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Autonomous Underwater Vehicle with Vision-based Navigation System for Underwater Robot Competition

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Abstract

The underwater robot competition in international conference Techno-Ocean 2021 was held to advance underwater technology, in Dec. 2021. The competition consists of five leagues including AUV (Autonomous Underwater Vehicle) league, and Kyushu underwater robotics which is the Underwater Student Project team at our university that joint the AUV league using developed AUV. The wet test of the AUV league includes a Gate Pass mission which requires passing through an underwater green gate, Buoy Touch mission requiring contact with the yellow and red buoys, and Special mission requiring contact with the Pinger which has an unknown location. Our AUV navigates by image processing using underwater camera to achieve the mission. This paper explains the AUV system, the mission strategy and detail of image processing.

Keywords: Autonomous Underwater Vehicle, Robot competition, Image processing

1. Introduction

The Japan NPO Underwater Robot Network holds an underwater robotics competition every year to improve practical underwater technology and foster underwater engineers. Underwater Robot Competition Techno-Ocean Underwater Robot 2021 has a mission to perform line tracking and buoy touching. These missions simulate the automatic docking of an underwater robot to a base station on the seafloor for long-term observation, and the inspection of submarine cables in oil pipelines. This is expected to improve practical underwater technology.[1,2,3] Our laboratory has developed the AUV "KYUBIC", which can be operated by a few people, as an educational platform for participating in this competition.[4] In this paper, we report the system configuration of "KYUBIC", strategies and results of Techno-Ocean Underwater Robot Competition 2021 held in December 2021.

2. The Hovering Type AUV KYUBIC and Underwater Robot Competition

An KYUBIC is a hovering AUV developed for educational purposes. It was developed based on the concept of a versatile testbed with a hardware structure that allows for additional functions depending on the mission. The fuselage has a box-shaped structure, and a water-resistant container is stored inside the outer shell, making it highly fragile and portable.

2.1. *KYUBIC's equipment*

As mentioned earlier, KYUBIC, shown in Figure 1, was developed as an educational platform and is equipped with various sensors necessary to accomplish the mission of the underwater robotics competition. During the competition, actions such as diving and surfacing, forward and backward, etc. are performed using the ground speed obtained from the DVL (Doppler Velocity Logs) attached to the bottom of the KYUBIC, and information from the IMU sensor and depth sensor mounted on the control hull. In addition, the control hull is equipped with two camera sensors to obtain visual information about the front and bottom of KYUBIC, and image processing can be used to obtain information about obstacles. The system is also equipped with an RGB sensor to cope with lighting light fluctuations predicted in the real environment, and can measure illuminance, etc. However, it has not been implemented in software in the competition reported in this paper. In addition to the

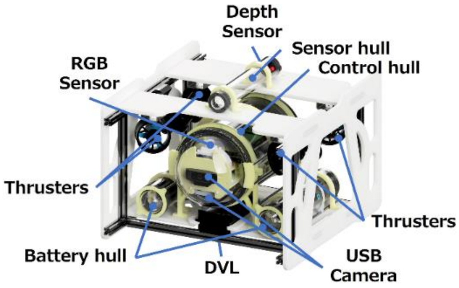

Fig. 1. Overview of KYUBIC

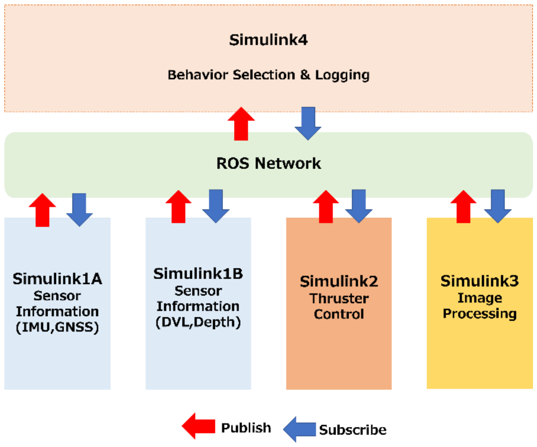

Fig. 2. system configuration

control hull, the AUV is equipped with sensor hull and two battery hulls. The sensor hull is equipped with a Wi-Fi module for wireless communication with an external PC, and a GNSS for self-positioning in competitions conducted in actual seas. The battery hull contains a control battery and a drive battery. By providing individual batteries, the risk of leakage can be distributed.

2.2. *KYUBIC's Software configuration*

The control system of KYUBIC is developed by using Mathworks' matlab/simulink and ROS. As mentioned earlier in 2.1, KYUBIC is equipped with many sensors, and it is necessary to acquire information using various sensors simultaneously while in action. In KYUBIC, a Simulink model is prepared for each sensor, and as shown in Figure. 2, a total of five Simulink (1~5) models are processed in parallel by returning ROS. There are two types of Simulink1 (Sim1), Sim1A and Sim1B. Sim1A acquires inertial data and position information from IMU and GNSS. In Sim1B, the ground speed is obtained from the DVL and the depth information from the depth sensor. In Sim2, PID control of the thrusters is performed, and in Sim3, image information acquired from the camera sensor is processed. Sim4 is a Simulink model that controls KYUBIC using the information obtained from each sensor by other Sims. Simu4 is designed using Stateflow, which is a tool for designing state transition control schemes, because Sim4 performs behavioral strategies for the KYUBIC which require complex state transitions. [4,5]

2.3. . *Competition Rules and Our Strategy*

According to the competition rules of the underwater robot competition 2021 AUV department, the robots challenge each mission set up in the indoor pool with autonomous motions. In the competition rules, the pool is divided into Area0, Area1, and Area2 as shown in Figure 3. AUVs start from (1)"Start position" and points are added by "passing through the gate" (2), "touching the buoy" (3) and “moving between areas”. The goal is reached when the AUV completes four round trips on the competition course. In this participation, we focused on the fact that each mission exists on a line, and developed strategies based on image information. Our goals were to complete missions such as "going back and forth between Area 1 and Area 2", "passing through the gate", "touching the buoy", and "surfacing at the end".
To achieve "going back and forth between areas" and "passing through the gate", we adopted line tracing as the mission strategy method. This is because, as shown in Figure 3, a buoy and a gate are located on a line at the bottom of the pool, and we thought that the robot could navigate to the front of a buoy by following the line. When the robot recognizes a buoy, it aborts line tracing, touches a buoy and transitions to the return behavior.

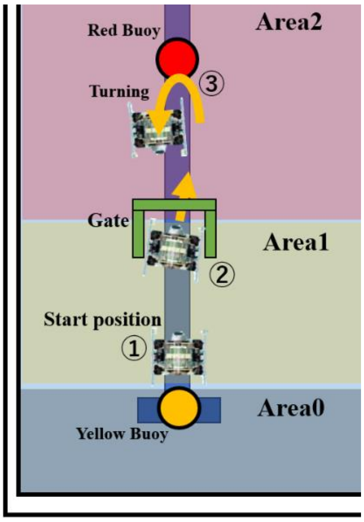

Fig. 3. Overview of competition's pool

2.4. . *Line trace method*

The robot navigates along the line using the angle information and image coordinate information of the line on the image captured by the camera for photographing underneath KYUBIC. This image processing uses the Hough transform to calculate the relative angle between the robot and the line. Figure 4 shows the flowchart to acquire angle data. In the first step, binarization is performed on the image obtained from the camera to extract the color components of the lines only, and denoising is performed by morphological transformation. Next, since the line to be traced is the boundary line between the line and the floor, edge extraction filtering is performed. For the edge image, straight line detection is performed by the Hough transform, and the angle of the line is calculated. The Yaw angle of the robot is controlled with the target angle being the sum of the line angle and the current angle of the robot. With this operation, the direction of travel of the robot becomes parallel to the line. To bring the line and KYUBIC close together, speed control is performed in the Sway direction until the difference between the line center of gravity point and the image center point becomes less than a threshold. During the line tracing, a buoy touch is performed on the front camera when a buoy is detected.

2.5. . *Buoy touch method*

As shown in Figure 5, buoy touch also performs binarization and denoising of images acquired from the

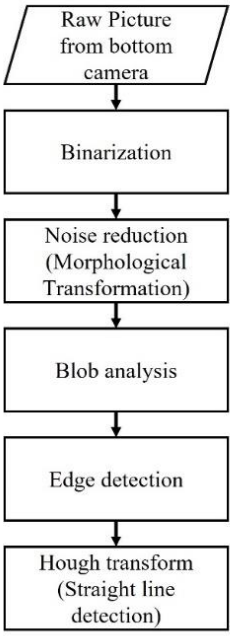

Fig. 4.
Image Processing for
Line Tracing

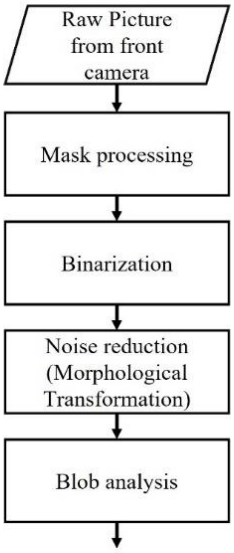

Fig. 5.
Image Processing for
Buoy touch

front camera using buoy color components. In addition to the pre-processing described above, buoy touches are masked at 10px above and 30px below the buoy and floor lines reflected on the water surface before binarization to prevent misrecognition. We label the processed binary image using connected components. Among the multiple labels, the label with the largest pixels in the region within the threshold is recognized as a buoy. It controls the speed in the Sway direction until the difference between the center of gravity of the area and the center of the image becomes less than a threshold, and then captures a buoy at the center of the KYUBIC. After that, the thrusters output thrust for a certain time, and the buoy is touched by inertial force. After the buoy touch, the robot moves backward for a certain time to avoid contact with the buoy during the round trip, and then rotates 180 degrees in the Yaw angle and returns.

3. Results of AUV Category and Consideration

The results of line tracing are shown in Figure 6. The top two graphs show the relationship between time and the difference between the region center coordinates of the detected line and the image center coordinate. The third graph shows the relationship between time and angle; between the horizontal axis of the image and the line detected by Hough transform. The fourth graph shows when the line is detected or not. A value of 1 means that the line is recognized, and a value of 0 means that the line is not recognized. Checking the Surge and Sway gap of KYUBIC, the value of the Sway gap swings. The reason for this may be that the line is not captured in the center of the image. However, Path detect was set to 1 for 140 seconds after the start of the action, indicating that the robot always detected the line and was on the line. In addition, the angle between the line and the horizontal axis of the image was recorded to be 0 degrees during that time, suggesting that the Yaw angle was kept parallel to the line on the initial position.

Figure 7 shows the motion data of KYUBIC against time. The black color indicates the target value, the blue color indicates the calculated velocity, the red color indicates the calculated thrust, and the blue and orange points in Angle indicate the Roll and Pitch. From the top, the graphs show the velocity in the Surge direction, the velocity in the Sway direction, the position in the Heave direction, the Roll angle, the Pitch angle, and the Yaw angle. The sixth graph shows whether DVL can get data or not. 1 means that DVL can get data, and 0 means that DVL is not able to get data. Focusing on the Surge velocity, Sway velocity, and DVL detection, both Surge and Sway are near the target values, but there are several periods when the DVL cannot get any data, making it unreliable. The graph shows that the thruster output is 4N during the period when the DVL is not available, because KYUBIC is set to navigate in the Surge direction with a constant thrust of 4N when the DVL is not available. The area surrounded by a green frame represents the period during which KYUBIC outputs 9N for a certain period to perform buoy touch.

Focusing on the Roll, Pitch, and Yaw angles, no significant changes were detected for Roll and Pitch and the movement of the Yaw angle was also in line with the target value. Based on these logs and the line angle information in Figure 6, we can conclude that the line trace was performed as intended during the period when DVL was available.

Figure 8 shows the results of buoy touch. From the top, each coordinate component of the detected area, the difference between the area center of gravity and the image center coordinate in the direction of the vertical axis of the image, and whether the buoy is captured at the center of the image and whether the buoy is detected. When Buoy center is 1, it means that the buoy has been detected at the center of the image, and when it is 0, it means that the buoy has not been detected at the center. When Buoy detect is 1, it means that the buoy has been detected, and when it is 0, it means that the buoy has not been detected. These graphs show that KYUBIC has recognized the buoy since about 100 seconds and has transitioned to the buoy touch.

Figure 9 shows the raw image and the binarized image during buoy touch. The markings near the center of the buoy and the two green line in the raw image are added for explanation purposes only and were not made during actual navigation. The mark near the center of the buoy corresponds to the center-of-gravity coordinate of the binarized region.

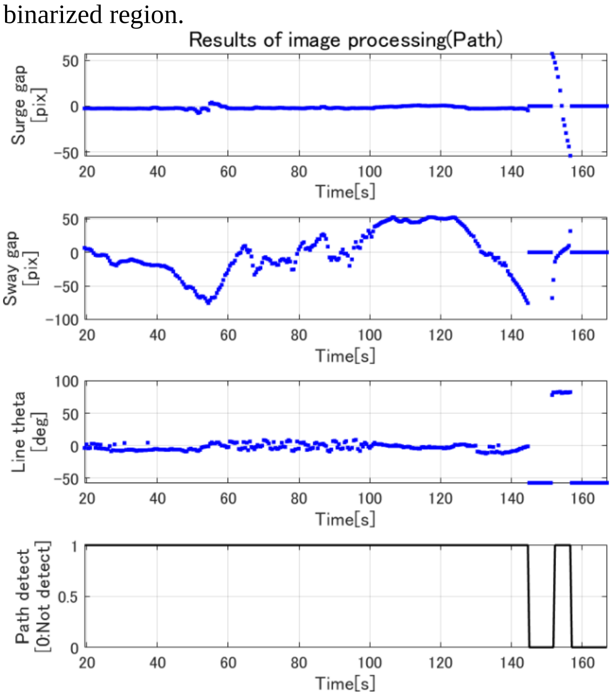

Fig. 6. Result of line trace

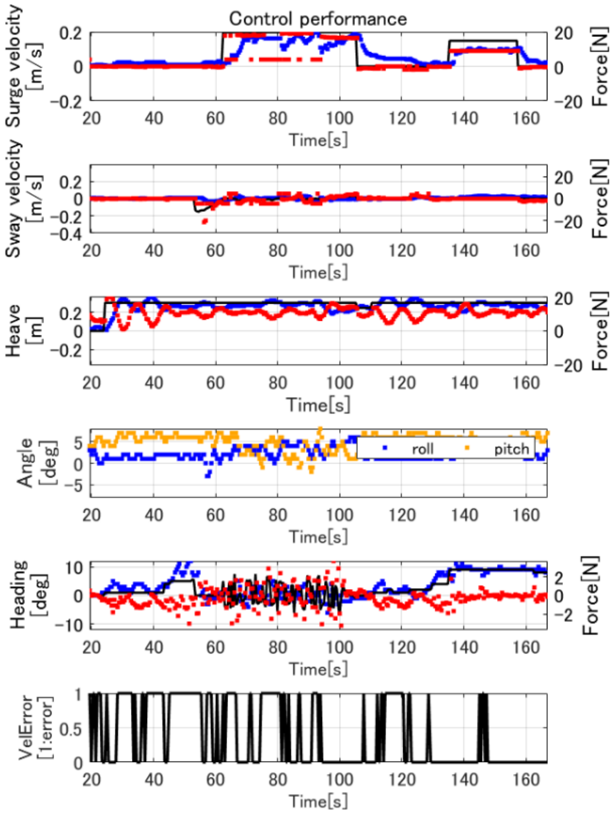

Fig. 7. Result of KYUBIC Control

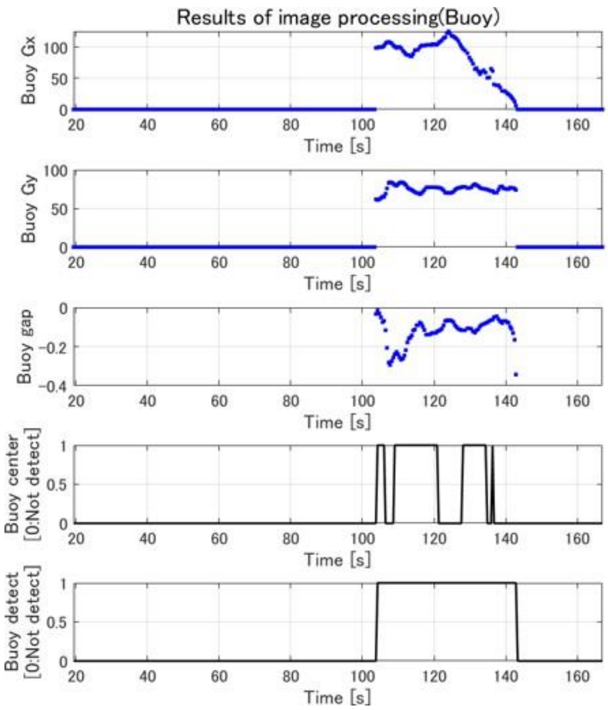

Fig. 8. Result of Buoy touch

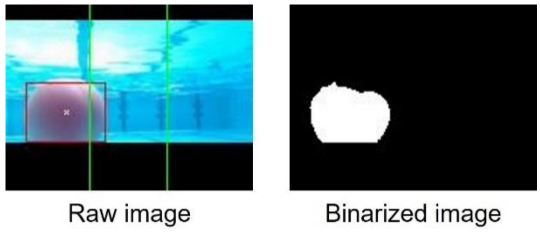

Fig. 9. Image processing results for buoy

The green line is a criterion used by KYUBIC to determine whether a buoy is centered. If the center of gravity of the detected area exists inside the two lines, the buoy is considered as centered. Figure 9 shows the image when the KYUBIC started to move forward toward the buoy. At the time of the competition, KYUBIC had once captured the buoy in the center of the screen before Figure 9 and started moving forward to the buoy, but it was unable to capture the buoy in the center of the screen in Figure 9. As a result, KYUBIC failed to touch the buoy and passed by it. The cause of these problems can be attributed to the tactics, once they started to move forward to the buoy, they did not take the tactic of canceling the buoy touch unless they lost sight of the buoy.

4. Conclusion

We implemented image processing and other processes to achieve the task of the Techno-Ocean2021 Underwater Robot Competition. As mentioned in the previous section, while we had detected the buoys, we had not been able to envision a strategy for when they were not captured in the center. As described in Chapter 2, the RGB sensor was not implemented, making the system vulnerable to changes in illumination, and in Figure 9, the camera was unable to respond to changes in illumination, resulting in blown-out areas. In the future, we will review our strategy and develop an image processing system that is robust to illumination variations.

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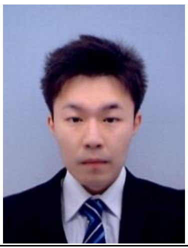

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