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Development of a Hovering AUV for Underwater Explorations

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Abstract

This paper describes the design and development of a hovering AUV constructed at Cheju National University and analyses the dynamic performance of the vehicle using simulation programs. The main purpose of this AUV is to carry out fundamental tests in its station keeping, attitude control, and desired position tracking. Its configuration is similar to the general ROV appearance for underwater works and its dimensions are 0.75m*0.5m*0.5m. It has 4 thrusters of 450 watts for longitudinal/lateral/vertical propulsion and is equipped with a pressure sensor for measuring water depth and a magnetic compass for measuring heading angle. The navigation of the vehicle is controlled by an on-board Pentium III-class computer, which runs with the help of the Windows XP operating system. These give us an appropriate environment for developing various algorithms needed for developing and advancing Hovering AUV.
Keywords: hovering AUV, station keeping, attitude control, position tracking, navigation

1 Introduction

In recent years, there have been intensive efforts toward the development of URVs (Underwater Robotic Vehicles) for oceanic development. Especially, the URVs are indispensable for collecting ocean data, subsea investigation, subsea construction, and the repair/maintenance of marine structures. In the past, the URVs strictly were for scientific research and military applications. These days the needs for URVs has gradually increased so that demands development of highly effective URVs out of past researches.

URVs are typically divided into AUV (Autonomous Underwater Vehicle) and ROV (Remotely Operated Vehicle). The AUV is used mainly with long-distance traveling, and the ROV is used with work in a specific area. At present, researchers have developed URVs that combine the respective efficiencies of the AUV and ROV, of which the ROV that has an autonomous navigation capacity (Negahdaripour and Madjidi 2003, Smallwood and Whitcomb 2003, Bulich et al. 2004) and the AUV that is used with work of a specific area (Marks et al. 1995, Kim and Yuh 2001) are representative examples. For the AUV that is used for work at the specific area, attitude control and station keeping are very important functions. We call it hovering AUV. This paper describes the design and development of a hovering AUV developed at the Cheju National University. The main purpose of this hovering AUV is to be a test-bed for testing the dynamic performance of controller and sensors, and developing a more efficient hovering AUV in a water tank.

2 Vehicle design goals

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 the drag, thrust, and hydrodynamic coefficients.

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

Table 1: Vehicle design goals

Parameters	Specifications
Hull	Frame Type
Dimension	0.75m × 0.5m × 0.5m
Weight	50kgf (in air)
Max. Depth	10m
Max. Speed	2m/s
Thrusters	450watt × 4
Control	4 DOF (Surge, Sway, Heave, Yaw)
Computer	On-board 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 whole structure of the hovering AUV is as shown in Figure 1 and the completed frame structure is like Figure 2. The mission of the hovering AUV made by Cheju National University is to be a test-bed for the development of attitude/position control algorithm and the performance test of the sensors. The body shape of this AUV is decided by considering the mission; this shape has advantages equip with sensors and more spaces for additional sensors. It also has 1 vertical thruster and 1 lateral thruster and 2 longitudinal thrusters, which control the 4DOF motions. An LBL (Long Base Line) system grasps the exact position of AUV in the water tank and sonar system is used for obstacle avoidance.

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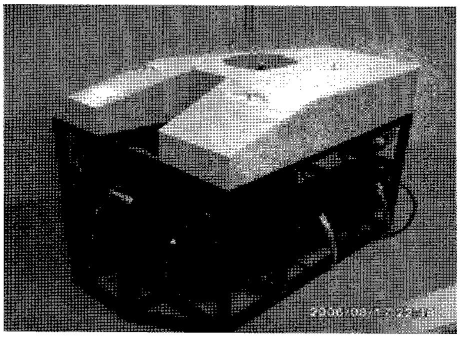


Figure 1: Overview of Hovering AUV

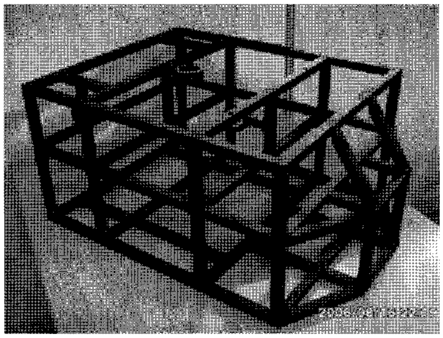


Figure 2: Frame structure

3.1 Hull

The hull shape of the AUV is similar to the general ROV structure shown in Figure 3. This structure is convenient for mounting are listed efficient use of space. The dimensions are 0.75m*0.5m*0.5m, 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 a loads and can that is made of acrylics because this AUV is not exposed to high pressure.

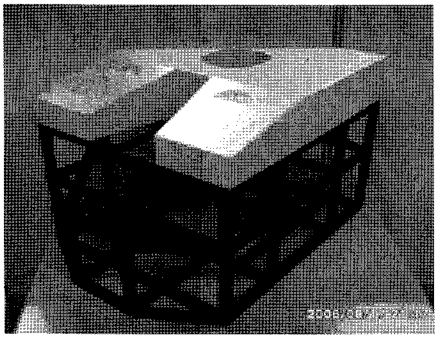


Figure 3: Hull shape

3.2 Thrusters

The thrusters used Brushless DC motors manufactured by Tecnadyne Inc. (Figure 4) are mounted. DC 24V is needed for the power supply with a maximum consumption of power being 450watts, and the bollard output of this thrusters is about 8.2kgf forward. Two thrusters are used for forward direction, and other two thrusters are used for vertical/lateral direction. These thrusters can control the 4 DOF motions.

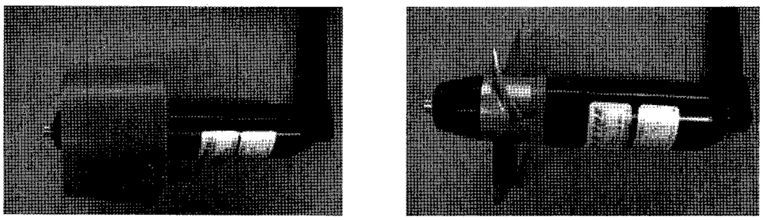


Figure 4: Thrusters

3.3 Sensors

The pressure sensor and magnetic compass are used to measure the depth and direction of the AUV (Figures 5 and 6). The range of the pressure sensor is 0-20m, has an accuracy of 0.1%, the signal being transmitted by a RS-485. The maximum tilt range of the magnetic compass is 50°, the accuracy being ±0.4° the resolution being 0.3°. The magnetic compass uses an RS-232 for communication; it has dimensions of 6.3cm*5cm*3.1cm 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 (Figures 7 and 8).

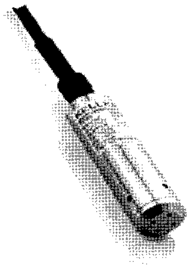


Figure 5: Pressure sensor

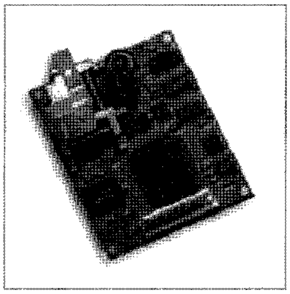


Figure 6: Magnetic compass

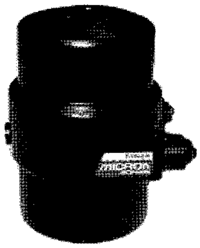


Figure 7: Sonar system

Figure 8: LBL system

3.4 Computer

The AUV uses an on-board PC for real-time control and monitoring of all of the sensors and thrusters or the AUV (Figure 9). The dimensions of the computer are 10cm*9cm; the CPU is Pentium III 700MHz. The RS-232/485 and Ethernet link are used for a communication port; an I/O board is also used. The operating system of the AUV is Window XP, and the control program is used C/C++.

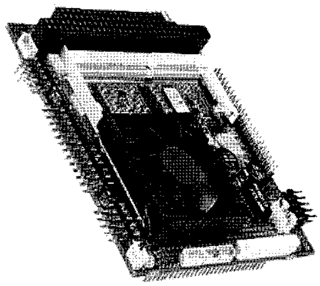


Figure 9: On-board PC

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 6 DOF contains hydrodynamic forces and moments expressed in terms of a set of hydrodynamic coefficients. Gertler and Hagen (1967) adjusted an equation of motion which is a standard of motion analysis for submarines. Feldman (1979) presented the modified equation of motion which approximates the real. Fossen (1994) proposed a model for design of a nonlinear controller system for underwater vehicles. Healey and Lienard (1993) proposed nonlinear equations of motion and specific hydrodynamic coefficients of 6 DOF.

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

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

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

4.2 Simulation Program

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

5 Controller design

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

Recently, findings have shown the AUV to have successful control of the position and attitude through the development of new control techniques, especially the sliding mode and the fuzzy controller. Yoerger and Slotine (1985) controlled the ROV with a sliding mode control. Cristi, Papoulias and Healey (1990) controlled vertical motion of the AUV by a sliding mode controller. Marco and Healey (2001) studied the control of 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. In this section, the PID controller was designed for navigation control, combined the attitude and position controls of the AUV; the designed controller is shown in Figure 11.

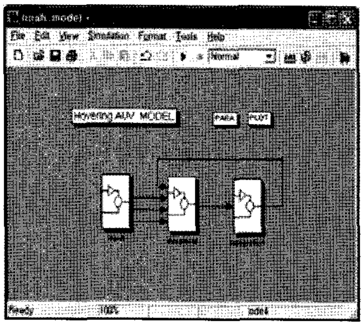


Figure 10: Simulation program

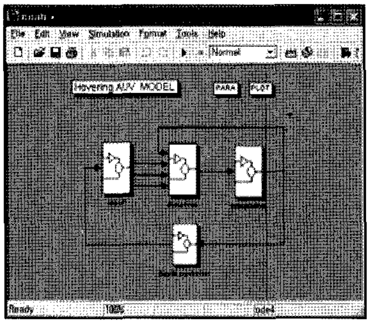


Figure 11: Controller design

The designed PID controller which is composed of attitude and position control was tested during the simulation. In Figure 12 shows the desired trajectory. The trajectory is to move to target 1 and then maintain the attitude and position; thereafter, pass through Target 2, Target3, and Target 1, and subsequently return to the initial position. The cruising speed is 1.0m/s. The simulation results are compared with the case which has no modeling error (Figure 13), the case which received the current (Figure 14) and the case which has sensor noise (Figure 15). In the case of being without disturbance and sensor noise, the attitude and position control of the Hovering AUV were handled well, but in the cases which have disturbance by the current and about 10% sensor noises, the Hovering AUV drifted from the desired tracking trajectory.

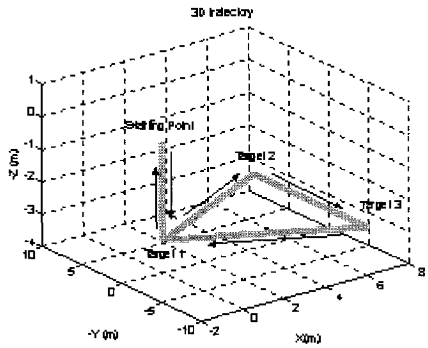
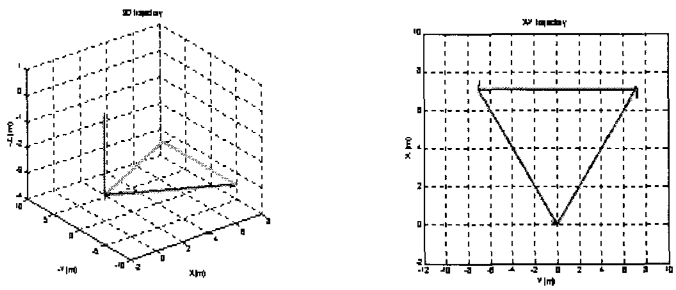
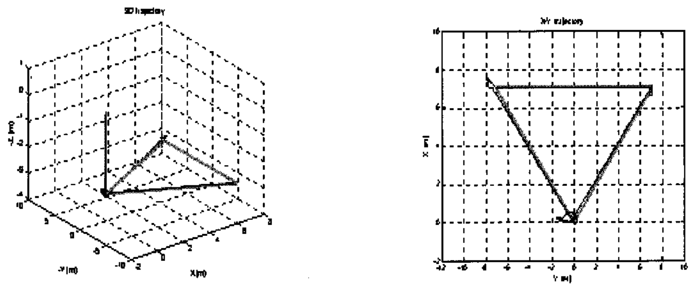


Figure 12: Simulation condition: desired trajectory



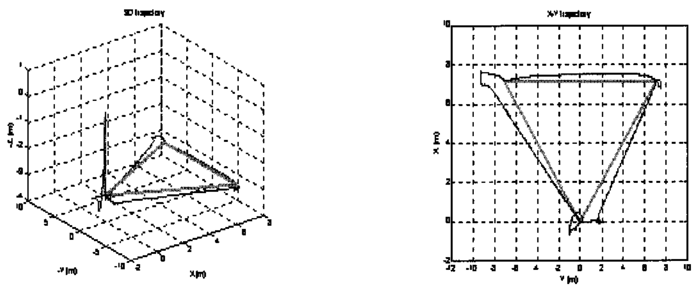
(a) 3-D trajectory (b) X-Y trajectory

Figure 13: Simulation results with nominal model



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

Figure 14: Simulation results under disturbance



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

Figure 15: Simulation results with sensor noise

6 Conclusions

This paper describes the design and development of a hovering AUV constructed at Cheju National University, of which main purposes are to be able to maintain attitude and position and to move to a desired attitude and position. This hovering AUV will be using the test-bed to test propulsion system and measuring instruments in order to actualize these abilities and improve its capacities.

For analyzing the dynamic performance of the hovering AUV, derive the 6 DOF equations of motion; then design a simulation program with these equations. At the same time, design the PID controller to control the attitude and position of the hovering AUV and analyze the performance of the controller by using a simulation program.

Future work will apply the designed controller to the real hovering AUV and test its performance. In addition, developing a communication system using the LBL and Sonar systems to recognize the position and the location of obstacles is also future work.

Acknowledgements

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