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Robust time-reversal is combined with distributed multiple-input multiple-output sonar for detection of small targets in shallow water environments

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ABSTRACT

The distributed multiple-input multiple-output (MIMO) system exploits the spatial diversity for enhancement of target detection. Time reversal processing (TRP) is based on the acoustic reciprocity to enhance target echoes and suppress reverberation. This paper presents an attempt of combining TRP with the distributed MIMO processing for detection of small targets in shallow water environments. For improvement of robustness of the distributed TR-MIMO sonar system, we consider the iterative time reversal mechanism in the processing framework. A probing signal is firstly transmitted to sense the environment and observe echoes of the likely targets. Then, the target of interest is simultaneously illuminated from different angles by time-reversal beams in the second transmission. With a broadband spatial-temporal model, we analyze the time-reversal gain in the distributed MIMO processing and design a MIMO detector in the Neyman-Pearson sense. Results of numerical simulation have shown that the distributed TR-MIMO sonar system outperforms the TR sonar system in the high SNR regime. Due to benefits of robust time-reversal focusing, the distributed TR-MIMO sonar system performs well in localization of a small target in at-lake experiments.

1. Introduction

Detection of small targets is a challenging problem for active sonar systems in most shallow water environments due to the weak target echoes masked by ocean bottom reverberation. In this paper, we attempt to combine the robust time-reversal (TR) [1,2] technique with the distributed multiple-input multiple-output (MIMO) [3,4] sonar system for detection of small targets. Robust time-reversal exploits spatial-temporal focusing for enhancement of target echoes and suppression of reverberation in an environment with significant multipath [5,6]. Robustness of time reversal is provided by the iterative time-reversal technique where echo of a likely target is used as a surrogate probe source (PS) in time-reversal [7]. The distributed MIMO sonar system capitalizes on the diversity of target scattering for stable target detection and localization with the widely spaced transmit/receive arrays. Thus, the distributed TR-MIMO sonar system is a trade-off between the TR sonar system and the distributed MIMO sonar system.

Time reversal demonstrates the spatial-temporal focusing properties of underwater acoustic channels (UACs). Time reversal achieves a high signal-to-noise (SNR) by the spatial focusing and mitigates the mulitpath time-delay spread by the temporal compression. A classical time-reversal at-sea experiment was performed in the May 1997 near Formiche island [8]. In the experiment, the time-revered signal of 445 Hz after propagation over 30 km focused at the original PS location for several days. Since then, time reversal has been widely investigated, such as tim-reversal acoustic communication [9–12], robust time-reversal methods [13–18], time-reversal imaging [19,20], etc.

The distributed MIMO sonar system can be viewed as a type of multistatic sonar systems. The widely separated transmit/receive arrays capture the spatial diversity to mitigate target fading [4]. A general MIMO processing framework was proposed for sonar and radar in 2006 [21]. Then the MIMO acquisition concepts are discussed in detail [22]. Due to delay and Doppler spreads of UACs resulting in the increasing of the cross correlation of waveforms, orthogonal waveform design is an important aspect of the MIMO sonar technology [23,24]. The cognitive technique is applied to MIMO sonar to improve its robustness and adaptability [25]. Due to independent views, MIMO sonar system can surpass the resolution of synthetic aperture sonar (SAS) systems using the same bandwidth [26,27].

The main contributions of the paper are as follows. (1) A jointly processing framework is proposed for the distributed TR-MIMO sonar system which benefits from the spatial diversity gain and the time-reversal array gain. The similar processing framework is presented in [28] only for a colocated MIMO radar system. (2) Robustness of the distributed TR-MIMO sonar system is improved due to time-reversal focusing based on the iterative strategy. A probing signal is firstly

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transmitted to sense the environment and observe echoes of the likely targets. Then, the target of interest is simultaneously illuminated from different angles by time-reversal beams in the second transmission. (3) On the basis of a broadband spatial-temporal model, we have analyzed the robust TRP gain at the transmit and receive ends, respectively. In addition, a MIMO detector is developed in the Neyman-Pearson sense and its performance is evaluated using numerical simulations. (4) The effectiveness of the joint processing framework is validated by at-lake experiments of localization of a small target in a shallow water area. To the best of our knowledge, few experimental results have been reported about the distributed MIMO sonar system.

The remainder of this paper is organized as follows. The distributed TR-MIMO sonar processing framework is provided in Section 2 where robust time reversal processing and the MIMO detector are respectively investigated. Section 3 compares the detection performance of the distributed TR-MIMO sonar system with that of the TR sonar system by numerical simulations. The distributed TR-MIMO sonar performance is further evaluated by at-lake experiments in Section 4. Some conclusions are given in Section 5.

2. Distributed TR-MIMO sonar processing framework

2.1. Constraint for array configuration

We consider a distributed TR-MIMO system consisting of M vertical sub-arrays covering the whole water column. To capture target diversity, the distance D between two neighbour sub-arrays meets the following constraint [3,29,30]:

$$D \geqslant \frac{\lambda R}{\Delta x} \tag{1}$$

where λ is wavelength, R denotes the target range, and Δx denotes the size of an extended target. Eq. (1) means that two neighbour sub-arrays are not within the same receiving beamwidth of the target when the target is viewed as a receiving array with the aperture size of Δx.

2.2. Robust time reversal

In robust time reversal, the first step is to omni-directionally transmit a probing signal to sense the environment and observe the echoes of likely targets. Then, the channel response function is estimated from the received echoes. We assume that the probing signal is one of the broadband signal set, $S_i(f_l)$ $\{i=1,\dots,M,l=0,1,\dots,L-1\}$ at frequency f_l:

$$\begin{aligned}&|S_i(f_l)|^2=1/L\\&\sum_{l=0}^{L-1}S_i(f_l)S_j^*(f_l)=\delta(i-j)\end{aligned}\tag{2}$$

The echo of a likely target received by the m-th $(m=1,2,\dots,M)$ vertical sub-array for the k-th $\{k=1,\dots,K\}$ data snapshot is expressed as a vector

$$\begin{aligned}\mathbf{X}_{m,k}(f_l)&=\mathbf{H}_{m,0}\lambda_{m,G}(f_l)G(f_l)S_m(f_l)+\mathbf{W}_{m,k}(f_l)\\&=\mathbf{H}_{m,0}\widetilde{S}_m(f_l)+\mathbf{W}_{m,k}(f_l)\end{aligned}\tag{3}$$

where $G(f_l)$ denotes the channel response from the PS to the target, and $\mathbf{H}_{m,0}(f_l)$ denotes the channel responses from the target to the m-th sub-array. $\lambda_{m,G}$ denotes the complex reflecting coefficient. $\mathbf{W}_{m,k}(f_l)$ denotes the measurement noise. The target echo $\widetilde{S}_m(f_l)=\lambda_{m,G}(f_l)G(f_l)S_m(f_l)$ can be viewed as a second acoustic source for guiding time-reversal transmission in next step. In addition, the channel response $\mathbf{H}_{m,0}(f_l)$ or $G(f_l)$ can also be achieved by running the Kraken model [31] with a virtual source and the geoacoustic parameters [5,32].

From Eq. (3), the equivalent channel response from the PS to the target and back to the sub-array can be estimated by

$$\widehat{\widetilde{\mathbf{G}}}_m(f_l)=\frac{\widehat{\mathbf{P}}_m(f_l)}{S_m(f_l)}\tag{4}$$

where

$$\widehat{\mathbf{P}}_m(f_l)=\frac{1}{K}\sum_{k=1}^{K}(\mathbf{X}_{m,k}(f_l)-\mathbf{W}_{m,k}(f_l))\tag{5}$$

2.3. TR transmitting

Correspondingly, the time-reversed signal transmitted by the m-th sub-array can be expressed as

$$\begin{aligned}\widetilde{\mathbf{X}}_m(f_l)&=\rho_{m,l}\widehat{\mathbf{P}}_m^*(f_l)\\&\approx\rho_{m,l}\mathbf{H}_{m,0}^*(f_l)\lambda_{m,G}^*(f_l)G^*(f_l)S_m^*(f_l)\end{aligned}\tag{6}$$

where ≈ describes the noise to be neglected for simplicity in the subsequent derivation. In practice, we would utilize $\mathbf{X}_{m,k}(f_l)$ in Eq. (3) as the signal to be time-reversal transmitted. The energy normalization factor ρ_m is defined as

$$\begin{aligned}\rho_{m,l}&=\sqrt{\frac{|S_m(f_l)|^2}{M\,||\,\widehat{\mathbf{P}}_m(f_l)\,||^2}}\\&\approx\frac{1}{\sqrt{M}\,|\,G(f_l)\,||\,\lambda_{m,G}(f_l)\,|||\,\mathbf{H}_{m,0}(f_l)\,||}\end{aligned}\tag{7}$$

In Eq. (7), M describes the total transmitted power distributed uniformly by M transmitting sub-arrays.

The signal incident to the q-th scatterer from the m-th sub-array can be expressed as

$$Z_{m,q}(f_l)=\rho_{m,l}\mathbf{H}_{m,q}^T(f_l)\mathbf{H}_{m,0}^*\lambda_{m,G}^*(f_l)G^*(f_l)S_m^*(f_l)\tag{8}$$

where $\mathbf{H}_{m,q}^T(f_l)$ denotes the channel response between the m-th sub-array and the q-th scatterer.

Further, we define

$$\begin{aligned}\mathbf{B}_m(f_l)&=[\mathbf{H}_{m,0}^T(f_l)\mathbf{H}_{m,0}^*(f_l),\dots,\mathbf{H}_{m,(Q-1)}^T(f_l)\mathbf{H}_{m,0}^*(f_l)]^T\\&=||\mathbf{H}_{m,0}(f_l)||^2\mathbf{g}_m(f_l)_{Q\times1}\end{aligned}\tag{9}$$

where $\mathbf{g}_m(f_l)=[g_{m,0}(f_l),\dots,g_{m,(Q-1)}(f_l)]^T,g_{m,q}(f_l)=\frac{\mathbf{H}_{m,q}^T(f_l)\mathbf{H}_{m,0}^*(f_l)}{||\,\mathbf{H}_{m,0}(f_l)\,||^2}$. $\mathbf{g}_m(f_l)$ describes the phase-shifts of the incident signal due to scatterers when the time-reversed signal focuses on the target center. Since the scatterers are close to each other, we can assume $|\mathbf{H}_{m,0}(f_l)|\approx\cdots\approx|\mathbf{H}_{m,(Q-1)}(f_l)|$. Thus, $g_{m,q}(f_l)\approx\frac{\mathbf{H}_{m,q}^T(f_l)\mathbf{H}_{m,0}^*(f_l)}{||\,\mathbf{H}_{m,q}(f_l)\,||||\,\mathbf{H}_{m,0}(f_l)\,||}$. $|g_{m,q}(f_l)|=1$ stands for completely focusing without mismatch. The smaller value of $|g_{m,q}(f_l)|$ denotes less energy on the scatterer. When time-reversal transmission is viewed as transmit beamforming, the term $|\mathbf{B}_m(f_l)|$ describes the transmit coherent gain. Thus, Eq. (8) can be rewritten as

$$\mathbf{Z}_m(f_l)=\rho_{m,l}||\mathbf{H}_{m,0}(f_l)||^2\lambda_{m,G}^*(f_l)G^*(f_l)S_m^*(f_l)\mathbf{g}_m(f_l)\tag{10}$$

Assuming that the environment does not change significant over the period of forward and backward propagation, namely the forward propagation channel being the same as the backward propagation channel, the signals received by the n-th sub-array corresponding the m-th sub-array transmission can be expressed as

$$\begin{aligned}\mathbf{R}'_{n,m}(f_l)=\;&\rho_{m,l}\mathbf{H}_n(f_l)\lambda_{n,m}(f_l)\mathbf{g}_m(f_l)||\mathbf{H}_{m,0}(f_l)||^2\lambda_{m,G}^*(f_l)G^*(f_l)S_m^*(f_l)\\&+\mathbf{N}_{n,m}(f_l)\end{aligned}\tag{11}$$

where $\mathbf{H}_n(f_l)=[\mathbf{H}_{n,0}(f_l),\dots,\mathbf{H}_{n,(Q-1)}(f_l)]$stands for the channel response functions from all scatterers to the n-th sub-array, $\lambda_{n,m}(f_l)$ denotes the complex reflection coefficient, and $\mathbf{N}_{n,m}(f_l)$ denotes the measurement noise.

2.3.1. TR beamforming

As previously mentioned, MIMO detection requires a high SNR.