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Modeling and controller design of manta-type unmanned underwater test vehicle †

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Abstract

This paper describes the mathematical model and controller design for Manta-type unmanned underwater test vehicle (MUUTV) with 6 DOF nonlinear dynamic equations. The mathematical model contains hydrodynamic forces and moments expressed in terms of a set of hydrodynamic coefficients which were obtained through the PMM (planar motion mechanism) test. Based on the 6 DOF dynamic equations, numerical simulations have been performed to analyze the dynamic performance of the MUUTV. In addition, using the mathematical model PID and sliding mode controller are constructed for the diving and steering maneuver. Simulation results show that the control performance of the MUUTV compared with that of NPS (Naval Postgraduate School) AUV II.

Keywords: Manta-type unmanned underwater test vehicle; Mathematical model; Planar motion mechanism; Controller design

1. Introduction

The unmanned underwater vehicle (UUV) has two kinds of purposes. One is a non-military purpose; it can be used in deep sea terrain for survey, mineral resources investigation and underwater structure maintenance. The other is a military purpose; for example, MDV (mine disposal vehicle) and underwater precision-guided munitions. Since 1996 the US Navy's NUWC (Naval Undersea Warfare Center) has been developing a concept for undersea warfare in the new century. This new unmanned undersea vehicle is called MTV (Manta Test Vehicle) [2]. These vehicles are intended to be multi-mission, re-configurable UUVs that will be capable of carrying surveillance, tactical oceanography, mine warfare, and anti-submarine warfare payloads. This MTV can be used as a tool of data acquisition and mission prosecution, but normally the MTV is a part of a submarine.

This paper deals with the dynamic and control performance of the MUUTV (Manta-type unmanned underwater test vehicle) using a mathematical model including hydrodynamic coefficients. Section 2 develops a 6DOF mathematical model using hydrodynamic coefficients from a PMM (planar motion mechanism) test. Section 3 designs simulation program based on modeling. Section 4 discusses the control performance of the MUUTV. Finally, Section 5 presents the conclusions.

2. Mathematical model

The mathematical model of an underwater vehicle is comprised of a vehicle body, thrusters and control surfaces. To simulate the 3-dimensional motion, the mathematical model is presented with 6DOF equations of motion with hydrodynamic coefficients [6].

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Table 1. Principal dimensions of MUUTV.

Parameters	Dimensions
Length (m)	12
Breadth (m)	4.4
Height (m)	1.2
Displacement (m^3)	31.88

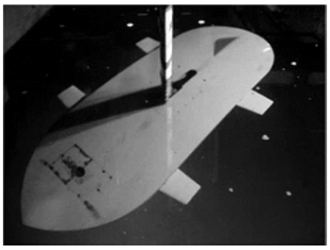

Fig. 1. MUUTV captive model for PMM test.

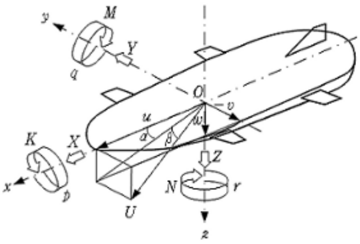

Fig. 2. Coordinate system and notations of MUUTV.

Table 1 shows the principal dimensions of the MUUTV, and Fig. 1 represents a captive model for estimating the hydrodynamic coefficients through the PMM test in a towing tank.

The related research on the modeling is as follows. Gertler and Hagen announced standard equations of motion of submarine simulation in an NSRDC report [8]. Based on the standard equations of motion, Abkowitz and Feldman presented equations of motion which are more close to a real situation [4,7]. Healey and Lienard presented equations of motion about NPS AUV II [1].

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. 2. The 6DOF equations of motion are represented in [6] where the external forces and moments are based on [4] and the hydrodynamic coefficients are estimated from the PMM test.

3. Simulation program

A simulation program was developed with the proposed mathematical model by using MATLAB/ SIMULINK as shown in Fig. 3.

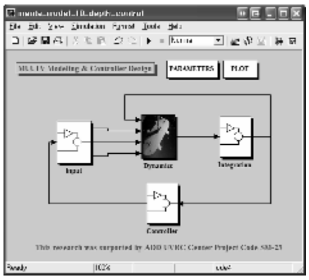

Fig. 3. Simulink model for MUUTV.

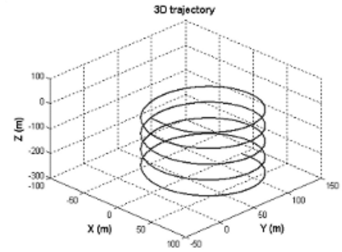

Fig. 4. Dynamic performance of the MUUTV.

The controller block is composed of a sliding mode controller and a PID controller for the depth and heading control. Using the developed simulation program we analyzed the dynamic performance. The MUUTV has an initial speed of 2.5 m/s and the rudder/elevator angle is applied 30° from the start. Fig. 4 shows the three-dimensional trajectory.

4. Controller design

The MUUTV 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 is completed. In this paper, modeling parameters were calculated and estimated from [6]. Then, the PID controller and sliding mode controller were designed by MATLAB/ SIMULINK [3, 5]. Designed controllers were applied to the MUUTV and the NPS AUV II [1].

4.1 Depth control

4.1.1 PID controller

Depth control by PID controller calculates elevator angle δs as follows.

$$\delta_s(t) = K_P(Z(t) - Z_d) + K_\theta \theta(t) + K_q q(t) \quad (1)$$

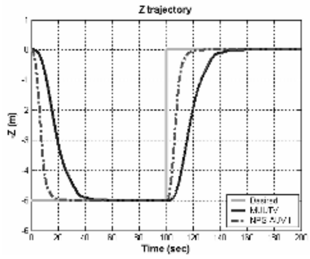

Fig. 5. Depth control result using PID controller.

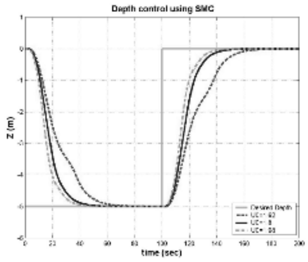

Fig. 6. Depth control result using sliding mode controller.

Fig. 5 shows the simulation results of the PID controller, which was applied to two vehicles of MUUTV and NPS AUV II.

The desired depth is 5m down from the initial depth during the first 100 seconds, and then it returns to the initial depth thereafter with an initial speed of 1.8 m/s. The NPS AUV II converges faster to the desired depth than MUUTV because AUV II has a slender body relative to MUUTV.

4.1.2 Sliding mode controller

To design a controller in the vertical plane, the linearized diving system dynamics are developed as follows.

$$\begin{aligned} (I_y - M_{\dot{q}})q &= M_q q - z_G W\theta + M_{\delta s}\delta_s \\ \dot{\theta} &= q \\ \dot{Z} &= -u\theta \end{aligned} \tag{2}$$

Then the dynamic model for depth control yields the state equation as (3). The δ_s is an input angle of vertical plane for depth control.

$$\begin{bmatrix} \dot{q} \\ \dot{\theta} \\ \dot{Z} \end{bmatrix} = \begin{bmatrix} -0.2648 & -0.0902 & 0 \\ 1 & 0 & 0 \\ 0 & -1.8 & 0 \end{bmatrix} \begin{bmatrix} q \\ \theta \\ Z \end{bmatrix} + \begin{bmatrix} 0.0158 \\ 0 \\ 0 \end{bmatrix} \delta_s \tag{3}$$

The sliding surface is defined as

$$\sigma_s(t) = -27.96\tilde{q} - 14.12\tilde{\theta} - \tilde{Z} \tag{4}$$

when the poles are placed at [0 -0.25 -0.26]. Finally, the depth control law is determined as follows.

$$\delta_s = 21.85q + 0.171\theta - 2.28\dot{Z}_d + 5\tanh(\sigma_s / 1.5) \tag{5}$$

Fig. 6 shows depth control simulation results using the sliding mode controller. The simulation scenario is the same with the PID controller. In addition, the initial speed was changed within ±10%. This result means that the sliding mode control is robust even though the initial speed is varied.

4.2 Heading control

4.2.1 PID controller

Heading control by PID controller calculates rudder angle δ_r using (6). Fig. 7 shows heading control simulation results using the PID controller. Heading control simulation is compared with NPS AUV II. The desired heading angle is 30° towards to starboard during the first 100 seconds, after that returning to initial position with initial speed 1.8m/s.

$$\delta_r(t) = K_P(\psi(t) - \psi_d) + K_d r(t) \tag{6}$$

Simulation results show the NPS AUV II has more rapid motion responses than MUUTV, as shown in Fig. 7. The AUV II converges to the desired heading angle 30° within 25 seconds and MUUTV converges to the desired angle in about 40 seconds.

4.2.2 Sliding mode controller

To design a controller in the horizontal plane, the linearized steering system dynamics are given as (7).

Then, the dynamic model for heading control yields the state equation as (8). The δr is an input angle of horizontal plane for heading control.

$$\begin{aligned} (m - Y_{\dot{v}})\dot{v} - Y_{\dot{r}}\dot{r} &= Y_v v + (Y_r - mu)r + Y_{\delta_r}\delta_r \\ -N_{\dot{v}}\dot{v} + (I_z - N_{\dot{r}}\dot{r}) &= N_v v + N_r r + N_{\delta_r}\delta_r \\ \dot{\psi} &= r \end{aligned} \tag{7}$$

$$\begin{bmatrix} \dot{v} \\ \dot{r} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} -0.1074 & -1.221 & 0 \\ -0.0066 & -0.1706 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v \\ r \\ \psi \end{bmatrix} + \begin{bmatrix} -0.0069 \\ 0.0123 \\ 0 \end{bmatrix} \delta_r \tag{8}$$

The values to place the poles of the steering system at [0 -0.35 -0.36] become (9).

$$\sigma_r(t) = 0.3762\tilde{v} + 1.0959\tilde{r} - 2\tilde{\psi} \tag{9}$$

The heading control law is as follows.

$$\delta_r = 4.378v - 32.5068r - 61.6032\psi_d + 1.8\tanh(\sigma_r / 0.08) \tag{10}$$

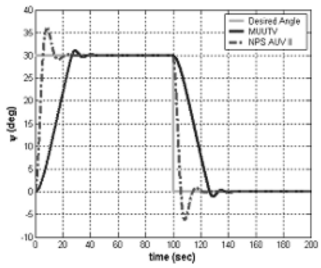

Fig. 7. Heading control result using PID controller.

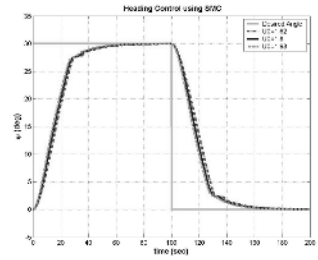

Fig. 8. Heading control result using sliding mode controller.

Fig. 8 shows the heading control results with the sliding mode controller. Simulation condition is to start from the current position turning 30° to starboard during 100 seconds and after that turning to the first position with initial speed 1.8m/s. Similarly, the initial speed was varied within ±10%. This case also shows the robustness of sliding mode controller.

5. Conclusions

In this paper, we developed 6DOF equations of motion of the MUUTV with hydrodynamic coefficients from a PMM test. Also, a simulation program of MUUTV was constructed based on the mathematical model. In addition, depth and heading controller were designed with PID and sliding mode algorithm. Designed controllers were applied to the MUUTV and the NPS AUV II for comparing the control performance. These simulation results can be used to analyze motion performance about MUUTV.

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