BOAT-GENERATED ACOUSTIC TARGET SIGNAL DETECTION BY USE OF AN ADAPTIVE MEDIAN CFAR AND MULTI-FRAME INTEGRATION ALGORITHM

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ABSTRACT

In this paper, an Adaptive Median Constant False Alarm Rate (AMCFAR) and multi-frame post detection integration algorithm is proposed for effective real time automatic target detection of boat-generated acoustic signals, in which, an observation space is created by sampling and dividing input analog acoustic signal into multiple frames and each frame is transformed into the frequency domain. In the created observation space, a Median Constant False Alarm Rate (MCFAR) and post detection integration algorithms have been proposed for an effective automatic target detection of boat generated acoustic signals, in which a low constant false alarm rate is kept with relative high detection rate. The proposed algorithm has been tested on several real acoustic signals from hydrophone sensors, and statistical analysis and experimental results showed it able to provide a very low false alarm rate and a relatively high detection rate in all cases.

1. INTRODUCTION

With the increase of unauthorized arrivals, drug smugglers, illegal fishing and a range of other border threatens, border protection becomes more and more important to the international community. Just in the case of Australia, in order to allow the Coast-Watch service to maintain its intensive program in the north and north-west, while still effectively managing other areas of the Australia's coastline, flying hours have increased by 1600 per annum, with a severe increase in costs for the Australian Government. Therefore, an alarm system which can detect and report the existence of alien boats is becoming of increasing importance for the authority. The authors are targeting the applications on these aspects by successfully developing a very effective acoustic signal detection algorithm, which can be used for detection and monitoring of illegal activities on the wide range of coastlines by detecting any unexpected boats by means of acoustic techniques.

This paper is devoted to theoretic algorithms development and experimental research of automatic target detection of acoustic signals, especially for boat (engine and propeller)-generated signals from hydrophone ([1], [2]). In this paper, an observation space is created by dividing input acoustic signals into multiple frames, with each frame sampled and transformed into the frequency domain. Then, an Adaptive Median Constant False Alarm Rate (AMCFAR) algorithm is proposed for automatic target detection of boat-generated acoustic signals in each frame to provide a low constant false alarm rate with relatively high detection rate. Finally, a multiple-frame integration algorithm is used for the purpose of increasing the signal-to-noise ratio (SNR) and adjusting observation for suitable target signals. The proposed algorithms have been tested on acoustic signals from real boats received and recorded from hydrophone, and their effectiveness proved.

2. MULTI-FRAME ACOUSTIC SIGNAL PROCESSING AND DETECTION ALGORITHM IN THE FREQUENCY DOMAIN

The Multi-Frame Acoustic Signal Processing and Detection Algorithms proposed in this paper are structured based on the Neyman-Pearson (NP) criterion ([3],[4]). This criterion is widely adopted for target detection application in either sonar or radar systems. The observation space of the detector is shown in Fig. 1.

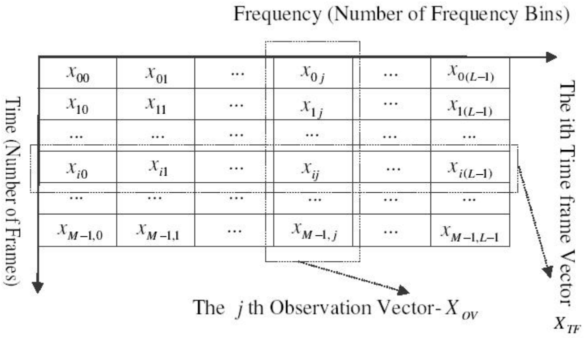


Figure 1 Observation space for the acoustic signal Neyman-Pearson detector

It can be proven that under the Neyman-Pearson criterion, the acoustic signal in the frequency domain needs to be normalized by the average noise power in the optimum detector [4]. Furthermore a multi-frame integration is carried out to increase the signal-to-noise ratio (SNR). The basic ideas of the Neyman-Pearson detector are to reduce the false alarm rate and maximize the target detection rate.

In our work, acoustic signals from hydrophone are sampled and converted into digital signals based on the Nyquist Sampling Theorem (Criterion) ([5], [6]). In our experiments, we used a sampling rate of 2048 Hz, since the maximum frequency we are interested in is 1024 Hz. Then, the digital signal converted from the analog input signal is divided into frames of T. With T chosen as 0.5 seconds, the data processing period in digital format is N = 1024.

The digital signals are then transformed into the frequency domain by using FFT (Fast Fourier transform). Since the data processing period is 1024, we chose the same length, 1024 points, as FFT length. Some frame pre-processing in the frequency domain is also necessary before detection including DC removal and spectrum frame vector normalization.

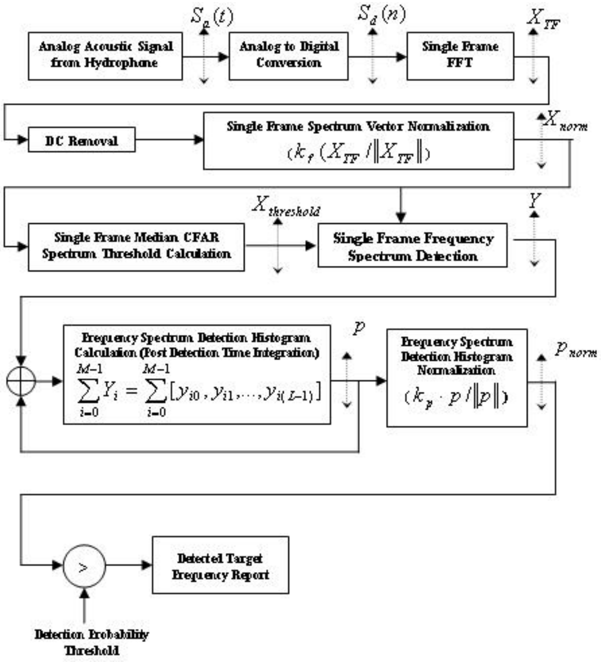


Figure 2 Multi-Frame Acoustic Signal Processing and Detection Algorithm

In order to deal with various input signal strength and make the whole automatic target detection robust, single-frame spectrum magnitude normalization is performed in the frequency domain. At this stage, each element in the frame vector is divided by the magnitude of the vector (geometric length). After normalization, a magnitude scaling factor of 40 dB (100 times) is used to give the signal a more practical range.

The single frame spectrum vector normalization is described as follows

$$X_i^{norm} = k_f \cdot X_{TF} \Big/ \|X_{TF}\| = k_f \cdot \frac{[x_{i0}, x_{i1}, \cdots, x_{i(L-1)}]^T}{\sqrt{x_{i0}^2 + x_{i1}^2 + \cdots + x_{i(L-1)}^2}} \quad (1)$$

in which i is the frame index, L the number of frequency components and k_f the scaling factor.

In typical sonar systems, signal detection is performed by thresholding such a normalized signal by a constant, ad-hoc threshold. In our approach, instead, an Adaptive Median CFAR algorithm is used to calculate the Constant False Alarm threshold in a single frame, in which the threshold for each frequency bin is adapted by the median frequency value over a sliding window. This is performed in two steps: in the first, the median threshold is subtracted from the normalized signal. In the second, the input signal spectrum is compared with a constant CFAR threshold, Δ, and if the difference is bigger, the bin is reported as the target frequency. The $1/\Delta$ parameter is called sensitivity, as the bigger the Δ is, the less sensitive our detection system is on weak signals. Since the CFAR threshold is adapted to the application and the neighborhood noise, it will keep our automatic target detection system at a very low and constant false alarm rate. In the following, the AMCFAR algorithm is described in details.

The Median Constant False Alarm Rate (Median CFAR) threshold vector,

$$X_i^{threshold} = [x_{i,0}^{threshold}, x_{i,1}^{threshold}, \cdots, x_{i,j}^{threshold}, \cdots, x_{i,L-1}^{threshold}]^T \quad (2)$$

is calculated by feeding X_i^{norm} into a Median filter (whose properties and size will be discussed in the next section) as follows:

$$x_{i,j}^{threshold} = Median\left\{x_{i,j-k}^{norm}, x_{i,j-k+1}^{norm}, \cdots, x_{i,j}^{norm}, x_{i,j+1}^{norm}, \cdots, x_{i,j+k}^{norm}\right\}. \quad (3)$$

The Median filter size is $(2k+1)$, with $k = 1,2,3$. In order to deal with the boundary case, both the input signal spectrum vector and the threshold vector are treated as wrapped period signals. The single-frame detection is based on the comparison of the difference between vectors X_i^{norm} and $X_i^{threshold}$ against a threshold, with the output being a binary vector:

$$Y_i = [y_{i0}, y_{i1}, \cdots, y_{i(L-1)}]^T. \quad (4)$$

with $y_{ij}\,(j = 0,1,\cdots,L-1)$ given by:

$$y_{ij} = \begin{cases} 1, & \left(x_{i,j}^{norm} - x_{i,j}^{threshold}\right) \geq \Delta \\ 0, & otherwise \end{cases}. \quad (5)$$

The y_{ij} values equal to 1 are the detected frequencies based on single-frame detection. In addition, the integration of single frame detection results over time (i.e. over a number of frames) was used here to increase the target detection probability. As boat-generated signals typically last in the order of tens of seconds, this approach can significantly improve the detection rate. A typical value of integration time for sonar buoy-acquired signals is about 15 seconds, which corresponds to 30 frames in our testing system.

The 'Integrated Detection vector' is defined as:

$$p = [p_0, p_1, \ldots, p_{(L-1)}] = \sum_{i=0}^{M-1} Y_i = \sum_{i=0}^{M-1} [y_{i0}, y_{i1}, \ldots, y_{i(L-1)}] \quad (6)$$

Where the M is the number of frames and the p vector is a description of the number of times single-frame detection occurred at each frequency bin over the integration window, and final detection is based on the distribution function. In order to make the performance of the detection system more robust, especially for weak signals, the 'Integrated Detection Vector' is eventually normalized by its geometric magnitude ($p/\|p\|$).

3. RELATED WORKS AND DISCUSSION

In this paper an Adaptive Median CFAR algorithm is proposed, in which acoustic target signals are detected with a low false alarm and relative high detection rates in the frequency domain. The input acoustic signals are transformed into the frequency domain by using FFT first. Then, the target generated frequency component will be detected. The basic idea of this algorithm is that of using, for each frequency bin, different, adaptive CFAR (Constant False Alarm Rate) thresholds [8] rather than a single, constant threshold (which is often the case in acoustic systems). First, based on the Neyman-Pearson criterion, the threshold of each frequency bin is computed based on the surrounding background noise. The higher the background noise, the higher the threshold is set. Moreover, our algorithm uses a median filter window centered about each frequency bin to adapt the threshold value. To the best of our knowledge, while this idea is often used in radar system to obtain lower false alarm rate with relatively higher target detection rate, it is applied here for the first time to sonar-generated acoustic signals.

Since the Median Filter is good at removing high frequency spike noise, it is a very effective way to calculate the threshold vector independently of specific signals. As such, the Adaptive Median CFAR algorithm proves superior to other common approaches such as constant thresholds or average-based thresholds. The major advantage of the Median filter is in its ability to remove interferences such as strong signal or noise spikes without affecting the sharpness of edges (retaining sharp edges after filtering). Conversely, with an Averaging Low Pass Filter, which is equivalent to the Average CFAR algorithm, sharp edges will be blurred after filtering. Moreover, every bin in the averaging window will affect the threshold value, especially when the signal or a noise spike is strong. Evidence of the superiority of the median filter with respect to average filters for signal detection can also be found in [7].

The size of Median Filter window is an odd number, which can be $3,5,7,\cdots,(2k+1)$. From our experiments, a window size of 5 has been proved to be the most appropriate.

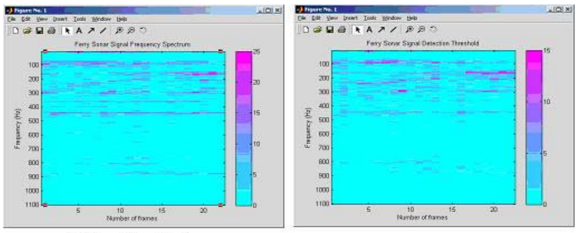
The Adaptive Median Filter Constant False Alarm Rate (Adaptive Median CFAR) algorithm can be used to detect targets with relatively high detection rate while maintaining a low and constant false alarm rate. In addition, as boat-generated signals have relatively long duration, we have added a time-integration step over multiple frames which significantly further improves the detection rate. Although this step introduces a delay in early detection of incoming boats in the order of 15 seconds, this is completely negligible with respect to the typical travelling speeds of monitored boats. The overall procedure is computationally light, thus allowing us cost-effective real-time implementation even on systems with limited computational power and size constraints such as on-board embedded computers.

4. EXPERIMENTAL RESULTS WITH THE ADAPTIVE MEDIAN CFAR AND MULTI-FRAME INTEGRATION ALGORITHM

The test signals are provided by Soncom PTY LTD from "C-Buoy/Off-Buoy Processor Sea Trials' at Low Islets, Australia (16.3833° S, 145.5667° E) on 17 June 2002. The proposed Adaptive Median CFAR and Multi-Frame Integration Algorithm has been successfully tested on many such signals. In the following, we provide results for signals called "Ferry" and "Reef Heron"for reference.

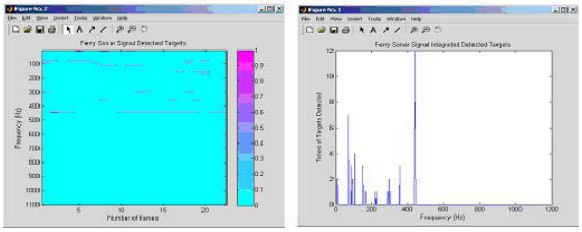
4.1 "FERRY" BOAT SIGNAL TEST

Fig. 3 (a) shows us that the "Ferry" boat signal has a pretty wide frequency band, which spreads between about 60 to 450 Hz, with the main frequency component at about 440 Hz and the strength of these frequency components between 10 to 25 dB. Fig. 3 (b) shows us the Median CFAR threshold image of Fig. 3 (a) in which we can see that the higher the neighboring values, the higher the threshold sets, and that threshold values are between 5 to 15 dB. Fig. 3 (c) shows us the detected target frequency components, in which we can see that the main frequency components around 440 Hz are successfully detected and some other frequency components between 60 to 450 Hz are also successfully detected.



(a) 'Ferry' Signal Spectrum over Multiple Frames

(b) 'Ferry' Signal Spectrum Threshold Image Calculated by Proposed Median CFAR Algorithm with Window Size of 5



(c) Detected Target Frequencies Using Median CFAR Algorithm with Window Size of 5 and Default Sensitivity

(b) 'Ferry' Signal Spectrum Threshold Image Calculated by Proposed Median CFAR Algorithm with Window Size of 5

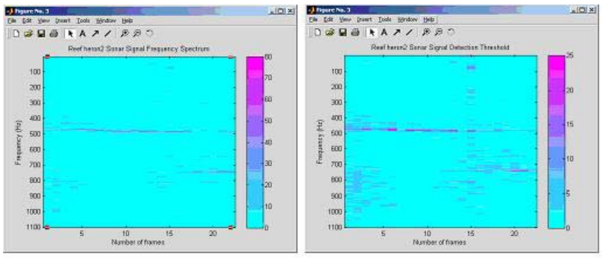
Figure 3 Multiple Frame Target Frequency Detection Integration Results of "Ferry" by using the proposed Adaptive Median CFAR Algorithm with window size = 5.

Fig. 3 (d) shows us the time-integrated detected target frequency components of Fig. 3 (c), in which we can see that the number of times the two biggest frequency components (around 440 and 70 Hz) were detected are 55% (12/22) and 32% (7/22). These two main frequency components are finally successfully detected by vector (distribution) normalization and final thresholding, and their detected frequencies are 71.06 Hz and 439.28 Hz. In Fig. 3 (d), we can also see that there are some frequency components between 60 and 450 Hz which were detected a relatively lower number of times; hence, they did not cross the final threshold after distribution normalization.

4.2 "REEF HERON2" BOAT SIGNAL TEST

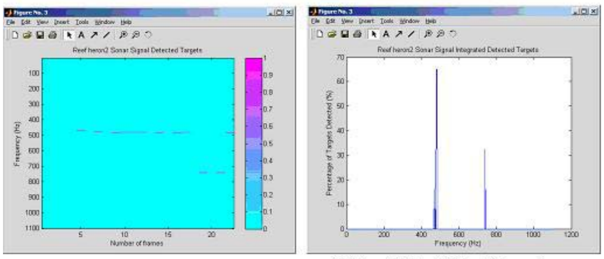
The proposed Adaptive Median CFAR and Multi-Frame Integration Algorithms have also been tested on "Reef

Heron2'" boat signal, and the test results of multiple frames of the 'Reef Heron2' test case are shown in Fig. 4.



(a) 'Reef heron2' Signal Spectrum over Multiple Frames

(b) 'Reef heron2' Signal Spectrum Threshold Image Calculated by Proposed Median CFAR Algorithm with Window Size of 5



(c) Detected Target Frequencies Using Median CFAR Algorithm with Window Size of 5 and Default Sensitivity

(d) Integrated Detected Target Frequencies Using Median CFAR Algorithm with Window Size of 5 and Default Sensitivity

Figure 4 Multiple Frame Target Frequency Detection Integration Results of "Reef Heron2" by Using the Proposed Median CFAR Algorithm with Window Size of 5.

Fig. 4 (a) shows us that the "Reef Heron2" boat signal has two main frequency components which are located around 480 and 740 Hz, and there are some unknown sea clutter (noise) frequency components that are around 800 Hz, and the strength of these frequency components are between 30 to 50 dB. Fig. 4 (b) shows us that Adaptive Median CFAR threshold image of Fig. 4 (a), and threshold image strength values are between 10 to 25 dB. Fig. 4 (c) shows us that the detected target frequency components are at around 480 and 740 Hz, and some other sea clutter frequency components did not cross the thresholds, so some false detections are avoided. Fig. 4 (d) shows us the integrated detected target frequency components of Fig. 4 (c), in which we can see that the detection rates of the biggest frequency component (around 680 Hz) is 65%, and this main frequency component was finally successfully detected by vector (distribution) normalization and final thresholding, and detected frequencies are 478.04Hz and 480.19 Hz. In Fig.4 (d), we can also see that the second biggest frequency component around 740 Hz, for which it's the detection rate is relatively lower, did not cross the final threshold after distribution normalization (under the 50% final detection threshold).

5. CONCLUSION

In this paper, an Adaptive Median Constant False Alarm Rate (AMCFAR) algorithm with post detection integration has been proposed based on the Neyman-Pearson criterion for effective automatic target detection of boat-generated acoustic signals, in which a low constant false alarm rate is kept with relatively high detection rate. The proposed algorithm has been tested on many real acoustic signals recorded from hydrophone at a site on the Australian coastline. The statistical analysis and experimental results showed that the proposed algorithm has kept a very low false alarm rate and relatively high detection rate.

The following conclusions can also be drawn:

1) The proposed Adaptive Median CFAR algorithm is used to detect target frequency component from a single frame, keeping our automatic target detection system at low and constant false alarm rate. This algorithm proved especially good for detecting LOFAR target frequency components.
2) A magnitude normalization (in the frequency domain) is used to keep our automatic detector more robust to noise and spurious frequencies.
3) With the default sensitivity value, most target frequency components are correctly detected. Further decreasing the sensitivity value makes the false detection rate (alarm rate) lower, but at the same time less target frequency components will be detected.
4) The integration of single frame detected targets makes detection significantly more robust. For example, with the integration of 20 frames, the possibility of correct target detection increases dramatically.
5) In order to deal with various kinds of detected targets situation and increase the probability of target detection, "Integrated Detection Vector" normalization ($p/\|p\|$) is used.
6) The boat-generated frequencies can be detected with high accuracy. In the experiment reported in this paper, the detected boat-generated frequencies of 'Ferry' and 'Reef Heron2' are very close to the "ground truth".

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