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Development Report:

Development of Testbed AUV for Formation Control and its Fundamental Experiment in Actual Sea Model Basin

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The formation control of multiple autonomous underwater vehicles (AUVs) is increasingly becoming a vital factor in enhancing the efficiency of ocean resources exploration. However, it is currently difficult to deploy such a package of AUVs for operation at sea because of their large size. The aim of our study is to create a demonstration system for formation control algorithms using actual hardware. To implement a prototype system, we developed a testbed AUV usable in a test basin and performed a simple formation control test in the Actual Sea Model Basin of the National Maritime Research Institute, Japan. Two AUVs, the simulated "virtual" leader and the developed "real" follower, communicate through an acoustic link and hence cruise to maintain a constant distance between them. Tests for more sophisticated formation control algorithms will be enabled using the system; consequently rapid implementation at sea will be realized.

Keywords: autonomous underwater vehicle (AUV), formation control, Actual Sea Model Basin

1. Introduction

Autonomous underwater vehicles (AUVs) contribute significantly to underwater research, such as topographic surveys using sonars [1], visual mapping using cameras [2–5], and benthic sampling [6].

To improve the efficiency of planar mapping survey, the National Maritime Research Institute (NMRI) proposed a method involving the simultaneous deployment of multiple AUVs and an autonomous surface vehicle (ASV) [7]. This strategy is effective in terms of the total extent of the surveyed area. However, the broader the extent of the area, the more difficult it is to control and monitor the AUVs from the ASV. This is because the available zone of acoustic positioning and communication link from the ASV is limited, and each AUV cruises its assigned area independently. Hence, multiple AUVs must be controlled and maintained in formation during a survey mission.

To date, some formation control algorithms for AUVs have been proposed [8–15] and computationally simulated. However, challenges occur in placing such algorithms into practical use because they are just only simulated on computers. Therefore, the hardware and environment for testing such algorithms are required before AUVs with such formation control systems are deployed at sea.

This paper outlines a demonstration scheme using a testbed AUV and a test basin for validating formation control algorithms. The newly developed AUV, which is equipped with an underwater communication modem required for formation control, and its fundamental test in a test basin are described in the following sections.

2. Testbed AUV for Formation Control

To implement the verification system of the AUV formation control in test basins, we developed a testbed AUV equipped with fundamental devices required for navigation and communication. As this AUV is for demonstration and the basin space is limited, the following requirements must be considered when designing its hardware and software:

- Sufficient compactness allowing handling by a few operators and maneuverability for turning in a small radius. In practice, multiple testbed AUVs operate simultaneously in a test basin.
- Communication network among AUVs. Each AUV shall obtain the status of the others and transmit its own information through acoustic links.
- Adaptive behavior correction based on received information. Each AUV shall be synchronized with the others to maintain the formation of AUVs.

By satisfying these conditions, any formation algorithms can be implemented and tested using AUVs in a basin environment.

Figure 1 and **Table 1** show the general arrangement and specifications of the developed AUV, namely, the NMRI small cruising AUV, "mini-AUV." It has a torpedo-shaped body, a thruster, and four independently movable

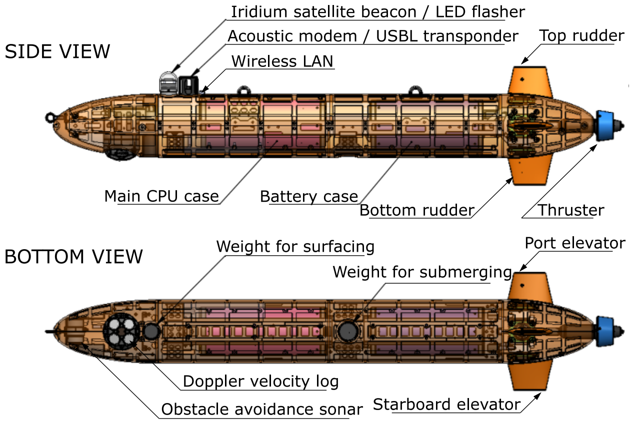

Fig. 1. Onboard equipment of testbed mini-AUV.

Table 1. Specifications of testbed mini-AUV.

General	
Weight in air	38 kg
Length	1.8 m
Diameter	0.2 m
Depth rating	120 m
Speed	1.5 m/s (max.) 1.0–1.5 m/s (cruising)
Turning radius	3.3 m (min.)
Endurance	2 h (cruising)
Equipment	
Communication positioning	Blueprint SeaTrac X150
CPU board	Armadillo-X1
OS	ROS Melodic Morenia on Debian stretch
Navigation	iXblue Phins C3
Bottom tracking	Nortek DVL1000
Obstacle avoidance	Tritech Micron Sonar
Thruster	Tecnadyne Model260
Power source	IKS Li-ion 18650 × 72 75.6 V, 10.4 Ah

fins, i.e., elevators and rudders. Its overall length is 1.8 m, which is reasonably small, and its weight is 38 kg. Hence, it can be operated by only two or three hands. Highly accurate navigation is enabled using an inertial navigation system with a fiber-optic gyroscope, aided by a Doppler velocity log (DVL). To construct an underwater communication network, an acoustic modem with an ultrashort baseline positioning system [16] is installed. In addition, buoyancy adjusting weights for submerging and surfacing, flashers, and satellite beacon enable the AUV to conduct trials in areas of water up to a depth of 120 m.

With regard to controlling the devices, a modified version of the software of AUV Hobalin [17], which was built using Robot Operating System (ROS) [a], was installed on an ARM-based embedded board. Fundamental

Fig. 2. Actual Sea Model Basin of the NMRI, measuring 80.0 m (length) × 40.0 m (width) × 4.50 m (depth).

functions such as following pre-planned waypoints in order, reporting their own state, and visiting a designated waypoint by orders via an acoustic communication link had already been implemented. Considering formation control, we assumed that several AUVs formed a leader-follower structure during cruising. A leader AUV transmits its state information such as its position and depth to the follower AUVs. To render AUVs cruise in formation, a function that generates waypoints dynamically based on received information was additionally implemented. Because the software system is composed of subdivided functions and nodes of ROS, each algorithm part can be easily replaced with a newly developed one.

Ship motion tests such as turning circle maneuvers, zig-zag tests, and planar motion mechanism (PMM) tests were conducted to obtain the kinematic performance of the AUV. For example, it was verified that the maximum speed exceeded 2.0 m/s and the minimum turning circle radius was 3.3 m, which is sufficiently small enough for tank tests. In addition, the equation of motion of the testbed AUV was obtained, which can be used to reconstruct the behavior during a mission sequence in the simulation (see Appendix A).

3. Experiment in Test Basin

3.1. Actual Sea Model Basin

The Actual Sea Model Basin (shown in **Fig. 2**) was used to test the fundamental formation control functions of the testbed AUV. This basin is typically used to perform various ship motion tests using model ships as well as to reconstruct and analyze maritime accidents [18, 19]. This basin was selected for an experiment environment because of its dimension, i.e., 80.0 m (length) × 40.0 m (width) × 4.50 m (depth), which was sufficiently broad for an AUV to move around horizontally. This experiment was the first attempt to use an AUV in the Actual Sea Model Basin.

3.2. Overview of Test Scenario

As the leader-follower structure was assumed in the formation control system, two AUVs at the least were required for each part. However, in the experiment, only

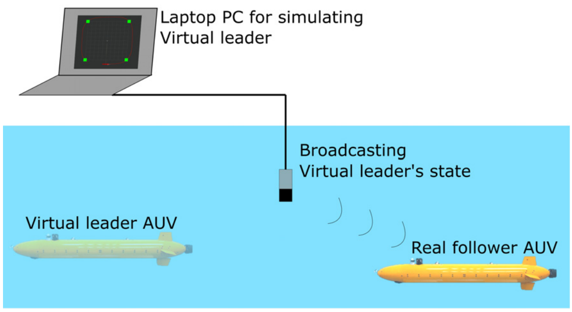

Fig. 3. Real follower AUV approaching simulated virtual leader AUV.

one of the series of the testbed AUVs had been built at that time; hence, the leader part was simulated using the kinetic model obtained by the motion tests (Appendix A). Meanwhile, the follower part was the physically existing AUV, which sought and chased such a "virtual" leader AUV.

Figure 3 shows a schematic of the experimental setup. The acoustic communication modem was submerged and fixed at the center of the basin and connected to a laptop computer, which simulated the virtual leader AUV. Information such as position, depth, and targeted waypoint ID were broadcasted and received by the follower AUV.

It is noteworthy that the position of the actual modem differed from the position of the imaginary modem of the leader AUV because the virtual leader AUV cruised around as simulated, whereas the modem was fixed.

3.3. Virtual Leader AUV

As mentioned previously, the leader AUV did not have its own hardware except for the acoustic modem, which was installed 1.0 m deep in the basin. A planned course was composed of four waypoints in a square with a 10-m-long side, and the leader AUV cruised several laps in a clockwise direction at a 2.0 m depth. In addition, navigational information such as position (latitude and longitude) and depth was transmitted at intervals of 3 s.

During the experiment, the state and trajectory of the leader AUV as well as the planned waypoints were visualized using Rviz, a three-dimensional visualization tool for ROS (**Fig. 4**).

3.4. Real Follower AUV

The AUV described in Section 2 was assigned to the "real" follower AUV. It was submerged to start at the center of the basin and waited for broadcasted information through the acoustic communication link (**Fig. 5**). The moment any information from the leader AUV was received, the follower AUV dynamically generated a new waypoint toward the position of the leader AUV and started to track it. Each time the latest information was received, the target waypoint was updated and the behavior was immediately altered.

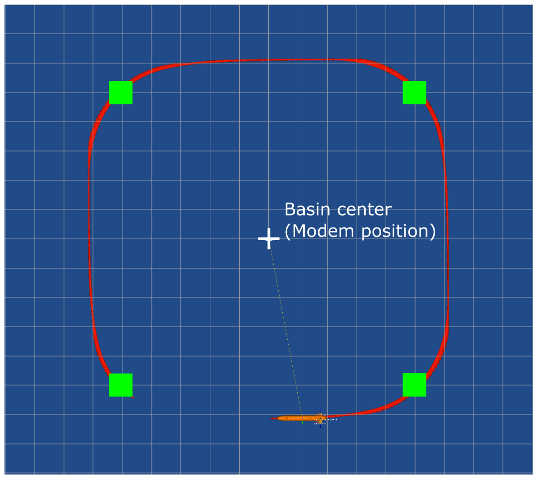

Fig. 4. Simulated motion and trajectory of virtual leader AUV displayed on Rviz (grid spacing = 1.0 m).

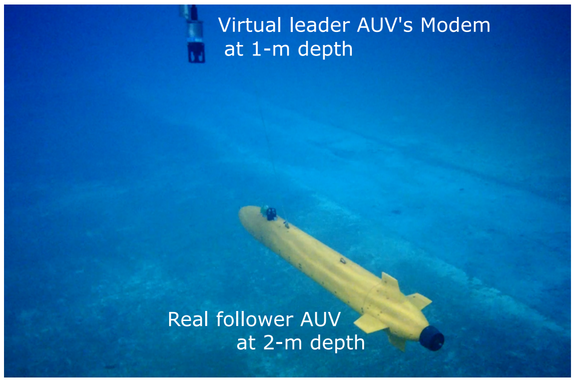

Fig. 5. Underwater image of fixed acoustic modem; follower AUV about to chase virtual leader AUV from starting point.

3.5. Results

The results of one of the laps are shown in **Fig. 6**. The dashed red line and the solid black line represent the trajectories of the leader and follower, respectively. The marks on the trajectories as well as the red circle, blue square, and blue cross are the moments at which acoustic communication occurred. Each number beside those marks indicates the moment the leader transmitted its state and the follower received the corresponding state, respectively. **Fig. 7(a)** shows the distances between the AUVs during the lap. Each mark denotes the moment at which the aforementioned transmissions occurred. The mean distance was 6.94 m, and the standard deviation was 0.33 m. **Figs. 7(b)** and **(c)** illustrate the maneuver of the follower AUV. In **Fig. 7(b)**, each time the target heading was updated based on a new waypoint of the received information, the follower AUV veered toward the direction of the waypoint. **Fig. 7(c)** shows the ordered values and output rudder angles. The orders to control the top and bottom rudders were calculated based on the deviation from the target heading and proportional gain. The actual output angle of the rudders was limited to $\pm$ 30°,

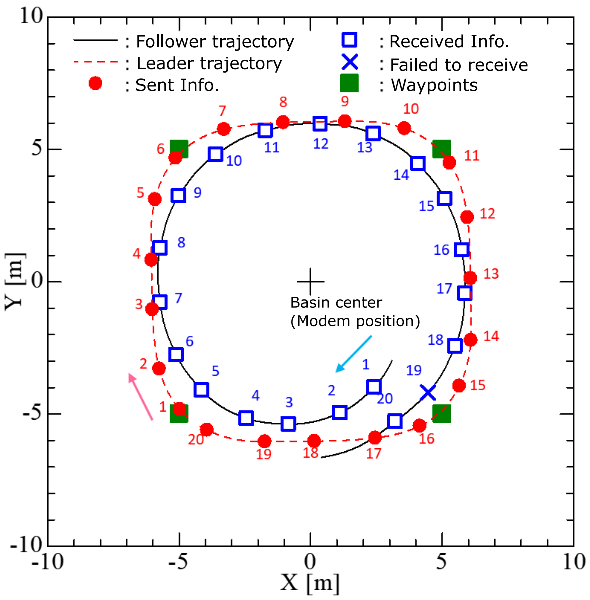

Fig. 6. Result of sending and receiving acoustic messages.

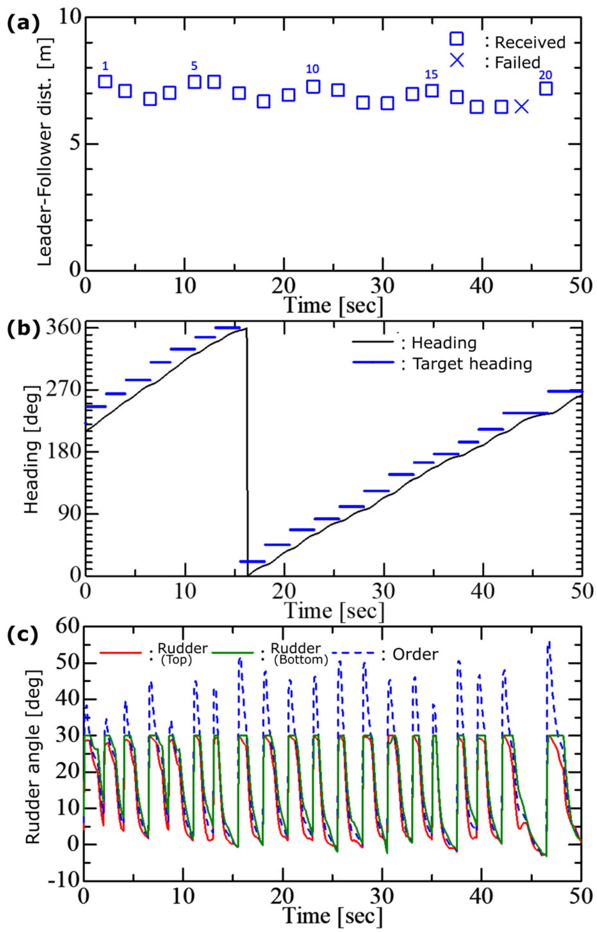

Fig. 7. Time-series data of experimental results. (a) Distances between leader and follower AUVs. (b) Fluctuation of headings of follower AUV. (c) Fluctuation of rudder angles of follower AUV.

although the larger the deviation, the larger were the ordered values.

Although not all the messages were conveyed successfully, it was observed that the follower AUV successfully maneuvered itself and cruised before the leader AUV. The fact that the leader-follower structure control can be implemented in the test basin was verified by these results.

4. Concluding Remarks

In this study, a testbed AUV was developed for formation control and a fundamental experiment in the Actual Sea Model Basin owned by the NMRI was performed. We obtained satisfactory results demonstrating that a real follower AUV tracked a virtual leader AUV whose motion was simulated on a laptop computer based on information through an acoustic link.

However, the experiment was performed under a desirable underwater communication quality. Acoustically severe environments can be presumed, such as longer distances among acoustic modems. Such conditions, which will degrade communication quality and cause intermittent information exchanges, should be considered in the future.

This study is the first step toward enhancing our development of a formation control system for multiple AUVs. For further developments, we are planning to build additional testbed AUVs and adapt existing AUVs to our formation control demonstration system.

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Appendix A. Kinetic Model of the Testbed AUV

In the tank test described in Section 3, the motion of the virtual leader AUV was computed based on the equation of motion as follows:

$$[M](\dot{V}) + [\tau][M](V) = (F_F) + (F_G) \quad \text{. . . . .} \quad (1)$$

$$(M) = \begin{bmatrix} m+a_{11} & 0 & 0 & 0 & mz_G & 0 \\ 0 & m+a_{22} & 0 & -mz_G & 0 & mx_G+a_{26} \\ 0 & 0 & m+a_{33} & 0 & -mx_G+a_{35} & 0 \\ 0 & -mz_G & 0 & I_{xx}+a_{44} & 0 & I_{xz} \\ mz_G & 0 & -mx_G+a_{53} & 0 & I_{yy}+a_{55} & 0 \\ 0 & mx_G+a_{62} & 0 & I_{zx} & 0 & I_{zz}+a_{66} \end{bmatrix} \quad \text{. . . . .} \quad (2)$$

$$\frac{d}{dt}\begin{pmatrix} \Phi \\ \Theta \\ \Psi \end{pmatrix} = \begin{pmatrix} P + Q\sin\Phi\tan\Theta + R\cos\Phi\tan\Theta \\ Q\cos\Phi - R\sin\Phi \\ Q\sin\Phi\csc\Theta + R\cos\Phi\csc\Theta \end{pmatrix} \quad (3)$$

$$(V) = \begin{pmatrix} U \\ V \\ W \\ P \\ Q \\ R \end{pmatrix} \quad \text{. . . . .} \quad (4)$$

$$\frac{d}{dt}(V) = (\dot{V}) = \begin{pmatrix} \dot{U} \\ \dot{V} \\ \dot{W} \\ \dot{P} \\ \dot{Q} \\ \dot{R} \end{pmatrix} \quad \text{. . . . .} \quad (5)$$

$$(F_F) = \begin{pmatrix} X \\ Y \\ Z \\ L \\ M \\ N \end{pmatrix} \quad \text{. . . . .} \quad (6)$$

$$[\tau] = \begin{bmatrix} 0 & -R & Q & 0 & 0 & 0 \\ R & 0 & -P & 0 & 0 & 0 \\ -Q & P & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -R & Q \\ 0 & 0 & 0 & R & 0 & -P \\ 0 & 0 & 0 & -Q & P & 0 \end{bmatrix} \quad \text{. .} \quad (7)$$

where,

m	: mass
a_{ij}	: added mass or added moment of inertia
x_G, z_G	: center of gravity
I_{ij}	: moment of inertia
U, V, W	: velocity (surge, sway, heave)
Φ, Θ, Ψ	: attitude angle (roll, pitch, yaw)
P, Q, R	: angular velocity (roll, pitch, yaw)
X, Y, Z	: fluid force excluding added mass
L, M, N	: fluid moment excluding added mass
F_F	: fluid force excluding added inertia force
F_G	: gravity and restoring force

To obtain the unknown parameters, the following ship motion tests were performed: resistance, oblique towing, PMM (surge, pure sway, and pure yaw), towing for measurement of rudder forces, free oscillation (roll and pitch), self-propulsion, circle, and zig-zag.

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