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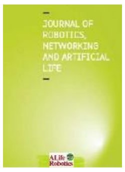

Research Article

An Inexpensive Acoustic Positioning System for Low-Cost Shallow Water AUV Operation

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ABSTRACT

Accurate localization of Autonomous Underwater Vehicles (AUVs) is fundamental to navigation accuracy, and robust control which leads to an overall success of vehicles' mission. Conventional positioning systems are expensive and cannot be implemented for lightweight/budget AUV systems. This paper describes the design and performance of an inexpensive acoustic positioning system (APS) used to guide the mission strategy of a lightweight AUV (KYUBIC) for the Underwater Robotics Competition in Okinawa. Using Position and Thrust control strategy, the AUV velocity is used for self-positioning estimation, and this is calculated from the equation of motion without integrating the acceleration. The acoustic positioning method is based on Super-short baseline (SSBL) principle comprising of 2 self-made hydrophone module using MEMS microphone. Our competition strategy searches and locates the position of a submerged Pinger using detection and angle estimates that are integrated for dynamic control of the AUV. Performance analysis show that the controller and low-cost acoustic system can search and localize at Pinger position within the accepted boundary.

1. Introduction

Global trends have recently shown an increase in the use of Autonomous Underwater Vehicles (AUVs) for data collection, observation, inspection, and other research related activities in the underwater environment. As a result, AUVs have become an important tool as relates to oceanography. However, a fundamental factor that improves the robust control of an AUV is its localization accuracy [1], [2]. Commercial systems that are commonly used for positioning AUVs are the inertial navigation system (INS), Doppler velocity log (DVL), and Acoustic positioning systems (APS). While pure inertial navigation operates using accelerometers and gyroscopes to track AUVs position and orientation; a drawback is that this system tends to drift overtime even for high-performance INS. Hence, pure INS navigation is not common due to this drawback. On the other hand, DVL systems operate by measuring AUVs velocity close to the seabed (about 200 meters high). This method tends to reduce positioning accuracy in deep sea operations.

Although popularly used, the above methods of navigation face increasing error measurements for in long distant/time missions. As such, navigation remains a challenge to AUV performance. High-performance versions can operate with minimal drift error but are too expensive and cannot be used in low-cost AUVs for shallow water operation.

Acoustic positioning systems (APS) do not suffer from drift error because they provide absolute measurements. They are mounted on a ship/AUV/Underwater environment for positioning information through an acoustic pulse, transmitter and receiver. However, acoustic positioning systems are also expensive to procure and cannot be implemented for low-cost/budget AUVs used for shallow water operation. Hence the need to bridge the gap of a low-cost positioning system for

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lightweight AUV operation in shallow water. This is one gap that Underwater Robotics Competition in Okinawa aims to address.

In this paper, we present a description of the solution proffered by the KYUTECH Underwater Robotics team towards bridging the gap of providing an inexpensive positioning system and participating in the 7th Underwater Robotics competition held in Okinawa. The following subsection describes the Underwater Robotics Competition in Okinawa and KYUTECH's Underwater Robotics Team. The second section briefly describes KYUBIC, the AUV platform used in the competition. The design of a self-made Hydrophone and acoustic position system (APS) are described in the third section. Section four describes the control and behavioral strategy implemented to meet the goals of the competition. The experiment and performance test are presented in the fifth section. The conclusion and contribution to knowledge are described in the sixth and seventh sections respectively.

1.1. *Underwater Robotics Competition in Okinawa*

Owing to the vast ocean area surrounding Japan, Okinawa Prefecture identifies the marine industry as a leading industry for the future. Against this background, the Okinawa marine robot competition was established to propel progress in the field of marine robotics. Popularly known as, Underwater Robotic Competition, it is an annual event that is organized by the Okinawa Marine Robot Competition Executive Committee and other affiliates and is held annually, in Okinawa, Japan.

The competition takes place in the actual sea and is open to all companies, research institutes, and higher institutes of education that have a desire to showcase results of their research and development solutions in tackling challenges of the underwater environment. This is achieved by using lightweight Underwater Autonomous/Remotely operated vehicles to compete [3].

The competition take place in 2 divisions as shown in Fig. 1. KYUTECH Underwater Robotics team participated in the "AUV Division: *Normal task and Intelligence/ Measurement Challenge*" and secured first positions in both challenges achieving 96% and 53% respectively based on our strategy.

In this paper, we present our strategy and results of experiments for the intelligence/ Measurement challenge. The challenge is purposed to proffer solution that bridges the gap of unavailable low-cost positioning systems. As such, the aim of the competition is to autonomously navigate to a goal point without using commercially available navigation devices, and to dock AUV within 2[m] of a submerged acoustic generators' (Pinger) position located 30[m] away from the start point and return to the start point with 5 minutes. Fig. 8 shows a top/side view description of the competition area and goal point. Participants are to design their navigation system and strategy to meet this target without using off-the-shelf navigation systems. For more details about the competition, the guidelines can be found in [3]. The following sections describe our team and strategy to meet the competition requirements.

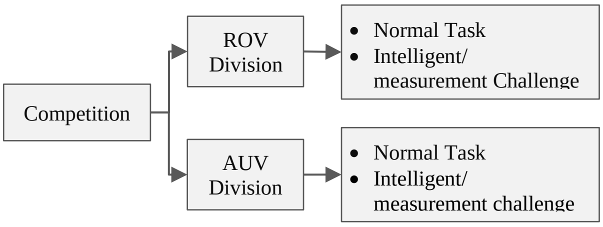

Figure 1: Division of Underwater Competition

1.2. *KYUTECH Underwater Robotics Team*

The KYUTECH Underwater Robotics Team is a team of research students and coordinated by students of Kyushu Institute of Technology under the supervision of Professors. The Team aims at developing competent engineers with technical skills to proffer practical solutions to real world challenges of the underwater environment through;

- AUV and ROV Mechanical/electrical design and software development.
- Acquisition of project management and teamwork skills.
- Improving critical problem-solving ability.

KYUTECH Underwater Robotics Team has annually participated in various Underwater competitions and conventions within Japan and Internationally from 2013 till date. Some regular annual events are Techno-Ocean, RoboSub Competition, Underwater Robot Convention in JAMSTEC, and Underwater Robotic Competition in Okinawa. More details of the Team's achievements are available in [5], [6].

2. Autonomous Underwater Vehicle: KYUBIC

In this section, a brief introduction to the AUV: "*KYUBIC*", we used for the competition is made. KYUBIC is a hovering type AUV. The name "KYUBIC" is derived from its boxed shape design as shown in Fig. 2. It has a light weight design that serves for its purpose as an educational platform that permits system expansion. KYUBIC has a compact structure that can be operated by few people either as an AUV or an ROV. Developed in 2020, it is designed to have a modular architecture to facilitates for safe operation, ease of maintenance and integrating additional systems without interrupting operation of systems that are essential to basic operation. A comprehensive documentation of KYUBIC's development is presented in [4]. However, to meet the goals of the competition, we modify KYUBIC's hydrophone system, control, and behavioral strategy. Further sections provide details.

3. Hydrophone System

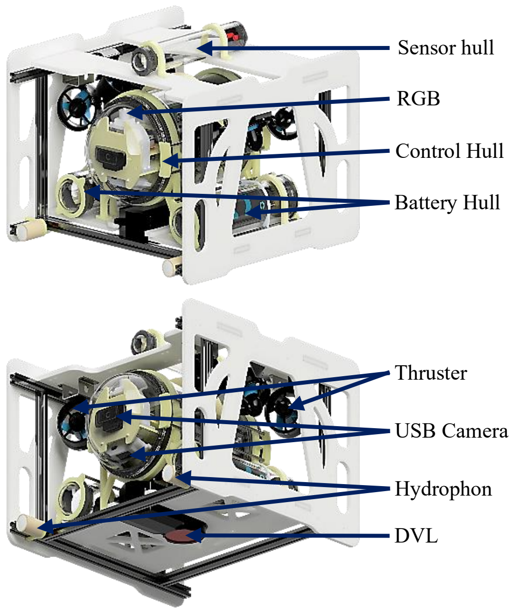

Figure 2: 3D Design of KYUBIC

3.1. *Acoustic Positioning System Design*

This section briefly describes the self-made hydrophone used for the acoustic positioning system. It is based on a MEMS microphone. Unlike conventional APS which cost thousands of dollars to procure and implement, our solution is inexpensive and can be used with existing audio device software to contribute to establishing an acoustic positioning technology for shallow water.

Our APS is based on the SSBL (Super Short Base Line) acoustic positioning method. Acoustic positioning technology using the SSBL method is generally used for self-position estimation of ships and submersibles, and has the advantage of being able to make modules smaller, however, a tradeoff is reduced accuracy relative to the LBL (Long Base Line) and SBL (Short Base Line) methods.

In SSBL method, the arrival angle of the sound wave and the distance from the sound source are used for positioning. Normally, the distance is measured by time of flight (ToF) using a transponder, but since a Pinger is used at the competition, the intensity of the sound received by the Hydrophone is used to estimate the distance.

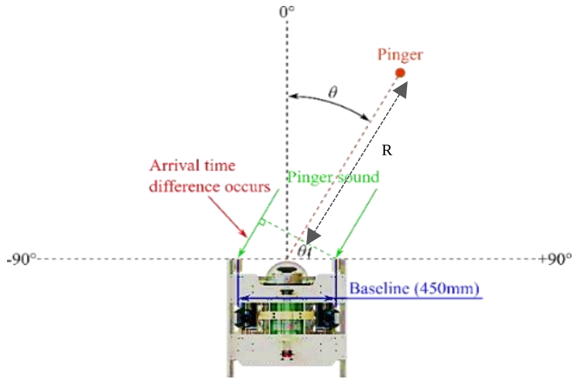

Figure 3: APS Architecture

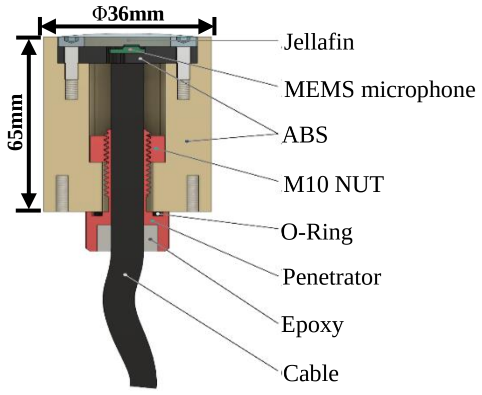

Figure 4: Self-made Hydrophone

In the implemented acoustic positioning system shown in Fig. 3, the position of the Pinger is estimated from the angle θ between the Pinger and the front of the robot and the distance R between the Pinger and the robot. As shown in Fig. 3, the angle was estimated by the method referred to as the SSBL method. The incoming sound waves are regarded as parallel, and θ is calculated from Eq. (1) using the difference in arrival time of the acoustic signal generated at θ, the baseline, which is the interval between hydrophones, and the speed of sound in water.

3.2. *Self-made Hydrophone*

The self-made Hydrophone has a size of 65 x Φ36 [mm] and weighs 200g. In making the Hydrophone, SPU0414HR5H-SB microphone module is used. As shown in Fig. 4, for the microphone to be used underwater, it needs to be molded in a waterproof/ pressure resistant material that will not hinder transmission of acoustic signals. The acoustic impedance of water is 1.48 x 10^5 [g/cm^2], as such the mold material selected is called Jellafin. It has similar acoustic impedance (1.55 x 10^5 [g/cm^2]) to water.

To ensure reception of acoustic signal, it is necessary to pour Jellafin into the hole of the microphones' sound port. The Hydrophone consists of a MEMS microphone, an ABS outer shell, and a penetrator. The space before and after the MEMS microphone is filled with pressure-resistant Jellafin.

3.3. *Hydrophone System Configuration*

A description of the hydrophone system is presented in this subsection. Two hydrophones are used in the system. They are connected to Raspberry Pi 4 through an audio device (ReSpeaker 4-Mic Array for Raspberry Pi). In doing so, signal from two devices can be received simultaneously. Using the ADC, signals from the Hydrophones are converted inside the ReSpeaker and sent to the Raspberry Pi via I2S signals. A pictorial description of the system configuration is shown in Fig. 5. A dedicated and isolated DCDC converter supplies the power to the system in order to ensure that noise from other devices are blocked out.

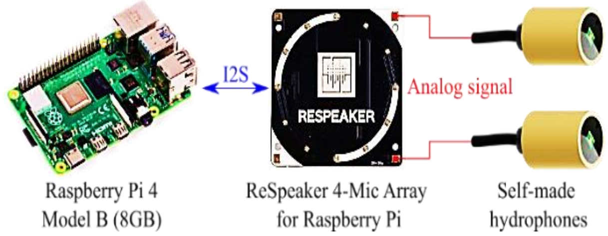

Figure 5: Hydrophone System Configuration

3.4. *Acoustic Positioning Method*

Fig. 3 shows how our APS estimates signal angle θ. By taking the incoming sound waves as parallel, θ is calculated from Eq. (1) based on time delay when acoustic signal generated by the Pinger reaches each Hydrophone (represented by channel 1 and 2 signals in Eq. (2)), the baseline, which is the distance between Hydrophones, and the speed of sound in water.

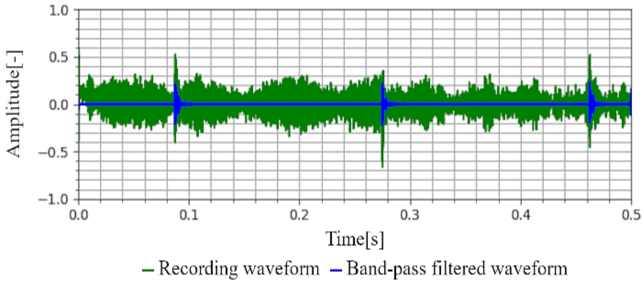

Figure 6: Band Pass Filtering

$$\theta = \sin^{-1}\frac{\textit{Sound velocity} \times \textit{Time delay}}{\textit{Baseline}} \qquad (1)$$

$$\textit{Time delay} = \textit{Signal}_{tCh1} - \textit{Signal}_{tCh2} \qquad (2)$$

Noise from the sea by movement of wave and also operation of KYUBICs thruster's envelope the generated signal from the Pinger. 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], and that of the band pass filter is 20 to 24 [kHz]. The sampling frequency of the hydrophone is 96[kHz]. Fig. 6 shows the raw data before filtering and data after processing using the band pass filter. The result shows that noise is greatly removed and the signal can be clearly confirmed.

3.5. *Hydrophone system Performance*

The results of the performance evaluation of the hydrophone system are shown in Fig. 7. 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.

From the experiment, the following conclusions can be drawn; that the inexpensive self-made hydrophone is capable of receiving Acoustic signals, and by applying a bandpass filter the signal can be clearly extracted from the noisy signal. Although the angle accuracy reduces for angles other than 0°, we are able to determine if the Pingers' location is to the left, centered at the front or right based on the estimated angle.

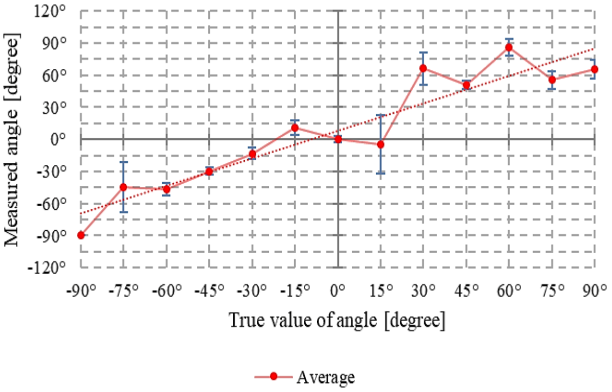

Figure 7: Result of Angle Measurement

4. AUV Control Method

In this section, a description of our teams' strategy for controlling KYUBIC's navigation in the AUV Intelligent/ Measurement Challenge Division of the competition. Bearing in mind that off-the-shelf navigational devices cannot be used, our strategy is to reach the goal point by combining *Position and Thrust control* to search for the Pinger signal and Pinger approach to locate it. As such, KYUBIC is programed to approach the challenge in 2 stages; *Pinger search* and *Pinger approach* missions respectively.

In the *Pinger search* stage, KYUBIC performs search missions by position control using preset target values for *Surge*, *Sway*, *Heave*, and *Yaw*. Once Pinger signal is detected by the Hydrophone system, KYUBIC automatically switches to the *Pinger approach* stage. In this stage KYUBIC employs *thrust control* based on preset values in the *X (Surge)* and *Y (Sway)* directions, while *Heave* and *Heading* control is maintained at the target value to reach the landmark. Each control is achieved by either feedback or feedforward control. Heave controls the depth using data obtained from the Depth sensor, and Yaw controls the heading using data obtained by integrating the Z-direction moment of the gyro sensor as feedback. We design a feedforward controller using the acceleration calculated based on the equation of motion.

Here we describe the methodology used to derive the position for the feedforward control of Surge and Sway in the section. From Eq. (3), the general equation of motion of an underwater robot as expressed in the robot coordinate system is [7].

$$\boldsymbol{M}\dot{\boldsymbol{v}}_{\boldsymbol{w}} + \boldsymbol{F}_{\boldsymbol{1}} = \boldsymbol{F}_{\boldsymbol{F}} + \boldsymbol{F}_{\boldsymbol{G}} + \boldsymbol{F}_{\boldsymbol{B}} + \boldsymbol{F}_{\boldsymbol{T}} \qquad (3)$$

Where $\boldsymbol{M}$: Inertia matrix, $\dot{\boldsymbol{v}}_{\boldsymbol{w}}$: acceleration vector, $\boldsymbol{F}_{\boldsymbol{1}}$: inertial fluid force, $\boldsymbol{F}_{\boldsymbol{F}}$: non-linear fluid force, $\boldsymbol{F}_{\boldsymbol{G}}$: gravity, $\boldsymbol{F}_{\boldsymbol{B}}$: buoyancy force, $\boldsymbol{F}_{\boldsymbol{T}}$: thrust force. However, a simplified equation that considers only the drag force proportional to inertia and the signed square of the velocity is a shown in Eq. (4).

$$\boldsymbol{M}\dot{\boldsymbol{v}}_{\boldsymbol{w}} + \boldsymbol{D}|\boldsymbol{v}_{\boldsymbol{w}}|\boldsymbol{v}_{\boldsymbol{w}} = \boldsymbol{F} \qquad (\boldsymbol{4})$$

where $\boldsymbol{M}$: inertial coefficient, $\boldsymbol{D}$: fluid drag coefficient, $\boldsymbol{v}_{\boldsymbol{w}}$: water velocity, $\boldsymbol{F}$: thrust. From the simplified equation, the equations for surge and sway respectively defined as shown in Eq. (5) and Eq. (6).

$$\boldsymbol{M}_{\boldsymbol{x}}\dot{\boldsymbol{v}}_{\boldsymbol{wx}} + \boldsymbol{D}_{\boldsymbol{x}}|\boldsymbol{v}_{\boldsymbol{wx}}|\boldsymbol{v}_{\boldsymbol{wx}} = \boldsymbol{F}_{\boldsymbol{x}} \qquad (5)$$

$$\boldsymbol{M}_{\boldsymbol{y}}\dot{\boldsymbol{v}}_{\boldsymbol{wy}} + \boldsymbol{D}_{\boldsymbol{y}}|\boldsymbol{v}_{\boldsymbol{wy}}|\boldsymbol{v}_{\boldsymbol{wy}} = \boldsymbol{F}_{\boldsymbol{y}} \qquad (6)$$

The parameters $\boldsymbol{M}_{\boldsymbol{x}}$, $\boldsymbol{M}_{\boldsymbol{y}}$, $\boldsymbol{D}_{\boldsymbol{x}}$ and $\boldsymbol{D}_{\boldsymbol{y}}$ in the above equations are estimated by conducting position control experiments for the *Surge* and *Sway* directions. In doing so, feedforward control is achieved by determining the acceleration force from the equations of motion by applying the estimated parameters.

5. Experiments

This section describes the experiment conducted to evaluate our strategy using feedforward control as well as the Hydrophone systems' ability to detect and locate the acoustic signal generator (Pinger). We conduct the experiments in the Shinmoji Marina, Kitakyushu, Japan as shown in Fig. 12. It is harbor that connects to the open sea. The experiment area is 10 x 8[m], with the distance to the goal point (Pinger) set at 8[m] from KYUBICs' start point. This is approximately a third ($\frac{1}{3}$) of the actual competition distance. In Fig. 8, a description of the experiment is shown. The experiment objectives are as follows;

- Evaluate the performance of the feedforward and feedback controllers.
- Evaluate the performance of the Self-made inexpensive Hydrophone in detecting the Pinger signal.
- Evaluate AUV behavioral strategy for navigation and positioning using the 2-stage control strategy (*Pinger search* and *Pinger approach*).

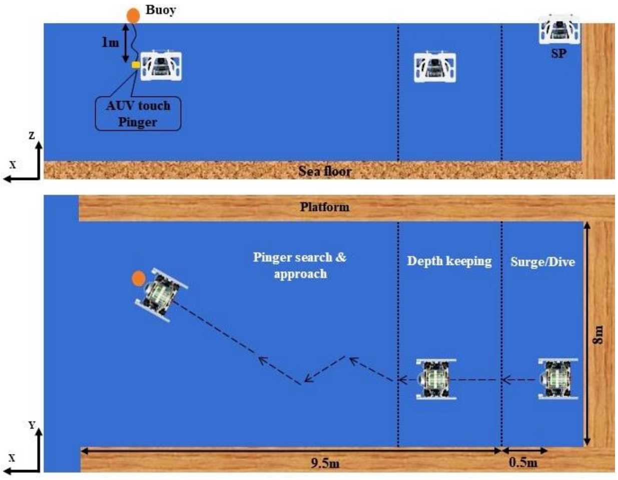

Figure 8: Behavioral Strategy

5.1. *Performance of KYUBIC*

From Fig. 8, the top illustration captures the XZ coordinate frame of the experiment area while the bottom illustration shows the XY coordinate frame. KYUBICs start position (SP) is about 8[m] from the Pingers position. According to the competition guidelines, AUV is to be submerged underwater after initialization till the end of the trial run. Hence, the objective of the first part of the experiment is achieving mission depth as shown in the *surge/dive* section of Fig. 8.

After initialization KYUBIC surges forward 0.5[m] while simultaneously diving to the target depth of 1[m]. Ones the target depth threshold is achieved, KYUBIC enters a *Depth keeping* mode and progresses to the *Pinger search* stage.

In *Pinger search* navigation, the feedforward controller uses target *surge/sway* values to achieve a zig-zag motion for KYUBIC. Navigating in a zig-zag pattern enables KYUBIC search for the acoustic signal by position control. As soon as the Hydrophone(s) receives acoustic signal generated by the Pinger, the *Pinger Approach* program is initiated, and the control strategy changes

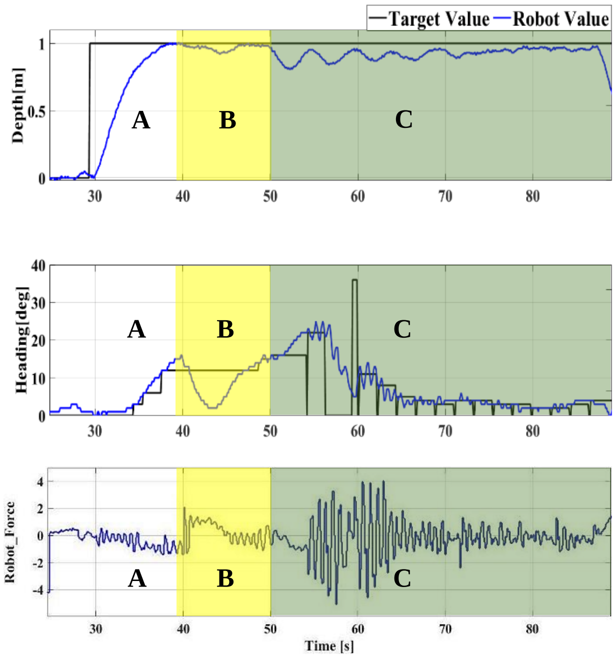

Figure 9: Feedback Controller Performance for Heave (top), Heading (middle) and Heading Force (bottom)

from *Position control* to *Thrust control.* In thrust control strategy, constant thrust force is applied in *forward-left, straight-forward*, and *forward-right* direction while maintaining KYUBICs *Heading.* Achieving this change in strategy and direction of thrust is based on the region of detected Pinger signal which is determined by the estimated angle.

During *Pinger approach, thrust control* is based on the information from the Hydrophone system which are *Hydro Detect*, and *Hydro_Region* data values. Using this information, thruster force and direction of thrust are determined until the threshold maximum signal from the Pinger is received then KYUBIC holds its position from a preset time and ascends to the surface to end the mission. A pictorial summary of the actual experiment in Shinmoji Marina has been documented in Fig. 12 (A, B, C and D).

5.2. *Result Analysis*

In this section, an analysis of experiment result based on the log data is carried out. Fig. 9, are graphical representation of the log data for the depth controller (top), heading controller (middle), and heading force data (bottom). The plots are each divided into 3 sections; “A” (white), “B” (yellow), and “C” (mint-green). These represent the periods in the experiment when KYUBICs modes of operation is *Surge/Dive, Pinger search* and *Pinger approach* respectively. The duration of the experiment is about 100[sec] from the time when KYUBICs program is initialized. However, the mission starts time is at 29.6[sec].

Heave Control

The depth controller receives target value of 1[m] at start time, and the log of the robot value shows a steady rise time for about 8.4[sec.] as depicted in section “A” of the plots in Fig. 9 (top). There is no overshoot and the controller steadily maintain the depth during *Pinger search* “B”, but the controller is unable to accurately maintain the target depth for a short period of time. However, the PID controller converges at the target value until the “C” when the controller changes to *Pinger approach* having detected the acoustic signal from the Pinger. In the “C” section, KYUBIC navigates based on the *Thrust control prog*ram and this significantly affects the depth keeping ability of the PID controller. When the Pinger is initially detected, the deviation from target depth is significantly large perhaps due to a large thrust force, however, as the thrust force reduces due to reducing distance to the Pingers’ location, the PID controller is increasingly tries to reach and keep the target depth. Therefore, there is need to improve the performance of the PID controller for depth keeping by tuning in order to minimize the effect of the thrusters when large force is demanded to approach the Pinger.

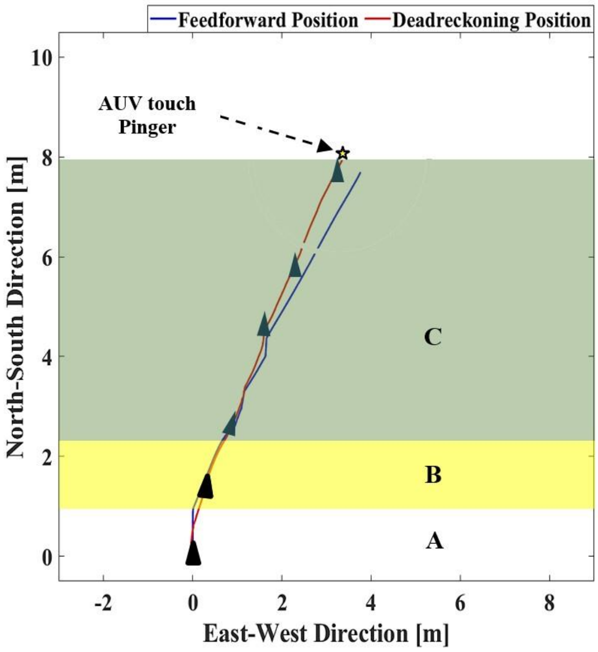

Figure 10: AUV Position Based on Feedforward vs Deadreckoning

Heading Control and Force

From the heading performance data, the PID controller for *Heading control* is unstable in maintaining the target heading. This can be seen in the target heading value that is set in section “A” (*Surge/Dive*) and “B” (*Pinger search)* part of the mission. In these parts of the mission, KYUBICs program is set to maintain the heading position set at initialization, no other target is prescribed this is so that the AUV can search for the Pinger signal and detect the region of signal origin angle relative to the desired heading. It can be observed from the heading force data, that the controller tries to maintain the target heading but does so insufficiently. This can be attributed to inadequate tuning of the PID controller and also due to the effect of sea currents opposing the desired path of KYUBICs is navigation. In the C part of the controller, we observe that the target heading is set to zero after every 3[secs], this is an error from the navigation algorithm that will be correct for the future trials.

Feedforward Control (Surge and Sway)

In Fig. 10, a comparison of KYUBIC's position from the feedforward controller to its actual position based on deadreckoning data is presented. The feedforward controller navigates based on preset targets in the *X (Surge)* and *Y (Sway)* position from the start position. The resultant motion is in a zig-zag pattern that improves the probability of detecting the unknown location of the generated signal. From the start point, KYUBICs targets are *Surge* 0.5m and *Heave* 1m. Although, there is no input value in the *Sway* direction, the feedforward controller shows KYUBIC reaches the target position without *Sway*, while the actual position from deadreckoning shows a *Sway position error* of 0.18m and *Surge position error* on 0.34m at the end of *Surge/Dive* mission "A". This shows that KYUBIC will *Sway* even when there is no target value in that direction and also that the drift data from the controller is not reliable for tuning the controller because it differs from the actual drift from Deadreckoning.

Table 1: Feed forward and Deadreckoning Position Error for Surge an and Sway

Section		A	B	C
Time (sec.)		39.7	50	87.8
Surge (m)	Dead Reckoning	0.63	2.84	7.84
	Feed Forward	0.97	2.62	7.47
Surge position Error		0.34	0.22	0.37
Sway (m)	Dead Reckoning	0.2	0.81	3.3
	Feed Forward	0.02	0.95	3.63
Sway position Error		0.18	0.14	0.33

Table 1 also shows the position error at the end of the *Pinger search* "B" and *Pinger approach* "C". The error increases from 0.22[m] at a distance of 2.84[m] to 0.37[m] at a distance of 7.84[m] for *Surge*. For *Sway*, the error increases from 0.14[m] at a distance of 0.95[m] to 0.33[m] at a distance of 3.63[m]. The feedforward controller logs a higher position error rate in the sway position than the surge position.

Note that although the feedforward controller logs KYUBICs position with increasing position error, we are able to verify that KYUBIC actually navigates to the Pingers' location, stops in front of the Pinger before ascending to the sea surface. Therefore, to improve on the position error, there is need for further tuning of the parameters ($\boldsymbol{M_x}$, $\boldsymbol{M_y}$, $\boldsymbol{D_x}$ and $\boldsymbol{D_y}$) used to determine the acceleration value in Eqs. (5) and (6). However, the tuning should be based on the data from deadreckoning not the feed forward controller.

Hydrophone system

The log from the Hydrophone system is divided into 5 sections; *Hydro_Angle*, *Hydro_Distance*, *Hydro_Center_Angle*, *Hydro_Detect and Hydro_Region*. However, estimation error in the first 3 data makes them unusable in determining KYUBICS behavioral strategy. The current strategy is therefore based on *Hydro_Detect* and *Hydro_Region* data which are used to determine the control strategy for KYUBICs navigation in this experiment.

Hydro_Detect is a flag that activates the Hydrophone system as when the acoustic signal it receives is above the preset threshold. *Hydro_Detect* flags "0" when there is no acoustic signal or signal is below the preset threshold and "1" when it detects the acoustic signal as can be seen in Fig. 11 (below).

Hydro_Region flags the position from where the acoustic signal originates relative to the KYUBICs position and heading. This *Hydro_Region* is implemented to meet the inaccurate angle estimation of the Hydrophone system. *Hydro_Region* flags "1" when estimated Pinger angle ranges from 1° to 90°. It is designated as the Right region of KYUBIC. *Hydro_Region* "2" is flagged when the estimated angle is 0° meaning the signal is straight ahead on KYUBICs path and "3" is flagged when the estimated angle ranges between -1° to -90°. It designates the signal originates from the Left region.

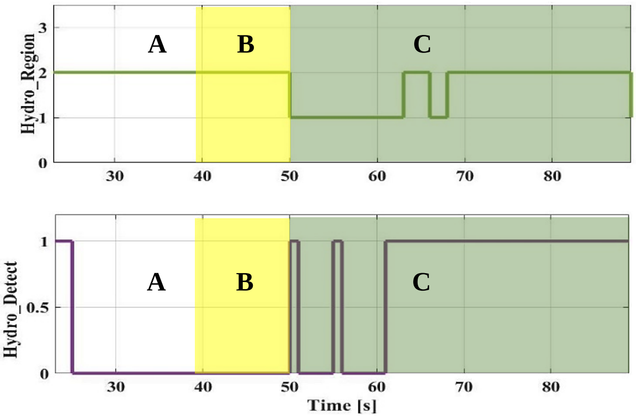

Figure 11: Time series Log of Hydro_Detect and Hydro_Region Data

Fig. 11 shows the *Hydro_Detect* and *Hydro_Region* log information plotted over the time of experiment. Firstly, it can be seen that KYUBICs strategy is fully dependent

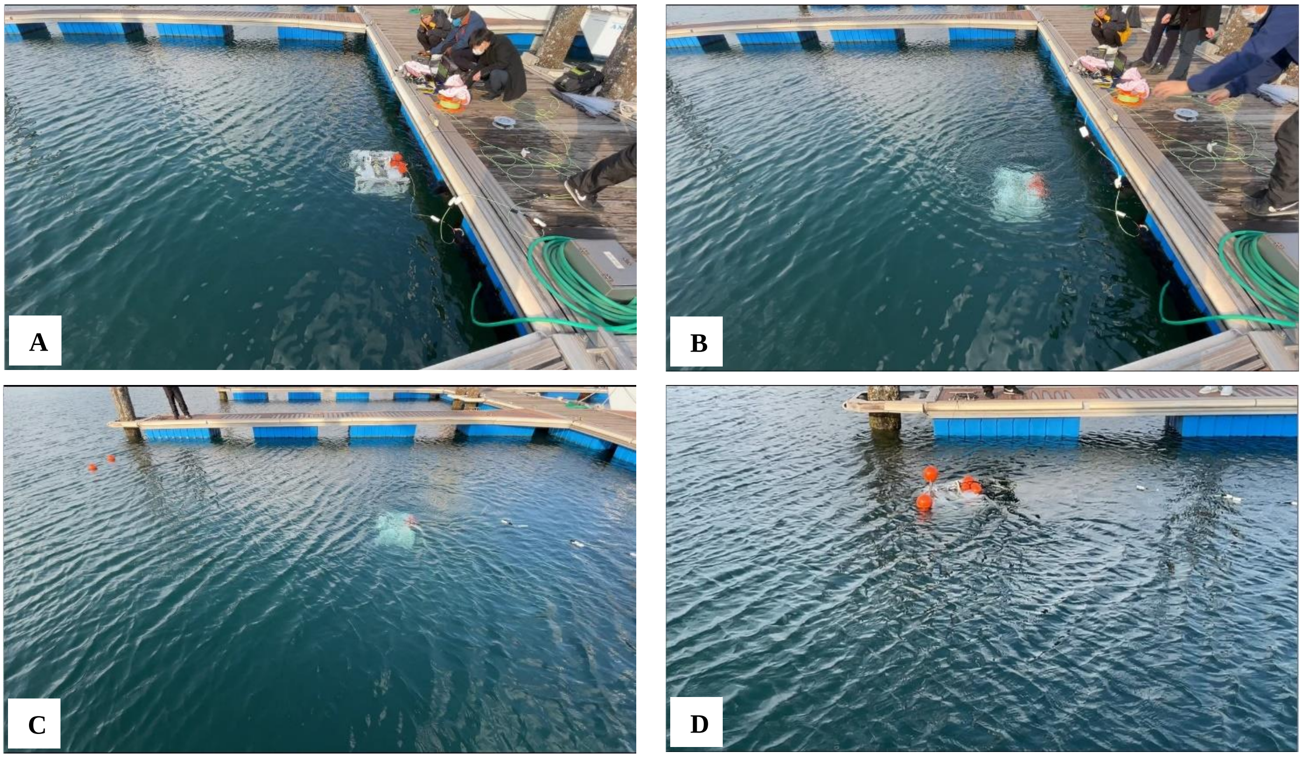

Figure 12: Experiment conducted at Shinmoji Marina, Kitakyushu, Japan. Picture A shows KYUBIC positioned at Start Position (SP). Picture B shows AUV in the *surge/dive* step after initialization and starting the mission. In Picture C KYUBIC is searching for the Pinger's' acoustic signal while *depth keeping.* In Picture D, Kyubic successfully reached the goal point and ascended to the surface.

on the Hydrophone system. In the *Hydro_Detect* result, section "A" and "B" (*Surg/Dive* and *Pinger search stage*), the flag remains "0", showing that no acoustic signal is detected (however, in A, for a brief period the flag "1" shows acoustic signal detection because the thruster were switched off for that time period) because KYUBIC is outside the range of signal detection or the signal received is below the threshold. For the same time, the *Hydro_Region* remains in position "2", this would mean that the Pinger is located straight ahead on KYUBICs path, this is however not the case. This is a false flag value that cannot influence the behavior of KYUBIC because the *Hydro_Detect* flag reads "0" for this period. (*Hydro_Region* flags "2" because it is the last detected region communicated over ROS network in a previous trial).

At 50[secs] in the time log, the *Hydro_Detect* flag detects the Pingers' signal for about 1[sec] to be located at the Right region in KYUBICs path as shown by the *Hydro_Region* switching to "1". The position can also be confirmed from Fig. 11 which shows the goal point (Pinger location) is actually at the Right region of KYUBICs path. This initiates the *Pinger approach* program, and changes the control strategy from *Position control* to *Thrust control* in the "C" part of Fig. 10. Hence, we are able to confirm that the hydrophone system can detect the signal from sea experiment at a distance of about 6[m]. However, the consistency of detection becomes stable when KYUBIC is about 5[m] from the Pingers position. This is seen from the 61st[sec], to the end of the experiment. Here, the *Hydro_Region* switches between "1" and "2" before finally settling on flag "2" implying that the region of the Pinger relative to KYUBICs path is straight ahead. This behavior is due to the variation in the KYUBICs *Heading*. Using the *Thrust control* and *Hydro_Region* strategy, KYUBIC intelligently approaches the Pinger. However, we manually stop KYUBICs program when it reaches the Pinger position because the estimated distance value (*Hydro_Distance*) is not reliable enough to stop KYUBIC based on our strategy.

6. Conclusion

In this paper, we briefly introduce the challenge of unavailable positioning systems for low-cost shallow water operated Autonomous Underwater Vehicles. In proffering solutions to bridge this gap, an annual Underwater Robotics Competition is held in the actual sea of Okinawa, Japan. KYUTECH Underwater Robotics Team amongst other institutions and organization participated in the 2021 competition and secured the First position in the AUV division using our novel acoustic positioning system and behavioral strategy by developing an inexpensive acoustic positioning system for low cost AUV operation in shallow water. We explain the *feedforward control* and *thruster control* strategies, and perform experiments with KYUBIC in the sea. Results of experiments show that the self-made Hydrophone system can detect and successfully track the Pinger position from a maximum distance of 6[m]. The feedforward controller has a position error in *Surge* and *Sway* direction. However, these errors can be reduced by tuning the estimated parameters used to derive the respective acceleration forces.

In our Hydrophone system, we use the *Hydro_Detect* and *Hydro_Region* data to implement our strategy. However, we manually stop the AUV when it reaches the goal point because the calculated distance value of the Pinger is unreliable. Further improvements and tuning of the controllers as well as calculation to accurately detect Pinger angle and distance will ensure the APS performs more efficiently in the future.

7. Contributions

Our team has contributed to knowledge by proffering an inexpensive solution to underwater Acoustic Positioning by using a MEMS microphone. A big improvement on the hardware that ensured the functionality of the hydrophone system when compared to the previous years was in isolating the power supply system with an isolated DCDC converter. The impact of this step was very significant in eliminating noise from other systems.

The software ingenuity is in the transmission of data over ROS network thereby making it easier to use the Hydrophone system alone or to change to another platform.

We also contributed by defining an intelligent behavioral strategy using stateflow. This strategy is able to automatically switch between the *Position control* and *Thrust control* strategy depending on the detection of the Acoustic signal by the Hydrophone system.

8. References

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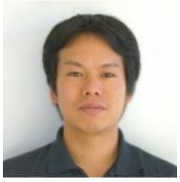

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