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Research Article

Development of a Testbed AUV for Shallow Water Observation and Its Controller Evaluation

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ABSTRACT

Recently, Autonomous Underwater Vehicles: AUVs are utilized as the tools for ocean survey and practical applications such as ocean mineral resources survey and marine biological investigations. We have developed an AUV "Tuna-Sand2" and have succeeded in automatic sampling of shells in sea trials at Suruga Bay in Japan. Tuna-Sand2 is designed for 2000m depth and 8 hours operation with the speed of 1 knot and has several computers for basic motion control with sensor handling, intelligent behaviors based on image processing and data transmission, however, the robot needs efforts in deployment and recovery because of weight and sizes, and must return to the surface in emergency conditions. That is, the system should be stable, reliable and conservative, and not suitable for testing new challenging algorithms and behaviors. We have developed a new AUV KYUBIC which can be operated by a few people as a small testbed of Tuna-Sand2 and have similar shape and thruster arrangement. In this paper, we describe the system architecture of KYUBIC and the experimental results in Underwater Robotics Competition in Okinawa 2020.

1. Introduction

The ocean is one of the most difficult environments for humans to access directly. Autonomous Underwater Vehicles (AUVs) are expected to be the tools for wide area of marine research, and recently, have been implemented for various practical applications for underwater exploration [1]. AUVs have been utilized for surveying and observation of the marine resources by sea floor mapping [2], [3], [4], [5], cracks and damages in underwater structures [6], and maintenance of underwater pipelines [7].

Nishida et al. developed the AUV Tuna-Sand2 which is capable of seafloor mapping and marine resource survey [8]. Tuna-Sand2 is designed to dive into 2000m depth and operates 8 hours with the speed of 1 knot and has multiple computers for intelligent behaviors. They also succeeded on sampling of shells on deep seafloor based on commands from support vessel operator at Suruga Bay [9].

In order to accomplish the sampling missions, Tuna-Sand2 consists of two main functions, the basic functions: autonomous control system to follow assigned waypoints, collision avoidance, emergency surfacing and position transmitting by satellite after the AUV surfaced, and advanced functions: image processing for seafloor image enhancement [10] and visual servo of target objects [11], acoustic image transmission, and sampling. To dive into deep ocean, the body should be strong enough to high pressure and becomes heavy and big in weight and sizes, and the system becomes conservative. So that the robot is not easy for testing new challenging algo that the robot is not easy for testing new challenging algorithms and behaviors. Therefore, we have developed

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a new AUV "KYUBIC" as a small testbed of Tuna-Sand2, which is designed to be operated by a few people and to have similar shape and thruster arrangement.

For the performance evaluation of KYUBIC, we had joined underwater robotics competitions held in a bay at Okinawa Island. In this paper, we describe the system configuration of the developed hovering type AUV "KYUBIC" and control system. We also report the results of the experimental results in the water tank and Underwater Robotics Competition in Okinawa 2020 to verify the effectiveness of KYUBIC.

2. Testbed AUV "KYUBIC"

2.1. *System architecture of KYUBIC*

The overview of AUV KYUBIC is shown in Figure.1, and the concept of KYUBIC is as follows,

(i) Small size and lightweight targeting at 30 kg or less.
(ii) Same arrangement thruster and basic sensor for navigation as Tuna-Sand2.
(iii) Boxed structure for easy handling to exchange payloads.

In order to realize concept (i), the maximum operating depth of AUV is 40 meters for light weight (570 mm length and 32 kg weight) with 4 pressure hulls; the control hull, the communication hull and two battery hulls. The control hull contains the power supply circuit, motor driver circuit, two computers for navigation and acoustic positioning and IMU sensor. The communication hull contains a Wi-Fi device for connecting to the host PC, and a GPS antenna. The two batteries for the control and actuator are mounted on a battery hull located below the AUV. Table1 shows the comparison of the specifications of KYUBIC and Tuna-Sand2.

In order to realize concept (ii), the AUV has 6 thrusters: 4 thrusters for horizontal motion and 2 thrusters for vertical motion. Mounted sensors are a depth sensor, a Doppler Velocity Log (DVL) for measuring the ground speed and altitude, and 4 hydrophones for acoustic positioning, 2 cameras for detecting obstacles in front and the other for observing the seabed.

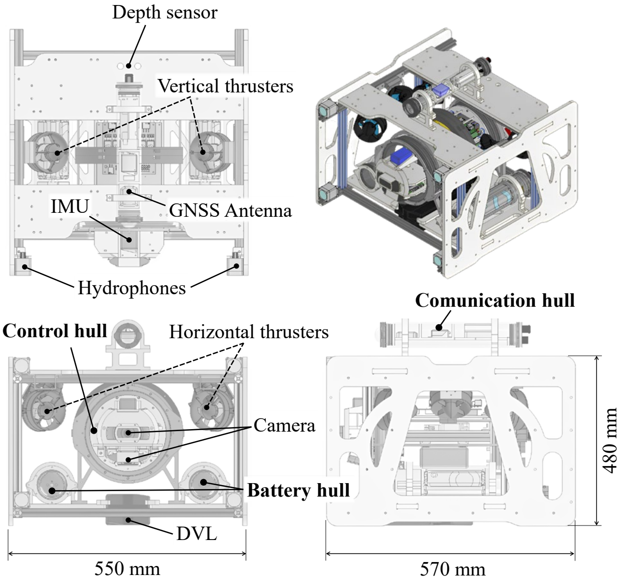


Fig.1 Overview the hovering type AUV KYUBIC

Table 1 Comparison of the specifications of KYUBIC and Tuna-Sand2

Category	Details	
	KYUBIC	Tuna-Sand2
Structures	0.48[m] × 0.55[m]×0.57[m]	1.4[m] × 1.2[m] × 1.3[m]
Weight (in air)	32 [kg]	380 [kg]
Max. depth	40 [m]	2000 [m]
Duration	3 [hour]	8 [hour]
Actuators	Horizontal thruster × 4 Vertical thruster × 2	Horizontal thruster × 4 Vertical thruster × 2 Ballast releaser × 2 Manipulator × 1
Batteries	Li-ion 266.4[Wh] × 2	Li-ion 5,000 [Wh]
Communications	Ethernet Wireless LAN Optical LAN	Wi-Fi Acoustic modem for command Acoustic modem for image transition
Sensors	USB Camera × 2 IMU DVL Depth sensor Hydrophone × 4 GNSS antenna	INS DVL Depth sensor USBL positioning device
Instrumentations	—	Obstacle detection device 3D mapping device Profiling sonar

Figure 2 shows the system architecture of the AUV. We selected a small computer with high processing capacity as the navigation computer to control the AUV by collecting information from various sensors. A micro-computer (Arduino compatible) acquires depth data, and the other sends the PWM signals to the motor drivers. The other computer calculates distance and azimuth to the sound source using data from 4 hydrophones.

In order to realize concept (iii), the AUV consists of open frame structure using a T-slotted frame and has connectors for additional payloads. Operators can easily add various functions according to the mission to be accomplished.

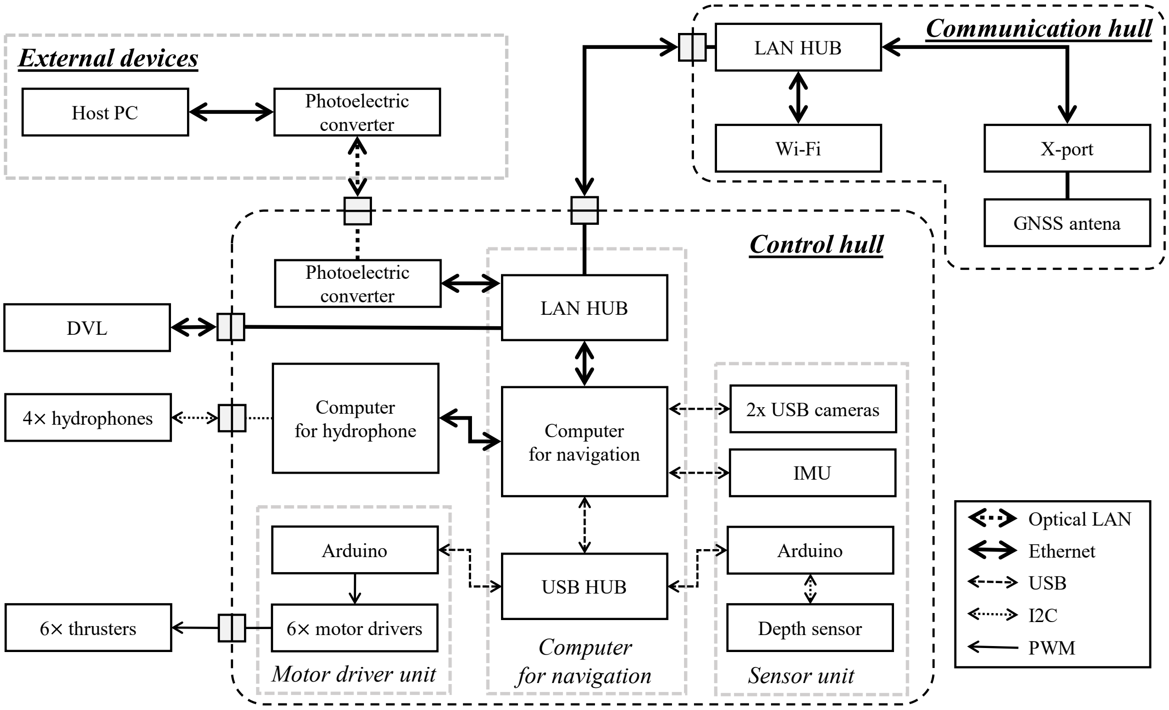


Fig.2 System architecture of the AUV KYUBIC

2.2. *Software*

The basic software for the control system is developed using MATLAB/Simulink. Figure 3 shows the architecture of the software, and the concepts of KYUBIC's software development are:

(i) Data transmission using ROS network possible to use various programming development environments.
(ii) Integrated software structure which consists of modular functions suitable for development by collaborative programming.

In order to realize concept (i), the programs for control, image processing, and communication interface with sensors are developed as independent Simulink models and communicate by ROS Network [12]. The Robotics System Toolbox supports ROS and enables highly functional and fast development. By using ROS environment, many debugging tools such as ROS bag are available and easy to track the process transitions, and it is possible to exchange data with other programs in various programming languages. Therefore, we can develop a system with high expandability in a short period of time.

For concept (ii), the Parallel Computing Toolbox is used. The Parallel Computing Toolbox is a script-based and Simulink model-based program which can build parallel computations using multi-core processors [13]. The software of the AUV consists of 5 Simulink models; Behavior model, Sensor model for IMU, Sensor model for DVL and depth sensor, Actuator model, Image processing model, and each model sends and receives data by ROS network. Behavior model selects control number and action which predefined by the operator. Behavior model also log data. AUV's behavior is managed by state flow, which is divided into modes. When a host PC and the AUV are connected by Optical LAN or Wi-Fi, the operator can easily check the value and transition status of the running process. After executing the behavior model, the AUV changes its mode to standby mode to be ready for dive and to set initial

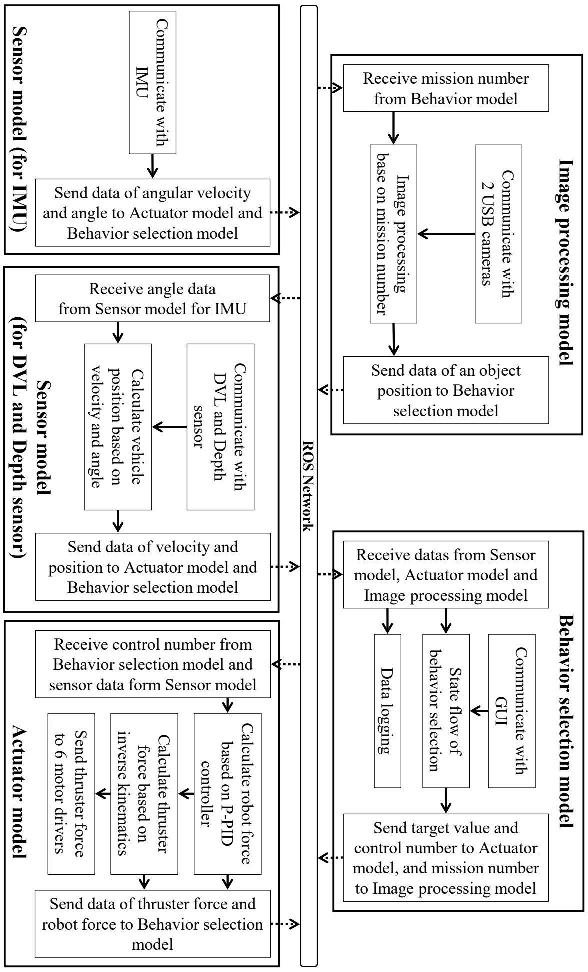


Fig.3 Software architecture of KYUBIC

position of the AUV by operator. After the initial position of the AUV is determined, the AUV starts to cruise according to the mode set by the operator in advance. The flow chart of KYUBIC's behavior selection is shown in Figure 4. We assign the mode numbers to the actions of the AUV. Therefore, the operator can determine the vehicle's behavior according to the applications by selecting mode number. In this paper, we explain the route tracking which is one of the basic behaviors. The AUV follows the route using the self-localization calculated by navigation computer and waypoints. Waypoint data are created in CSV format and includes waypoint number, target position (x, y, z), target attitude (roll, pitch, yaw), threshold for waypoint arrival judgement, time limit, mission flag, and self-localization flag. Mission flag is used to determine whether to transition to another mode. If the mission flag is not set in the CSV file, the AUV will enter the surfacing mode after the completion of the route tracking mission. Self-localization flag is used to select the self-localization data of the AUV. By changing the localization flag in the CSV

file, the operator can select either position control based on dead reckoning or position control based on GPS position data. The sensor model for IMU acquires the heading data, attitude data, and angular velocity data of AUV and the GNSS positions. The sensor model for

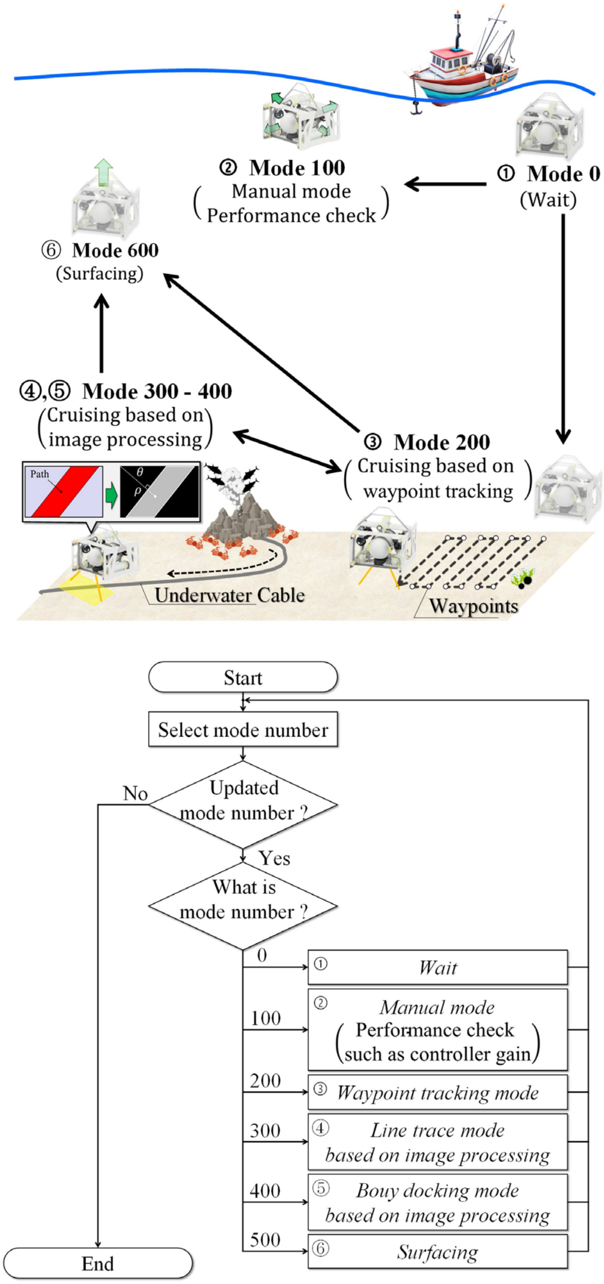


Fig.4 Flow chart of AUV's behavior

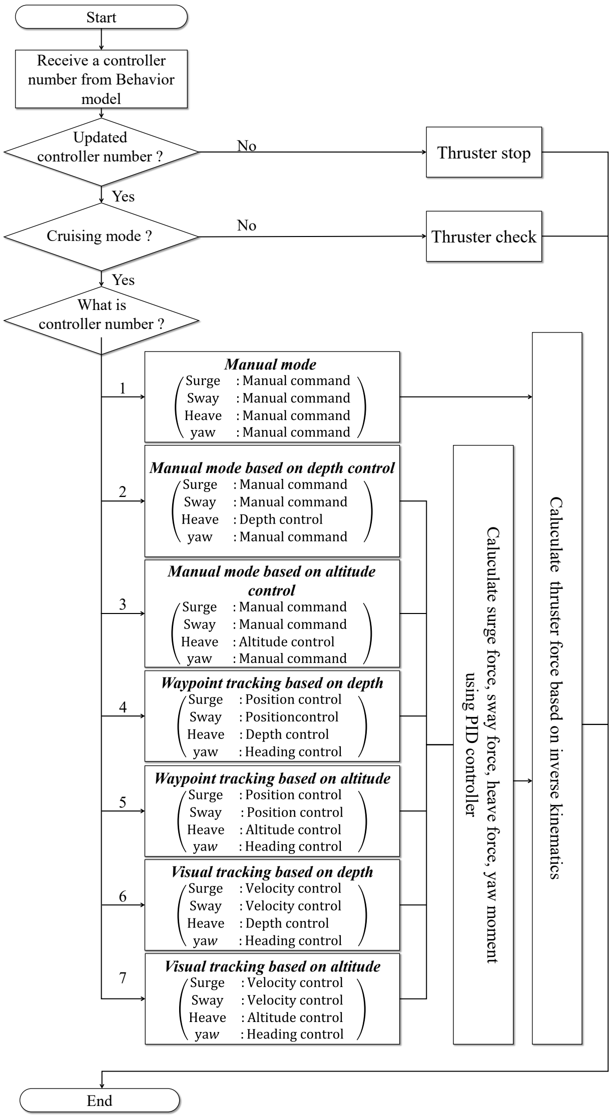


Fig.5 Flow chart of controller for the AUV

DVL and depth sensor measures the ground speed and altitude data and the depth data and calculates self-localization using the ground speed data from the DVL and the heading data from the sensor model for IMU. The actuator model calculates the thrust forces for the AUV based on the positioning data, depth data, heading data received from Sensor model for DVL and depth sensor and the target trajectory commanded from the behavior model. The AUV is controlled by sending the thrust forces to the motor drivers calculated by using inverse kinematics. The controller of AUV consists of velocity and position control in the surge and sway, depth control, altitude control and heading control. The operator combines these controllers needed to follow desired path according to the flowchart in Figure 5. The PID controller is often used in AUVs because of its reliability [1], [14]. Shome et al. adopted a PID controller for a modular shallow water AUV and controlled with 5 degrees of freedom modes and showed enough performance based on the results at sea trials [15]. Scillai et al. used a PID controller as a depth control for flight style AUV to evaluate the terrain collision and suitable flight style vehicle for terrains [16]. The image processing model captures forward image and bottom image of the AUV by two web-cameras to detect objects in front of or on the sea floor.

3. Experimental results

3.1. *Sea trial*

To evaluate the performance of KYUBIC, we participated in the Underwater Robotics Competition in Okinawa and performed a cruising test in the shallow water. The regulation of Competition, please refer to [17]. Figure 6 shows the waypoints and trajectory which was actually cruised by the AUV. Our strategy is to set the target depth in the diving area to 0.5 m and to cruise by route tracking based on waypoints. The AUV was controlled by the P-PID controller shown in Figure 7, and the parameters shown in Table 2 was used in the competition. In the surfacing area, the AUV turned 90 deg, then moved 1m in the surge direction, and turned 90 deg again to prevent the equipped safety rope from entrapment. In the competition, the AUV was not able to reach the goal point within the time limit, but the AUV was able to cruise autonomously for about 50 m to the turnaround point. Figure 8 shows the target value, the sensor data, and force data of the AUV during cruising. Table 3 shows the performance of controller. The position control in the surge direction is controlled with an error of less than ±0.1 m against the target position. The maximum velocity of the AUV during cruising was about 0.3 m/s, and the speed of response was poor because of the settling time was about 98 s. One of the reasons was the gain adjustment of PID controller, and the sufficient thrust of the AUV was not generated where the position error was large because of the proportional gain was dominant to the controller. In addition, pitch angle of the vehicle occurs at the point where the thrust force changed significantly. It means that the thrusters are not mounted on the same plane as the center of drag.

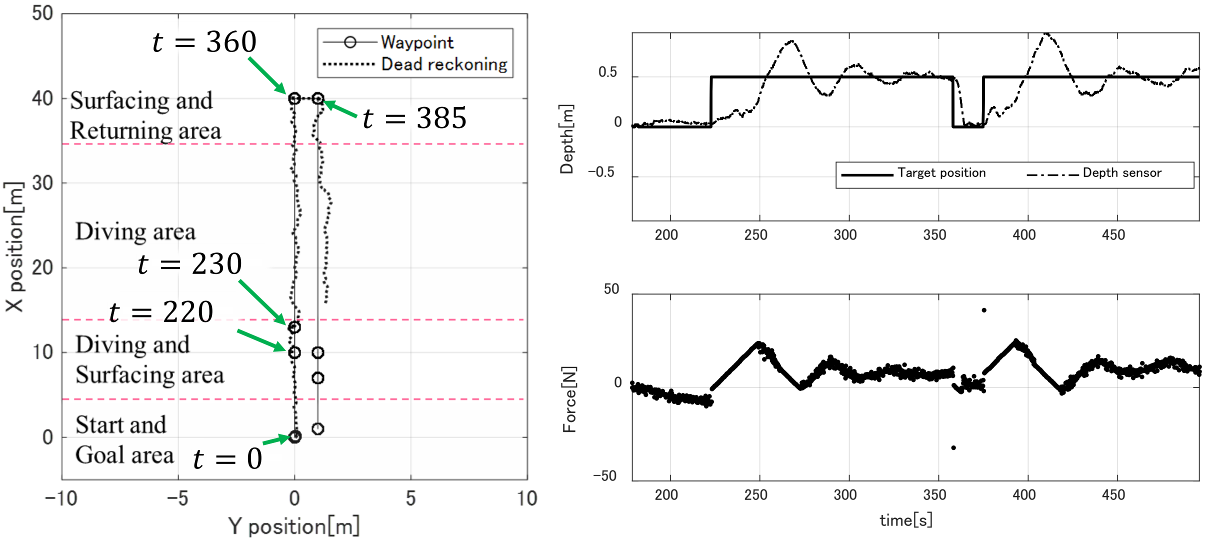


Fig.6 Trajectory of the AUV vs. waypoints

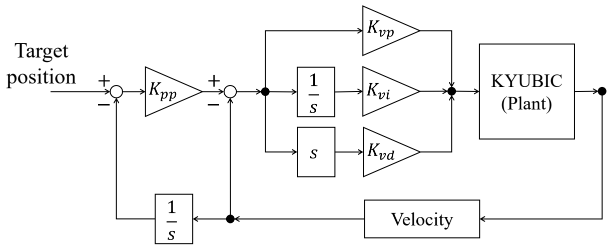


Fig.7 P-PID controller of the AUV

Table 2 Parameters of the P-PID controller for Underwater Robotics Competition in Okinawa 2020

	K_{pp}	K_{vp}	K_{vi}	K_{vd}
Surge	1.3	50.0	1.0×10^{-3}	5.0
Sway	1.3	50.0	1.0×10^{-3}	5.0
Heave	5.0	5.0	0.8	2.5
Heading	1.0	0.2	8.0×10^{-2}	1.7×10^{-5}

The position control in the sway direction was controlled with an error of less than ±0.3m against the target value until the surfacing area. However, the AUV was away from the waypoint while cruising in the diving area past the turnaround point. By evaluating the position control in the sway direction, we estimate that about 260 s after the start of the competition, there was disturbance over the thrust output in the sway direction of AUV during the dive. In addition, roll angle of the vehicle was generated at the point where the thrust force changes. This is because the velocity generated by the rotational motion of the vehicle is included as an error in the velocity data measured by DVL. The position control in heave direction had an overshoot of about 0.9 m against the target and confirmed the transient characteristic. The AUV's position was controlled with an error of the less than ±0.05 m against the target, but we could not adjust the optimal PID gain. The heading control in yaw direction, an overshoot of about 10deg occurs at the point where the change in the target value is large, but the AUV's heading was controlled with an error of less than ±1 deg against the target. From competition's result, it was confirmed that AUV KYUBIC is capable of stable cruising in the shallow water. However, the controllers in surge direction, in sway direction, and heave direction need to be adjusted. In the sea, the velocity data which measured by DVL includes errors caused by AUV's oscillation [18]. Therefore, it is necessary to develop an algorithm for correcting velocity considering the effects of AUV's oscillation.

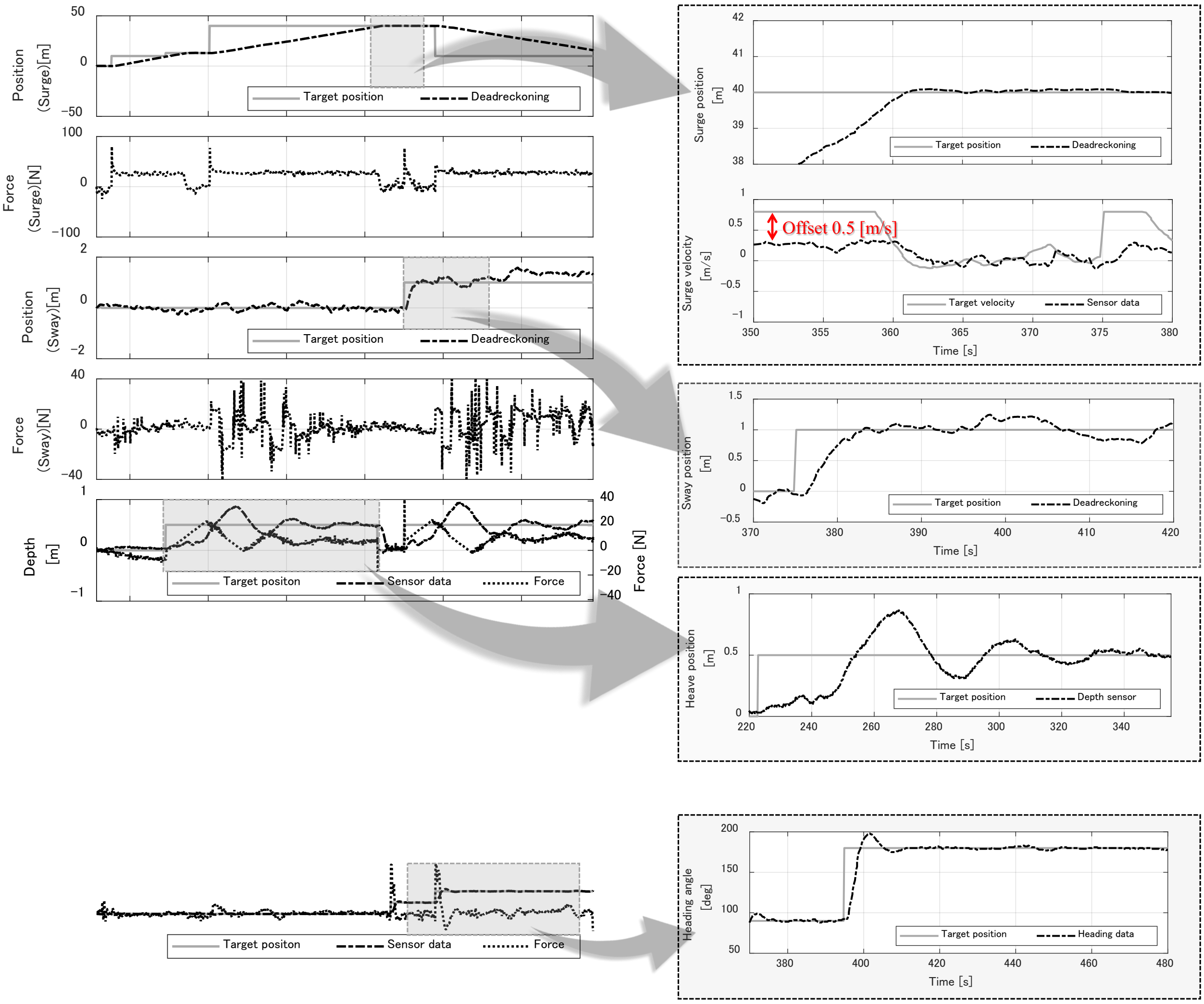
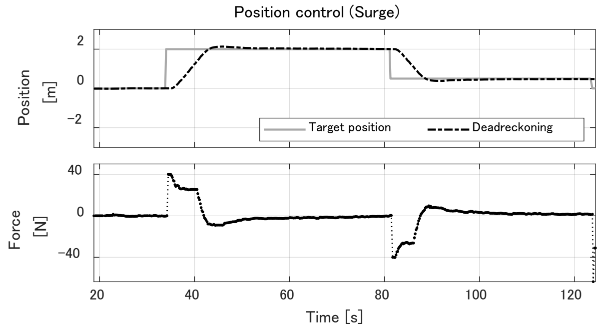


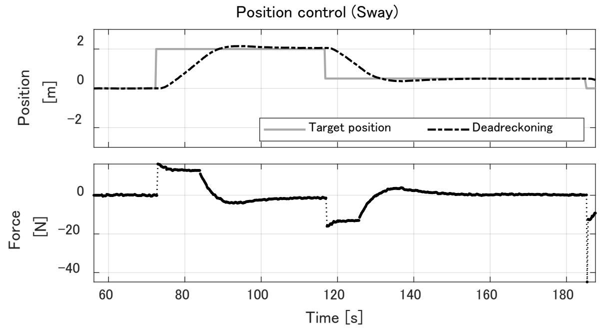
Fig.8 Position during waypoint tracking at Underwater Robotics Competition in Okinawa 2020

1. *Gain adjustment*

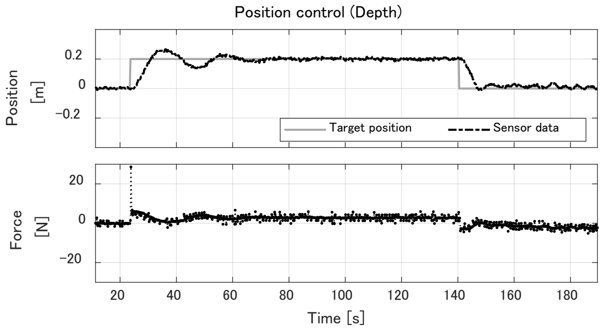
To evaluate the basic motion control of the AUV in environment, we carried out experiments in a water tank with a diameter of 6.0 m and a depth of 1.2 m. After diving, the AUV cruises according to the target position and heading set by the operator. The AUV does not control in the Roll and Pitch directions because we assumed the restoring moment generated by gravity and buoyancy is sufficiently larger than the moments in the Roll and Pitch direction. Figure 9 shows the sensor data and thrust data when the target values in each direction are input. The parameters of the P-PID controller were used the same value shown in Table 2. Table 4 shows the performance of controller. The position control in the surge direction had an overshoot of about 0.13 m and a rise time of about 6 s, but the AUV was controlled with



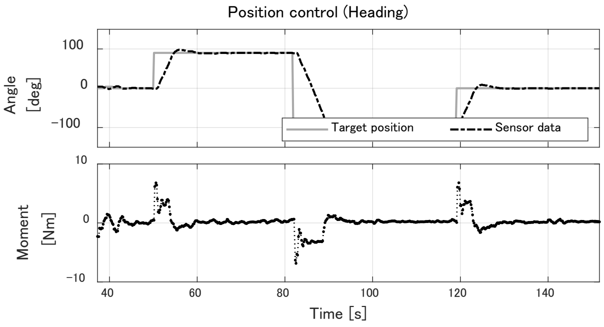
(a) Position control in surge direction



(b) Position control in sway direction



(c) Position control in heave direction



(d) Position control in yaw direction

Fig.9 Position during waypoint tracking using the parameters shown in Table 3

Table 4 Performance of controller using P-PID parameters shown in Table 2

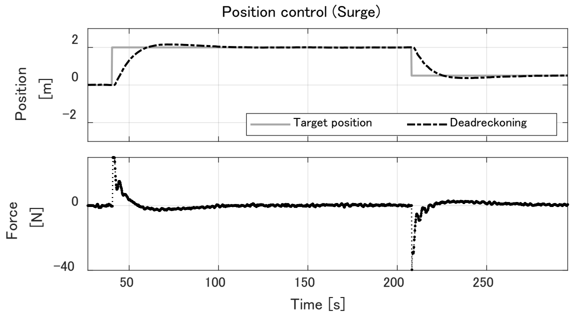
	Overshoot	Settling time	RMSE
Surge	0.13 m	14.11 s	± 0.03 m
Sway	0.15 m	27.61 s	± 0.05 m
Heave	0.16 m	48.71 s	± 0.05 m
Heading	8 deg	7.66 s	± 1 deg

Table 5 Parameters of P-PID controller based on the ultimate sensitivity method

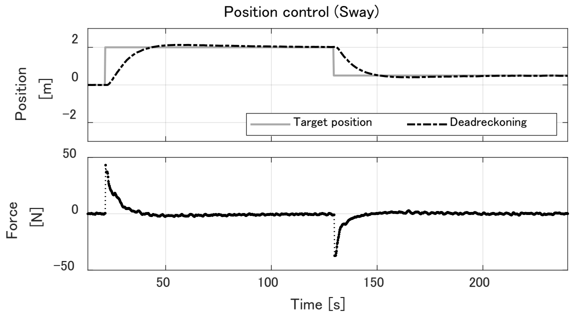
	K_{pp}	K_{vp}	K_{vi}	K_{vd}
Surge	0.2	99.0	1.7	3.5
Sway	0.2	123.0	1.9	2.0
Heave	0.6	72.0	3.3	1.1
Heading	1.0	0.2	8.0×10^{-2}	5.0×10^{-3}

an error of less than ±0.03 m against the target value in finally. The position control in the sway direction had an overshoot of about 0.15 m and a rise time of about 11 s, but the AUV was controlled with an error of less than ±0.05 m against the target value in finally. The position control in the heave direction had an overshoot of about 0.1m compared with the target value to 0.2 m, and it has transient characteristic because of settling time was 80 s. The heading control in the yaw direction had an overshoot of about 10 deg, but the AUV was controlled with an error of less than ±1 deg against the target value in finally. However, the control in the heave direction was not stable, so it is necessary to adjust the parameters of the it's controller.

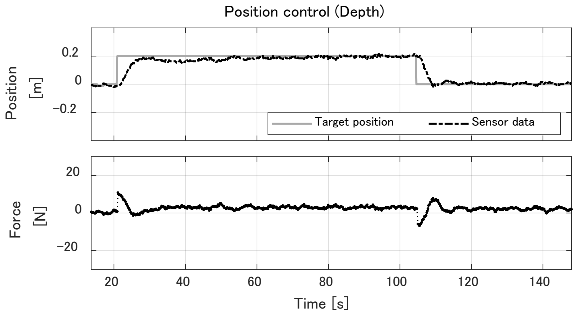
To improve the control performance in each direction (surge, sway, heave, and yaw), we adjusted the parameters of the P-PID controller individually using the ultimate sensitivity method. Table 5 shows the parameters which are adjusted by the ultimate sensitivity method, and Figure 10 shows the target value, sensor data, and thrust data. Table 6 shows the performance of controller. The position control in the surge direction had an overshoot of about 0.12 m and a rise time was of about 13 s, and the AUV was controlled with an error of less than 0.01 m finally. The position control in the sway direction had an overshoot of about 0.13 m and a rise time was of about 14 s, and the AUV was controlled with an error of less than 0.02 m finally. The position control in



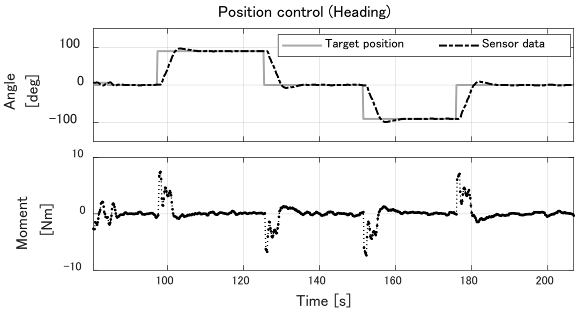
(a) Position control in surge direction



(b) Position control in sway direction



(c) Position control in heave direction



(d) Position control in yaw direction

Fig.10 Position during waypoint tracking using the parameters shown in Table 5

Table 6 Performance of controller using P-PID parameters shown in Table 5

	Overshoot	Settling time	Error
Surge	0.15 m	47.53 s	±0.01 m
Sway	0.14 m	44.91 s	±0.02 m
Heave	-0.05 m (Undershoot)	55.08 s	±0.02 m
Heading	7 deg	7.92 s	±1 deg

the heave direction had an undershoot of about 0.05 m, and the AUV was controlled with an error of within ±0.02 m. The heading control had an overshoot of about 10 deg, and the AUV was controlled with an error of less than ±1 deg. From these results, the AUV can cruise stable using the parameters which we adjusted based on the ultimate sensitivity method.

4. Conclusion

We developed the testbed AUV KYUBIC for observation in shallow water similar structure with Tuna-Sand2. From the experimental results of the tank test and sea trial showed that the motion controllers are well adjusted. For the AUV KYUBIC, P-PID controller is adopted and showed the control results with cm-order errors and good performance in the experiments, therefore, the next target is the implementation of P-PID control system to Tuna-Sand2. We can use the AUV KYUBIC as the testbed for Tuna-Sand2 and evaluate the navigation algorithms before the actual sea trials. Tuna-Sand2 has more accurate sensors and powerful thrusters, so that we can expect more robust and accurate trajectory control. As future works, we will develop a feedback and feedforward combined controller to adapt external disturbances of tidal current and oscillational forces, acoustic positioning system and visual servo control system.

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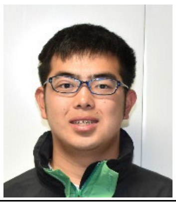

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