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Underwater Acoustic Positioning System Design for Shallow Water Depth Application

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Abstract

This paper describes the design and implementation of a practical underwater positioning system, which is applicable for shallow water depth conditions. In this paper, two strategies are used to enhance the navigation performance. First, a low-cost acoustic-ranging-based precise navigation solution for shallow water is designed. Then, the outlier rejection algorithm is introduced by designing a velocity gate. The acoustic-ranging-based navigation is implemented by modifying the long base line solution. To enhance the tracking precision, the outlier rejection algorithm is introduced. The performance of the developed approach is evaluated using experiments. The results demonstrate that precise shallow water depth navigation can be implemented using the suggested approaches.

Keywords: Underwater precise navigation, Shallow water depth navigation, Ranging sonar

1. Introduction

This paper presents the design of a precise underwater navigation solution.

Accurately estimating positions and attitudes is a key issue to achieve a complicated mission such as underwater work class ROV operation.

Fig. 1 shows a conventional LBL system used for the precise operation of a work class ROV.

To survey a wide area of the seafloor, the quality of the navigation information is very important. In this paper, two strategies are used to enhance the navigation performance. First, a low-cost acoustic-ranging-based precise navigation solution for shallow water is designed. Then, an outlier rejection algorithm is introduced by designing a velocity gate.

The acoustic-ranging-based navigation is implemented by modifying the long baseline solution of Link-quest® Pinpoint LBL.

Only two transponders are used to shorten the recurrence time of tracking as soon as possible and to operate the system efficiently.

To enhance the tracking precision, an outlier rejection algorithm is implemented, which rejects the outliers in absolute position data such as north and east position updates. Outliers are noisy sensor outputs that are not correct as a result of acoustic sensor noise. Outliers degrade the total navigation algorithm performance and should be dealt with cautiously.

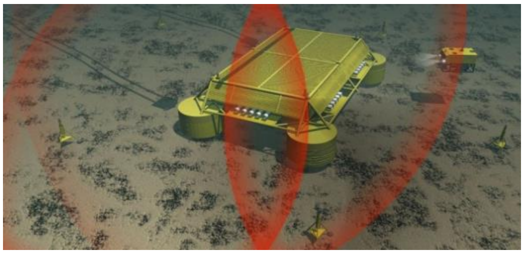

Fig. 1. Conventional Sonardyne® LBL system for work class ROV operation

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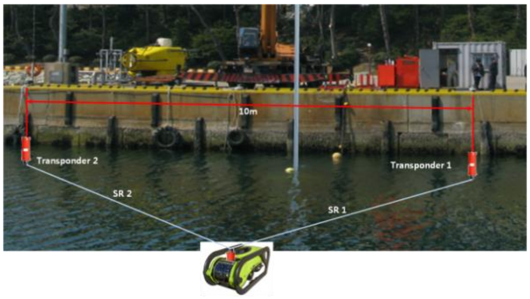

Fig. 2. Installed transponders for acoustic positioning

In this paper a gate (watch circle) is designed to determine whether a new measurement update is an outlier or true data, which is determined by the relative position or velocity.

The performance of the developed approach is evaluated using a sea trial. Experimental results demonstrate that precise shallow water depth navigation can be implemented using the suggested approaches.

2. Kinematic Relation

In this paper, the authors develop a precise underwater navigation solution that can be used even for extremely shallow water depths (0.5 m~10 m). This solution is implemented by developing software to use the commercial LBL system of Link-quest. Because the Link-quest system uses the same frequency, acoustic ranging is performed sequentially to estimate the vehicle position. The implemented tracking accuracy is about 30~40 cm, and the update rate is every 0.7 s. Fig. 2 shows an operation example with the designed navigation system at a pier.

Table 1. Specifications of acoustic positioning system

Vehicle	ROV (Low-speed vehicle with tether)
Operation Depth	0.5 m~1,500 m
Precision	30~40 cm
Update rate	0.7~2 s (depends on range)
Maximum range	800 m (shallow), 1,000 m (deep)

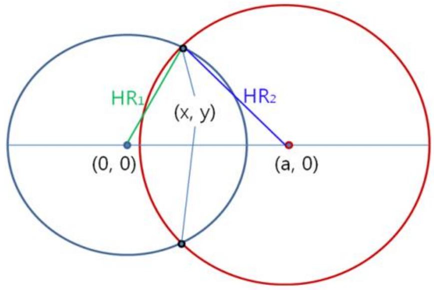

Fig. 3. Kinematic relation in horizontal plane

$$\begin{cases} x^2 + y^2 = HR_1^2 \\ (x-a)^2 + y^2 = HR_2^2 \end{cases} \quad (1)$$

$$\begin{cases} x = \frac{a^2+HR_1^2-HR_2^2}{2a} \\ y = \pm\sqrt{HR_1^2 - x^2} \end{cases} \quad (2)$$

$$\begin{cases} HR_1 = \sqrt{SR_1^2 - D_1^2} \\ HR_2 = \sqrt{SR_2^2 - D_2^2} \end{cases} \quad (3)$$

Fig. 3 shows the kinematic relation of the acoustic positioning system designed in this paper, where (0, 0) and (a, 0) are the positions of the transponders.

One transceiver and two transponders are used to determine a vehicle's position.

The vehicle's current position x, y can be calculated using Eq. (2), where HR means the horizontal range calculated by Eq. (3) and SR means the slant range between the transceiver and transponder. Two possible solution candidates are present. Between these two candidates, the vehicle's current position can be determined by its operating side.

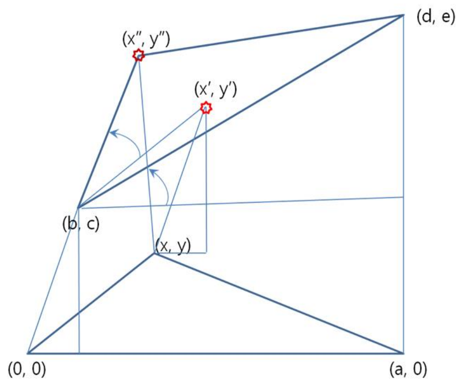

Fig. 4. Kinematic relation considering generalized positions of transponders

$$\begin{cases} x' = x + b \\ y' = y + c \end{cases} \quad (3)$$

$$\begin{pmatrix} x'' \\ y'' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x' \\ y' \end{pmatrix} \quad (4)$$

$$\theta = \operatorname{atan}\left(\frac{e-c}{d-b}\right) \quad (5)$$

To obtain the vehicle position using any two transponders' geo-referential positions, translation and rotation formulas are needed, such as (3)–(5). Fig. 4 describes the kinematic relation of the generalized transponder positions. Eq(4) gives the final geo-reference position of the vehicle.

3. Experimental Results and Discussion

In this study, acoustic-ranging-based navigation is designed by modifying the commercial long baseline solution of Link-quest® Pinpoint LBL.

Two transponders are used to shorten the recurrence time of tracking as soon as possible and to lower the cost of the overall navigation system by selecting only essential items, in contrast to the typical LBL systems, which use three or four transponders to enhance accuracy and reliability by the least square method or a filtering technique such as a Kalman filter.

The outlier rejection algorithm is introduced to enhance the tracking precision and reliability. Outliers are the calculated results of range measurements with error caused by the presence of multipath acoustic noise. Outliers degrade the total navigation algorithm performance and should be dealt with cautiously.

In this paper, a gate (watch circle) is designed to determine whether or not a new measurement update is an outlier, based on the relative position or velocity.

Fig. 5 shows the tracking results of the implemented precise acoustic positioning system for a shallow water application. Outliers exist and degrade the overall positioning performance.

Fig. 6 shows the time series for the north and east positions before the outlier rejection.

Fig. 7 shows the residuals of the new measurements against the estimated true positions, which are mainly due to ranging errors caused by the multi-path of the acoustic signal.

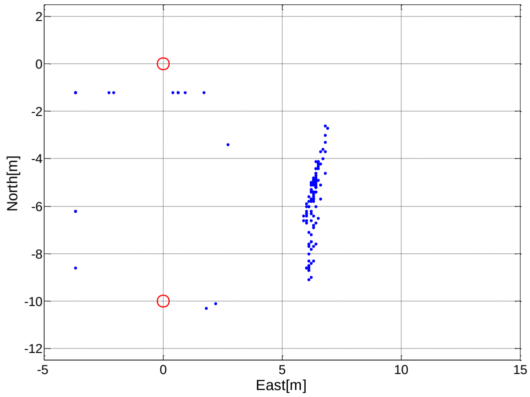

Fig. 5. Tracking results for designed acoustic positioning system before outlier rejection

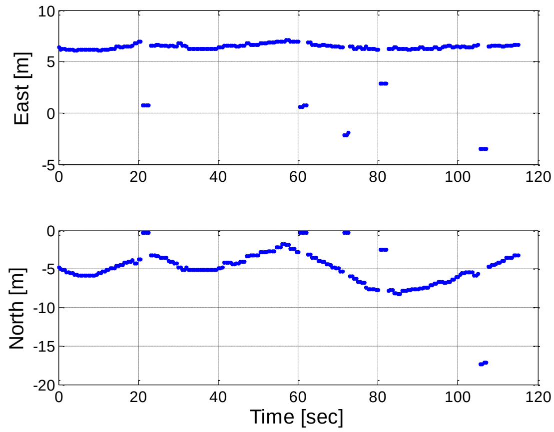

Fig. 6. Time series of east and north positions before outlier rejection

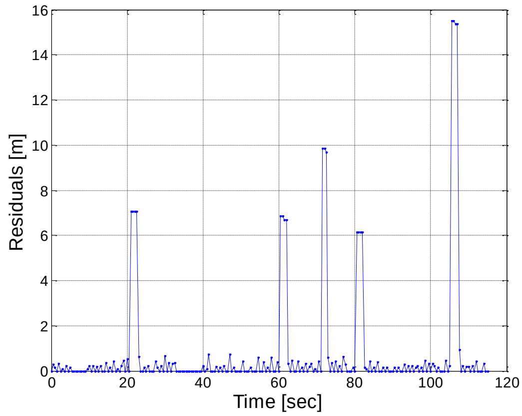

Fig. 7. Measurement residuals

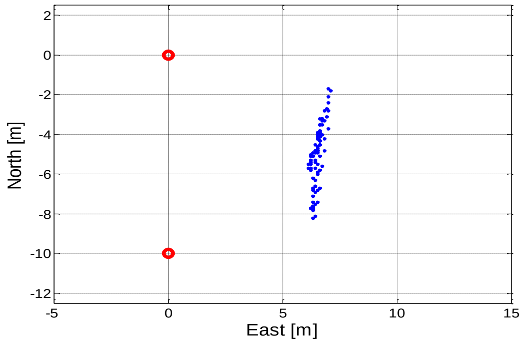

Fig. 8 Acoustic tracking results after outlier rejection

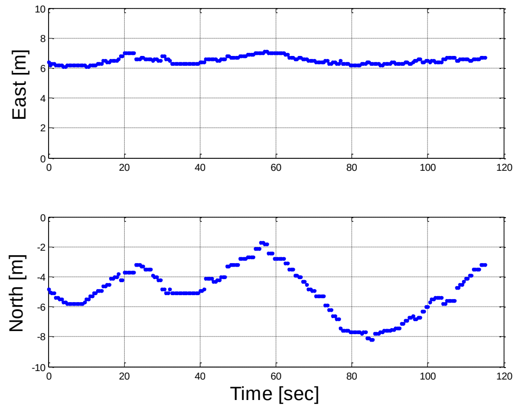

Fig. 9. East and north time series after outlier rejection

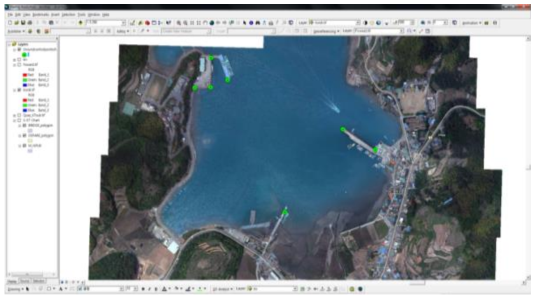

Fig. 10. Correction of aerial photo mosaic by DGPS measurements

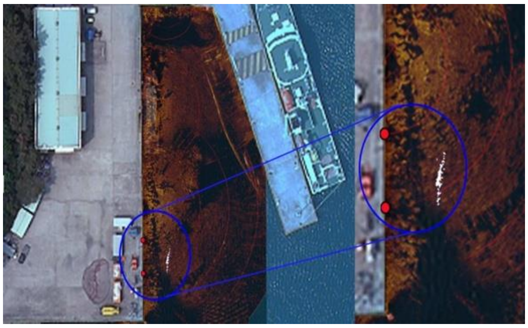

Fig. 11. Acoustic tracking results on photo and sonar image mosaic

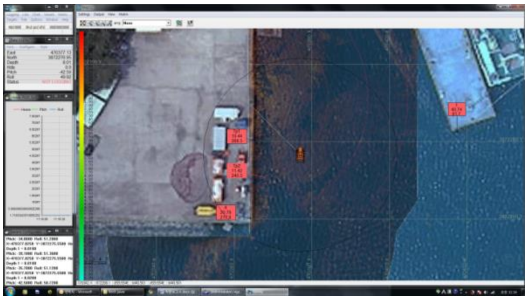

Fig. 12. Online display of tracking during operation

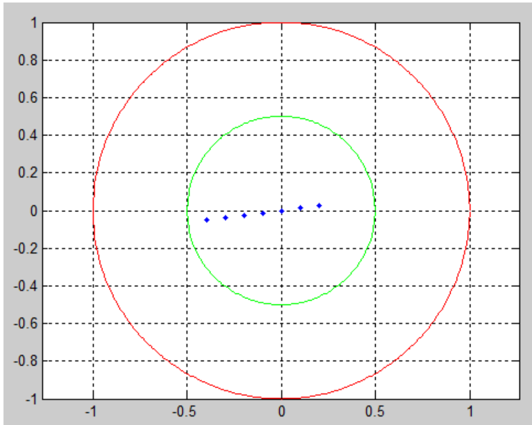

Fig. 13. Positioning performance analysis in static status

Fig. 8 depicts the tracking results after applying the outlier rejection algorithm. Outliers are removed effectively by applying the velocity gate. Fig. 9 shows the time series of the east and north positions. From these results, an ROV vehicle can be monitored stably even for a shallow water depth condition. The water depth was only 7 m. The field experiment was executed from the pier of the South Sea Research Institute.

Fig. 10 shows the geographic information correction for the operation of the Hypack® survey program (Fig. 12). Fig. 11 shows the acoustic tracking results on the aerial photo and sonar image mosaic.

Fig. 13 shows an analysis of the positioning performance of the designed acoustic navigation system. In this case, transponders were installed on a barge, and the water depth was 20 m. The standard deviation in the east and north positioning were 0.1493 m and 0.0192 m, respectively, and the maximum values were 0.3960 m and 0.0510 m, respectively.

Fig. 14 shows the time series of the east and north positions for the performance analysis in the static case. The deviation in the east direction could be reduced, along with that in the north direction, when transponders were laid on the sea bottom. The major reason for the deviation was motion of the barge where the two transponders were installed due to strong wind disturbance.

Based on this analysis, the authors can conclude that the designed underwater navigation solution has a performance with a precision of 30~40 cm.

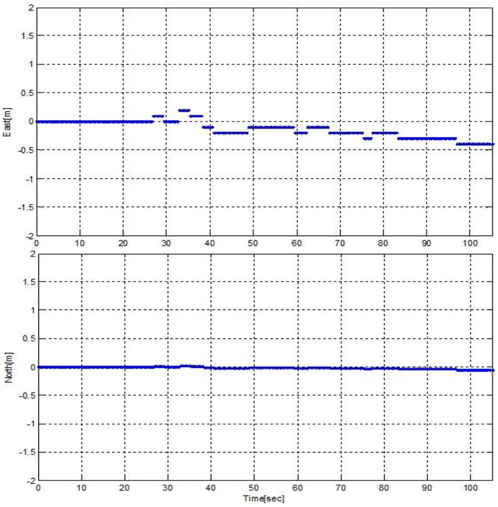

Fig. 14. Time series for positioning performance analysis in static status

5. Summary

To implement a precise underwater navigation solution, even when working under shallow water depth conditions, the authors developed a software algorithm for the operation of a simplified and inverted long baseline (in other words, a two-point ranging solution).

In future work, a covariance intersection-based fusion algorithm, with the DR algorithm and designed acoustic positioning system, will be investigated to enhance the precision and reliability, considering various complicated missions.

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