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Development of Hovering AUV Test-bed for Underwater Explorations and Operations

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Abstract

This paper describes the design and control of a hovering AUV test-bed and analyzes the dynamic performance of the vehicle using simulation programs. The main purpose of this vehicle is to carry out fundamental tests of its station keeping, attitude control, and desired position tracking. Its configuration is similar to the general appearance of an ROV for underwater operations, and its dimensions are 0.75 m × 0.5 m × 0.5 m. It has four 450-W thrusters for longitudinal/lateral/vertical propulsion and is equipped with a pressure sensor for measuring the water depth and a magnetic compass for measuring its heading angle. The navigation of the vehicle is controlled by an onboard Pentium III-class computer, which runs with the help of the Windows XP operating system. This provides an appropriate environment for developing the various algorithms needed for developing and advancing a hovering AUV.

Keywords: Hovering AUV, Station Keeping, Attitude Control, Position tracking, Navigation

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1. Introduction

In recent years, there have been intensive efforts to develop URVs (Underwater Robotic Vehicles) for oceanic development. In particular, URVs are indispensable for collecting ocean data, subsea investigation, subsea construction, and the repair/maintenance of marine structures. In the past, URVs were used strictly for scientific research and military applications. However, the demand for URVs has gradually increased, which has prompted the development of highly effective URVs in previous studies.

URVs are typically divided into AUVs (Autonomous Underwater Vehicles) and ROVs (Remotely Operated Vehicles). An AUV is used mainly for long-distance traveling, and an ROV is used for work in a specific area. At present, researchers have developed URVs that combine the respective efficiencies of the AUV and ROV, such as the autonomous navigation capacity of an ROV (Negahdaripour and Madjidi 2003, Smallwood and Whitcomb 2003, Bulich, Klein, Watson, and Kitts 2004) and the ability of an AUV to work in a specific area (Marks, Rock and Lee 1995, Kim and Yuh 2001). For an AUV that is used for work in a specific area, attitude control and station keeping are very important functions. We call this a hovering AUV. This paper describes the design and development of a hovering AUV developed at Korea Maritime and Ocean University. The main purpose of this vehicle is to serve as a test-bed for testing the dynamic performance of a controller and sensors, with the goal of developing a more efficient hovering AUV.

2. Vehicle Design Goals

In the AUV design procedures, the mission is decided first; then, a suitable shape, payload,

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operating depth, and cruising speed that correspond to the mission are chosen. The hull shape of the AUV is determined according to the mission, and the payload contains the weight of the sensors and propulsion systems. The operating depth is determined by considering the design of a pressure can. The cruising speed must accommodate the estimated drag, thrust, and hydrodynamic coefficients.

The design goal for this hovering AUV is to act as a test-bed for testing the capacity of its cruising autonomy and the performance of its sensors and controllers in a water tank. The principal objective of the test-bed is to serve as a convenient, cost-effective platform for the research, development, and experimental validation of control systems, navigation techniques, and control algorithms for the vehicle. The vehicle design goals are listed in Table 1.

Table1 Vehicle design goals

Parameters	Specifications
Hull	Frame Type
Dimension	0.75 m × 0.5 m × 0.5 m
Weight	50 kgf (in air)
Max. Depth	10 m
Max. Speed	2 m/s
Thrusters	450 watt × 4
Control	4 DOF (Surge, Sway, Heave, Yaw)
Computer	Onboard PC (Pentium III 700MHz)
Sensors	Pressure, Compass, LBL, Sonar
Power	12V-12AH Lead Acid Battery × 5EA
Communication	RS-232/485, Ethernet

3 Vehicle Configurations

The entire structure of the hovering AUV is shown in Fig. 1, and the completed frame structure is like that shown in Fig. 2. The mission of the hovering AUV is to be a test-bed for the development of attitude/position control algorithms and performance tests of the sensors. The body shape of this AUV was determined by considering the mission; this shape has the advantage of providing more spaces for additional sensors. It also has one vertical thruster, one lateral thruster, and two longitudinal thrusters, which control the 4-DOF motions. An LBL (Long Base Line) system grasps the exact position of the AUV in the water tank, and a sonar system is used for obstacle avoidance.

In the AUV design procedures, the mission is decided first; then the suitable shape, payload, operating depth, and cruising speed that correspond to the mission are chosen. The hull shape of the AUV is determined according to the mission, and the payload contains the weight of the sensors and propulsion systems. The operating depth is determined by considering the design of a pressure can. The cruising speed must accommodate the estimated drag, thrust, and hydrodynamic coefficients.

3.1 Hull

The hull shape of the AUV is similar to the general ROV structure shown in Fig. 3. This structure is convenient for mounting equipment and is an efficient use of space. The dimensions are 0.75 m × 0.5 m × 0.5 m, which form a rectangular parallelepiped shape. The frame material is stainless steel to prevent rusting, and the buoyancy material is extruded polystyrene foam. The bottom space carries loads and a can that is made of acrylic because this AUV is not exposed to high pressure.

Fig. 1 Overview of hovering AUV

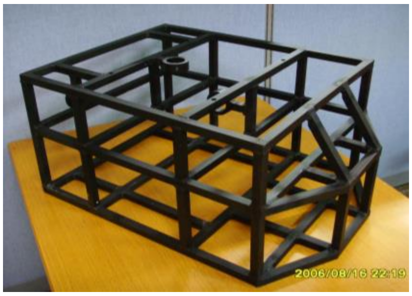


Fig. 2 Frame structure

Fig. 3 Hull shape

Fig. 4 Thrusters

3.2 Thrusters

The thrusters use brushless DC motors manufactured by Tecnadyne Inc. (Fig. 4). A 24-V DC power supply is needed, and the maximum power consumption is 450 W. The bollard output of the thrusters is about 8.2 kgf forward. Two thrusters are used for the forward direction, and the other two thrusters are used for the vertical/lateral directions. These thrusters can produce 4-DOF motions.

3.3 Sensors

The pressure sensor and magnetic compass are used to measure the depth and direction of the AUV (Figs. 5 and 6), respectively. The range of the pressure sensor is 0–20 m, and it has an accuracy of 0.1%. It produces an RS-485 signal. The maximum tilt range of the magnetic compass is 50°. It has an accuracy of ±0.4° and a resolution of 0.3°. The magnetic compass uses an RS-232 signal for communication; it has a size of 6.3 cm × 5 cm × 3.1 cm and offers roll/pitch/yaw signals. Later, an LBL (Long Base Line) system for measuring the position of the AUV and a sonar system for avoiding obstacles will be affixed (Figs. 7 and 8).

3.4 Computer

The AUV uses an onboard PC for the real-time control and monitoring of all of its sensors and thrusters (Fig. 9). This computer is 10 cm × 9 cm in size; the CPU is a Pentium III running at 700 MHz. RS-232/485 and Ethernet links are used for communication, along with an I/O board. The operating system of the AUV is Windows XP, and the control program was written in C/C++.

4 Analysis of Dynamic Performance

In order to design an AUV, it is usually necessary to analyze its maneuverability and controllability based on a mathematical model. The mathematical model for most of the 6 DOFs contains hydrodynamic forces and moments expressed in terms of a set of hydrodynamic coefficients. Gertler and Hagen (1967) adjusted an equation of motion that is a standard for the motion analysis of a submarine. Feldman (1979) presented a modified equation of motion that approximates the real motion. Fossen (1994) proposed a model for the design of a nonlinear controller system for underwater vehicles. Healey and Lienard (1993) proposed nonlinear equations of motion and specific hydrodynamic coefficients for 6 DOFs.

Fig. 5 Pressure sensor

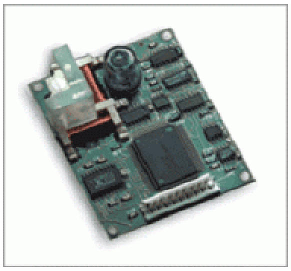


Fig. 6 Magnetic compass

Fig. 7 Sonar system

Fig. 8 LBL system

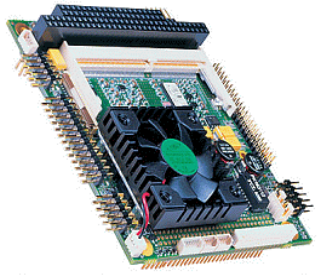


Fig. 9 Onboard PC

In this paper, nonlinear equations of motion are used to describe the analyses of all of the motion conditions of the hovering AUV. Thereafter, a simulation program is developed that is able to solve the equations of motion and then analyze the performance of the hovering AUV under a variety of pressures and environments.

4.1 Equations of Motion

The 6-DOF equations of motion were used for analyzing the performance of the hovering AUV. The coordinate system uses earth-fixed coordinates and body-fixed coordinates: the x axis is the bow, the y axis is starboard, and the z axis is downward. The 6-DOF model describes the surge, sway, heave, roll, pitch, and yaw, and the general 6-DOF model is as follows in Eq. 1. In this paper, this hovering AUV has neutral buoyancy, with the origin of the coordinates located in the center of buoyancy. The 6 DOFs are described by Eq. (1), which assumes a symmetrical body. Eq. (2) is a state-space form described by Eq. (1); M is an inertia matrix, X' is the external force and moment, and X_m is the inertial force and moment. Kim, Kim, Choi, Seong, and Lee (2002) describe this in detail.

$$
\begin{aligned}
& m\left[\dot{u}-vr+wq+z_G(pr+\dot{q})\right]=X \\
& m\left[\dot{v}+ur-wp+z_G(qr-\dot{p})\right]=Y \\
& m\left[\dot{w}-uq+vp-z_G(p^2+q^2)\right]=Z \\
& I_x\dot{p}+(I_z-I_y)qr-mz_G(\dot{v}+ur-wp)=K \\
& I_y\dot{q}+(I_x-I_z)pr+mz_G(\dot{u}-vr+wq)=M \\
& I_z\dot{r}+(I_y-I_x)pq=N
\end{aligned} \qquad (1)
$$

$$
\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{p} \\ \dot{q} \\ \dot{r} \\ \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix}
=[M]^{-1}
\begin{bmatrix} X'+X_m \\ Y'+Y_m \\ Z'+Z_m \\ K'+K_m \\ M'+M_m \\ N'+N_m \\ p+q\sin\phi\tan\theta+r\cos\phi\tan\theta \\ q\cos\phi-r\sin\phi \\ (q\sin\phi+r\cos\phi)\sec\theta \end{bmatrix} \qquad (2)
$$

4.2 Simulation Program

The simulation program for analyzing the performance of the AUV was designed in Matlab/Simulink and developed on the basis of the 6-DOF equation of motion. Fig. 10 shows a Simulink model for simulating the AUV, where each block is composed of subblocks. Because it provides a graphic environment, this modulation method makes it easy to grasp whole structures and makes it convenient to extend and modify the models.

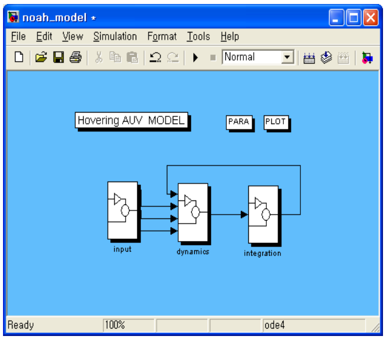


Fig. 10 Simulation program

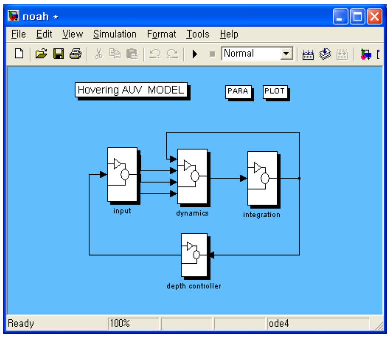


Fig. 11 Controller design

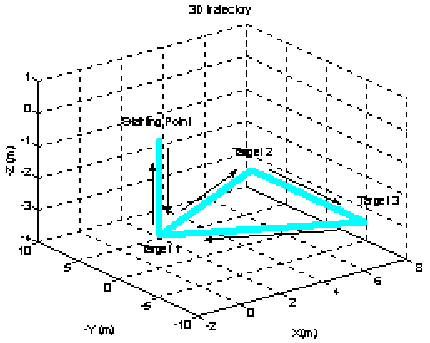


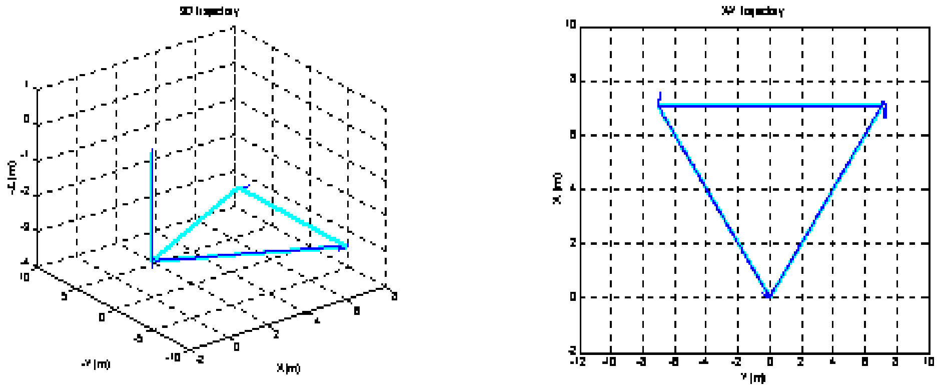
Fig. 12 Simulation condition: desired trajectory

5. Controller Design

The AUV demands robust control systems because it must be able to both return on a path and finish the mission while autonomously cruising in an uncertain ocean environment. The hydrodynamic coefficients of the AUV are changed by the dynamic characteristics such as the cruising speed and attitude and angles of the rudder and elevator. Therefore, a classical control algorithm will not guarantee robustness because the control gain must be scheduled during any change in the cruising state.

Recently, it has been shown that the position and attitude of an AUV can be successfully controlled using new control techniques, especially the sliding mode and fuzzy controller. Yoerger and Slotine (1985) controlled an ROV using a sliding mode control. Cristi, Papoulias, and Healey (1990) controlled the vertical motion of an AUV using a sliding mode controller. Marco and Healey (2001) studied the control of the speed, depth, and direction with a sliding mode controller. Lee, Hong, Lim, Lee, Jeon, and Park (1999) designed a discrete-time quasi-sliding mode controller and applied it to Lea, Allen and Merry (1999), and Smith, Rae, Anderson and Shein (1994) designed a fussy controller to control the depth and position. A PID controller was designed for navigation control, which combined the attitude and position controls of the AUV. The designed controller is shown in Fig. 11.

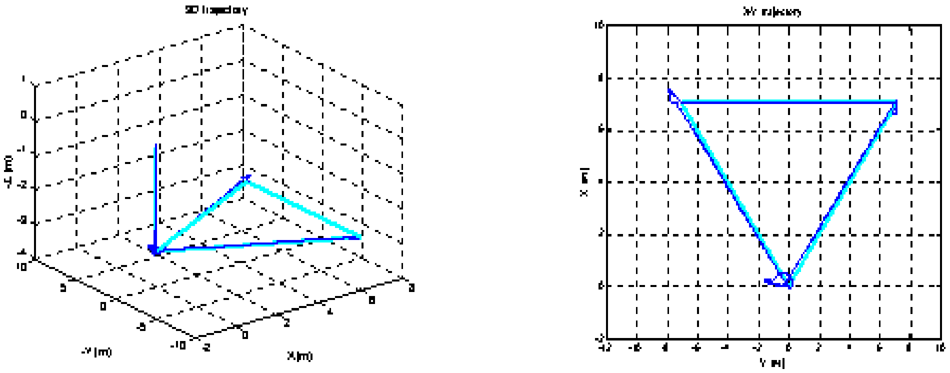
The designed PID controller, which is composed of attitude and position controls, was tested in a simulation. Fig. 12 shows the desired trajectory. The objective is to move to target 1 and then maintain the attitude and position; thereafter, it should pass through Target 2, Target 3, and Target 1, and then return to its initial position. The cruising speed is 1.0 m/s. The simulation results are compared with the results for a case that had no modeling error (Fig. 13), a case that included the current (Fig. 14), and a case that included sensor noise (Fig. 15). In the case without disturbance and sensor noise, the attitude and position control of the hovering AUV were handled well, but in the cases that had disturbance by the current and about 10% sensor noise, the hovering AUV drifted from the desired tracking trajectory.



(a) 3-D trajectory

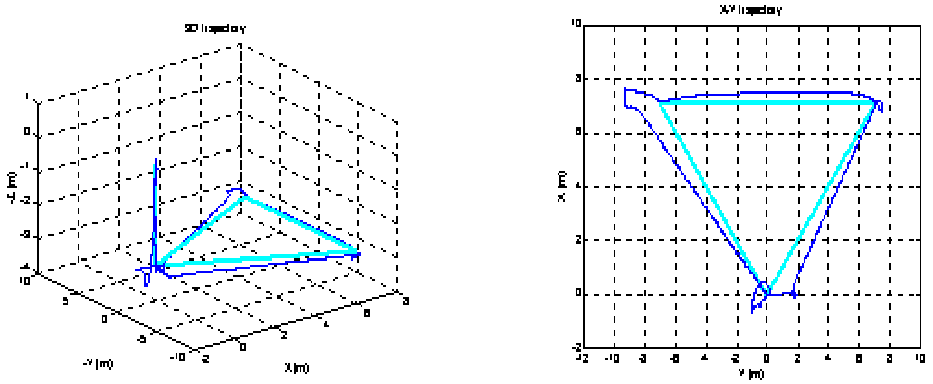
(b) X-Y trajectory

Fig. 13 Simulation results with nominal model



(a) 3-D trajectory (b) X-Y trajectory

Fig. 14 Simulation results under disturbance



(a) 3-D trajectory (b) X-Y trajectory

Fig. 15 Simulation results with sensor noise

6. Conclusions

This paper described the design and development of a hovering AUV constructed at Korea Maritime and Ocean University, which has the main goals of maintaining its attitude and position and moving to a desired attitude and position. This hovering AUV will be used as a test-bed to test propulsion systems and measuring instruments in order to actualize these abilities and improve their capacities.

To analyze the dynamic performance of the hovering AUV, the 6-DOF equations of motion were derived, and a simulation program was designed with these equations. At the same time, a PID controller was designed to control the attitude and position of the hovering AUV, its performance was analyzed by using a simulation program.

Future work will apply the designed controller to a real hovering AUV and test its performance. In addition, developing a communication system and using the LBL and sonar systems to recognize its position and the locations of obstacles remain to be done in future work.

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