Digital Signal Processing ••• (••••) •••–•••

Contents lists available at ScienceDirect

Digital Signal Processing

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Joint underwater target detection and tracking with the Bernoulli filter using an acoustic vector sensor ☆

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A R T I C L E I N F O

Article history:
Available online xxxx

Keywords:
Acoustic vector sensor
The Bernoulli filter
Random finite sets
Target tracking
Track before detect

A B S T R A C T

In this paper, we study the problem of joint underwater target detection and tracking using an acoustic vector sensor (AVS). For this challenging problem, first a realistic frequency domain simulation is set up. The outputs of this simulation generate the two dimensional FRequency–AZimuth (FRAZ) image. On this image, the random finite set (RFS) framework is employed to characterize the target state and sensor measurements. We propose to use the Bernoulli filter, which is the optimal Bayes filter emerged from the RFS framework for randomly on/off switching single dynamic systems. Moreover, to increase the performance of detection and azimuth tracking in low signal-to-noise ratio (SNR) scenarios, a track-before-detect (TBD) measurement model for AVS is proposed to be used with the Bernoulli filter. Sequential Monte Carlo (SMC) implementation is preferred for the Bernoulli filter recursions. Extensive simulation results prove the performance gain obtained by the proposed approach both in estimation accuracy and detection range of the system.

1. Introduction

Acoustic vector sensor (AVS) is a single sensor technology which can yield azimuth information of the acoustic sources at a single point in space. This is achieved by measuring two physical quantities namely the pressure in scalar form and the acceleration in vectorial form. AVSs are found in many important applications, underwater vehicle detection/tracking [1], waterway security [2], underwater communications [3] and geo-acoustic inversion [4], just to name a few.

The azimuth estimation of underwater acoustic sources is usually done by an array of pressure sensors, called the hydrophones [1]. As the frequency of source gets lower the required aperture size of the hydrophone array gets larger [5]. The operational frequency band of a flank array sonar equipped in submarines is usually about 100–1500 Hz and aperture is about 30–40 m [1]. Though small in size, AVSs can be used for low frequency azimuth estimation of underwater sources. With frequency band extending from 10 Hz to several kHz, commercial AVSs are not larger than 30 cm in diameter. In this regard, AVS is a smaller and cheaper alternative for azimuth estimation of low-frequency underwater targets.

The azimuth estimation using an AVS is based on a scalar pressure measurement and three accelerometer outputs which sense the acceleration based on the physical entity of particle velocity on orthogonal axes. Due to the structure of the AVS, the array gain cannot be high enough to detect low Signal-to-Noise Ratio (SNR) targets. In addition to this, the azimuth estimations, done with the traditional AVS beamforming techniques, result in poor azimuth estimations. To improve the detection and azimuth estimation performance of targets with low SNR, firstly we formulate our framework in frequency domain. Owing to frequency domain approach, the estimations are affected only by the noise in one frequency bin. As a result, for the same level of target emitted noise frequency domain beamforming algorithms perform better than their time domain counterparts [6,7]. The frequency domain beamforming yields beams for each frequency band. These beams form an image, which has an azimuth and a frequency axis. This 2-dimensional FRequency-vs-AZimuth image is called FRAZ [8]. Despite the obvious benefits in real applications, to the best of authors' knowledge, so far a frequency domain AVS simulation is not proposed in the literature. In time domain simulations, one is restricted to one beam, one detection only [9]. This limitation oversimplifies the complexity of the frequency domain detection and azimuth tracking problem of AVS and renders the proposed time domain tracking algorithms useless in FRAZ, which resembles a heavy clutter environment. To overcome these limitations, we propose a new simulation scheme to form a basis for FRAZ based detection and azimuth tracking.

☆ This work was supported in part by The Scientific and Technological Research Council of Turkey (TUBITAK) under grant No. 114E214.
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http://dx.doi.org/10.1016/j.dsp.2015.09.020

Moreover, in studies based on real data the detection of a target under heavy clutter is not performed efficiently and detections on frequency bands are filtered so that only one detection remains, i.e. no false alarms occur [10]. Unfortunately, this strategy of eliminating clutter is applicable only to high SNR targets where the target can be seen clearly in FRAZ image. A more robust detection and tracking scheme, which is applicable to both low and high SNR situations, is proposed in this work.

Multiple target tracking is a subfield of signal processing with applications spanning many different engineering disciplines [11]. In this subfield of signal processing, the random finite sets (RFS) approach is the newest development that provides a general systematic framework for multi-target systems by modeling the multi-target state as an RFS [12,13]. The RFS approach treats the collection of individual measurements and the individual targets as a set-valued measurement and set-valued state, respectively. It is shown that the sequential estimation of multiple targets buried in clutter with association uncertainties can be formulated in a Bayesian filtering framework by modeling set-valued measurements and set-valued states as RFSs [12]. Since the implementation of the RFS formulation of the optimal Bayes filter is computationally demanding, several approximations have appeared recently [12,14]. One of those approximations is the Bernoulli filter (also known as joint target detection and tracking filter or JoTT) [15]. The Bernoulli filter is the optimal Bayes filter for randomly on/off switching single dynamic systems. There are two implementations of the Bernoulli filter; one is using sequential Monte Carlo (SMC) method, the other one is using Gaussian mixtures (GM) [12]. Each implementation method has its own pros and cons [12]. GM implementation provides a closed form analytical solution to Bernoulli recursions under linear Gaussian target dynamics and measurement models [15–17]. Alternatively, SMC implementation imposes no such restrictions and has the ability of handling nonlinear target dynamics and measurement models [18]. It can be said that SMC implementation is a more general framework for Bernoulli recursions.

There are two major measurement models used in target tracking applications: i) detect-before-track (DBT) ii) track-before-detect (TBD) [19]. The DBT is the classical one where the measurements are the output of a detector. In the DBT approach, output values higher than a threshold value is considered as a detection. Setting a high threshold will cause the system lose valuable information. Setting a low threshold will result in high rate of false alarms. On the other hand, in the TBD measurement model, no thresholding is conducted and raw intensity signals are used as measurements (e.g. images, range-Doppler-azimuth data cubes, FRAZ) [20,21]. Although it is known that TBD methods increase the performance of tracking systems with respect to the DBT methods, so far, no TBD based formulations for AVS is proposed in the literature.

The novelty of this work is threefold: First, a method for colored ambient noise generation is proposed and added to the pressure and acceleration signals. The additive noise is generated by using empirical formulation of the ambient noise spectrum [22]. The generation of realistic pressure and acceleration signals made the beamforming stage and generation of FRAZ possible. The results of the proposed simulation yielded the ability to track not only azimuth but also frequency. Another result of this addition to the simulation is that, even if the source level (SL) is the same for two narrowband sources with different frequencies, signal-to-noise ratios (SNR) at those frequency bins are different. Second, AVS target detection is handled jointly with tracking problem using SMC-Bernoulli filter using both detection outputs and FRAZ intensities. Third, the detection range and the coverage of a single AVS is increased by using a TBD Bernoulli filter (TBD-Ber filter). At the end of this study, for the first time in the literature, a full frequency-domain simulation of an AVS is run and using the

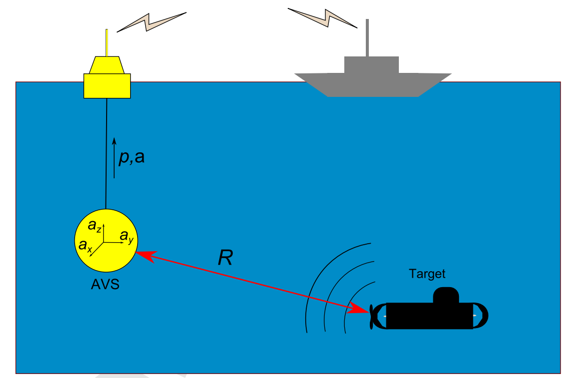

Fig. 1. Basic operation of an AVS which measures the acceleration, a, and pressure, p, emitted from a moving target at distance R. A sonobuoy can transmit the raw information to the ship to be processed or it can process the raw information itself and pass the direction information to the ship.

simulation outputs, azimuth and frequency tracking of a target is achieved using robust and high performance target detection and tracking algorithms.

The organization of this paper is as follows. Mathematical formulation of the problem, the noise generation and the measurement models are presented in Section 2. In Section 3, RFS formulation of Bernoulli filter and its SMC implementation are presented for detector output and intensity-based models. The details and modifications of the implementation of Bernoulli filter on the problem is explained in Section 4. The results are presented and discussed in Section 5 and the conclusion is given in Section 6.

2. Sensor and measurement model

Classical azimuth estimation with AVS is done using particle velocity and pressure. The basic passive AVS operation concept and the physical identities can be seen in Fig. 1. The theoretical relation between the pressure gradient and the accelerometer measurements is formulated by Euler's equation [23],

$$\nabla p\left(\mathbf{r},t\right) = -\rho \frac{\partial \mathbf{v}\left(\mathbf{r},t\right)}{\partial t} \quad . \tag{1}$$

Here, ∇p represents the gradient vector for the pressure, $\mathbf{r}$ and t are the position vector and the time stamp, respectively. ρ is the density of the environment where acoustic waves are radiated. $\mathbf{v}$ is the particle velocity vector and its projections on the sensors can be seen in Fig. 2.

Based on this relationship, the scalar pressure measurement is used as phase reference and exploited to avoid sign ambiguity in azimuth estimation [24]. For a monochromatic source, the function of pressure signal under far-field assumption can be written as

$$p\left(\mathbf{r},t\right) = e^{i\left(\mathbf{k}^T\mathbf{r}-2\pi f t\right)} \quad , \tag{2}$$

f is the temporal frequency of the signal and $\mathbf{k}$ is the unit direction vector which is given by

$$\mathbf{k} = \left[\,\cos\theta\cos\phi \quad \sin\theta\cos\phi \quad \sin\phi\,\right]^T = -\frac{\mathbf{v}}{|\mathbf{v}|} \quad , \tag{3}$$

where $[\cdot]^T$ is the transpose operator.

When (2) is written in (1), we obtain

$$\mathbf{v}\left(\mathbf{r},t\right) = -\frac{1}{\rho c}\mathbf{k}p\left(\mathbf{r},t\right) \quad , \tag{4}$$

where c is the sound speed in the medium [24].

In today's AVS technology, accelerometers are used rather than velocity sensors. In order to have the acceleration equations, both

Please cite this article in press as: A. Gunes, M.B. Guldogan, Joint underwater target detection and tracking with the Bernoulli filter using an acoustic vector sensor, Digital Signal Process. (2015), http://dx.doi.org/10.1016/j.dsp.2015.09.020