Development of passive acoustic landmark using imaging sonar for AUV's localization

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***Abstract*— We proposed and tested a passive acoustic landmark that can provide accurate navigation information for an autonomous underwater vehicle (AUV). The AUV used imaging sonar mounted on the vehicle to recognize shadows of the column-type landmark, and can measure vehicle's own pose and relative position from the landmark which was set in a known position. The results of the proposed method had acceptable error (<1 %) in the calculated position of the AUV. The proposed localization method will be useful to correct drift errors of inertial navigation systems for the AUV or to find the same position repeatedly.**

Keywords— passive acoustic landmark; underwater navigation; underwater localization; object recognition; acoustic sensor; imaging sonar

I. Introduction

Underwater navigation is a key technology for Autonomous Underwater Vehicles (AUVs) [1]. AUVs used the dead reckoning method which has drift errors [2]. When the AUV scans large areas such as during photo mosaicking, outside references are needed, to correct accumulated errors [3].

Optical and acoustic sensors can be used for underwater sensing. Optical sensors have limited range of view. In contrast, acoustic sensors does not affected by water turbidity. Therefore, acoustic sensors are widely used for AUVs in the ocean [4]. Among these acoustic sensors, imaging sonar which has high-resolution output is suitable to detect an object [5].

We proposed a column-type acoustic landmark that can provide accurate positioning information for an AUV. The proposed landmark was passive and appropriate for longtime operation. This landmark will be useful to correct drift errors and to find the same position repeatedly.

II. PROPOSED ACOUSTIC LANDMARK

A. Overview of System

In this paper, we proposed a passive acoustic landmark that can serve as a navigational aid for the AUV (Fig. 1). The AUV used imaging sonar mounted on the vehicle to recognize the acoustic landmark, and can measure its pose and relative position from the landmark which was set in the known position. From provided information, accuracy and reliability of the localization for AUV's tasks could be increased.

Proposed man-made acoustic landmark and localization method can be used in underwater tasks for AUV, such as photo mosaicking and docking mission. During these missions, the AUV uses imaging sonar to detect the acoustic landmark, and can measure the relative position from the landmark which was set in AUV's path.

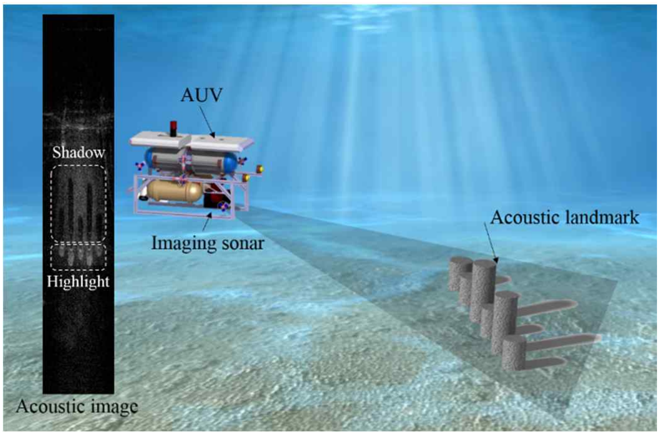

Fig. 1. Overview of the localization method using an imaging sonar and a column-type acoustic landmark. Acoustic image (left) to recognize shadows of the landmark.

B. Modeling of Landmark System

In this section, we explain the imaging sonar model which include coordinate system and acoustic image formation, and landmark model to calculate the distance between landmark and imaging sonar.

1) Imaging sonar model: The imaging sonar emits 96 ultrasound beams forward and measures the reflected beams respectively. In the sonar coordinate (Fig. 2), sonar image was generated by orthogonal projection of vector P_S to X-Y plane. The degree of brightness in sonar image shows acoustic reflection intensity. For the image processing to calculate distance, sonar image was represented by raw image (Fig. 3). In the raw image, row means the distance from the imaging sonar, and column means each beam angle. Highlight area represents the ultrasound beams which reflect from the object or background (seafloor). A shadow area means that ultrasound beams are not returned. The shadow area is easier to classify than a highlight area. Therefore, we designed the landmark as a column to maximize the shadow area toward the beam direction.

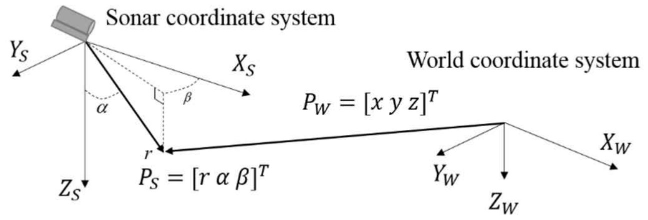

Fig. 2. Coordinate transformation from world coordinate system to sonar coordinate system.

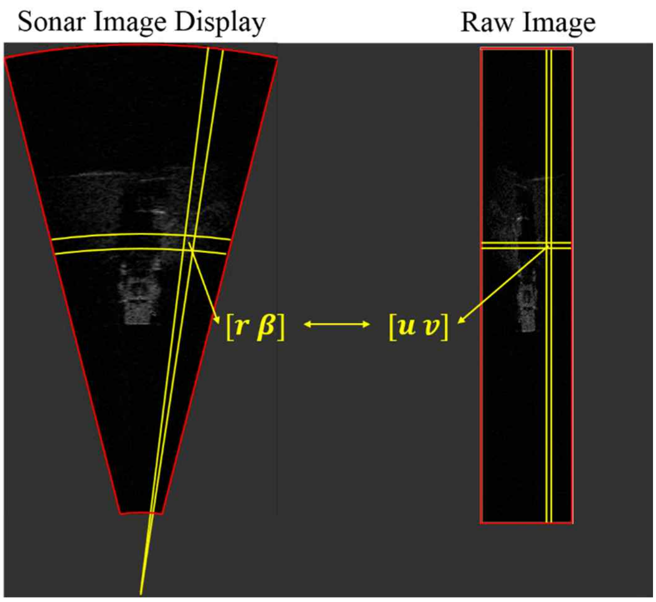

Fig. 3. Correspondence between sonar image display and raw image.

2) Landmark model: The acoustic image of the imaging sonar was modeled as 2D (Fig. 4). The end of shadow ($\overline{OD}$) and the shadow length ($\overline{OD} - \overline{OA}$) were calculated from each acoustic images. Altitude ($\overline{OE}$: distance between AUV and the seafloor) was measured by the doppler velocity log sensor in real time. From these data, if we know the height ($\overline{AB}$) and the diameter ($\overline{BC}$) of the landmark, the distance ($\overline{AE}$) between the imaging sonar and the landmark can be calculated by

$$\overline{DE} = \sqrt{\overline{OD}^2 - \overline{OE}^2}, \tag{1}$$

$$\overline{OE} : \overline{DE} = \overline{AB} : (\overline{AD} - \overline{BC}), \tag{2}$$

$$\overline{AE} = \overline{DE} - \overline{AD} = \left(\sqrt{\overline{OD}^2 - \overline{OE}^2}\right) * (1 - \overline{AB}/\overline{OE}) - \overline{BC}. \tag{3}$$

The shadow length $L = \overline{OD} - \overline{OA}$ was varied with the height ($\overline{AB}$) and the diameter ($\overline{BC}$) of the landmark. From this relationship, AUV can distinguish the ID of the landmark.

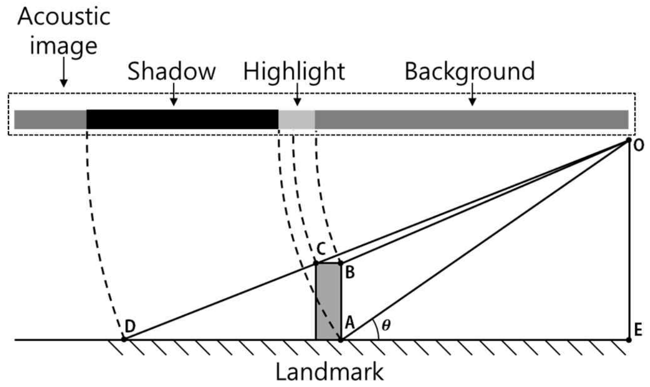

Fig. 4. The acoustic image was separated as shadow, highlight and background. Point O: Source of the ultrasound beams, Point A, B, C, D: Points which beams meet, ϴ: Angle between the imaging sonar and the landmark.

C. *Design of Passive Acoustic Landmark*

We chose a 2D structure as a landmark, because 2D structures yield simple acoustic images in any position and angle, and therefore reduces shape uncertainty in the acoustic image. The highlight area of the acoustic image was difficult to separate from the background in the acoustic image.

We constructed a prototype of the acoustic landmark (Fig. 5) which consists of large and small concrete columns. The columns were placed on the seabed in parallel as the barcode. Each landmark was distinguished by varying the width/height of each column and the spacing between of columns. A cylindrical shape of the column has no distortion in any direction of view. The AUV knew the size of the landmark in advance. In an acoustic image, a shadow area is easier to classify than a highlight area. Therefore, we designed the landmark as columns to maximize the shadow area.

The proposed landmark was passive concrete columns and appropriated for longtime operation without maintenance load. The passive acoustic landmark 1) did not need any support such as power and communication, 2) was not affected by biofouling, and 3) had high recognition rate in real time.

Fig. 5. The landmark consists of two large concrete columns (75 mm x 210 mm, D x H) and three small concrete columns (75 mm x 105 mm, D x H).

III. LOCALIZATION METHOD

The proposed localization method stochastically updated the vehicle's position using 3 steps: landmark recognition, mapping and registration.

A. Landmark Recognition

In the image processing, the preprocessing, segmentation, labeling, and applying the template matching were conducted to distinguish the shadows of the landmark from others. The preprocessing include the image normalization and image blurring to reduce noise using Gaussian filter. In the template matching, the template size and shape were modified by view range of the imaging sonar in every process. This landmark recgnition process generated the probability density function of the landmark position for a next process.

B. Landmark Mapping

Landmark mapping represented a map of the environment as the probabilistic presence of the landmarks using an occupancy grid mapping algorithm. This algorithm enables independencies between neighboring cells.

C. Landmark Registration

Landmark registration is the estimation process which is based on the stochastic approach called the particle filter.

IV. EXPERIMENT

A. Test Setup

We constructed a prototype of the landmark by modeling of this for an experiment to evaluate its recognition accuracy. The shape and size of the landmark were selected by modeling according to the operation environment. The water tank has a restricted volume for using the imaging sonar to detect the landmark, so landmark size was 210 mm or 105 mm in height and 75 mm in diameter. We tested the landmark in a water tank (3 m x 1.5 m x 1.8 m, L x W x H). The water tank is constructed of transparent acrylic plate which has low acoustic intensity. To increase the acoustic intensity of the background, we laid plywood on the bottom of the water tank. The imaging sonar and the pan-tilt equipment were installed on the top of the water tank and take an acoustic image.

We used a DIDSON instrument (1.1/1.8 MHz) [6] as the imaging sonar. This sonar has limited view angle, 14° vertically and 29° horizontally. Therefore, the AUV must use pan-tilt equipment to rotate the sonar without moving the AUV. The imaging sonar and the pan-tilt equipment were connected to the laptop by transmission control protocol/internet protocol (TCP/IP) to receive acoustic images in real time and to adjust the angle of the imaging sonar.

B. Accuracy Test

We conducted an experiment to verify the model of the acoustic landmark at different horizontal distances between the imaging sonar and the landmark (Fig. 6). In this test, the altitude of the imaging sonar was fixed at 1235 mm, and the horizontal distance was varied from 1492.5 mm to 1892.5 mm in increments of 100 mm. In each step, the imaging sonar took an acoustic image, and horizontal distance was calculated by previously model of the landmark using the geometrical relationship between the landmark and the imaging sonar.

From received acoustic images (Fig. 7), the end and length of shadows were output using image processing such as denoising, binarizing, labeling and template matching.

V. RESULTS

We calculated the end and length of the shadows of large columns (Fig. 8, Table I). The end of shadows showed more accurate results than the length of the shadows, so the end of the shadow was used to calculate distance. The length of the shadows can be used to distinguish the height of the column. Experimental results had acceptable error (<1 %) in the calculated distance between imaging sonar and landmark. This error is small enough that the system can be used in AUV navigation.

We measured the end and length of the shadows of columns to compare the results of geometric models to those of experiments. Experimental results of the distance had acceptable errors (<1 %), so the columns can be used in AUV navigation. The ends of the shadows were more accurate than their lengths. Because the beginning of the shadow overlapped the highlight area, the boundary line had gradation area instead of edge line. From the relatively accurate end of the shadows, we used the geometric model to calculate the actual position of the landmark.

More than two columns can provide more accurate navigation information than single column, because the position of AUV could be calculated by triangulation.

Sometimes the shadow was not detected due to excessive noise in the acoustic image or limited detecting range. Each image had a different probability of detection. To improve recognition rate of the landmark, we will try to use a series of images, and compare their correlation.

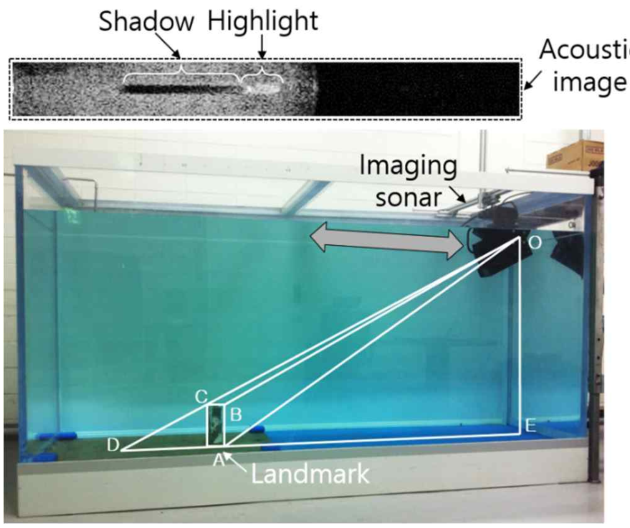

Fig. 6. The acoustic image was separated as shadow and highlight. $\overline{OE}$: Altitude of the imaging sonar, $\overline{AE}$: Horizontal distance between the imaging sonar and the landmark, $\overline{CD}$: Length of the shadow. Imaging sonar can move along the surface of water.

distance to estimate a position of the AVU for a navigation. Experimental results of the distance had acceptable errors (<1 %) and therefore can be used in AUV navigation.

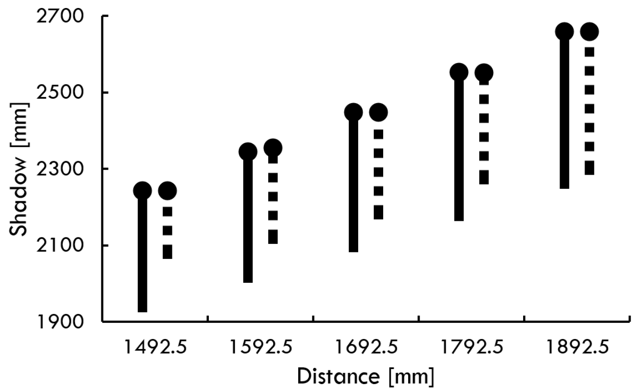

Fig. 8. Distance between imaging sonar and landmark vs. end of the shadow (solid circle) and length of the shadow (line). Solid line: modeling results. Dashed line: experimental results

The proposed acoustic landmark will be useful to correct drift errors of inertial navigation systems for the AUV or to find the same position repeatedly. We plan to test the proposed localization method in the field.

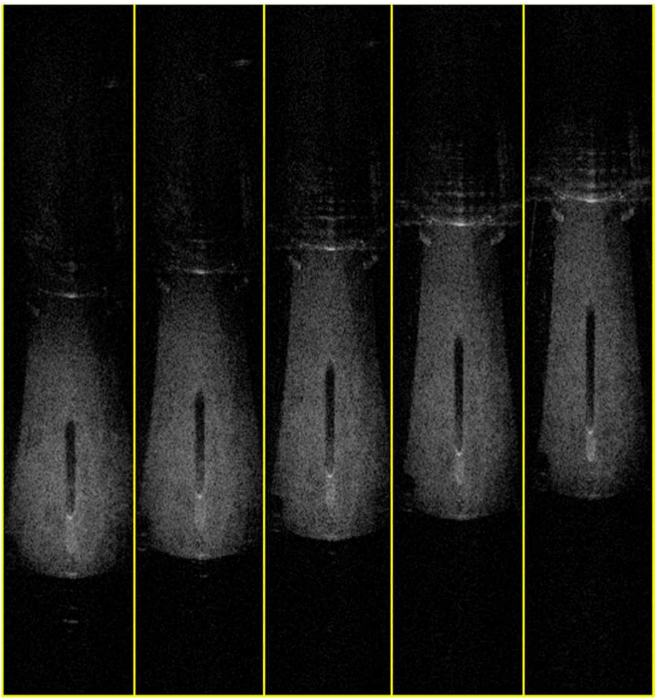

Fig. 7. Results of acoustic images were taken in horizontal distance which was varied from 1492.5 mm to 1892.5 mm in increments of 100 mm.

TABLE I
END AND LENGTH OF THE SHADOWS OF COLUMNS WERE COMPARED FROM MODEL AND EXPERIMENT IN EACH DISTANCE [mm] AND ERROR [%] BETWEEN IMAGING SONAR AND LANDMARK.

	End of shadow			Length of shadow		
Distance	Model	Exp.	Error	Model	Exp.	Error
1492.5	2243.7	2243.3	0.02	306.5	327.1	6.72
1592.5	2345.3	2355.6	0.44	330.0	361.3	9.48
1692.5	2448.5	2448.4	0.00	353.3	380.9	7.81
1792.5	2553.3	2550.9	0.09	376.5	410.1	8.92
1892.5	2659.4	2658.4	0.04	399.6	424.8	6.31

VI. CONCLUSION

We proposed and tested a column-type acoustic landmark that can provide accurate navigation information for an AUV. The proposed acoustic landmark was passive and appropriate for longtime operation. We designed the landmark to maximize a shadow in an acoustic image. The shadow area is easier to classify than a highlight area. We measured the end and length of the shadows of each columns to compare the results of the model.

Because calculated length of the shadows were not accurate (>5 %), the end points of the shadows were used as the reference

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