

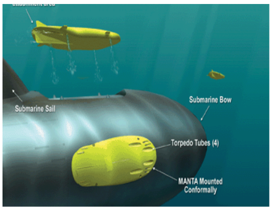

Fig. 1. Operating concept of MUUV.

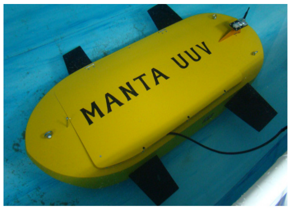

Fig. 2. Appearance of MUUV.

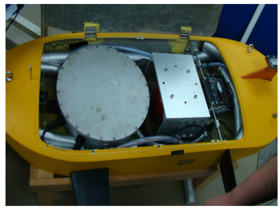

Fig. 3. General arrangement of MUUV.

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.[2] The hydrodynamic coefficients are obtained from the PMM (Planar Motion Mechanism) test and estimation.[3] The proposed 6DOF mathematical model of the MUUV is referenced in Ref. 2 and the simulation program is developed using MATLAB/SIMULINK.

4. Structural Analysis

Structural analysis of MUUV is achieved by the commercial finite element analysis program, ANSYS V13.0. The mechanical properties of the composite material are summarized in Table 1. Fig. 4 shows the result of the MUUV diving to a depth of 20 meters. The vehicle receives the water pressure of 202.65KPa, which is about 2 atm. The maximum deformation is 0.327cm, which occurred in the middle of the cover, and the maximum stress is 216.13MPa, which occured on left/right upper edges of the body.

Table 1. Composite material properties of MUUV.

Elastic modulus (GPa)	Poisson's ratio	Density (g/cm^3)	Tensile Strength (kg/mm^2)
181	0.28	1.9	7.8

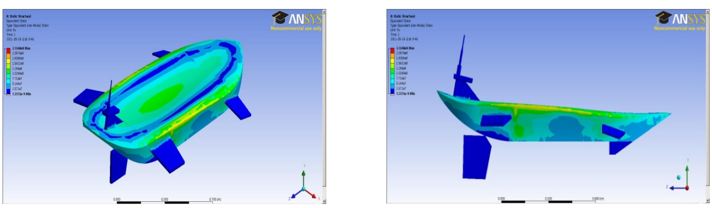

Fig. 4. Deformation and stress distribution of MUUV.

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5. 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 is completed. In this paper, the PID, sliding mode, fuzzy and H∞ controller were designed by the mathematical model.

PID controller: The depth and the heading control by the PID controller calculate the elevator angle δs and the rudder angle δr as follows.

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

$$\delta_r(t) = K_p\left(\psi(t) - \psi_d\right) + K_d r(t). \tag{2}$$

Sliding mode controller: The sliding surface σ_s and σ_r are defined as Eq. (3) ~ (4) and the depth and the heading control laws are determined as follows.

$$\begin{aligned} \sigma_s &= 28.18\tilde{q} + 14.37\tilde{\theta} - \tilde{z} \\ \delta_s(t) &= 21.85q + 0.17\theta - 2.28\dot{z}_d + 5\tanh(\sigma_s/1.5) \end{aligned}. \tag{3}$$

$$\begin{aligned} \sigma_r &= 0.15\tilde{q} + 1.65\tilde{r} + \tilde{\psi} \\ \delta_r(t) &= 4.37v - 32.5r - 61.6\dot{\psi}_d + 1.8\tanh(\sigma_r/0.08) \end{aligned}. \tag{4}$$

Fuzzy controller: Input parameters of fuzzy logic are the error and the time derivative of the error. The control inputs δs and δr are calculated as follows.

$$\delta_s(t) = \mathit{Depth\ Membership\ Function}. \tag{5}$$

$$\delta_r(t) = \mathit{Heading\ Membership\ Function}. \tag{6}$$

H∞ controller: To design the H∞ controller for depth and heading control, we need to decide the weighting function for the linearised equation. The designed transfer function of the depth and the heading control are as follows.

$$K_{depth}(s) = \frac{0.004478s^4 + 44.79s^3 + 102s^2 + 112.2s + 67.68}{s^5 + 103.1s^4 + 309.6s^3 + 425s^2 + 356.9s + 109.9}. \tag{7}$$

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

Fig. 5 and 6 show that the proposed 4 controllers have similar performance. It is noted that PID controller has good performance and is convenient for hardware implementation.

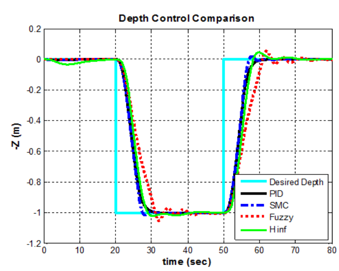

Fig. 5. Depth control simulation results.

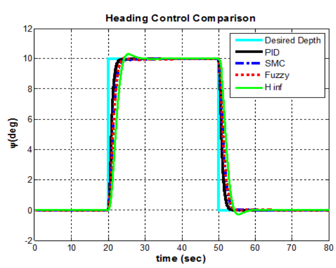

Fig. 6. Heading control simulation results.

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6. 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. 7. As the basic functions of the MUUV test-bed, 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 depth control is shown in Fig. 8 and that of heading control is shown in Fig. 9. The results show that the vehicle follows the desired depth and heading angle with some disturbance.

Fig. 7. Free running test.

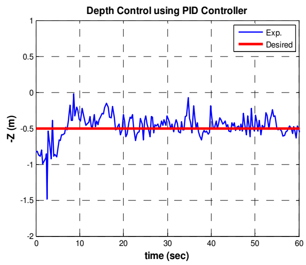

Fig. 8. Depth control test using PID.

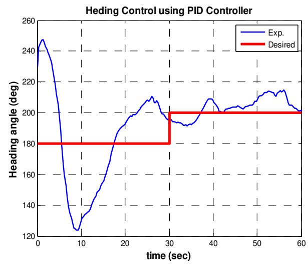

Fig. 9. Heading control test using PID.

7. Conclusions

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

Experiment results are poorer than what we expected because of the depth sensor noise and the magnetic field of the towing tank. In future work, various controllers will be adopted on the MUUV for a free running test.

Acknowledgments

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