Acoustic positioning system for compact underwater vehicle

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Abstract: - Currently a platform to investigate the underwater environment is required. In this paper, we propose an autonomous underwater vehicle (AUV) with an accurate positioning system. The positioning system is developed to be accurate enough to utilize the superior navigation ability of our AUV feature. The navigation ability is acquired by the variable vector propeller mechanism. The accurate positioning became possible by introducing two acoustic signals with different frequencies. The range data were obtained satisfactorily with maximum error less than 0.006m. Using the positioning system, the navigation trajectory of the AUV could be measured.

Key-Words: - Autonomous underwater vehicle (AUV), Acoustic positioning system (APS), Ultrasonic, VARIVEC propeller, PLD, Marine investigation.

1 Introduction

Currently in the ocean and underwater environments pollutions and exhaustions of the natural resources are important social issues. In order to deal with these issues the investigation techniques of underwater environments are being developed. Target fields of the investigations are various covering from the deep oceans, shallow sea area, port and harbor, dam in the lake and so on. In the shallow sea area, human divers often investigate the sea floor of the seaweed cultivation fields and breakwater. In order to enable safe and convenient investigation in the shallow sea area various kinds of autonomous underwater vehicles (AUVs) are developed [1][2][3]. Every AUV has significant features based on the target missions. We already proposed an AUV, which is used as a platform to investigate the environmental situation in the shallow sea area [4][5]. A feature of our AUV is that it employed a variable vector (VARIVEC) propeller enabling three-dimensional navigation using only one thrust propeller. Following the conventional technique, multiple thruster mechanisms are required to enable three-dimensional navigation. However, our AUV can navigate three-dimensionally using only one VARIVEC propeller [6]. Due to the simple thrust mechanism our AUV is applicable to narrow and hazardous underwater environment like the cultivation sea surrounded by nets or the bottom of sea having many sea grass. We intend to apply our AUV as a platform to investigate environmental situations and robotic tasks in such hazardous environment. In order to utilize the superior navigation ability of our AUV in such hazardous underwater environment, a precise navigation system and control system are required. The navigations are classified to acoustic positioning system (APS) and inertial navigation system (INS). The APS is classified to long base line (LBL), short base line (SBL) and ultra short base line (USBL). In the narrow and shallow sea, APS are more preferable since it gives absolute position with simple configuration. The principle of the SBL is based on the trigonometric survey (Fig. 1).

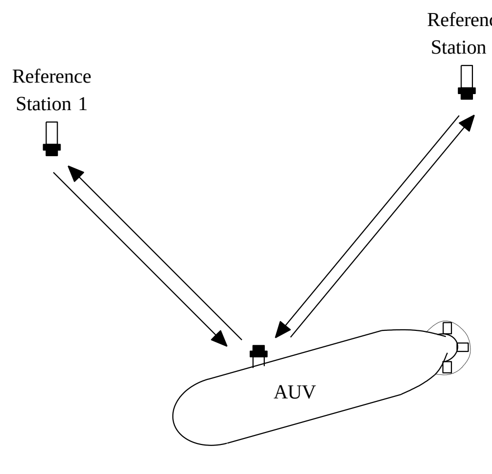

Fig. 1 Principle of SBL positioning system

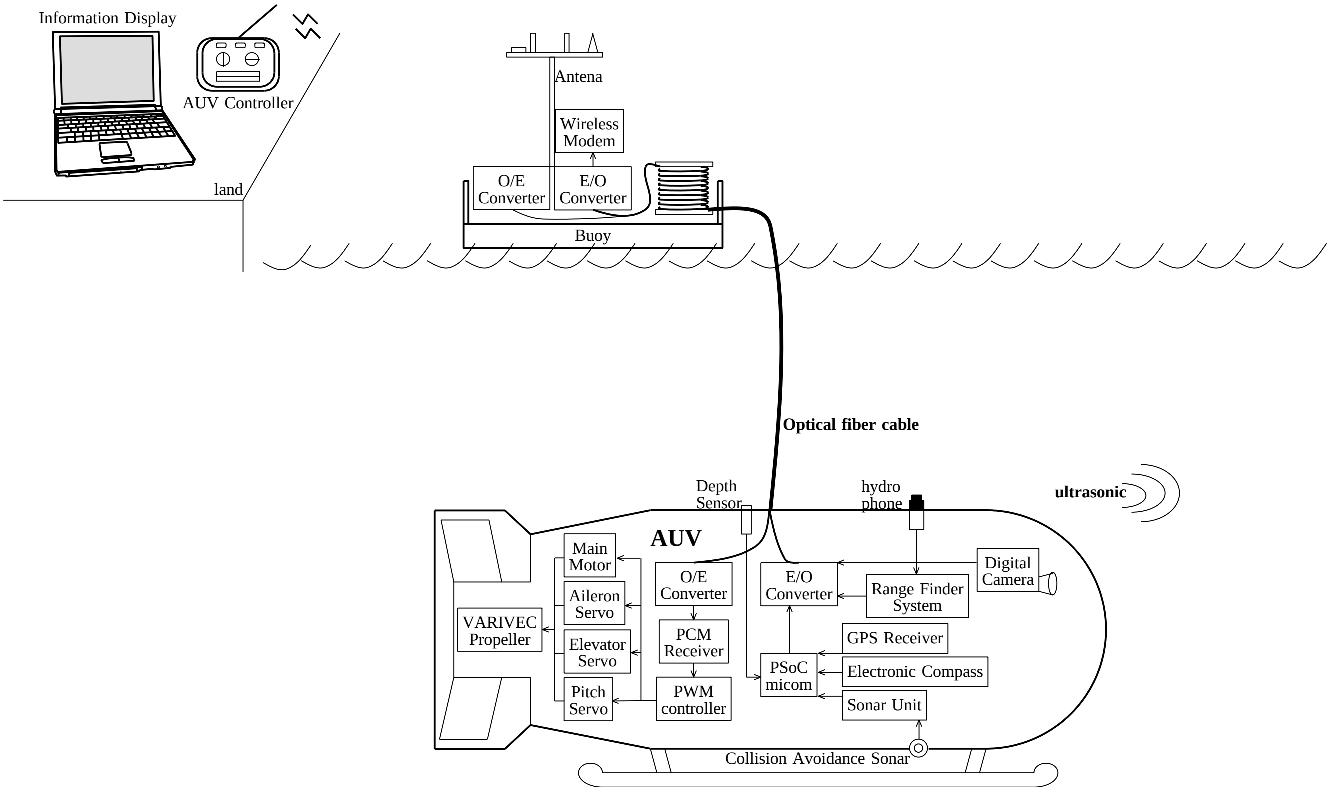

Fig. 2 Configuration of AUV

Multiple reference stations are required to be installed at sea floor or surface. The transducer on the AUV transmits acoustic signal and the multiple reference stations respond with interrogation signals to the vehicle. The range data are calculated by the travel time of the acoustic signals. Using these range data the position can be determined. Therefore, the accuracy of the range data depends on the accuracy of the positioning data. Based on the conventional technique the range data are obtained by the traveling time of burst acoustic signal with pre-specified frequency. Measurement of the traveling time is achieved by detecting the arrival of the acoustic signal. It can be readily recognized that the detection of the arrival of the acoustic signal is affected by inevitable signal noise. And the range error becomes more than wave length of the acoustic signal.

In this paper an accurate positioning system to use acoustic signals with two frequencies is introduced. By employing two frequency signals the accuracy of the positioning data is increased. The positioning system can be achieved as a compact module by using sophisticated IC technology. The experiments in the test tank showed the applicability of our AUV installed with original positioning system.

2 Compact Underwater Vehicle with VARIVEC Propeller

2.1 Configuration of Compact Underwater Vehicle

The configuration of AUV is shown in Fig. 2. This AUV is designed as follows:

1) The size is designed compact enough to be handled by one or two people. The AUV has main body with 0.90m length, 0.22m in diameter and 30kg in weight. At the front side acrylic dome is employed so that vision camera can be installed.
2) The AUV is able to operate for more than one hour at a speed 0.7 knots.
3) At rear side of the AUV an original VARIVEC propeller is installed. The idea of this VAIVEC propeller comes from the variable pitch propeller used at helicopter. An advantage of this VARIVEC propeller lies in the capability to generate thrust force in longitudinal and lateral direction continuously by controlling the collective pitch and cyclic pitch.
4) In order to achieve auto-navigation, a depth sensor, an acoustic transducer, an acoustic sensor and acoustic collision avoidance sensors

are installed. Furthermore, an accurate positioning system is installed.
5) Optical fiber cable network system is installed to transmit control signals, sensor data and underwater image data. The data are transmitted to the ship on the sea surface.

A prototyped AUV is shown in Fig. 3.

Fig. 3 Prototyped AUV

2.2 Variable Vector Propeller

The variable vector propeller enable the AUV navigate toward any of the three-dimensional directions using on one propeller. Thus the mechanism made it possible to construct the AUV as a compact body. The VARIVEC propeller is shown in Fig. 4.

The functions of the AUV as a propeller are shown in Fig. 5 where four blades are routing clockwise. Pitch angles of four propellers can be changed continuously during one rotation. In case (a) where the pitch angles of four propellers are zero, the thrust force does not be generated. In case (b) where the pitch angles of four propellers positive, the thrust force is generated forward. In the case (c) where the pitch angles of four propellers negative, the thrust force is generated backward. In case (d) where the pitch angle of propeller in the upper position is positive and that in the lower position is negative, the thrust force in the upper half is positive and that in lower half is negative. This means the propeller generates tilting force toward sea floor. In case (e) where the pitch angle of propeller in the upper position is positive and that in the lower position is zero, the propeller generates downward thrust force. In case (f) where the pitch angle of propeller in the left position is positive and that in the right position is negative, the propeller generates rotating thrust force around vertical axis.

Fig. 4 VARIVEC propeller

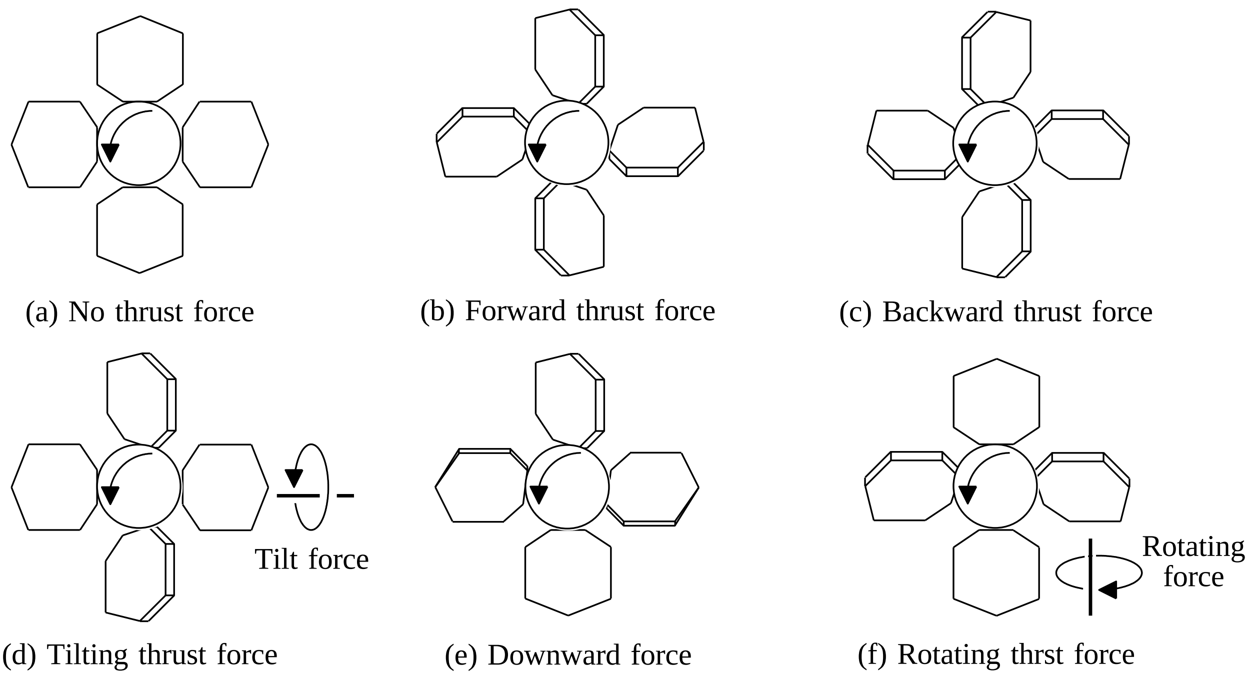

Fig. 5 Functions of VARIVEC Propeller (rear view of AUV)

2.3 Accurate Acoustic Positioning System

By employing VARIVEC propeller our AUV has superior navigation ability. In order to utilize this navigation ability accurate APS is required. Therefore, we employed an accurate APS based on SBL. Conventional APS uses the acoustic burst signal as shown in Fig. 6.

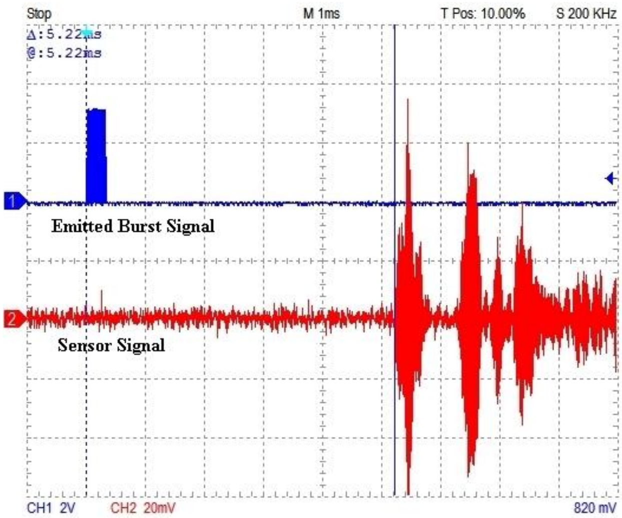

Fig. 6 Acoustic burst signals obtained

The traveling time of this acoustic burst signal is determined considering traveling speed in the water. One crucial problem is how to detect the arrival of this burst signal, which is disturbed by the noise. The range error often corresponds to twice or tenth of the wavelength since the accurate arrival time is often disturbed by the steady noise. On practical technique to deal with this problem is to use the following equation

$$L = (N + \frac{\varphi}{2\pi})\frac{c}{f} \qquad (1)$$

where L is the traveling distance between the transducer and the acoustic sensor, c is traveling speed of ultrasonic in the water, f is frequency of the acoustic signals, $N+\varphi/2\pi$ corresponds to the number and the phase difference between the transmitting signal and the sensor signal. While the phase difference φ in Eq.(1) can be obtained, wave number N cannot be determined from the sensor data accurately. Estimated N often involves an integer number. It means that range data involves range error which corresponds to a multiple number of wave length. The wave number N can be estimated by introducing two acoustic signals with frequency f_1 and f_2. Applying Eq.(1) for frequency f_1 and f_2, the following equation can be obtained.

$$L = \left\{(N_1 - N_2) + \frac{\varphi_1 - \varphi_2}{2\pi}\right\}\frac{c}{f_1 - f_2} \qquad (2)$$

where $N_1+\varphi_1/2\pi$ and $N_2+\varphi_2/2\pi$ corresponds to the number of acoustic wave between the transducer and the sensor with frequency f_1 and f_2. This relation is often used in the microwave range finder. The equation means that range measurement using two frequencies wave corresponds to the measurement using ultrasonic wave whose wave length is $c/(f_1–f_2)$. The equation also means that range measurement by using the ultrasonic wave whose frequency is $(f_1–f_2)$ gives the wave and the phase difference as $(N_1–N_2)+(\varphi_1/2\pi–\varphi_2/2\pi)$. Suppose two acoustic signals are emitted alternatively. By comparing the phase φ_1 and φ_2 of emitting signal and sensor signal the phase difference $\varphi_1–\varphi_2$ can be obtained. In order to determine L, $N_1–N_2$ needs to be determined. The parameter $(N_1–N_2)$ can be estimated based on the traveling time of the burst signal. The procedure to estimate this parameter $(N_1–N_2)$ can be explained in the next section.

2.4 Experiments of Range Finder

The measuring procedure to obtain the accurate range data is explained by using experimental data. A transducer and sensor (H5503:System Giken Ltd.) were moved from 1.77m to 1.96m with 0.01m displacement in the anechoic tank as shown in Fig.7.

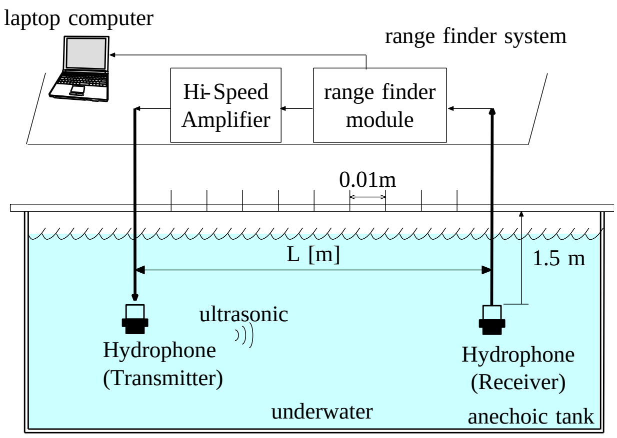

Fig. 7 Measurement of range data

Acoustic burst signals with frequency 54.35 kHz and 44.64 kHz were emitted alternatively. The burst signal composed of 54.35 kHz and 44.64 kHz frequency is shown in Fig. 8. The frequency of the first half of the burst signal is 44.64 kHz frequency and the last half of the burst signal is 54.35 kHz.

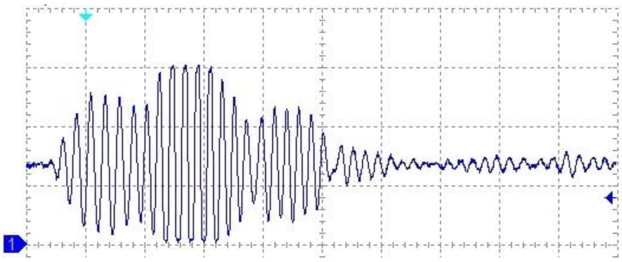

Fig.8 Transmitted burst signal with two frequencies

The procedures to obtain the accurate range data are as follows:

(Step1) Measuring the traveling time of the bust signal, the traveling distance L can be estimated as L_1. The error corresponds to plural number time of the wave length of the wave.

(Step2) From the burst signals phase φ_1 and φ_2 can be obtained by the phase detector circuit. By substituting the φ_1 and φ_2 into Eq.(2) and considering the estimated L_1, the integer number $(N_1–N_2)$ can be determined. Once the $(N_1–N_2)$ can be estimated, the range L can be estimated as L_2, which is more accurate than L_1.

(Step3) Using the estimated L_2, the wave number of N in Eq.(1) can be estimated. Using the estimated N the range data L can be estimated as the final estimated value L_3.

Fig. 9 and Table 1 shows the estimated range data L_1 obtained by Eq.(1) where root means square error was 2.37 cm. It can be recognized that the estimated range L_1 comprises the error which corresponds to one or two times of wave length.

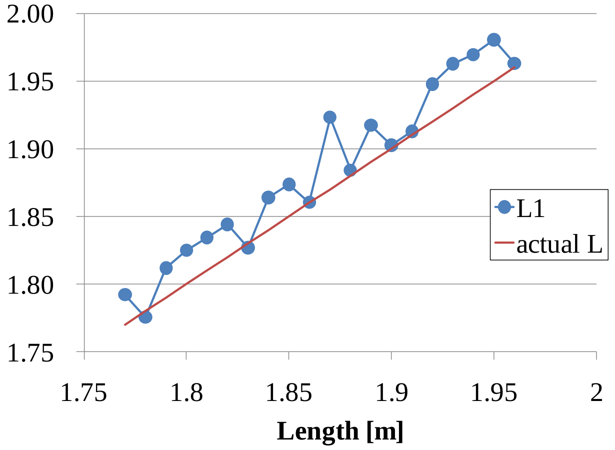

Fig. 9 Estimated range data L_1

Table 1 Estimated L_1 using single frequency

L[m]	f1=54.35kHz			
	N1	φ1	L1[m]	e1[m]
1.77	65	89	1.79	0.02
1.78	65	33	1.78	0.00
1.79	66	64	1.81	0.02
1.80	67	16	1.82	0.02
1.81	67	48	1.83	0.02
1.82	67	81	1.84	0.02
1.83	67	23	1.83	0.00
1.84	68	56	1.86	0.02
1.85	68	89	1.87	0.02
1.86	68	44	1.86	0.00
1.87	70	73	1.92	0.05
1.88	69	33	1.88	0.00
1.89	70	53	1.92	0.03
1.90	70	3	1.90	0.00
1.91	70	38	1.91	0.00
1.92	71	64	1.95	0.03
1.93	72	23	1.96	0.03
1.94	72	46	1.97	0.03
1.95	72	83	1.98	0.03
1.96	72	24	1.96	0.00

Table 2 shows the estimated range data L_2 and also final estimated data L_3.

Table 2 Range data L_2 and L_3

L[m]	L1[m]	N2	L2[m]	N3	L3[m]	e3[m]
1.77	1.79	11	1.77	64	1.76	-0.005
1.78	1.78	12	1.78	65	1.78	-0.004
1.79	1.81	12	1.79	65	1.78	-0.005
1.80	1.82	12	1.81	66	1.80	-0.002
1.81	1.83	12	1.81	66	1.81	-0.003
1.82	1.84	12	1.82	66	1.82	-0.003
1.83	1.83	12	1.84	67	1.83	-0.003
1.84	1.86	12	1.85	67	1.84	-0.003
1.85	1.87	12	1.85	67	1.85	-0.004
1.86	1.86	12	1.87	68	1.86	0.000
1.87	1.92	12	1.87	68	1.87	-0.001
1.88	1.88	13	1.90	69	1.88	0.004
1.89	1.92	12	1.90	69	1.89	0.000
1.90	1.90	13	1.91	70	1.90	0.003
1.91	1.91	13	1.92	70	1.91	0.003
1.92	1.95	12	1.93	70	1.92	0.001
1.93	1.96	13	1.95	71	1.94	0.006
1.94	1.97	13	1.95	71	1.94	0.002
1.95	1.98	12	1.96	71	1.95	0.003
1.96	1.96	13	1.97	72	1.96	0.003

Since the traveling speed of acoustic signal in the water is 1476.5 m/s, the parameter $c/(f_1–f_2)$ in the right-hand term in Eq.(2) becomes 15.20 cm. This means that if the error of the estimated range L_1 is less than 15.20 cm which corresponds to five wavelengths, the integer number $(N_1–N_2)$ in Eq.(2) can be obtained. Fig. 9 shows the estimated error of L_1 was less than one or two wave length. Therefore, the integer number $(N_1–N_2)$ in Eq.(2) can be obtained correctly as N_2 in Table 2. The final estimated range data L_3 can be obtained accurately as shown in Fig. 10 where maximum range error 0.56 cm.

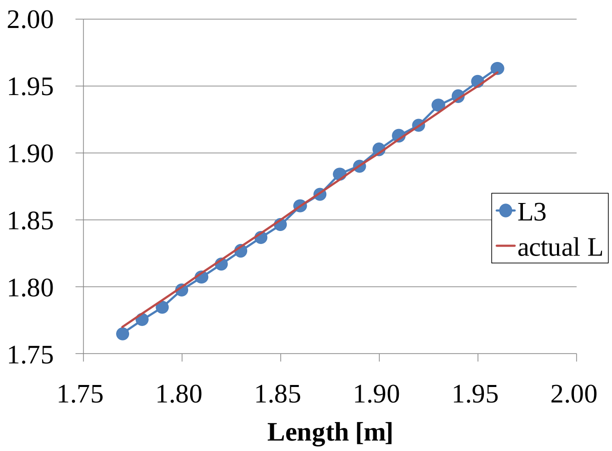

Fig. 10 Estimated range data L_3

3 Implementation of Range Finder

Fig.11 shows the function diagram of the range finder realized by sophisticated IC called PSoC (Programmable System on Chip). FPGA (Field Programmable Gate Array) is also introduced to achieve real time data processing by logic circuit. The range data are calculated and displayed on the laptop computer which is connected with the range finder via serial links. The photograph of range finder module is shown in Fig. 12. The length of range finder module is 155 mm and the width is 120 mm.

In the range finder, the detection of ultrasonic signal can be achieved by PSoC (CY8C29466: Cypress Co. Ltd). The signal detector circuit is composed of the buffer amplifier, band pass-filter and comparator. The center frequency of band pass-filter was designed as 50 kHz and band width was 10 kHz. Amplifying gain was designed to 96.

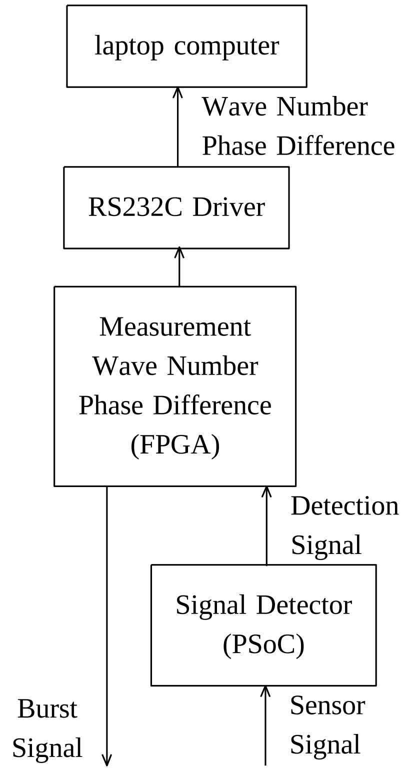

Fig. 11 Function diagram of range finder

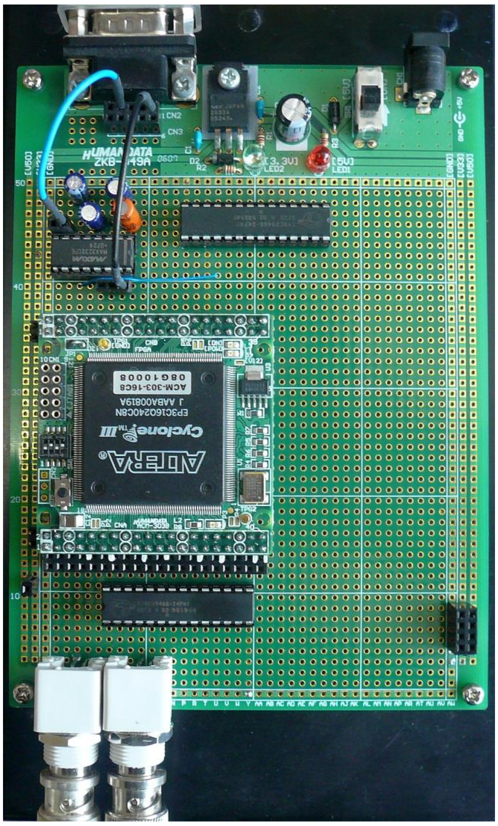

Fig. 12 Range finder module

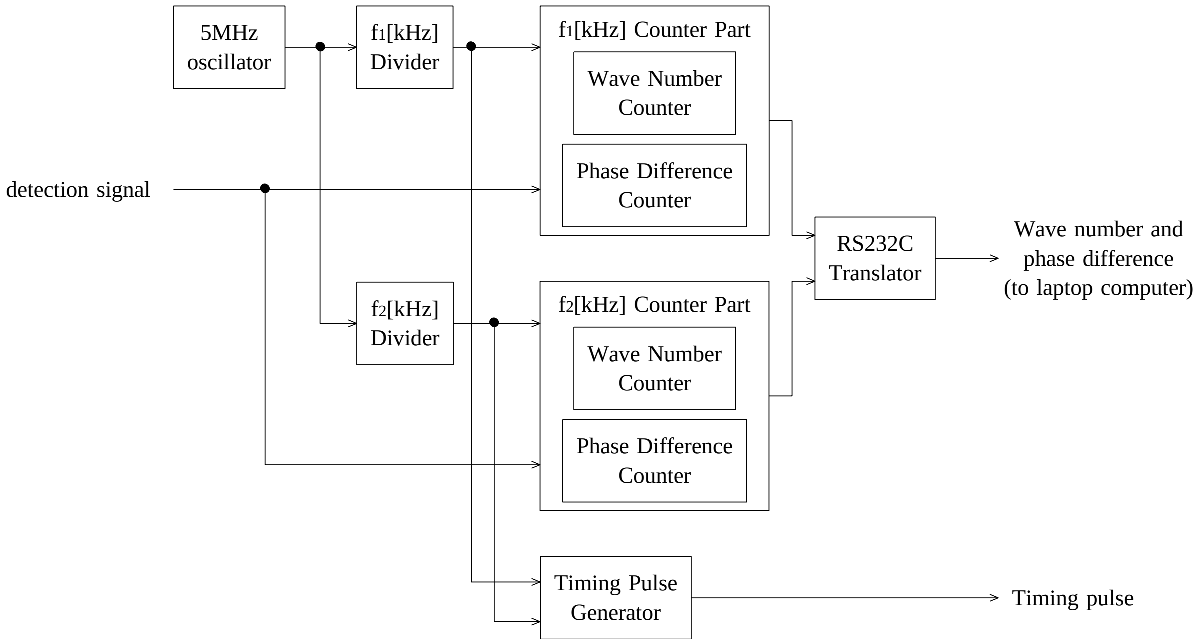

Fig. 13 Measurement of wave number and phase difference

The measurement of wave number and phase difference are achieved by FPGA (Cyclone III EP3C: Altera Co. Ltd), whose block diagram is shown in Fig. 13. Ultrasonic signal from the sensor is compared with base reference signals with frequencies f_1 and f_2. The phase differences are measured using clock signal with 5.0 MHz. The data are transmitted to laptop computer every 819 ms via serial link.

4 Experiments

4.1 Navigation in test tank

A prototyped AUV was tested in the test tank as shown in Fig. 14.

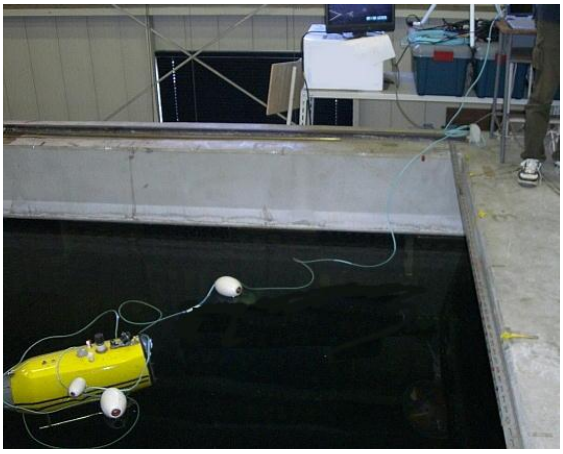

Fig. 14 AUV in the test tank

Inside the test tank, two acoustic hydrophones are installed with 1.9 m apart and 1.5 m in depth. The size of the test tank was 11.0 m in length, 4.3 m in width and 3.0 m in depth. And inner surface of the test tank was covered with sound sealing rubber with sealing efficiency 83%. Fig. 15 shows the traveling path in the test tank.

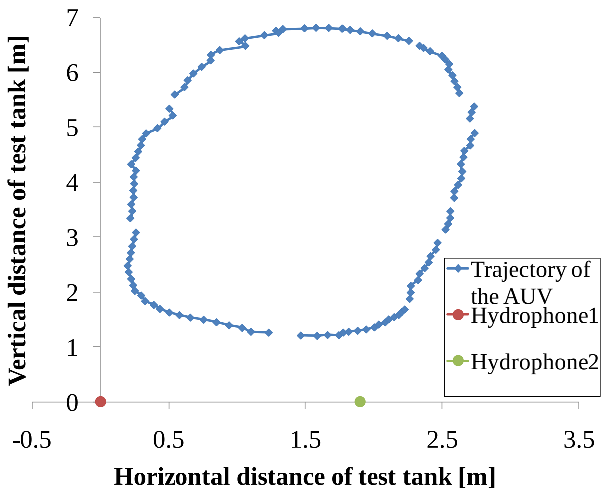

Fig. 15 Trajectory of the navigation

4.2 Underwater environment at a shallow sea

To evaluate the applicability of the AUV at the shallow sea, we performed environmental investigation at the mouth of the river in Sasebo city, Nagasaki. By mounting the measuring devices in the AUV, the conductivity and temperature in the shallow sea were measured. The navigating route of the AUV was pre-specified as shown straight line in Fig. 16. The AUV was manually controlled to navigate along the route using remote controlling system on the land. Fig. 16 also shows the actual navigation route. The navigation route data couldn't be obtained at some points since the disturbing sounds come from neighboring ships.

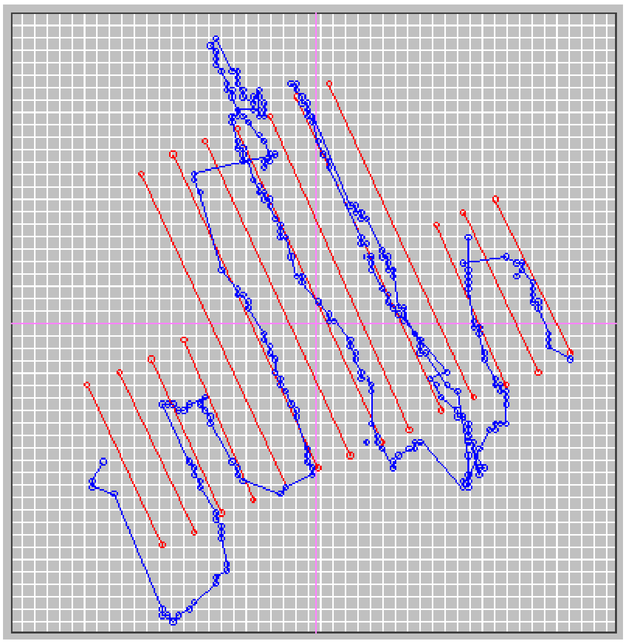

Fig. 16 Navigation route

After the investigation by the AUV, the measurement data were analyzed. Fig. 17 shows the conductivity distribution at the sea surface around the shallow sea. Also Fig. 18 shows the temperature distribution. Fig. 19 shows the situation during the measurement.

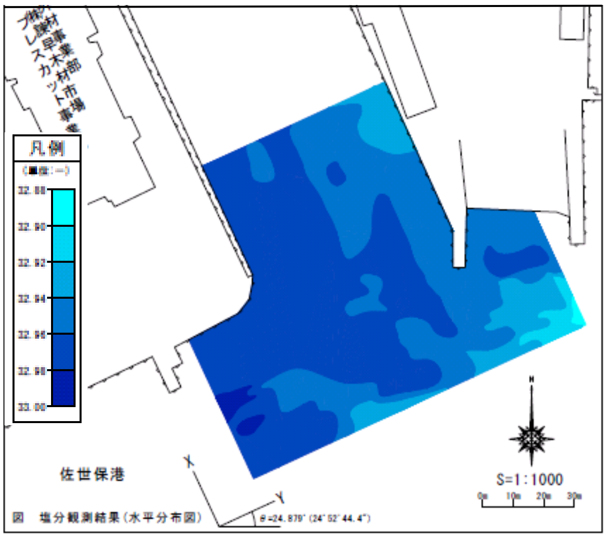

Fig. 17 Conductivity data at the sea surface

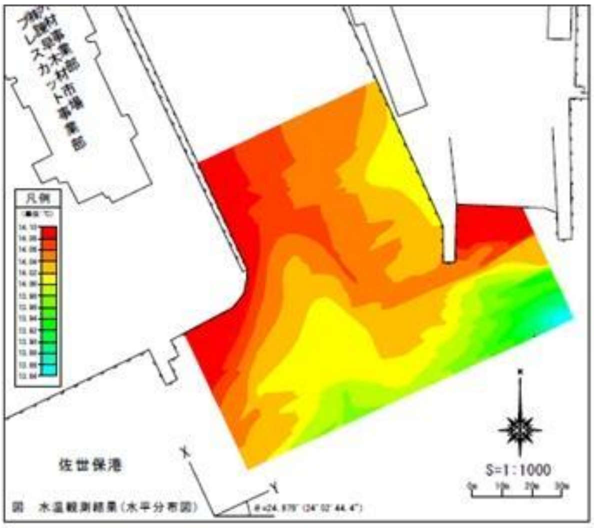

Fig. 18 Temperature distribution at the sea surface

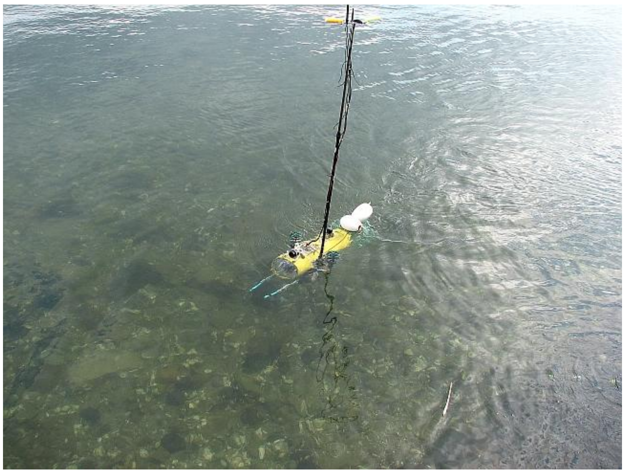

Fig. 19 AUV in the shallow sea

4.3 Investigation of aqua plant in a pond

Our AUV was tested as a monitoring platform in a pond. It is requested to investigate the situation of aqua plant called Potamogeton dentatus which is one of the red data species in Japan. The pond is specified as nature refuge. Therefore, taking pictures by the divers is not allowed. It was confirmed that our AUV was effective to this investigation since the VARIVEC propeller mechanism has a feature that it causes only small disturbances to the environments without any thrusters. Fig. 20 shows our AUV in the nature refuge. Fig.21 shows a picture of Potamogeton dentatus in the nature refuge obtained by our AUV.

Fig. 20 AUV in the nature refuge

Fig. 21 Potamogeton dentatus in the pond

4.4 Investigation at sea bottom

We used the AUV to investigate the harmful sea urchin (shown in Fig. 22) at the bottom of a sea. The depth of the bottom was 11m.

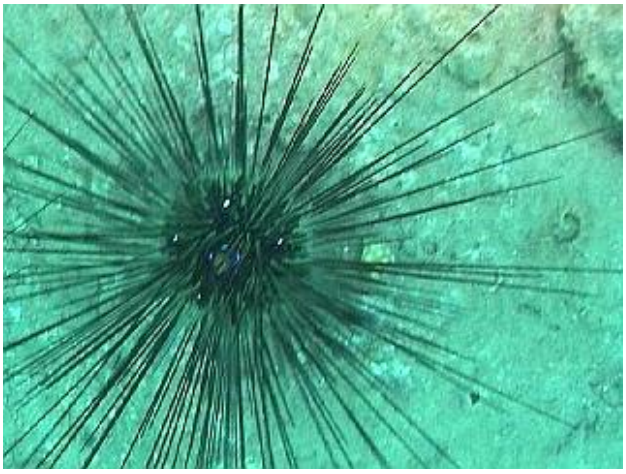

Fig. 22 Harmful sea Urchin

All the signals of the AUV were transmitted from the AUV to the buoy on the sea surface which is shown in Fig.23. Fig.24 shows the AUV at the bottom.

Fig 23 Buoy on the surface

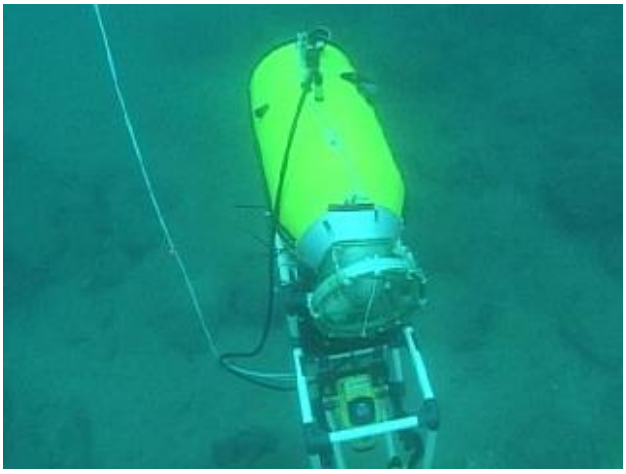

Fig. 24 AUV at the bottom

5 Conclusion

In this paper, we proposed an accurate positioning system using acoustic signals with two different frequencies. Based on the phase difference between the two acoustic signals the accuracy of the range data could be improved so that the maximum error was 0.006m. Using the improved range finder, the accurate positioning system could be achieved. The positioning system could be implemented as the compact and light weighted device by using the sophisticated IC technologies. The navigation experiments were successfully conducted in the test tank.

Furthermore, the AUV was practically used as a monitoring platform to measure the conductivity and the temperature at the sea in the shallow sea.

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