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14. ABSTRACT
We seek to address two important signal processing aspects of multistatic active sonar systems, namely enhanced range-Doppler imaging and improved target parameter estimation. For the former, a hybrid dense-sparse method is considered to generate range-Doppler images with both low sidelobe levels and high accuracy. For the latter, a generalized K-Means clustering (GKC) method for target association is developed to associate the range measurements from different transmitter-receiver pairs, which is actually a range fitting procedure. Moreover, the extended invariance principle-based weighted least-squares (EXIP-WLS) method is developed for accurate target position and velocity estimation. The effectiveness of the considered multistatic active sonar signal processing techniques is verified using numerical examples.

15. SUBJECT TERMS
Multistatic active sonar, range-Doppler imaging, iterative adaptive approach, sparse learning via iterative minimization, IAA-MAP, target parameter estimation, generalized K-Means clustering, extended invariance principle, weighted least squares

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Enhanced Multistatic Active Sonar via Innovative Signal Processing

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LONG-TERM GOALS

Our goal is to address fundamental signal processing research issues for enhanced multistatic active sonar systems. To effectively mitigate the reverberation problems and direct blasts encountered in shallow water, both probing waveform synthesis and adaptive receive filter design techniques should be investigated. To efficiently and accurately estimate the target positions and velocities, both target association schemes and weighted target parameter estimation methods should be devised.

OBJECTIVES

Our objectives of the current effort are 1) to devise robust, computationally efficient, and data-adaptive receiver signal processing algorithms to effectively mitigate the mutual interferences among multiple transmitters and suppress direct blasts, and 2) to provide enhanced post-detection position and velocity estimation of targets of interest using distributed multi-static active sonar systems.

APPROACH

For Doppler-sensitive probing waveforms, we consider random phase sequence sets. The probing waveforms, such as the random phase sequence sets, can never be perfect, as dictated by fundamental performance bounds and principles. In general, the ambiguity function of any probing waveform can never be shaped like a perfect thumb-tack. Fortunately, novel receiver design techniques can serve to improve the overall performance of the active sonar system and can be used to compensate for the deficiencies in the probing waveform sets. For receive filter design, we consider the conventional matched filter as well as state-of-the-art adaptive filters to form range-Doppler images. The adaptive filters, in particular, will be developed to suppress direct blasts and mutual interferences among all probing waveforms. They are also devised to significantly reduce the mutual interferences of scatterers in different range and Doppler bins and to improve the Doppler resolution. We also estimate the target parameters after the range-Doppler images are obtained and we develop an efficient clustering-based target association scheme and an enhanced target position and velocity estimation method using the weighted least-squares approach. We obtain the weighting matrices through Cramer-Rao bound analyses of the range-Doppler imaging problems.

The key individuals participating in this work include the PI, Dr. Jian Li, her Ph.D. student, Mr. Kexin Zhao, her postdoctoral associate Dr. Junli Liang, and her visiting scientist, Dr. Johan Karlsson, all of the University of Florida.

WORK COMPLETED

We have considered novel receiver design techniques to improve the overall performance of the active sonar system and to compensate for the deficiencies in waveform synthesis. We have developed two adaptive receiver designs, namely the iterative adaptive approach (IAA) and the sparse learning via iterative minimization (SLIM) method. Both approaches outperform the classical data-independent matched filter (MF) significantly. Moreover, as a Bayesian signal recovery approach, the SLIM algorithm gives the *a posteriori* distribution of the target amplitudes. This information could be used for enhanced target detection and automatic target recognition. We have also developed a hybrid method that first uses IAA to compute a dense range-Doppler image, which is then, upon convergence, followed by a single step of SLIM. Since SLIM achieves sparsity based on solving a hierarchical Bayesian model through maximizing *a posteriori* probability density function, this single step of SLIM is referred to as a MAP step, and the resulting algorithm as the IAA-MAP algorithm. SLIM provides sparse results but is relatively sensitive to noise and disturbances. IAA tends to be more robust against noise and disturbances than SLIM. Due to the accurate and robust IAA result and a single step of SLIM, IAA-MAP is robust, sparse and accurate. The merits of IAA-MAP are desirable for achieving improved target parameter estimation after range-Doppler imaging.

Specifically, we have focused on developing adaptive signal processing techniques in a multistatic active sonar system that employs multiple trnasmitters and multiple receivers. In the presence of severe interferences, as encountered in multistatic active sonar, the multiple simultaneously transmitted probing sequences act as interferences to one another, making the matched filter based receiver ineffective. In these cases where the problem is no longer noise limited, but rather interference limited, advanced adaptive receiver designs, such as IAA, SLIM and IAA-MAP, become necessary. In a multistatic setup, IAA, SLIM and IAA-MAP all significantly outperform the conventional MF for target range-Doppler imaging and interference suppression.

Given the range-Doppler images, we use a model-order selection tool, i.e., the Bayesian information criterion (BIC), to estimate the target number and locate the corresponding peaks before moving on to the task of target parameter estimation. The target parameters can then be estimated using the so-obtained peaks (after the direct blasts are removed) of the range-Doppler images. However, when there are multiple targets in the field of interest, we need to solve the target association problem, which aims to determine a proper one-to-one correspondence between the targets and the peaks of each range-Doppler image. Given an assumed association pattern, all the range values obtained from peaks that are assigned to a specific target are collected to estimate the target position and the incorrect association assumption would lead to severe performance degradations. This association problem can also be viewed as a range fitting problem. This is a combinatorial optimization problem involving both the peak association and target position estimation. To efficiently solve this problem, we develop a generalized K-Means clustering (GKC) method for peak association, where the "Means" update step is to estimate the target position under the current association pattern, and the Label Re-assignment step is to adjust the association pattern based on the current target position estimates. (We remark that if each of the receivers is equipped with a large array that can provide accurate angle estimates of the targets, the peak association problem becomes an easy problem or even disappears entirely.)

Based on the fact that different transmitter-receiver pairs have different reflection coefficients, we develop an extended invariance principle-based weighted least-squares (EXIP-WLS) method for target position determination (which is the aforementioned "Means" update step) and velocity estimation. More specifically, nonlinear algebraic position equations are approximated as linear ones via Taylor expansion and the target position and velocity estimates are refined in an iterative manner using proper weighting matrices. The weighting matrices we use are the blocks of the Fisher information matrix (FIM) corresponding to an unstructured data model.

RESULTS

Consider a multistatic active sonar system equipped with two stationary transmitters and two stationary receivers (by stationary, we mean that their positions are fixed during the sensing operation). The system geometry is illustrated in Figure 1. The coordinate vectors of the two receivers Rx1 and Rx2 are (2000, 0) and (0, 2000), respectively (the unit of distance is meter). Two transmitters, Tx1 and Tx2, are located at (0, 0) and (2000, 2000), respectively, and transmit two random phase (RP) sequences simultaneously. The RP sequences are unimodular with phases independently and uniformly distributed over $[0, 2\pi)$. There are two targets moving in the filed of view. The first target, located at (1000, 995), is moving at -135° (with respect to east) at a radial velocity of 1.8 knots. The second target is located at (1050, 965) and is moving at -90° at 2 knots knots. The Doppler bins correspond to Doppler scaling factors ranging from 0.9976 to 1.0024 with a step size of 0.0003. The zero-mean white Gaussian noise with a power of -10 dB is added to the received measurements. The system parameters are given in Table I.

The receiver outputs are processed using MF, IAA, SLIM, and IAA-MAP. The intensity of all range-Doppler images is normalized so that the peak is at 0 dB and is clipped at -40 dB. For the sake of clarity and also due to the fact that the location of the direct blast in the range-Doppler images is predictable given the positions of the transmitters and receivers, the range-Doppler images presented henceforth show the target range only. Figure 2 shows the range-Doppler images produced by the four receiver filter designs. The MF images with respect to the two transmitters formed by Rx1 (Rx2) are shown in Figures 2(a) and 2(b) (Figures 2(c) and 2(d)), respectively. One observes that due to the mutual interferences of the target reflections and strong direct blasts, the MF images are mired with background noise, making it difficult to detect the two targets. The range-Doppler images produced by IAA, SLIM and IAA-MAP are shown in Figures 2(e)–2(h), Figures 2(i)–2(l) and Figures 2(m)–2(p), respectively. We can see that IAA, SLIM, and IAA-MAP all possess excellent interference suppression capabilities and produce much sharper images than MF. In particular, IAA can provide quite accurate estimation results, but the resulting dense sidelobes may bury targets with weak reflection coefficients. In contrast, SLIM enforces sparsity and provides range-Doppler images with much less sidelobes than IAA. As the hybrid of IAA and SLIM, the IAA-MAP method takes advantages of their merits while overcoming their limitations. Specifically, IAA-MAP provides more accurate estimates than SLIM, while maintaining a significantly lower sidelobe level than IAA. IAA-MAP provides the cleanest range-Doppler images among all methods considered herein.

From the two peaks of each range-Doppler image given by IAA-MAP, we obtain four pairs of range measurements (in unit of kilometer), i.e., {2.7825, 2.8200}, {2.7600, 2.8275}, {2.8275, 2.9025}, and {2.8350, 2.8800}. For this multistatic active sonar system equipped with 2 transmitters and 2 receivers, there are 8 possible associations for the case of 2 targets. The brute-force approach needs to consider all possibilities, and obtains the correct association pattern at the cost of 1.23 seconds on an ordinary workstation (Intel Xeon E5506 processor 2.13G Hz, 12GB RAM, Windows 7 64-bit, and MATLAB

R2010b). In comparison, the proposed GKC method only requires 0.56 seconds due to its efficient search. (The more targets are present in the field of view, the more computational saving the GKC method can provide. For example, when there are 3 targets, GKC requires 3.47 seconds while the brute-force method needs a much longer 26.01 seconds.) Finally, two groups of associated range measurements are obtained as: {2.7825, 2.7600, 2.9025, 2.8800} and {2.8200, 2.8275, 2.8275, 2.8350}. Actually, the "Means" update step in the association procedure involves the estimation of the positions of the targets under the current association assignment. Therefore, the association pattern and the corresponding target position estimates are obtained simultaneously at the conclusion of the GKC iterations. Once the target position estimates are available, we can determine their velocity estimates in a similar manner. To evaluate the performance of the proposed EXIP-WLS algorithm, the root mean-squared error (RMSE) of the estimated target positions (denoted as $\hat{\theta}_1$ and $\hat{\theta}_2$, respectively) and velocities (denoted as $\hat{\mathbf{v}}_1$ and $\hat{\mathbf{v}}_2$, respectively) obtained via the EXIP-WLS and unweighted least-squares (ULS) methods (for both methods, the so-obtained target position estimates are utilized to facilitate the subsequent velocity estimation) from 100 Monte Carlo trials are listed in Table II, from which we can see that the EXIP-based weighting scheme significantly improves the estimation accuracy.

IMPACT/APPLICATIONS

The littoral submarines are small, quiet, and non-nuclear, making active sonar an essential technology needed for their detection. Enhancing the multistatic active sonar network's capability through innovative waveform synthesis and receive filter design is critical to improving the Navy's ability to conduct anti-submarine warfare.

The unimodular probing waveform sets we adopt are hard to guess by the foe since the phase of each sample of the probing sequence is anywhere between 0 and 2 π. This facilitates covert sensing. Moreover, the Doppler sensitive nature of each probing waveform obviates the need to transmit two separate sequences, with one to achieve good range resolution and another to yield good Doppler resolution. Using the Doppler sensitive probing waveforms, we can achieve both good range resolution and good Doppler resoltuion simutaneously.

By using data-adaptive receive filters to process the received signals, the sidelobe problems of Doppler sensitive probing waveforms can be mitigated. Indeed, the range-Doppler images formed by using the adaptive receivers we devise possess low sidelobe level and high resolution properties. By using the efficient target association scheme and effective target parameter estimation method, the positions and velocities of the targets in the field of interest can be accurately estimated.

In a multistatic active sonar system that employs multiple transmitters and multiple receivers, we have shown that reliable adaptive receiver filters, via enhancing resolution and reducing sidelobe levels of the so-obtained range-Doppler images, significantly enhance the target detection ability and that refining the target position and velocity estimates using weighting provides significantly improved parameter estimation performance.

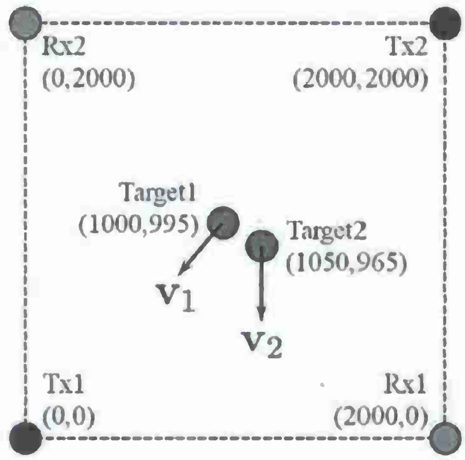

Figure 1. The simulation geometry.

[graph: The coordinate vectors of the two receivers Rx1 and Rx2 are (2000, 0) and (0, 2000), respectively (the unit of distance is meter). Two transmitters, Tx1 and Tx2, are located at (0, 0) and (2000, 2000), respectively. There are two targets moving in the filed of view. The first target, located at (1000, 995), is moving at −135° (with respect to east) at a radial velocity of 1.8 knots. The second target is located at (1050, 965) and is moving at −90° at 2 knots.]

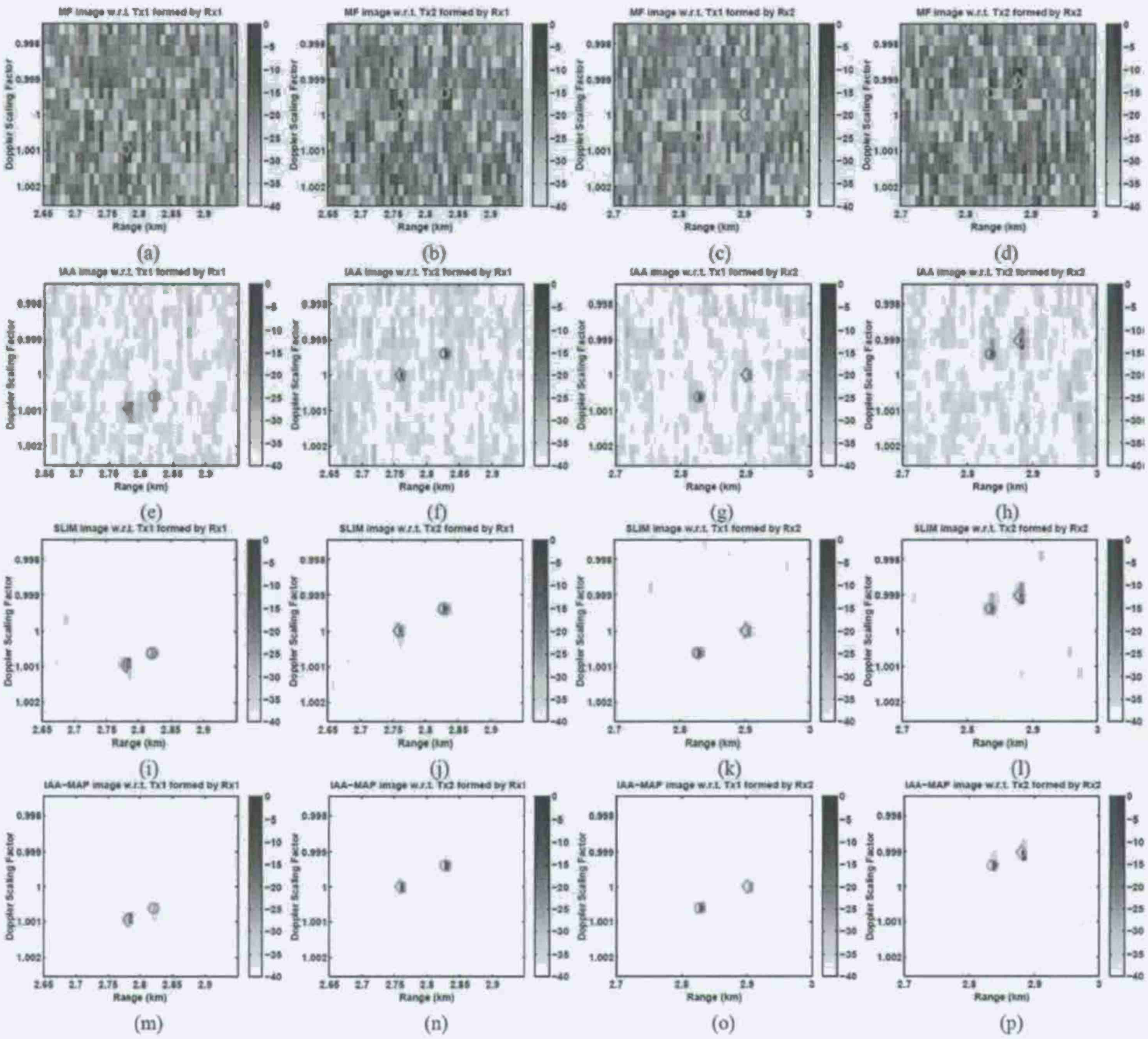

Figure 2. Range-Doppler images produced by a multistatic active sonar system using various receiver filters. Circles and diamonds indicatethe true locations of the first and second targets, respectively.

[graph: IAA, SLIM and IAA-MAP prossess excellent interference suppression capabilities and produce much sharper images than MF. For the adaptive receiver designs, the range and Doppler estimates of both targets are quite accurate.]

Table I. The system parameters.

underwater sound speed	1500 m/s or 2915.77 knots
length of the transmitted pings	400
bandwidth of the transmitted pings	200 Hz
number of Doppler bins	17
carrier frequency	900 Hz
sampling frequency at transmitter and receiver	8000 Hz
duration of the transmitted pings	2 s

Table II. RMSE of paramter estimates using ULS and EXIP-WLS.

Method	Target 1		Target 2	
	$\hat{\theta}_1$	$\hat{\mathrm{v}}_1$	$\hat{\theta}_2$	$\hat{\mathrm{v}}_2$
ULS	-9.8561(dB)	-19.7429(dB)	-5.7636(dB)	-15.6197(dB)
EXIP-WLS	-13.6826(dB)	-22.3587(dB)	-8.8532(dB)	-18.1237(dB)

TRANSITIONS

We have provided several CAN sequences to Dr. Michael S. Datum of the Applied Physical Sciences Corporation. He has used some of the sequences as active sonar probing sequences and generated simulated datasets for ASW scenarios using the sonar simulation toolset (SST). The simulated datasets will be shared with us for further analysis. We plan to use the SST simulated datasets to evaluate the performance of our receive filter designs. We plan to publish joint papers based on our discoveries. This has been a fruitful collaboration.

We have also sent our probing waveform synthesis papers to Dr. James Alsup (alsup@cox.net) and our IAA papers to Dr. Roy Streit (streit@metsci.com).

RELATED PROJECTS

NONE.

PUBLICATIONS

Book

H. He, J. Li, and P. Stoica, *Waveform Design for Active Sensing Systems -- A computational approach*, Cambridge University Press, 2012. [published, refereed].

Journal Publications

J. Ling, L. Xu, and J. Li, "Adaptive Range-Doppler Imaging and Target Parameter Estimation in Multistatic Active Sonar Systems," *IEEE Journal of Oceanic Engineering*. [submitted, under review].

K. Zhao, J. Liang, J. Karlsson, and J. Li, "Enhanced Multistatic Active Sonar Signal Processing," *Journal of the Acoustical Society of America*. [submitted, under review].

Conference Publications

K. Zhao, J. Liang, J. Karlsson, and J. Li, "Enhanced Multistatic Active Sonar Signal Processing," *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Vancouver, Canada, May 26-31, 2013. [submitted, under review].

HONORS/AWARDS/PRIZES

Dr. Jian Li gave a plenary talk at the IEEE Sensor Array and Multichannel Signal Processing Workshop, in Hoboken NJ, in June 2012.