Underwater Acoustic Positioning Based on MEMS Microphone for a Lightweight Autonomous Underwater Vehicle "Kyubic"

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Abstract

Autonomous Underwater Vehicle positioning is important for accurate control and high-quality data collection. Conventional positioning systems are expensive. This paper describes the design and performance results of control using equations of motion and an inexpensive acoustic positioning system implemented on a lightweight AUV "KYUBIC" for Underwater Robotic competition in Okinawa 2021. The velocity used to estimate the self-position of the AUV is calculated form the equation of motion without integrating the acceleration. The acoustic positioning method is based on Super-short baseline (SSBL) principle. The system design comprises of self-made hydrophone module using MEMS microphone. The estimated distance and angle are integrated for dynamic control of AUV to locate the position of a Pinger.

Keywords: Autonomous Underwater Vehicle, Acoustic Positioning System, MEMS Mic, Underwater Competition

1. Introduction

The increasing use of Autonomous Underwater Vehicles (AUV) for underwater investigations ocean resources and installed infrastructure has made it an important tool. However, navigation remains a challenge to AUV performance because navigational accuracy is based on the accuracy of AUV position estimation underwater [1], [2]. Hybrid systems like the inertial navigation system (INS) and doppler velocity log (DVL) are expensive. Acoustic positioning systems (APS) are also expensive and are mounted on a ship and AUV for positioning. As such no available APS for low-cost AUV operation in shallow waters. This is one gap the Underwater Robotics Competition in Okinawa aims to address.

This paper describes the design of an inexpensive APS using MEMS microphone and performance results using a feedforward control on a lightweight AUV "KYUBIC" for Underwater Robotic competition in Okinawa 2021.

1.1. *Underwater Robotic Competition in Okinawa*

The Underwater Robotic Competition in Okinawa is an annual event aimed at promoting research solutions to the challenges of the underwater environment. It takes place in the actual sea. The KYUTECH Underwater Robotics team participated in the AUV Division: Intelligence/ Measurement Challenge. The purpose is to bridge the gap by designing an APS for low cost AUV operation in shallow waters. Details of the competition can be found in [3]. The following sections describes our team's strategy to meet the competition requirements.

2. Autonomous Underwater Vehicle: KYUBIC

KYUBIC is a boxed shape light weight AUV. It is a compact structure that can be operated by few people as an AUV or ROV. It has a modular architecture to facilitates for easy maintenance. A comprehensive documentation of KYUBIC development is presented in [4]. KYUBIC's control, strategy and hydrophone system are modified for the competition.

3. Hydrophone System

3.1. *System Configuration*

This section describes the configuration of the hydrophone system. The two hydrophones used in this system are connected to the Raspberry Pi 4 via an audio device (ReSpeaker 4-Mic Array for Raspberry Pi). This makes it possible to receive two devices simultaneously. The analog signals from the hydrophones are converted by the ADC inside the ReSpeaker and sent to the Raspberry Pi via I2S signals. The power supply is provided by an isolated DCDC converter to block noise from other devices.

3.2. *Acoustic Positioning Methods*

Figure 1 shows how APS estimates signal angle θ. By taking the incoming sound waves as parallel, θ is calculated from Equation (1) using the arrival time difference of the sound waves generated by Pinger, the baseline, which is the interval between hydrophones, and the speed of sound in water.

$$\boldsymbol{\theta} = \sin^{-1}\frac{\boldsymbol{Sound\ velocity} \times \boldsymbol{Time\ difference}}{\boldsymbol{Baseline}} \qquad 1$$

To remove the noise of thrusters and sea, a band-pass filter is applied to extract the Pinger signal. The frequency of the Pinger is 21.164[kHz]. The sampling frequency of the hydrophone is 96[kHz]. Figure 2 shows the raw and processed data. The frequency of the bandpass filter was set to 20-22 [kHz], which is the range of the Pinger's transmission frequency.

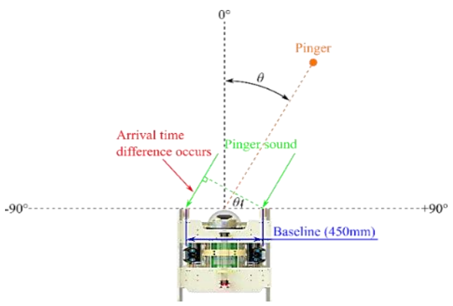

Figure 1: APS Architecture

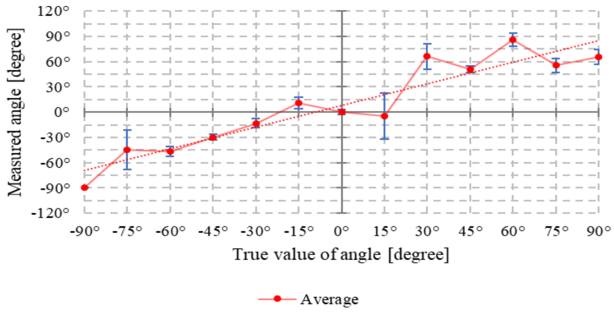

Figure 1: Result of Angle Measurement

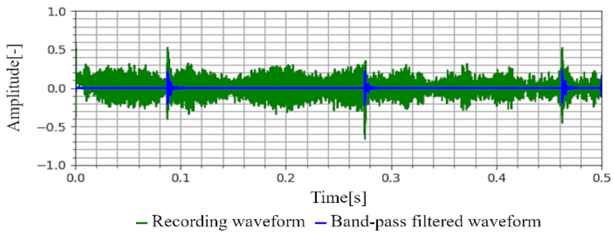

Figure 2: Band Pass Filtering

3.3. *Performance of hydrophone system*

The results of the performance evaluation of the hydrophone system are shown in Figure 3. The experiment was conducted in a pool with a diameter of 6.0[m] and a depth of 1.2[m]. The Pinger was placed in the center of the pool at a depth of 0.6[m]. The distance between the Pinger and the hydrophone array was 2.4[m]. The measurements were made at intervals of 15 degrees in the range of -90 to +90 degrees, five times each. Although the accuracy for angles other than 0° was low, the direction of the Pinger (left, front, right, etc.) could be estimated to some extent.

4. AUV Control Method

This section shows how our team controlled KYUBIC's navigation in the Intelligent/ Measurement Challenge Division of the competition. Our team aimed to reach the goal by combining position and thrust control. Until Pinger is detected. KYUBIC performs search missions by position control from target values for *Surge*, *Sway*, *Heave*, and *Yaw*.

Once Pinger signal is detected, the *thrust* is specified in the *X* and *Y* directions, while *Heave* and *Heading* control is maintained at the target value to reach the landmark. Each control was realized by feedback and feedforward control. Heave controlled the depth obtained from the Depth sensor, and Yaw controlled the heading obtained by integrating the Z-direction moment of the gyro sensor as feedback. Therefore, a feedforward control was

designed using the acceleration calculated based on the equation of motion.
A description of the method for deriving the position for the feedforward control of Surge and Sway is presented. The general equation of motion of an underwater robot as expressed in the robot coordinate system is

$$\boldsymbol{M}\dot{\boldsymbol{v}}_{\boldsymbol{w}} + \boldsymbol{D}|\boldsymbol{v}_{\boldsymbol{w}}|\boldsymbol{v}_{\boldsymbol{w}} = \boldsymbol{F} \quad 2$$

where $\boldsymbol{M}$: inertial coefficient, $\boldsymbol{D}$: fluid drag coefficient, $\boldsymbol{v}_{\boldsymbol{w}}$: water velocity, $\boldsymbol{F}$: thrust. The parameters $\boldsymbol{M}$, $\boldsymbol{D}$ in this equation were estimated by performing position control experiments. Acceleration was obtained from the equation of motion to which this estimated parameter was applied, and feedforward control was achieved.

Table 1: Parameters used for Experiment

Surge/Dive area	Surge (X)	0.5[m]
	Depth (Z)	0.2[m]
Pinger search area	Surge	0.5[m]
	Sway (Y & -Y)	1[m]
Search cycle limit	2	

5. Experimentation

5.1. *Performance of KYUBIC*

To evaluate KYUBIC's performance, experiments were conducted in a pool with diameter of 6[m] and depth of 1.2[m]. The Pinger is positioned 4.5[m] away from KYUBIC's position. The target values for the Pinger search and approach mission are as presented in Table 1. From Figure 4, the control performance for depth and heading controllers are shown. Measured value for depth has a short rise time to the target value overshoots reaching approximately 0.3[m] against the target value of 0.2[m]. Over time, the PID controller converges at the target value with smaller overshoots. This performance can be attributed inadequate tuning of the PID control. The heading control seems to keep the heading at the onset of the mission but becomes increasingly unstable when KYUBIC begins the Pinger search navigation. This is because the thrusters power navigates KYUBIC to the forward-left, forward, or forward-right direction. For better performance, adequate PID tuning of the heading controller is needed.
Figure 5 compares KYUBIC's position tracking from feedforward control to its actual position which is gotten from the DVL log. The feedforward controller navigates the *X* and *Y* target points in from start position of KYUBIC's mission. Ones the Pinger signal is detected, the thruster control program is initiated to approach the Pinger based on information from the hydrophone system.

Table 1 defines the parameters for the feedforward controller navigation.
From the Figure 5, positions [0,0] is KYUBIC's initial position. Firstly. KYUBIC's target surge value is 0.5[m] while diving to the mission depth position. However, although, the feedforward controller shows KYUBIC reaches the target position of 0.5[m], the actual position is 0.2[m] from the start position. This shows an error of 0.3[m] in the surge direction. The actual position also

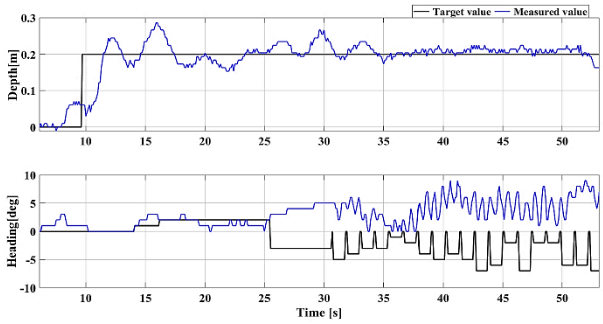

Figure 2: Controller Performance

dome drift to a maximum distance of -0.04[m] in the sway direction.

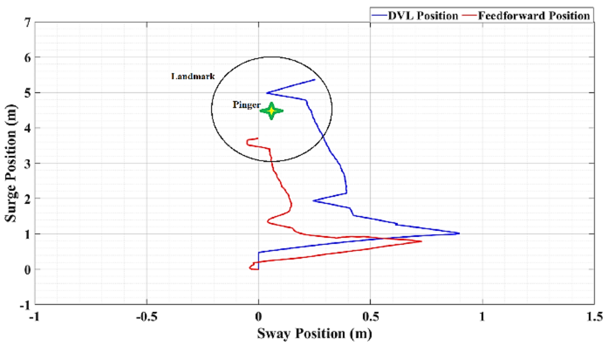

Figure 3: AUV Control and Actual Position

In the Pinger search navigation, the feedforward controller positions KYUBIC at 0.9[m] to the 1[m] target. However, it is positioned at 0.73[m] to the target position. Showing a position error of 0.27[m] without any drift error is log. This implies the feedforward controller will drift in either the surge or sway direction when there is no target value in that direction.
The Pinger is detected by the Hydrophone system is phase when KYUBIC's actual position is at 0.9[m] from the start position and the search program is terminated.
The Pinger Approach program is initiated, and the control strategy changes from *position control* to *thruster control*. In this control strategy, constant thrust in

forward-left, forward, and *forward-right* direction based on the region of detected Pinger signal.

Figure 6 shows a relationship between KYUBIC's position and Hydrophone system information. Here, the logged information of AUV position, Hydrophone signal region and detection are presented with respect to the time of the experiment.

The previous section discusses the error in feedforward position to actual position. However, the time graph shows that KYUBIC state transition takes place at the same time in both the actual and controlled positions.

From the *Hydro_Detect* log in Figure 6, '1' means the Hydrophones can detect the Pinger signal and '0' means no detection. But, due to the limited pool size, the signal can be detected from all positions. Therefore, there is detection '1' all through the experiment.

Hydro_Region '0', '1', and '2' means the position of the Pinger is at the Left, Center, and Right for KYUBIC's position. Based on the region, controlled thrust is applied in line with the identified *Hydro_Region*. It is worth noting that due to the high detection within the pool, the search program is modified to implement Pinger search before receiving considering detected information as shown in the position arrows *A* and *B* of KYUBIC's position.

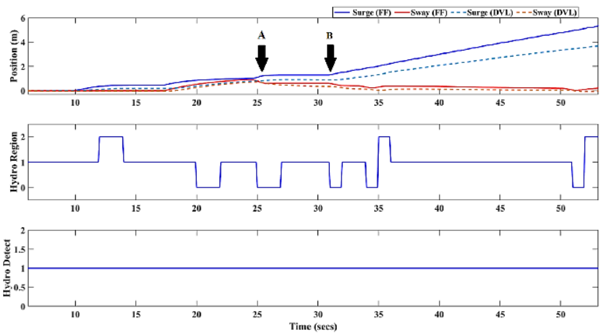

Figure 4: AUV Position vs Hydrophone System Information

In position *A*, the control strategy receives hydrophone information and switches from the *Position control* to *Thruster control*. The time for this change takes place between *A* and *B* where AUV position is seen to remain constant. At *B*, the region is Left, as such a *forward-left* thrust is applied as seen in Figure 5 from surge position of 0.9[m]. AUV navigate in the *forward-left* and then *forward* when the region is '1'. A sharp switch is seen from *forward-left* to *forward-right* when region changes from '0' to '2' at 35 [secs]. The long *forward* thrust (that drifts to the left) in Figure 5 shows the period of the region at '1'. AUV reaches Pinger position when region detects '1' and '2'while it is within the Landmark.

6. Conclusion

We developed an inexpensive acoustic positioning system for low cost AUV operation in shallow water. Using *feedforward control* and *thruster control*, we perform experiments with a KYUBIC. Results show hydrophone system can detect and successfully track the Pinger position. The feedforward controller has a 60% and 27% position error in the surge and sway directions respectively. It also drifts in either the surge or sway direction when a target value is not defined. Further improvements and tuning of the controllers as well as calculation to accurately detect Pinger angle and distance will make the APS more efficient. Sea trial are also needed to validate the performance of the hydrophone and control system because that is the basis of the developed system.

7. References

1. A. Miller, B. Miller, and G. Miller, "AUV position estimation via acoustic seabed profile measurements," AUV 2018 - 2018 IEEE/OES Auton. Underw. Veh. Work. Proc., pp. 1–5, 2018, doi: 10.1109/AUV.2018.8729708.
2. Y. Watanabe, Y. Ota, S. Ishibashi, T. Shimura, M. Sugesawa, and K. Tanaka, "An ocean experiment of inverse SSBL acoustic positioning using underwater vehicle OTOHIME," Ocean. 2016 MTS/IEEE Monterey, OCE 2016, pp. 1–5, 2016, doi: 10.1109/OCEANS.2016.7761498.
3. "7th Underwater Robot Competition in Okinawa," 2021.(Accessed Dec. 19, 2021) http://www.robo-underwater.jp/2021/rchp/JPN/index.php
4. T. Matsumura, Y. Uemura, K. Yanagise, Y. Tanaka, Y. Nishida, and K. Ishii, "Development of a handy autonomous underwater vehicle'kyubic,'" Proc. Int. Conf. Artif. Life Robot., vol. 2021, pp. 405–408, 2021, doi: 10.5954/icarob.2021.os22-4.

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