Low-speed, Low-altitude AUV Control

KAZUKI EGUCHI*1 YUSUKE YASHIRO*2
SHUSAKU YASUDA*3 ICHIRO AWAYA*4
TAKEHIRO ADACHI*1 YOSHIAKI YAMAUCHI*5

An autonomous underwater vehicle (AUV) is an unmanned, self-driving submersible mainly used for exploration of offshore resources and defense purposes. Global demand for AUVs is projected to increase by about 37% between 2018 and 2022. In recent years, there has been increasing demand for low-speed operations at low altitudes. Technology enabling the stable control of the vehicles under a tidal environment is required to make such operations possible.

1. Introduction

Mitsubishi Heavy Industries, Ltd. (MHI) has delivered AUVs for deep-sea exploration including "URASHIMA", "JINBEI" and "YUMEIRUKA", as presented in past articles of the MHI Technical Review. Human occupied vehicles (HOVs) and remotely operated vehicles (ROVs) traditionally conducted detailed near-seabed, low-altitude surveys while operating at low speed. However, the necessity of large-scale ancillary facilities and skilled operators, as well as the viewpoint of realizing automation, increases the demand for low-speed AUV operations at low altitudes. The technological challenges for such AUV operations include robustness against tidal currents and improvement in the accuracy of altitude estimation. This report proposes an autonomous control technology to realize low-speed operation of AUVs at low altitudes and presents its effectiveness through simulation results.

2. AUV system

The AUV in this study is configured as depicted in **Figure 1**. Considering the realization of the stable collection of observational data through optical camera imaging and sonar systems by diving down near the seabed, there are limitations to correct the effect of sensor noise resulting from seabed undulations and the AUV's attitude angle. It is therefore effective to operate the vehicle without changing its attitude angle. Our research focused on the development of a control system that enables stable operation at a speed of 1 kt and at an altitude of 5 m while maintaining a certain pitch angle. The major system components are as follows:

- Actuators: In addition to an x-rudder and a thruster at the stern, an azimuth thruster is also equipped in the middle of the hull. The simultaneous use of the azimuth thruster and the rudder makes it possible to control the altitude/depth while keeping the pitch angle constant. The azimuth thruster controls not only the forward/backward thrust, but also the angle of elevation/depression by itself when the depth changes during low-speed operation. The azimuth thruster also has the advantage of having lower drag than a vertical thruster.
- Sensors: The inertial navigation system (INS) is used to measure the attitude angle and attitude angle rate, while the speed over ground and speed over water are obtained based

*1 Chief Staff Manager, CIS Department, ICT Solution Headquarters
*2 CIS Department, ICT Solution Headquarters
*3 EPI Department, ICT Solution Headquarters
*4 Managing Expert, CIS Department, ICT Solution Headquarters
*5 Chief Staff Manager, Integrated Defense & Space Systems, Naval Ship & Maritime Systems Division

on the Doppler effect of acoustic waves by the Doppler velocity log (DVL). The distance to the seabed can also be measured using multiple acoustic beams. The location of the AUV is determined based on the INS and DVL sensor values.

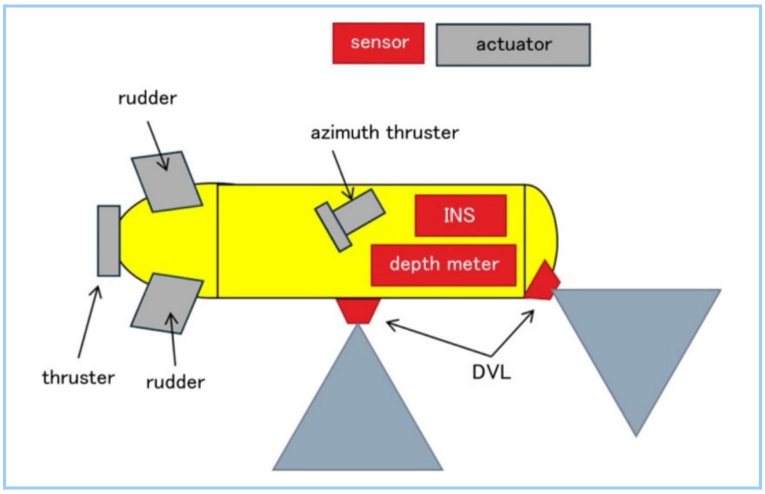

Figure 1 A schematic diagram of the AUV in this study

3. Autonomous control system

To operate an AUV at a low altitude, it is important to estimate the surrounding seabed topography especially the terrain in front of the vehicle, generate a trajectory path for the AUV to follow, and accurately estimate/control the altitude. With regard to the autonomous control system obtained after these considerations, the functional configuration diagram is given in **Figure 2**, and the control system block diagram is shown in **Figure 3**. The autonomous control system primarily provides the following functions:

1. Estimation of seabed topography and altitude
2. Generation of target trajectory path
3. Tidal current estimation
4. Cooperative motion control among actuators

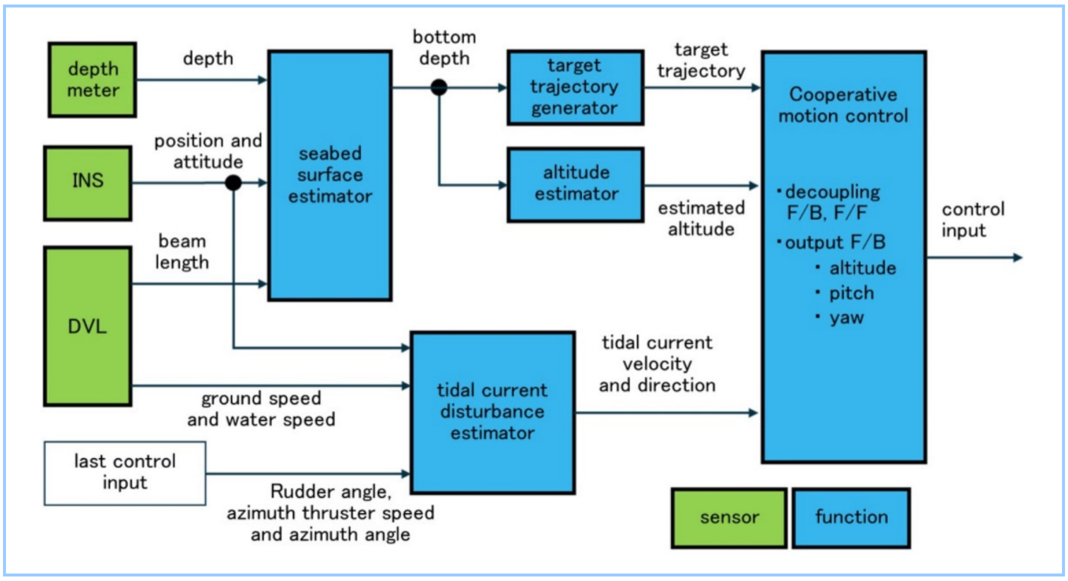

Figure 2 Functional configuration diagram of the autonomous control system

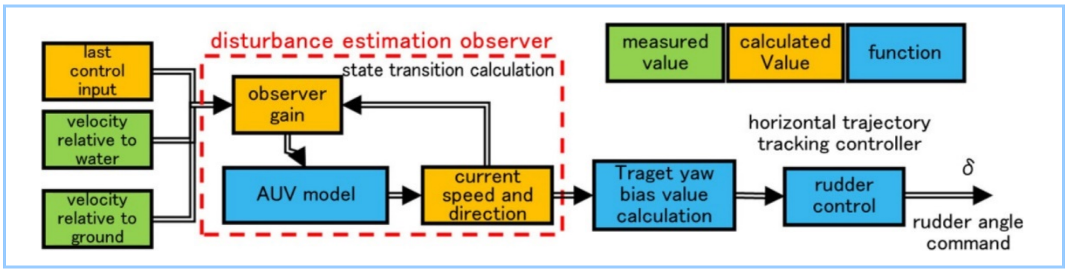

Figure 3 Tidal current estimation and direction control

3.1 Estimation of seabed topography and altitude

The key to successful AUV operation at a low altitude lies in accurate estimation of altitude. In this study, seabed topography is obtained (by the "seabed surface estimator" in Figure 2) to calculate the altitude (by the "altitude estimator" in Figure 2). The terms "depth" and "bottom depth" in the figure denote vertical distances from the sea surface to the AUV and the seabed, respectively. The altitude is determined based on the DLV measured distances between the AUV and multiple locations on the seabed. The estimation steps are as follows:

(1) Obtain distance data measured by DVL and position/attitude data by INS.

(2) Based on the aforementioned data, calculate the coordinates of measurement points on the seabed to construct a mesh-based representation of seabed surface topography. The mesh data are stored in the database, which will be updated by deleting and replacing old data with new data for the same location, whenever available. The estimation between measurement points is based on liner interpolation.

(3) Estimate the altitude using the data from the aforementioned mesh database and the AUV's position/attitude data.

When an AUV travels at an altitude of 5 m, a roughly estimated seabed topography of representation using the aforementioned method is 10 m ahead of the AUV and 5 m to the left and right.

3.2 Generation of target trajectory path

Based on the estimated seabed topography, a trajectory path to maintain the desired altitude can be determined (by the "target trajectory generator" in Figure 2). To make it possible for an AUV to follow the path in a stable manner while minimizing pitching, we have added an extra function that allows the target trajectory to be modified in advance considering the AUV's motion performance in the case of steep seabed topography.

3.3 Tidal current estimation

In some AUV operations, it is crucial to enable a vehicle to stay on a pre-determined course. An issue to address in the case of low-speed operation is the vehicle's deviation from the course because of relatively large tidal disturbance. Estimating the tidal current velocity and direction to control the AUV is considered to be a solution. More specifically, the estimated tidal current velocity and direction are used to correct the target values of AUV orientation control. An observer is employed for tidal current estimation. Figure 3 shows the control system configuration diagram in which the tidal current is estimated and the obtained result is used for control.

3.4 Cooperative motion control among actuators

By configuring the actuators as shown in Figure 1, the AUV has become capable of the motion of diving down and up while keeping the pitch angle constant. However, as there is strong interference between the input (regarding the rudder and azimuth thruster control) and the output (regarding the pitch angle and depth or altitude), a decoupling control method has been adopted to minimize the interference. Specifically, we have set the rudder to take control over the pitch angle and the azimuth thruster over depth (altitude). For the input of each control, extra control terms have been added to cancel out the interference terms, thereby minimizing the interference. The interference terms are calculated using the linear time-varying model for AUV ("decoupling(F/F)" and "decoupling(F/B)" in **Figure 4**).

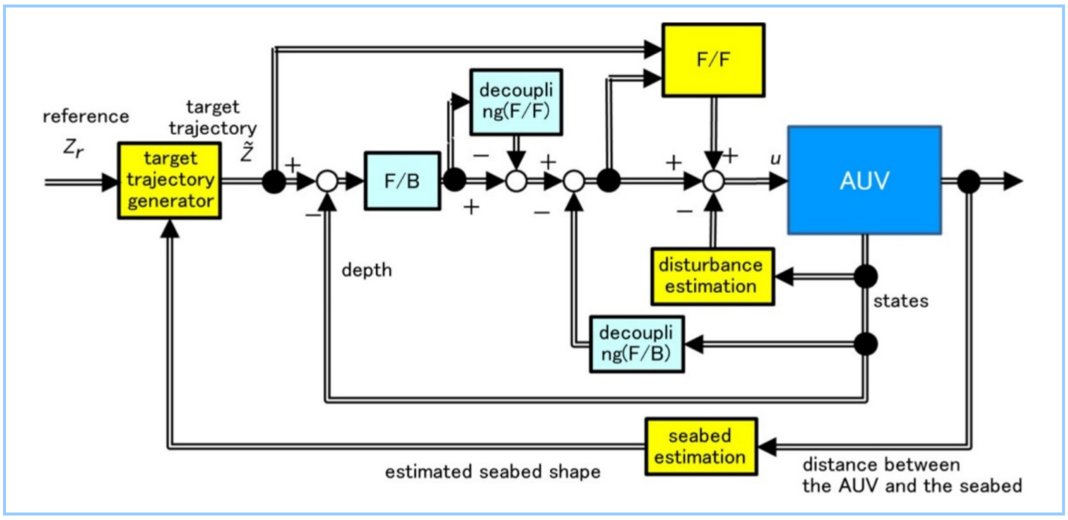

Figure 4 Block diagram of the autonomous control system

4. Simulation

Simulation was performed using actual seabed topography data, with the steepest slope being +11 degrees. The tidal current from behind the vehicle is 3 kt at the sea surface (approximately 0.5 to 0.1 kt at where the AUV is positioned under the sea). The target altitude is 5 m, and the AUV is supposed to operate at a speed of 1 kt. Considering the vehicle body balance, the target pitch angle is set at 5 degrees. Of the simulation results, the seabed surface topography and the AUV's trajectory are given in **Figure 5**. The changes in the depth, altitude deviation and pitch angle over the travelled distance are shown in **Figure 6**. As illustrated in the figure, the altitude deviation was about 0.6 m on the flat seabed, and it was kept at 0.68 m even on the steep seabed terrain. The results also indicate that the target pitch angle of 5 degrees was maintained throughout the travel.

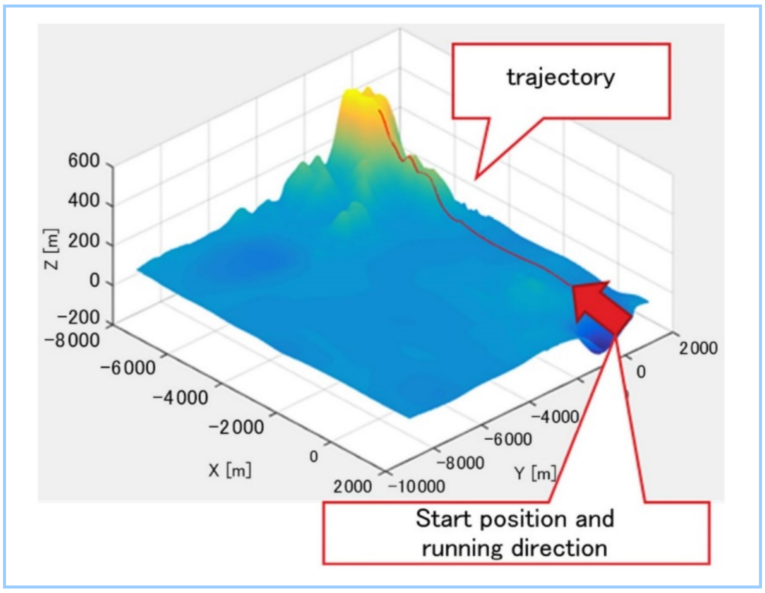

Figure 5 Seabed surface topography and the AUV's trajectory

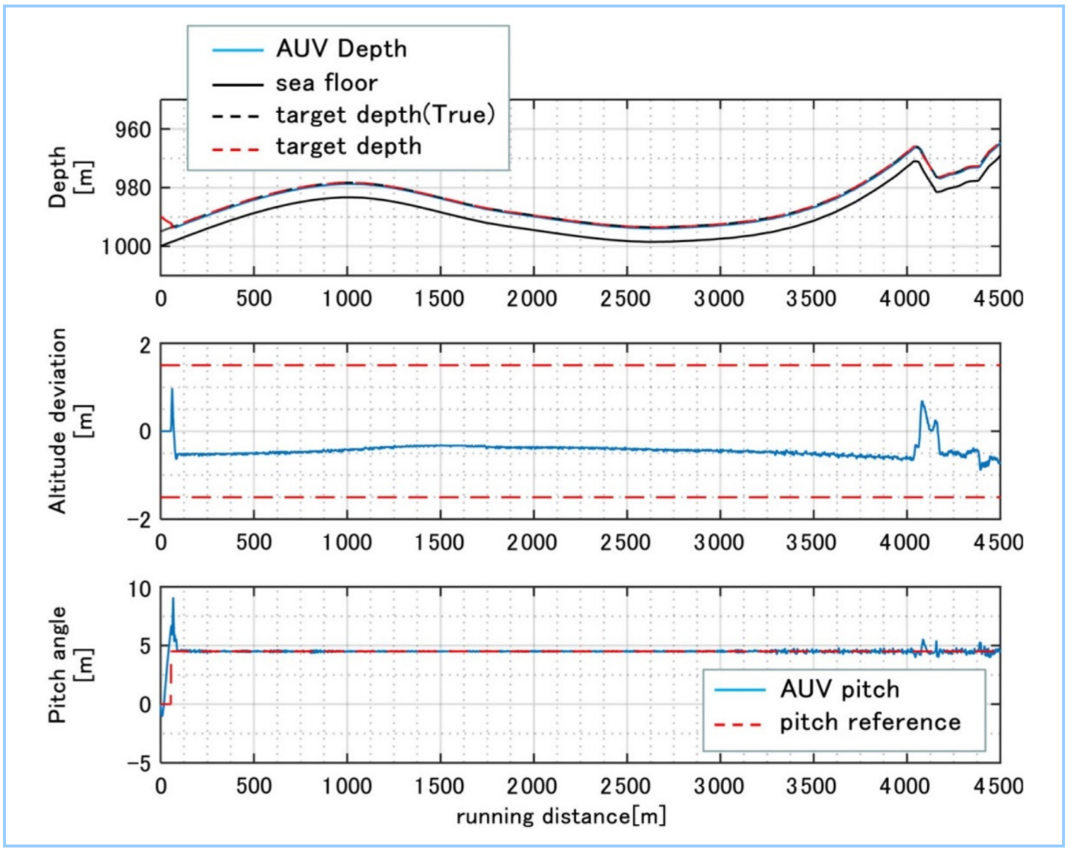

Figure 6 Control results (above: depth, seabed topography and target trajectory; middle: altitude deviation; and below: pitch angle)

5. Conclusion

This report presents the study results of autonomous control technology to realize low-speed AUV operation at low altitudes. As the AUV market further expands, user demand for functionality is expected to become more advanced. We will continue to develop AUV technologies that can meet the needs of users.

References

(1) Wakita et al., Development of Autonomous Underwater Vehicle (AUV) for Exploring Deep Sea Marine Mineral Resources, Mitsubishi Heavy Industries Technical Review, Vol.47 No.3 (2010) p.37~44

(2) K. Eguchi, et al., Low-speed and Low-Altitude AUV Control, AUV2020