Development of Hovering-Type AUV “Cyclops” for Precision Observation

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***Abstract*— This paper presents a novel hovering-type AUV(Autonomous Underwater Vehicle) system for precision observation. The vehicle design focused on precise localization and maneuverability to acquire precise visual data. The concept of the proposed vehicle hardware/software system is described in detail. To maximize the system’s flexibility, the thrusters’ layout can easily be adjusted for optimal performance. Experiments were carried out to verify the positioning accuracy because high-accuracy positioning is required to enable AUVs to acquire precise data and excellent maneuvering performance.**

Keywords— AUV, image sonar, vision, automation, image mosaicking

I. INTRODUCTION

Recently, underwater structures such as harbors, bridges, underwater tunnels, pipelines, cables, etc. have been rapidly increasing near shallow water. Investigations of marine resources and oceanic materials have attracted much attention. Thus, there has been an increase in the demand for underwater tasks.

Risky tasks can be carried out using AUVs. In recent years, AUVs have been developed around the world, such as REMUS, HUGIN, HAUV, TUNA-SAND, and Tri-Dog. These AUVs have been applied in various fields and missions.[1]-[7]

For several underwater missions, AUVs require a high level of positioning accuracy to acquire precise data, along with excellent maneuvering performance to position sensors at the required viewing points and move the vehicle around intricate objects such as underwater structures.

For example, underwater safety inspection requires a precise image of the target area. Collecting precise visual data requires the vehicle to get close to the target object. In many cases, the task must be carried out in a shallow water environment where the visibility is restricted (1–2 m). A sensor fusion using acoustic and optical sensing is required to solve conflicting needs.

To overcome the above-mentioned difficulties, a task oriented AUV system is proposed, and its features and test results are described. For high-accuracy positioning and excellent maneuverability, hovering-type AUVs could be suitable, and various sensors and specialized vehicle designs are required.

In the next section, we describe the proposed hovering-type AUV, called “Cyclops,” which can be used for precise underwater imaging.

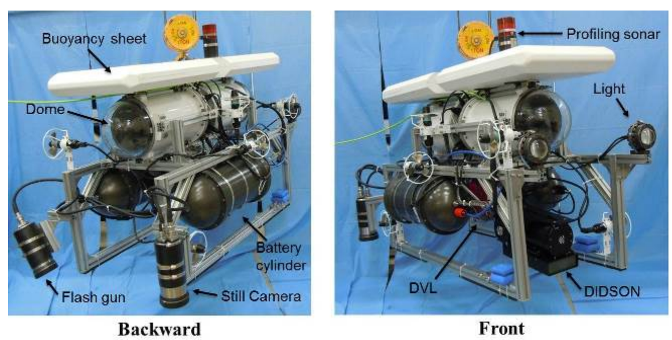

Fig. 1. Overview of the AUV, ‘Cyclops’

TABLE I Specification of the AUV system

Dimension	0.87 x 1.48 x 0.92 (m)
Weight	210kg (in air)
Max. operating depth	100 m
Propulsion	8 thrusters with 475W DC motors
Max. Speed	2 knots
Batteries	24VDC / 600WH Li-Po Batt. x 2
Duration	2 hours
Computer system	PC104(P4 1.4MHz) x 2
Sensors	- Dual Frequency Imaging Sonar(1.1/1.8MHz) - Profiling Sonar - Digital Pressure Transducer - Doppler Velocity Log(1.2 MHz) - Still Camera and Flash Gun - MEMS Gyro - Pan-Tilt Camera with Dome x 2

II. PROPOSED AUV SYSTEM

As shown in Fig. 1, we developed a hovering-type AUV called "Cyclops" for precision observation. This vehicle has the specifications shown in Table 1.

The proposed vehicle has the following critical advantages. The developed vehicle platform has been optimized for precision imaging missions. The system configuration can be flexibly reassigned based on the environment for the mission.

A. Imaging sensors

Underwater, visual data can be divided into optical and acoustic data. The vehicle is designed to obtain the optimal visual data collection performance. Using the complementary characteristics of underwater optical cameras and acoustic sensors, the AUV recognizes and approaches the target object with high reliability.

1) Acoustic sensor: The vehicle has two kinds of sonar sensors. The profiling sonar (881A, Imagenex) is a medium-range (<100 m) sonar that is used to find the target and understand the environment. It can reproduce images of 360° circular sections using mechanical rotation. The other is a short-range (<25 m) image sonar (DIDSON, 1.1/1.8 MHz) and provides high-resolution sonar images at a rate of 4–21 frames/s in real time. A pan/tilt mechanism (X2) maximizes the inspection performance.

2) Optical sensor: Pan-tilt cameras with two acrylic domes are mounted in front of and behind the main cylinder for real-time imaging. A high-resolution still camera with a flash gun looks down for image mosaicking.

B. Flexible configuration

The vehicle's design is configured for fast and easy maintenance. The thrusters' specific layout is sufficient for imaging under the current status. For zig-zag scanning, eight thrusters were used on the vehicle. Two thrusters were used for heave motion; two thrusters were used for surge motion; and four thrusters were used for sway motion. The thrusters' layout can be easily adjusted for optimal performance.

C. Specialized design and maneuverability

The accuracy of the imaging is mainly determined by the vehicle's maneuverability and dynamic performance. The vehicle has a symmetric design to minimize the yawing motion and maximize the mobility in a complex environment such as inside an underwater structure. In most cases, the target areas on the surface or underwater are huge and require mosaicking for inspection. In the mosaicking, AUVs scan a target area with a zig-zag motion, as shown on the left side of Fig. 2. Rotation is inevitable, which changes the lighting or acoustic beam transmitting condition. These changes hinder precision mosaicking. The proposed vehicle could scan a wide area without any rotation, as shown on the right side of Fig. 2. By maintaining almost constant dynamic surge, sway, heave, and yaw performances, the vehicle can scan with high accuracy and shorten the mission time.

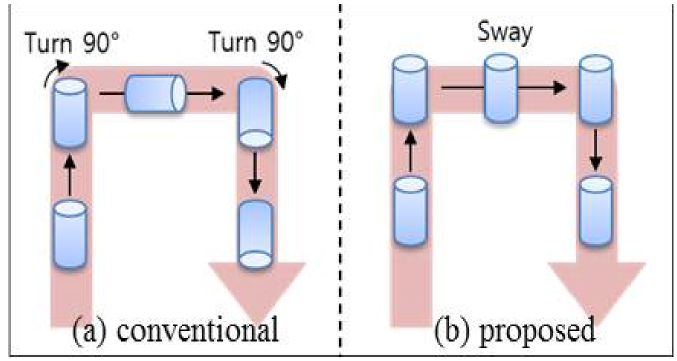

Fig. 2. Precision surface scanning example

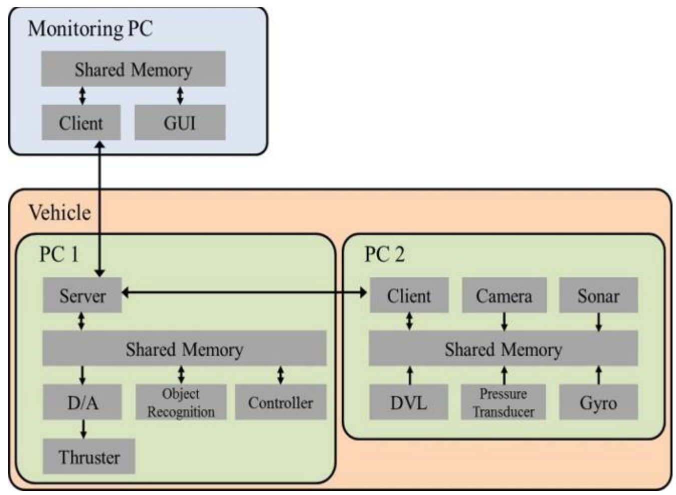

Fig. 3. AUV system configuration

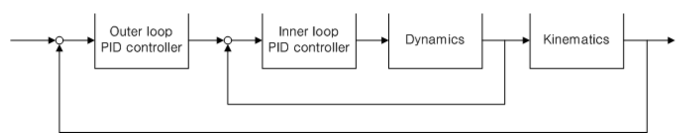

Fig. 4. Dual loop PID controller

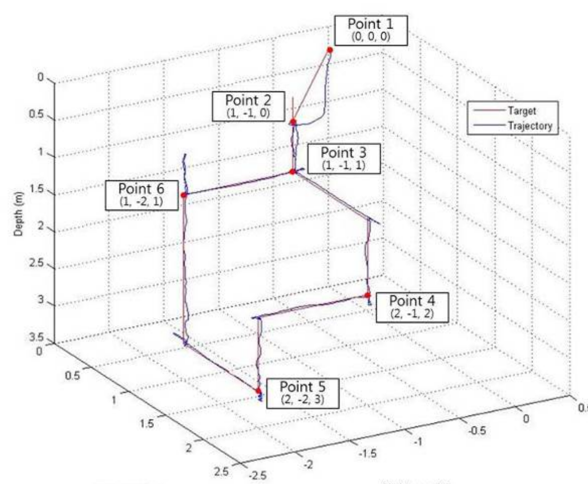

Fig. 5. AUV's trajectory in 3D Waypoint tracking

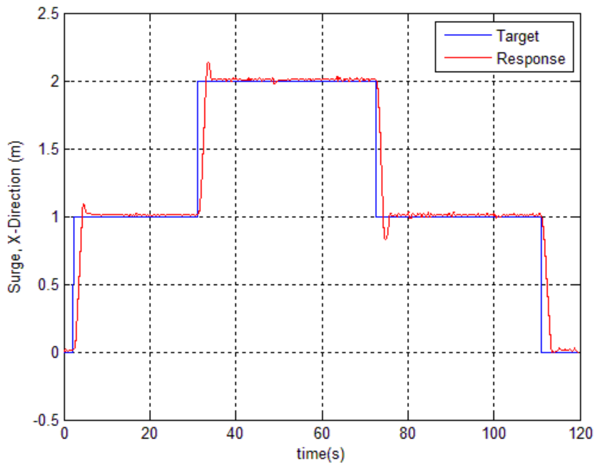

Fig. 6. Experiment result of surge control

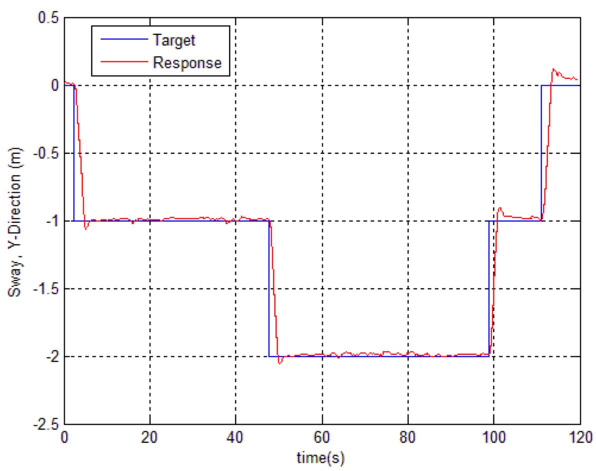

Fig. 7. Experiment result of sway control

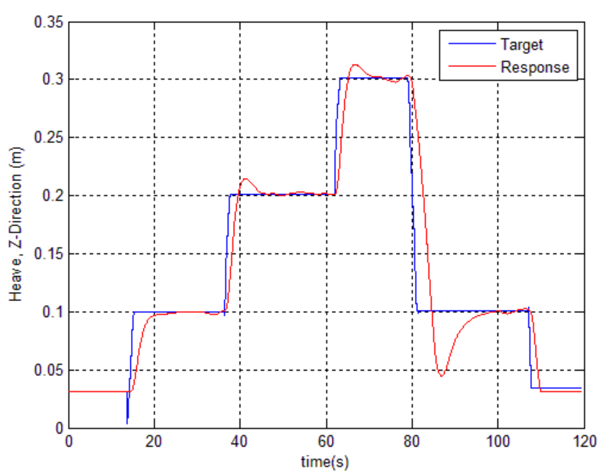

Fig. 8. Experiment result of heave control

D. Navigation

This vehicle is equipped with various sensors to enhance the reliability of the inertial navigation system[8]-[9]. The vehicle has the following navigation sensors: a Doppler Velocity Log (DVL), MEMS gyro, and digital pressure transducer. These sensors are fused to maximize the localization's accuracy.

E. Localization

In the proposed concept for the localization method, the AUV deploys reference objects to determine its location by itself and adjust for the errors that come from the inertial navigation system.

The accumulated errors become larger the deeper the AUV dives. The vehicle deploys an object like a vertical buoy as a reference object and determines its location through recognition using the profiling sonar on the vehicle. This is explained in more detail in the following text. After launching, the vehicle dives to the seafloor with a few errors. Then, it stops and deploys a base object at the initial landing point. The AUV moves to the work area from this initial base object using dead reckoning, where it stops and deploys a second base object and a third base object at the beginning of the work area, which becomes the zero point of the work coordinate system.

The coordinate system utilized by the AUV assists it, not only to overcome the disadvantages of dead reckoning such as the drift error problem over long working hours, but also to minimize the absolute coordinate errors. There are only a few errors before the AUV establishes the work coordinate system because it simultaneously adjusts for the drift error occurring from internal sensors using a range measurement to the base object.

While performing a mission in the work area, the range data obtained from the second and third objects allow the AUV to know its precise location with little error.

The installed landmarks guarantee the reliable and accurate positioning of the AUV under any circumstances such as in the open sea with featureless terrain.

III. SYSTEM CONFIGURATION

As shown in Fig. 3, the software processes have different loop cycles and communicate with each other asynchronously. They exchange data using the shared memory. The main processor controls the vehicle at each level of the command system using the hierarchical architecture.

For the vehicle system, the hierarchical architecture, dead reckoning, and centralized sensing method were adopted. The sensor fusion technique was used to improve the navigation module. DVL (Doppler Velocity Log), FOG (Fiber Optic Gyro), and magnetic compass data are used.

IV. MODELING AND CONTROL

To improve the reliability and accuracy of the system, mathematical modeling was carried out. A simplified model for the AUV dynamics was considered, neglecting the pitch and roll motions. The hydrodynamics is defined as follows:[10]

$$m_u \dot{u} = m_v v r - k_u u - k_{u|u|} u|u| + F_u \tag{1}$$

$$m_v \dot{v} = -m_u u r - k_v v - k_{v|v|} v|v| + F_v \tag{2}$$

$$m_w \dot{w} = -k_w w - k_{w|w|} w|w| + F_w + W \tag{3}$$

$$I_r \dot{r} = -(m_v - m_u) u v - k_r r - k_{r|r|} r|r| + T_r \tag{4}$$

where u, v, w, and r are the vehicle's linear and angular velocities in surge, sway, heave, and yaw directions, respectively; and m_u, m_v, m_w and I_r are the masses and moment of inertia, including the hydrodynamic added mass. F_u, F_v and F_w are the forces applied by the thrusters in the surge, sway, and heave directions, respectively; T_r is the torque in the yaw direction, and W is the summation of the vehicle's weight and buoyancy force.

Fig. 9. Indoor water tank

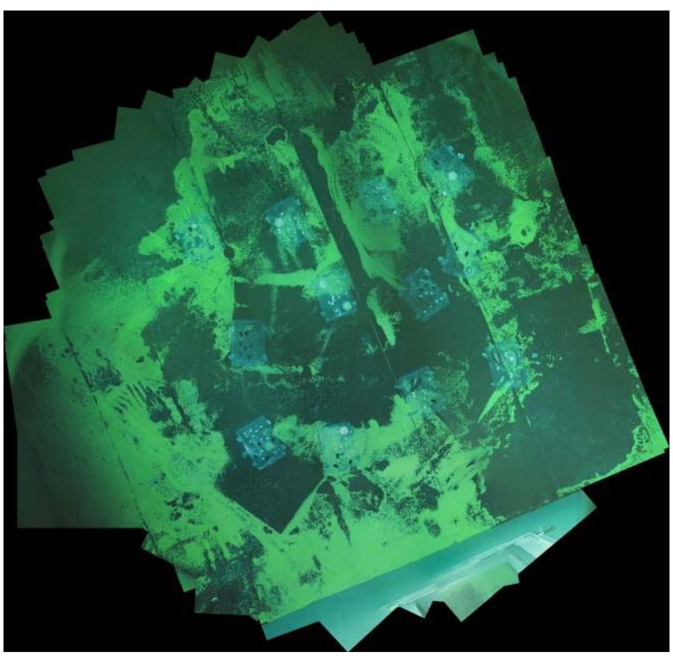
Fig. 10. Image mosaicking result

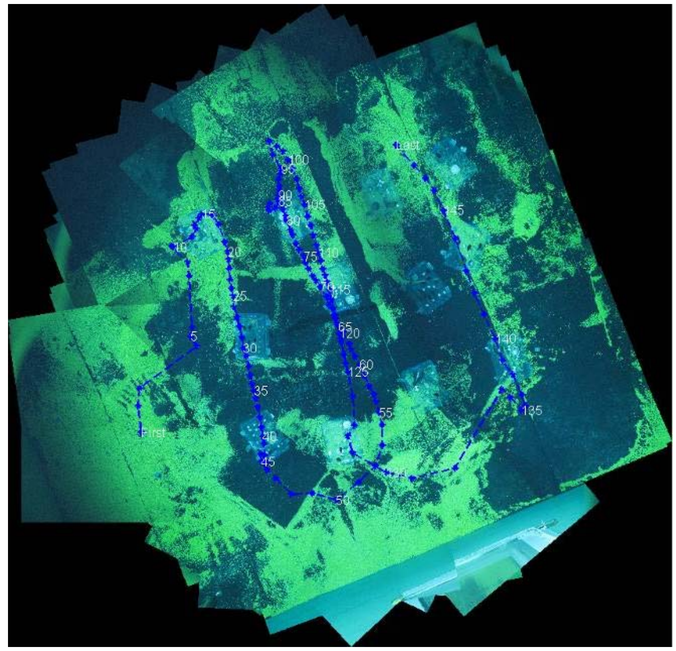
Fig. 11. AUV's trajectory in image mosaicking

To actually control the AUV system, we applied a conventional dual-loop PID controller. As shown in Fig. 4, the inner loop controller stabilizes the dynamics in advance, and the outer loop controller stabilizes the inner loop system and kinematics by generating a reference velocity.

V. Experiment

Experiments were conducted to evaluate the performance of the controller.

A. Three-dimensional waypoint tracking

A waypoint tracking test was carried out to evaluate the maneuverability and dynamic performance of the vehicle in an indoor water tank. As shown in Fig. 5, the vehicle followed each target waypoint well. The control results for each direction (surge, sway, and heave) are shown in Figs. 6–8, respectively. The surge and sway results showed good convergence with the target position. The overshoot of the heave motion response in the control results was larger than that in the experimental results. Based on the results, the dual loop PID controller was successfully applied to the control of the vehicle.

B. Image mosaicking

An image mosaicking test was carried out in the same water tank. The water tank was 8 m in width, 12 m in length, and 8 m in depth. We installed sampling plates to recognize objects on the flat bottom of the water tank. The vehicle took photos while following a zig-zag scanning pattern. The result of the image mosaicking is shown in Fig. 10. Fig. 11 shows the trajectory used for the image mosaicking.

Fig. 12. Sea trial, Pohang, South Korea(Dec. 22, 2012)

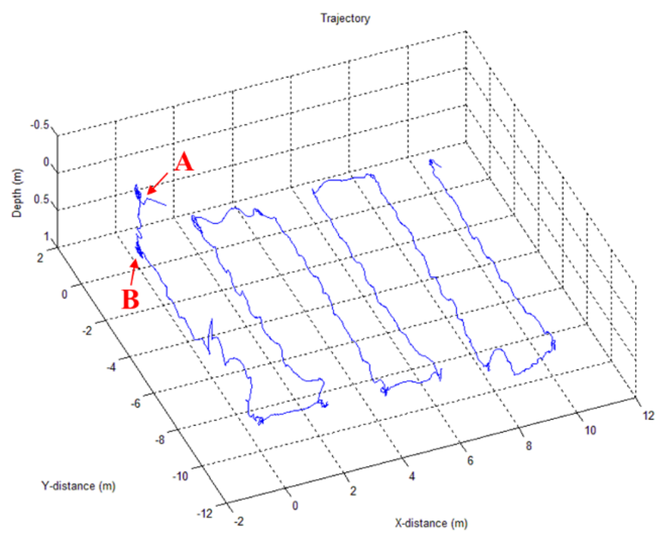

Fig. 13. AUV's trajectory in zig-zag scanning

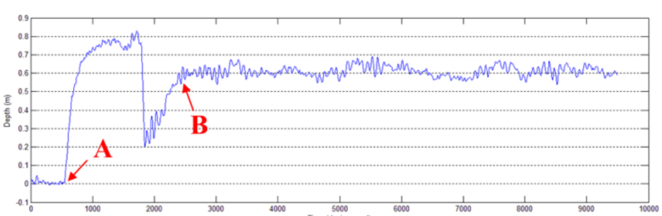

Fig. 14. Depth history in zig-zag scanning

C. *Sea trial*

Zig-zag scanning by the vehicle was carried out in the field. This test was intended to validate the developed vehicle's maneuvering characteristics. The test results are shown in Figs. 13–14. The scanning area was 10 m^2. The vehicle scanned the target area using 2-m grid units and maintained a constant depth. Because of wave effects, the vehicle's trajectory showed some vibration. To minimize these effects, the vehicle should be operated at a depth greater than 2 m, and a robust control technique could be considered.

VI. CONCLUSION

We proposed a novel hovering-type AUV system for precision observation. The details of the system were addressed, and its performance was verified in experiments. The developed AUV system focuses on accurate positioning and image data acquisition. For accurate maneuverability, the vehicle was symmetrically designed and customized using a flexible configuration. Using nearly constant dynamic surge, sway, heave, and yaw performances, the vehicle can scan a wide subsea area with high accuracy in a short mission time. For precise observations, the vehicle was equipped with complementary sensors consisting of underwater optical cameras and acoustic sensors. The AUV could recognize and approach a target object with high reliability. These characteristics provide high efficiency when inspecting underwater structures in shallow water.

In experiments, the AUV system has sufficient maneuverability to perform precise observations for underwater tasks. In future work, object recognition using the acoustic/optical sensor fusion, image mosaicking in the field, and improvements in the AUV's controller are planned.

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