Ray-tracing-based time-domain wideband fractional delay beamforming for underwater acoustic positioning

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Abstract. Underwater acoustic positioning systems are essential for underwater vehicles positioning and navigation. In this paper, a time-domain wideband fractional delay beamforming (WFDB) technique is proposed to improve underwater localization capability of planar arrays. In our method, digital delay lines are combined with adaptive-finite-impulse-response filters to achieve high accuracy beamforming results and reduce the design burden of the WFDB systems. Further, the beamforming results are used in the ray-tracing method to eliminate curvature effect of sound rays caused by the inhomogeneity of water, and therefore improving the computation accuracy of target position. We further develop a hexagonal planar array of 30 elements to verify the WFDB method in an indoor experimental pool. The experimental results demonstrate that the proposed method could successfully mitigate the ray bending problem and accurately estimate the position of targets in low SNR condition.

1 Introduction

The sound wave is the most effective carrier for underwater information transmission [1,2]. Underwater acoustic positioning systems (UAPs) are regarded as essential positioning and navigation components for underwater vehicles [3-6]. UAPs, in which a sonar array is employed to determine the range and bearing to the vehicles, are indeed routinely used today [7]. Compared with the linear array, the planar array has better spatial angular resolution. It can not only determine the pitch angle of the direction-of-arrival (DOA), but also determine the azimuth angle.

Conventional beamforming (CBF) is a widely used method for array signal processing [8]. The received signals are delayed and summed based on the relationship between the configuration of sensors and the incident angle of the signal [9]. When the steering angle is aligned with the incident angle of the signal, the signals are coherently summed while the noise are not (the noise is assumed uncorrelated) which resulting in a higher signal-to-noise ratio (SNR) at the output compared with the input SNR[10].

Sound velocity in the sea changes with the depth [1]. Sound velocity bias is the primary cause of position error in the UAPs over a long range. Thus, the unique characteristics of underwater acoustic channels necessitate a sound velocity correction algorithm which properly accounts for sound trajectory bending. ray-tracing is the most commonly used method for the problem. In ray-tracing theory, the sound trajectory

consists of many arcs under the assumption of a stratified sound velocity gradient [11]. It makes use of standard ray equations to model the sound trajectories in water and could achieve more accurate results as compared with other methods [12, 13].

In this paper, we propose a ray-tracing-based time-domain wideband fractional delay beamforming for UAPs. We combine digital delay line with adaptive FIR filter in CBF, where the beamforming accuracy can be ensured, and the design burden of the beamforming systems can be reduced. Further, we apply the beamforming result as an initial grazing angle for ray-tracing to eliminate the curvature effect of the sound trajectory caused by the inhomogeneity of water, which is the main factor that influences the computation accuracy of target position. Moreover, a hexagonal planar array (UHL) of 30 elements is developed to verify our method algorithm. The experimental results show that, the proposed method can effectively reduce the effect of ray bending and accurately estimate the position of target in low SNR.

2 DOA estimation via conventional beamforming (CBF)

CBF is a well-known array processing method favoured for its strong robustness for DOA estimation. We consider a far-field point source detected by an arbitrary array with N sensors. The incident wave signal could be assumed as a plane wave when the source-receiver

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distance is large as compared with the array aperture size. The sensor array has a look direction $[\theta_m, \phi_m]$, where θ_m denotes the azimuth angle and ϕ_m represents the pitch angle. The basic model of the input signal is shown in Fig.1.

Fig. 1. Basic Model.

The output signal of the array is deduced by

$$x_m(t) = \sum_{i=1}^N [s_i(t - \tau_{i,m}) + n_i(t)] \quad (1)$$

where $s_i(t), i = 1, 2, \dots, N$ is the incident signal, $n_i(t)$ is the noise vector, $\tau_{i,m}$ is the time delay of i_{th} sensor.

$$\tau_{i,m} = -\mathbf{r}_m \mathbf{p}_i / c \quad (2)$$

where $\mathbf{r}_m$ is the look-direction dependent vector, $\mathbf{p}_i$ is the coordinates of the receiver.

$$\mathbf{r}_m = (\sin \phi_m \cos \theta_m, \sin \phi_m \sin \theta_m, \cos \phi_m) \quad (3)$$

$$\mathbf{p}_i = (x_i, y_i, z_i) \quad (4)$$

The DOA of the signal can be estimated by beam scanning, and the highest SNR will be achieved when the steering angle is aligned with the incident angle of the signal.

3 Ray-tracing-based beamforming

It should be noted that due to the curved wave propagation trajectory the DOA of signal may not be accurately estimated by using conventional beamforming method. To solve the above problem, one could use ray-tracing theory based on geometrical acoustics. The general expressions of the horizontal propagation distance and propagation time of sound are as follows.

$$r(z) = \int_{z_0}^z \frac{nc(z')}{\sqrt{1 - n^2 c^2(z')}} dz' \quad (5)$$

$$\tau(z) = \int_{z_0}^z \frac{1}{c(z') \sqrt{1 - n^2 c^2(z')}} dz' \quad (6)$$

$$n = \frac{\cos(\theta(z_0))}{c(z_0)} = \frac{\cos(\theta(z_1))}{c(z_1)} = \dots = \frac{\cos(\theta(z_n))}{c(z_n)} \quad (7)$$

where r is the horizontal propagation distance; τ is the propagation time; $c(z')$ is the sound velocity at depth z' ;

n is Snell-satisfying ray-parameters, and $\theta(z_i)$ is the grazing angle at depth z_i .

The complex sound speed profile (SSP) is assumed to be a stratified medium with a constant sound speed gradient. The propagation time and horizontal distance are deduced by the following

$$r = \sum_{i=0}^{N-1} \frac{c_i}{g_i \cos \theta_i} |\sin \theta_i - \sin \theta_{i+1}| \quad (8)$$

$$\tau = \sum_{i=0}^{N-1} \frac{1}{2g_i} \left| \ln \frac{1 + \sin \theta_i}{1 - \sin \theta_i} - \ln \frac{1 + \sin \theta_{i+1}}{1 - \sin \theta_{i+1}} \right| \quad (9)$$

where g_i is the gradient of each layer.

In this paper, we propose a ray-tracing-based beamforming method, which combines CBF with ray-tracing to obtain the advantages of each method, for UAPSSs. We first apply CBF, which combines digital delay line with adaptive FIR filter to get precise spatial direction-of-arrival (DOA). Next, we apply the DOA as an initial grazing angle for ray-tracing to eliminate the curvature of the wave trajectory caused by the inhomogeneity of water, after that the position of target can be calculated with improved accuracy. The process of the proposed method is shown in Fig.2 and Fig.3.

Fig. 2. Process of the proposed method.

Fig. 3. Adaptive FIR filter.

4 Test results

4.1 DOA estimation

A pool test is conducted to verify our method. A 30-elements uniform hexagonal array (Fig.4) and a sound source are fixed underwater, with a pitch angle of 45 and a azimuth angle of 187 (Fig.5). A linear frequency modulation (LFM) signal is used in this test, whose bandwidth is 9kHz-15kHz and pulse width is 25ms. The sound speed profile (SSP) of the pool is measured by a sound speed profiler (Fig.6).

Fig. 4. 30-elements hexagonal planar array.

Fig. 5. The fixed system.

Fig. 6. Sound speed profile of the test pool.

CBF is used to get the DOA of the sound source by beam-scanning in the entire angular space. The spatial spectrum is shown in Fig.7. The SNR of the output signal of the array reaches the maximum value (Fig.8) when the main beam is aligned with the sound source.

Fig. 7. Spatial spectrum of the input signals.

From Fig.7 we can calculate the pitch angle $\phi = 49.01^\circ$ and the azimuth angle $\theta = 187.6^\circ$ and think of them as the input value of ray-tracing. The

comparison of the results is shown in Table 1, which show that the pitch angle calculated.

Fig. 8. Array input/output signal.

Fig. 9. Partial enlargement of Fig.8.

By CBF may not be well consistent with the true position of target because of the curved propagation effect. As a comparison, the Ray-tracing method solved this problem very well and reduced the horizontal positioning error ($\sqrt{\Delta x^2 + \Delta y^2}$) from 0.53m to 0.13m (75%).

Table 1. Results comparison.

Margin	$\phi(^{\circ})$	$\theta(^{\circ})$	$x(m)$	$y(m)$
Theoretical value	45.00	187.0	4.00	4.00
CBF	49.01	187.6	4.53	3.94
CBF& Ray-tracing	46.20	187.6	4.13	3.97

4.2 Performance of the method in different SNR

We further study the proposed method in different SNR conditions, whose performance is found to depend on the array gain of CBF. Here, the cross-correlation method is used for bearing estimation in UAPSSs. We test the performance of the method by changing the SNR from 0dB to -15dB, and then verifying the correlation peak of input and output signals (Fig.10-Fig.13).

Fig. 10. Cross-correlation with SNR=0dB.

Fig. 11. Cross-correlation with SNR=-5dB.

Fig. 12. Cross-correlation with SNR=-10dB.

Fig. 13. Cross-correlation with SNR=-15dB.

It can be seen from the Fig.10-Fig.13 that the correlation peak of the input signal is weak at -5dB SNR while the correlation peak of the output signal is obvious until -15dB SNR. The phenomenon is consistent with the array gain whose value is 10.25dB (Fig.8).

5 Conclusions

In this paper, a ray-tracing based time-domain wideband fractional delay beamforming method for UAPSs is proposed. We take advantage of the array gain by CBF combining with digital delay lines and adaptive FIR filters. Ray-tracing is applied to improve positioning accuracy by eliminating the curvature of the trajectory caused by the inhomogeneity of water. The experimental results indicate that the method can effectively reduce the effect of ray bending and accurately estimate the position of target at low SNR.

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References

1. R Urick, and J Robert. *McGraw-Hill*, 1983:1-100.
2. Y Han, C Zheng, D Sun. *Ocean. Eng.*, **117**(2016).
3. S Li, X Wang, L Zhang. *IEEE J Oceanic Eng.*, **40**(2015).
4. M Isik, and O Akan. *IEEE Trans Commun*, **8**(2009):4457-4463.
5. L Liu, S Zhou, J Cui. *Wire Commun Mob Com*, **8**(2010):977-994.
6. D Lambrinos, R Möller, T Labhart. *Robo & Auto Sys*, **30**(2000).
7. Z Li, S Dosso, D Sun. *IEEE J Oceanic Eng.*, **41**(2016).
8. A Douglass, H Song, D Dowling. *J Acoust Soc Am*, **142**(2017).
9. T Yang. *J Acoust Soc Am*, **141**(2017).
10. E Ruigrok, S Gibbons, K Wapenaar. *J Seis*, **21**(2017).
11. P Ameer, L Jacob. *IEEE Commun Lett*, **14**(2010), 930-932.
12. R Coates. *Underwater Acoustic Systems*. 1990:1-100.
13. T Harold, J Vincent. *J Acoust Soc Am*, **102**(1997), 3099-3100.