Advances in Group Filter Applications to Sea Mine Detection

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Abstract— **Automatic detection of sea mines in coastal regions is a difficult task due to the highly variable sea bottom conditions present in the underwater environment. Detection systems must be able to discriminate objects which vary in size, shape, and orientation from naturally occurring and man-made clutter. Additionally, these automated systems must be computationally efficient to be incorporated into unmanned underwater vehicle (UUV) sensor systems characterized by high sensor data rates and limited processing abilities. Using noncommutative group harmonic analysis, a fast, robust sea mine detection system is created. A family of unitary image transforms associated to noncommutative groups is generated and applied to side scan sonar image files supplied by Naval Surface Warfare Center Panama City (NSWC PC). These transforms project key image features, geometrically defined structures with orientations, and localized spectral information into distinct orthogonal components or feature subspaces of the image. The performance of the detection system is compared against the performance of an independent detection system in terms of probability of detection ($\mathbf{P_d}$) and probability of false alarm ($\mathbf{P_{fa}}$).**

keywords commutative group, noncommutative group, group filters, probability of detection, probability of false alarm, sea mine detection and classification, unmanned underwater vehicle

I. Introduction

Unmanned underwater vehicles (UUV) are a key technology in reducing the dangerous work of surveying and clearing underwater mine fields. Side-scan sonar is the sensor of choice on many of today's UUVs because of its mature high-resolution imaging capability. However, without automated detection and classification algorithms, all sonar data must be reviewed by a human operator prior to marking and removing mine-like objects. Robust, accurate and computationally efficient computer-automated detection and classification (D/C) algorithms enable UUVs to carry out D/C onboard and in real time. Automated D/C expedites mine clearing operations and may automate tasks such as identification and neutralization in the future.

Naval Surface Warfare Center Panama City (NSWC PC) has been involved in side-scan sonar computer-aided and computer-automated D/C development efforts for over 10 years. Dobeck, et. al. have shown that fusing multiple algorithms can be effective in reducing the number of false alarms called by these D/C systems [**?**], [**?**], [**?**]. NSWC PC has working versions of computer-aided D/C based on algorithm fusion for both operator workstations and real-time onboard UUV computers [**?**]. To make the leap from computer-aided D/C to fully-automated D/C, new algorithms must further reduce false alarms so operators gain vital confidence in D/C system accuracy. Noncommutative group filter based D/C algorithms are substantially different and have the potential of a large intersection on target sets with small intersection on false alarm sets when fused with other algorithms.

The very shallow water (VSW) and surf zone ocean environment is particularly troublesome for locating objects in side-scan imagery. Mines placed in these areas are typically small, odd-shaped, partially occluded by natural and man-made obstructions, and partially buried by strong currents. To find small VSW mines, operators use high-frequency, high-resolution sensors. However, many organic artifacts such as kelp and sea grass that are invisible to low-frequency, low-resolution sonars produce strong high-frequency returns.

This paper describes a sea mine detection algorithm for the VSW environment based on group filter theory. Noncommutative group filters are used to rapidly detect mine-like regions of interest in high-resolution side-scan sonar imagery. The filters process imagery at near $NlogN$ speed. This algorithm was applied to process an unclassified side-scan sonar data base accumulated by NSWC PC, with promising results [**?**]. In the following sections we describe the group filter algorithm and show its performance against the synthetic sonar data base and a new database with larger variances in ocean environment and target signature.

II. Group Filter Theory

Group Theory provides a convenient framework to discuss the nature of translations and unitary transformations in digital signal processing (DSP). Conventional signal and image processing techniques rely on translation-invariant convolution operations for filtering applications. This translation-invariance is directly related to the properties of commutative groups representing data indexing sets. By expanding the use of noncommutative groups as indexing sets, a much richer spectral representation of localized spatial data is possible.

The works of Holmes, Karpovsky, and Trachtenberg are the basis for much of the research in the application of noncommutative group theory to DSP [**?**], [**?**], [**?**], [**?**]. Building upon the work by Holmes and others, Foote, et. al. describe group theory as a general framework for DSP and define noncommutative finite group convolutions for image processing applications [**?**], [**?**]. An and Tolimieri also describe a group theory framework for DSP using commutative and noncommutative indexing sets and

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detail the process for building the group filters that are used in this application [?].

III. VSW Target Detection

Many pattern classification algorithms rely on accurate data segmentation prior to feature extraction. The goal of the algorithm described in this section is to accurately and quickly segment regions of interest (ROI) in VSW side-scan sonar data using group filters. The detection algorithm breaks the original image into overlapping frames, projects each frame onto a spectral basis defined by a noncommutative group, uses group filters to find rectangles at three distinct orientations, and makes a final ROI call based on the intensity of clustered pixels in the original image. The VSW database and detection algorithm are outlined in the following subsections.

A. Database Description

NSWC PC generated an unclassified side-scan sonar database to allow non-government research and development organizations to create and evaluate side-scan D/C algorithms. The database consists of 512 sonar images, each 512×1000, containing a total of 312 synthesized targets of 4 different types. The sonar image files cover a variety of sea bottom types, depths, and surface conditions. Three of the target types are rotationally-invariant while the fourth target type has three different aspects, which simulates a wedge-shaped target viewed from target angles of 315^o, 000^o, and 045^o. Figure **??** is a closeup of the four target types including the three rotations of the wedge-shaped target.

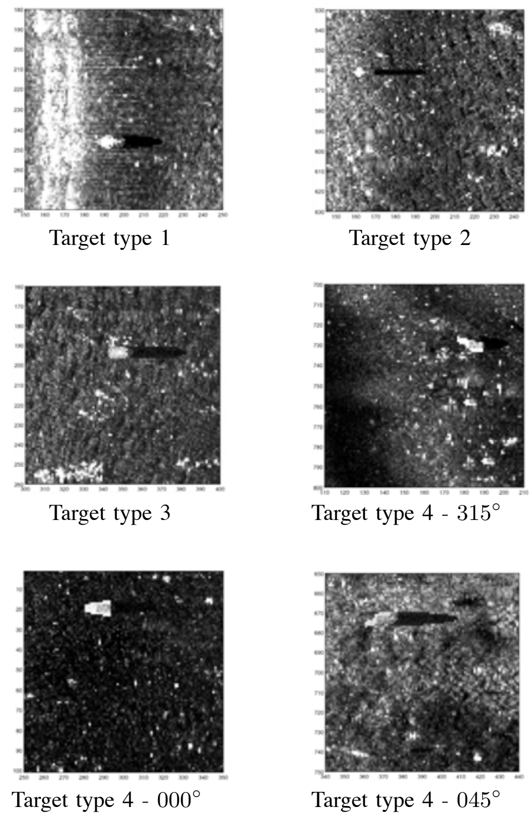

Fig. 1. Image snippets of different synthetic target types in the side scan sonar data base

B. Detection Algorithm Description

For the purpose of evaluating the detection algorithm, the database is divided into a training set and testing set. The training set comprises 256 images containing 179 targets, and the test set comprises 256 images containing 143 targets. The training set is used to set the initial filter parameters and the test set is used to measure the robustness of the algorithm to new data.

An outline of algorithm steps is given below. Details of the algorithm with flow diagrams can be found in [?].

1) **Frame Extraction** - Each sonar image file is divided into 128×128 pixel frames with 15 pixels of horizontal overlap and 40 pixels of vertical overlap. The overlap ensures at least one complete target signature is contained in an extracted frame.
2) **Apply Group Filters** - Each 128×128 frame is processed by three group filters. This filtering step serves as a data reduction process in the algorithm. That is, only regions of the image that have a certain geometric structure of appropriate size and orientation are passed on as candidate ROIs to the next stage.

- **Apply Unitary Transform** - Each 128×128 frame is transformed to the spectral domain via a unitary transform defined by the non-commutative group structure. For this application, the group structure was chosen so that the unitary transform of the spatial frame decomposes the spectral domain into 16 32×32 subframes. The unitary transform is approximated in the algorithm by dividing the 128×128 spatial frame into 16 32×32 frames and then taking the 32×32 2-D DFT of each subframe in place.
- **Select Line Spectral Coefficients** - In three independent actions, spectral coefficients pertaining to horizontal lines, lines of slope 1, and lines of slope -1 are selected from each 32×32 subframe using an operation equivalent to a binary mask. The masks select coefficients so that the mean of the original image is removed (DC spectral components are not selected). Details of creating the binary masks for different geometric structures can be found

in [**?**].

- **Inverse Unitary Transform** - To implement the inverse unitary transform, the inverse 2-D DFT is taken of each masked 32×32 subframe. There are now 3 128×128 filtered frames or projections composed of the 32×32 subframes from the previous filtering step. In terms of number of coefficients, there are $3 \times 4 \times 128$ distinct coefficients, due directly to the property of DFT and the binary masks. These projections give locations of horizontal, slope = 1, and slope = -1 lines in the original sonar image.

3) **Threshold Projections and Measure Cluster Intensity** - The four target types of the side-scan sonar database are separated into three categories for processing based on their geometric structure: two distinct target types are lumped into the single category because they have similar highlight and shadow shapes; one of the four target types is placed into a category because its small highlight and thin shadow makes it fairly unique; the fourth target type is placed into the last category accommodating rotationally-varying and oddly-shaped highlights. While each of the target categories is processed the same way by the group filters described above, the thresholding of horizontal and sloped line projections and the final cluster measuring and thresholding are different for each category.
4) **Final Detection Call** - The detection calls from the three target categories are ORed into a set of final detection calls. Duplicate calls resulting from frame overlap are removed.

IV. Results

Filtering and detecting ROIs consumed about 3 seconds per sonar image of processing time in MATLAB on a MS Windows laptop. Using a receiver-operator characteristic (ROC) curve, the performance of the group filter detection algorithm on the blind test set is compared against the performance of another independent algorithm developed to detect ROIs in the same sonar data base containing synthetic targets. The ROC curves in Figure **??** show that the group filter algorithm clearly outperforms the independent algorithm.

V. Work in Progress

The next step is to implement the algorithm on sonar data containing realistic targets. In the previous work, post group filter operations such as thresholding the projections and measuring cluster intensity were tightly married to the characteristics of the synthetic targets. The

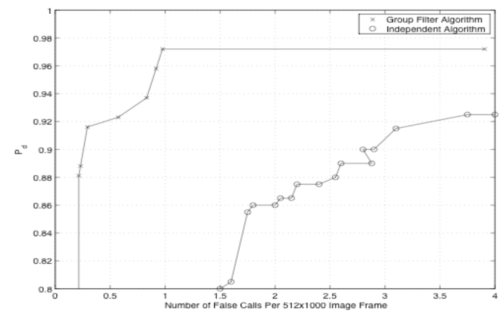

Fig. 2. ROC curve results of the group filter algorithm and an independent algorithm versus the NSWC PC side-scan sonar database.

targets in the new data set have much more variation in their geometric structure and target strength.

To test the performance of the implemented algorithm, we have applied the same group filters to side-scan sonar data set comprised of 223 sonar image files each of size 1000×1024, containing 272 targets, which were supplied by NSWC PC. These targets are more varied in size, shape and strength as compared with those contained in the previous data set. While group filters were not changed, clustering has been modified by relaxing the size and shape constraints. With this slight modification, the algorithm was tested for its performance. A main interest in this test was to verify that even with a relaxation of threshold parameters to accommodate less uniform targets, the false alarm rate will remain low. Magnification of several example targets in the new data set are displayed in Figure **??**.

From the viewpoint of group filters, the target shown in (a) was treated as a type. Targets shown in (b) and (c) were treated as a type, (d) and (e) as the same type, while that in (f) was treated as a type. Current clustering uses heuristic approaches, based on visual methods, with room for much improvement.

The ROC curve in Figure 4 summarizes the performance on the new data set.

To take advantage of the inherent flexibility of non-commutative group filter-based detection methods, parameterized thresholding is being implemented in a MATLAB graphical interface that allows a set of sonar imagery to be processed using a selection of group filters based on target types present, a desired $(P_d)/(P_{fa})$, and processing speed. This interface will facilitate the development of additional group filters matched to variations in target types being introduced. Currently, when the ground truth data of the set is incorporated, the interface allows automated statistical analysis of processing results from a variety of scenarios. By examining the ground truth of a small portion of a given data set, the software can learn the behavior of different detection/classification

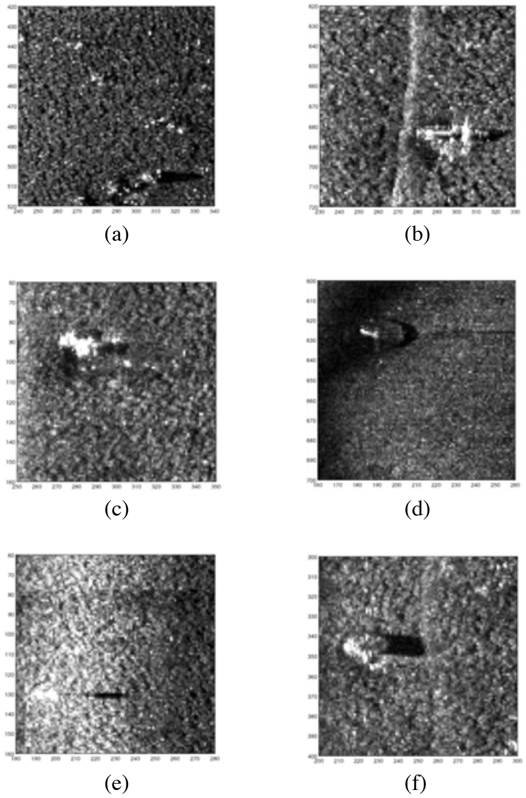

Fig. 3. Image snippets of examples of targets in the side scan sonar data base

routines and train the threshold parameters to optimize $(P_d)/(P_{fa})$. The set of images for which ground truth data exist should be sufficiently diverse with regard to the whole data set. Based on performance in a training scenario, a confidence rating to each detection or classification can be assigned. Processing results from different group filter applications can be weighted according to reliability and threshold parameters to provide a confidence statistic for each detected target.

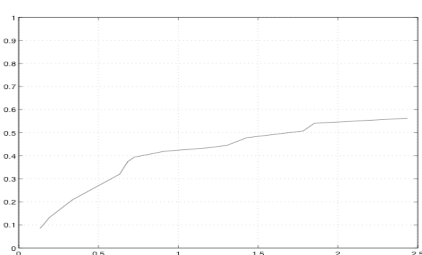

Figure 4. ROC curve results of the group filter algorithm on the new NSWC PC side-scan sonar database.

VI. Conclusion

Noncommutative group filters provide a fast, robust detection method for finding colinear extents of various orientations in noisy environments. The noncommutative spectral basis allows for spatial domain localization of objects that is not possible with a commutative spectral basis. The designed noncommutative group filtering algorithm has been shown to be fast, robust, and successful in locating mine like targets in VSW side-scan data. One of the promising outcomes of this research is that the group filters did very well at extracting the salient geometric structure of the targets while rejecting the background. Very complex backgrounds were reduced to a series of projections of line segments at 3 orientations, yet these projections yielded enough information to localize target candidates very effectively. With positive results in futher testing and validation, the algorithm might be suitable for future inclusion into a UUV onboard real-time D/C algorithm.

VII. Acknowledgements

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