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MVDR Beamformer with Subband Peak Energy Detector for Detection and Tracking of Fast Moving Underwater Targets Using Towed Array Sonars

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Summary

Detection and tracking of fast moving underwater targets like torpedoes within cluttered acoustic environment is a challenging task in anti-submarine warfare. Adaptive Minimum Variance Distortion less Response (MVDR) beamformer with Subband Peak Energy Detector (SPED) offers narrow beam width and low side lobe levels, which is an essential requirement for torpedo detection and tracking. A novel algorithm for torpedo detection and tracking using MVDR with SPED for towed array sonar is presented in this paper. Measures to make the adaptive beamformer more robust to any array perturbations are discussed. These algorithms are tested and validated using simulated and towed array experimental data. Hardware implementation of a real-time broad band adaptive MVDR beamformer with SPED for uniform linear array is presented. Various computational aspects of real time implementation are looked at and an efficient and parallel implementation scheme is proposed.

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1. Introduction

Passive Sonars use beamforming techniques to detect presence and direction of arrival of underwater sound sources [1]. Conventional beamforming technique is the delay summing technique where the data obtained from an array of elements is delayed and summed so that waves incident from a particular direction are made to the same phase and summed up [2]. A number of such beams are simultaneously formed and a bearing versus time graph is plotted. A marked intensity line in the bearing versus time graph indicates the presence of a target. The exact bearing of the target is then obtained by a tracking mechanism, which follows the target trajectory.

Beam former is a spatial filter, which enhances the amplitude of the signal wavefront from a given direction with respect to background noise by operating on the data obtained from an array of sensors [3, 4]. Sonar systems use the beamforming technique to estimate the direction of arrival of the target signal by digital processing of the signals obtained from a uniform linear array of hydrophones. Conventional beamforming techniques for linear arrays give a phase delay to the sampled array vector so that all elements add up in phase for the specified look direction. Thus the delay vectors for specified look directions or the steering vectors themselves act as the weight vectors for beamforming. These weight vectors are constant and are independent of the incoming data.

Conventional beamforming results in relatively large beam widths and limits the resolution of the beamformer to distinguish between closely spaced targets. Adaptive beamformers give minimum beamwidth independent of the number of sensors [5, 6]. Here the weight vector is adaptively estimated from the incoming data so as to obtain high-resolution detection in a noisy environment. Minimum Variance Distortion less Response (MVDR) is an adaptive algorithm, which minimizes the output power in all directions subject to the condition that gain in the steering direction is unity [7]. This algorithm gives optimum performance by steering nulls in the direction of interferences and other correlated noise sources.

Detection of fast-moving torpedoes under cluttered acoustic environment is difficult with conventional beamforming and detection algorithms. Narrow beamwidth and low sidelobe levels are essential for efficient detection and tracking of such targets with fast maneuvering capability. An adaptive MVDR with Subband Peak Energy Detector (SPED) is presented here for this purpose. MVDR and SPED are two well-known algorithms. This paper presents a novel processing method for torpedo detection and tracking using a combination of these algorithms.

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2. MVDR Beamformer with Energy Detector

Consider a frequency-domain beamformer with maximum response at angle θ. A planar wavefront is assumed for the target signal and the receiver sensors are in a uniform linear towed array. The signals from the M sensors are transformed into the frequency domain using the discrete Fourier transform. Let this input vector for kth frequency bin be $X_k = [x_{k1}, x_{k2}, x_{k3}, \ldots, x_{km}]$. The beamformer output for direction θ and for kth frequency bin can be expressed as

$$y_k(\theta) = w_k^H X_k, \tag{1}$$

where w_k is the complex-weight vector for kth frequency bin and w_k^H denotes its complex-conjugate transposition. The power at the beamformer output for direction θ is given by

$$P_k = E\{|y_k^2|\} = w_k^H E\{X_k X_k^H\} w_k = w_k^H R_k w_k, \tag{2}$$

where R_k is the Cross Spectral density Matrix (CSM) of the incoming data and is defined as

$$R_k = E\{X_k X_k^H\}. \tag{3}$$

The steering vector corresponding to the direction θ and for kth frequency bin is given by Equation (4).

$$s_k(\theta) = \Big\{ 1, \mathrm{e}^{-\mathrm{j}\omega d \sin\theta/c}, \mathrm{e}^{-\mathrm{j}2\omega d \sin\theta/c}, \ldots, \mathrm{e}^{-\mathrm{j}(m-1)\omega d \sin\theta/c} \Big\}, \tag{4}$$

where d is the distance between individual sensors of the linear array, m is the number of sensors and $\omega = 2\pi f$, the angular frequency of the signal, where f is the frequency corresponding to the kth frequency bin.

The optimum MVDR weights are given by minimizing the power output under the constraint $w_k^H = 1$, for the given direction. The MVDR weight vectors are obtained by the Lagrange Multiplier [8] method as

$$w_k = \frac{s_k^H(\theta) R_k^{-1} s_k(\theta)}{R_k^{-1} s_k(\theta)}. \tag{5}$$

The optimum MVDR weight calculated in Equation (5) is for a narrow-band source with frequency corresponding to kth frequency bin. For broadband beamformer the narrow-band output for each frequency bin of interest needs to be computed and the power is added over all the frequency bins in the band for the desired direction as shown in Figure 1. Broadband MVDR beamformer with Energy Detector (MVDR-ED) output along a given direction θ can be calculated as

$$P(\theta) = \sum_k |y_k(\theta)|^2. \tag{6}$$

The computation of the CSM inverse is the most computationally challenging part of broadband MVDR. Depending on the number of bins to be processed, many CSM matrices need to be averaged and updated for every snapshot of input data. After exponentially averaging for the desired integration time the matrices need to be inverted for finding the optimum weight vectors. The Gauss Jordan elimination method is used for finding the inverse of the complex CSM matrix [9].

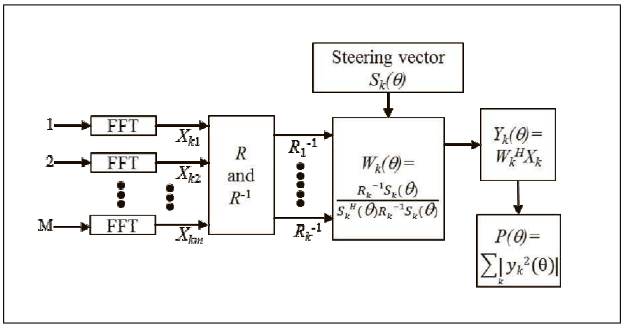

Figure 1. Broadband MVDR with Energy Detector.

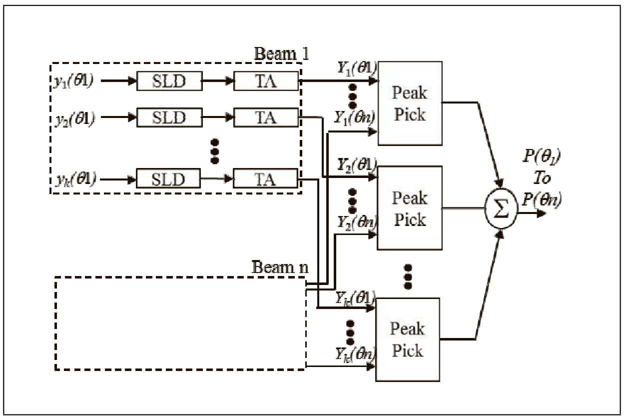

Figure 2. SPED Implementation.

3. SPED for Torpedo Detection

Subband Peak Energy Detection (SPED) is an important processing method that provides improved performance to sonar systems [10]. SPED can provide thinner target traces, improved bearing resolution, and better detection advantage in cluttered acoustic environments, which is an essential requirement for torpedo detection. In a multi-beam towed array sonar system, SPED broadband processor block diagram is given in Figure 2. The output of MVDR beamformer for every frequency bin is processed using a Square Law Detector (SLD) function. After that, the outputs are Time Averaged (TA) and then normalized. Averaging time is selected based on the the observation time and the signal stationarity. For a fast moving torpedo target, multiple averaging times are provided to account for different target movement regimes. The normalization is accomplished in the frequency domain separately at each beam [11]. Subsequently, the output data are summed over frequencies for each single azimuth bin to provide an energy estimate. The data from the beamformer for each frequency bin is just the same with ED while in SPED the energy detection algorithm is different.

Acoustic energy from a target signal or random noise features “peaks” and “valleys” in both time and frequency. Looking at the frequency spectrum of a target with low Signal to Noise Ratio (SNR), the background noise occasionally drops below the level of the target signal. When this happens, there is a peak due to the target signal. Now, looking at one frequency bin of the beam noise versus azimuth spectrum there may be several peaks due to the signal but still many more due to noise.

Instead of summing the energy in a single azimuth bin for all frequency bins, SPED utilizes only the “peak” information to estimate the detection probability. It looks for peaks through peak picking in the azimuth spectrum for every single frequency bin. Ultimately, sum of the ‘energy’ values of the peaks is calculated over all frequency bins for each azimuth bin. Peaks due to the directional source will occur in the same azimuth bin for each frequency bin. These peaks have spatial coherence and can add “constructively” when summed over the entire range of frequency bins.

In SPED, the peak-picking effectively reduces the bearing ambiguity between adjacent beams and provides sharper, more clearly defined target traces thus improved spatial resolution of the acoustic targets. Bearing Time Record (BTR) plotted for conventional frequency domain beamformer, MVDR-ED and MVDR-SPED beamformer for a linear array are shown in Figure 3. In BTR display, x-axis represents the bearing and y-axis represent time history. The current time is marked on top of the display and the history is on the bottom. Target energy is marked as intensity levels on the display.

The experimental data was collected during sea trials using a towed array of 32 hydrophones spaced for 2-kHz frequency, and sampled at 10 kHz using a 12-bit quantiser. It was collected while the array and the noise source were both on the move: the towing ship sailed at 12 knots and the target was a torpedo fired from a submarine. The array was towed 750 m behind the ship at a 30-m depth. The experiment was conducted under a sea-state of 2, on an ocean area deeper than 1000 m.

The same data is used for comparing the performance of different algorithms. Narrow target traces on the display indicate better target bearing resolution and bearing accuracy. The BTR plot clearly indicates sharper detection for MVDR-SPED compared to conventional and MVDR-ED beamformer.

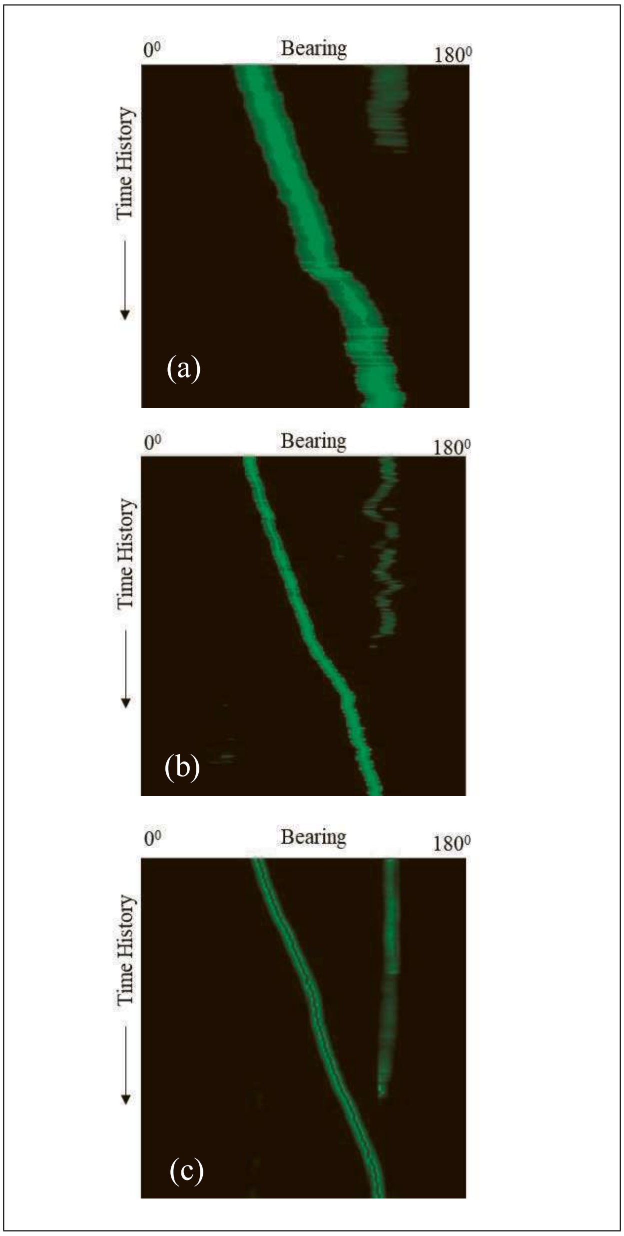

Figure 3. BTR plot of (a) Frequency domain, (b) MVDR-ED and (c) MVDR-SPED beamformer.

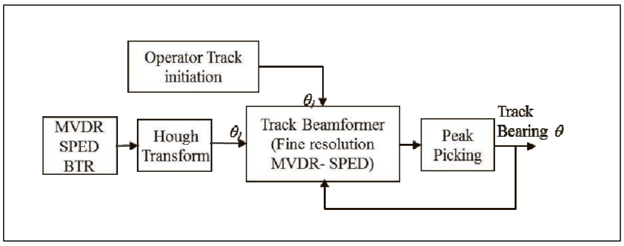

Figure 4. Tracking using MVDR with SPED.

4. MVDR with SPED for Torpedo Tracking

After estimating the direction of arrival of the target, the target is tracked continuously in bearing to estimate target motion parameters. Conventional tracking methods use the split-beam correlation technique by forming two half-beams and correlating between them to detect the path delay between the two beams and then estimate the accurate bearing [12]. This scheme does not offer good performance at low SNRs. A novel tracking algorithm using MVDR with SPED for tracking fast moving torpedo target is shown in Figure 4. This algorithm provides sufficient track accuracy required by the fire control system for computing torpedo target motion parameters. Unlike conventional Anti-Submarine warfare, where target is persistent, in Torpedo defence systems, the target appears suddenly and is alive for very short time, either achieving its mission or failing. This demands that the system detects and initiates torpedo tracking automatically instead of relying on a human operator.

Target tracking is done by finding the SPED power output in a window around the designated target direction at close spacing and then choosing the direction with the maximum beam power. At the next iteration a window with the previous selected maximum power direction as the center is chosen and again the peak position is obtained. Each time the weights are updated using the MVDR scheme so as to get the optimum result. For a fast moving target we need to consider a window width which would cover its angle range in the given integration time. The accuracy or the required resolution of the tracked target bearing decides how closely spaced the beams should be or how many beams should be formed in a given window. Typically for an integration time of 1 s we need to form a window of ±3° around the designated direction. For a bearing resolution of 0.1°, beams are formed at 0.10 separation, giving a total number of 6/0.1 = 60 beams per target. These 60 beams are formed for every new update of the target bearing.

4.1. Bearing accuracy for track output

Accuracy of the bearing values computed by track processor is an important parameter in quantifying the performance of a tracking processor. Target track bearings computed using MVDR-SPED were extensively evaluated using a calibrated signal and noise simulator. The simulator is capable of generating sensor level signals at various SNRs for a linear array of 32 sensors spaced for 2 kHz. Broadband acoustic targets were simulated for different SNRs and at different bearings. The standard deviation of the error in the track output is computed for different target bearings relative to the linear array and at different SNRs. The results are plotted in Figure 5. The bearing error is observed to be minimum for target at 0° (Broadside) and increases as target move towards 90° (End-fire). Bearing error increases as SNR goes down. The graph indicates that the bearing errors for track processor using MVDR-SPED is well within the acceptable limit of 2° rms under most-conditions, meeting the requirements of a fire control system [13] computing target motion parameters using these bearings.

4.2. Hough Transform for Contact Designation

Target tracking is initiated either manually by the operator from BTR display or automatically using the Hough Transform (HT). Initiated target bearing θ_i will be used by track beamformer to compute the center bearing of the track window. For automatic track initiation, the HT uses N recent updates of normalized SPED output vs. bearing plots to form a history matrix. The columns and rows of the matrix represent bearing and time respectively. A primary threshold is set on the History Matrix, all the points above this threshold are mapped into points in the Hough plane using Equation (7) and the corresponding cell in the accumulator is incremented.

$$\rho = x\cos(\theta) + y\sin(\theta), \qquad (7)$$

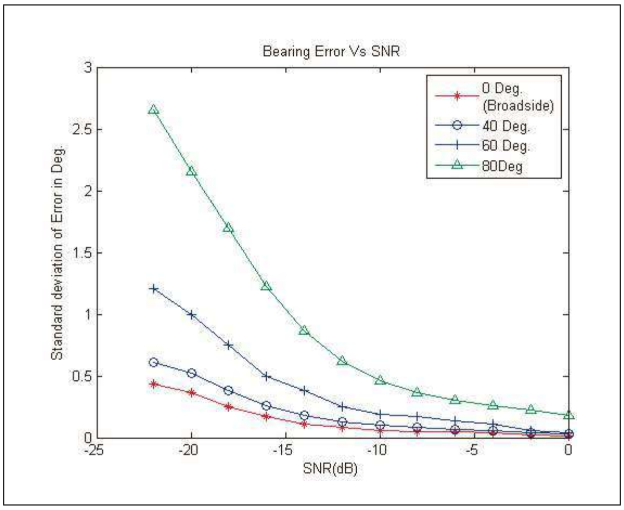

Figure 5. Standard Deviation of bearing error vs SNR of MVDR-SPED based track output.

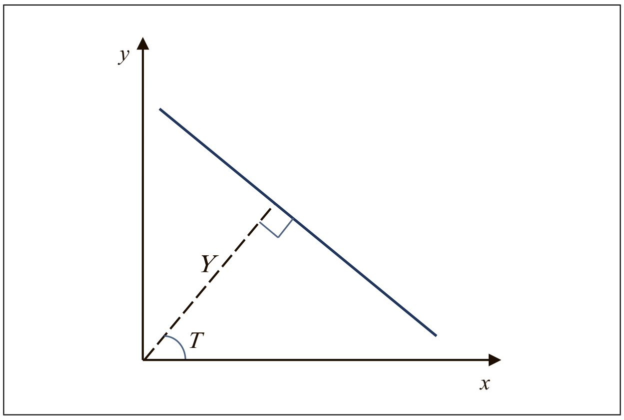

Figure 6. ρ and θ representation of a straight line.

where θ is the angle of the line from the origin orthogonal to the line and ρ is the perpendicular distance from the origin to the line as shown in Figure 6. After mapping all the points above the primary threshold, a secondary threshold is applied on the accumulator to get the polar parameters (ρ and θ) of the lines detected. After mapping ρ to bearing axis, estimate target bearing θ_i at regular intervals for initiating the track.

4.3. Bearing Rate Computation

The bearing rate of the detected contact is an essential input for classification of torpedo targets. Bearing rate is computed with least square fit of the target bearing history. The target bearing is computed using the HT in contact identification and the history of HT output is maintained in the information processor. The least square fit is done on the bearing history of 5 recent measures to find the bearing rate. Let $\theta[i]$ be the ith bearing update and $t[i]$ the corresponding time stamp, the bearing rate can be computed as

$$\theta^* = \frac{\left(\sum_{i=1}^{n}\theta[i]\right)^2 - n\sum_{i=1}^{n}\theta^2[i]}{\sum_{i=1}^{n}\theta[i]\sum_{i=1}^{n}t[i] - n\sum_{i=1}^{n}\theta[i]t[i]}. \qquad (8)$$

Here $\theta[i]$ represents ith bearing in the bearing history and $t[i]$ represents the corresponding time stamp and $n = 5$. When a new contact is detected it takes n times the update rate to compute θ^*. Subsequently the latest five θ values are used to compute θ^* so that θ^* is updated at the display update rate.

4.4. Steps to build a robust R matrix

The Cross Spectral density matrix of the input data vector is estimated as the exponentially averaged matrix of the input cross spectral matrix averaged over successive snapshots in time.

$$R_{i+1} = \alpha R_i + (1 - \alpha) x_{i+1} x_{i+1}^H, \tag{9}$$

where i is the iteration number and α is an exponential forgetting factor which determines the exponential averaging time and is bounded as $0 < \alpha < 1$. The integration time of the CSM matrix is an important parameter which needs to be fine-tuned for optimum detection. Integration time for a fast-moving target like a torpedo needs to be fixed by considering the presence time of the target within a beam. Typical integration time for torpedo detection can be 1 s.

Purely adaptive beamformers are extremely sensitive to even small perturbations in the array characteristics, especially errors in look direction. When the direction of the signal source does not exactly coincide with the steering angle the signal tends to be suppressed at the output of the beamformer. A small diagonal loading of the cross spectral density matrix is used to make the beamformer less susceptible to look direction errors. The choice of the diagonal loading factor represents a tradeoff between sharper beams and robustness. So before the CSM inverse is found out the CSM matrix is diagonally loaded with a factor ε and the weights are calculated using $(R + \varepsilon I)$ instead of R. For $\varepsilon = 0$, the beamformer is purely adaptive and large values of ε make it identical to conventional beamformer.

The CSM matrix may also become ill-conditioned or rank-deficient owing to sensor failures. For a rank deficient matrix the inversion process will fail, leading to erroneous results. So it is imperative to take a precaution against the matrix being non-invertible. Spatial averaging is a technique used to make the array robust for beamforming applications. A simple first-order spatial averaging is done in the following manner. Consider an N element array. Using the first $(N - 1)$ sensors a CSM matrix is obtained. Then using the last $N - 1$ elements another CSM matrix is computed. These two matrices are averaged to give a CSM matrix of order $(N - 1, N - 1)$. If we had not gone for spatial averaging the CSM matrix would have been of the order of (N, N). The CSM matrix obtained after spatial averaging is robust to random sensor failures and any other array perturbations. But since spatial averaging reduces the effective length of the array there will be a small increase in the beamwidth obtained.

5. Hardware implementation

Hardware realisation of MVDR with SPED is presented in this section. Hardware configuration presented here is designed and developed for the real time data processing of the experimental array described in Section 3. Array data is received in the form of Ethernet packets and the processed output is send to display processor.

Adaptive beamforming for uniform linear arrays require enormous amount of computation power. For a broadband beamformer implementation a highly parallel implementation strategy is envisaged. The algorithm uses the properties of the Cross-Spectral-Matrix (CSM) to eliminate all interferences. The inversion of the complex CSM matrix is the most computationally demanding task of MVDR implementation. It is often found that the matrix inversion fails when the estimated CSM matrix is rank deficient. So some methods of making the MVDR more robust to ill-conditioned CSM matrices are also implemented in the system. The processing is done on individual frequency subbands of the sensor data in a parallel fashion. The data path which includes estimation of the CSM, inverse computation, weight computation and beamforming are designed to run in parallel and the output beams are summed together to produce the final high resolution detection output. The data paths corresponding to different bins are segregated and implemented on different processing nodes in a highly parallel structure.

The array snapshots are sent from the array to the signal processing modules over the Ethernet format. The front-end interface of the signal processing module is the Ethernet reception module. The signal processing functions which include the Fourier transform, CSM computation and updation, CSM inversion, weight computation and beamforming, peak picking and summing are implemented on ADSP 21062 based signal processing cards [14]. The SPED output is sent out to the final BTR display system over Ethernet link.

The incoming array vector is collected and split into different frequency bins using the discrete Fourier transform. The observation time of the array should be greater than the array transit time for the acoustic wave. This condition will give the length of the Fourier transform to be taken. Once the signal is split into different frequency bins, the CSM matrix is formed for all the bins. This CSM formation and consequent CSM inversion is done in parallel for all the frequency bins using parallel signal processing modules leading to real time performance. The weight vectors are computed and depending on the weight vectors the beamformer output is obtained for each bin and direction. The final SPED output is obtained by peak picking and summing up all bins along one direction for detection. For tracking with a typical case of eight targets, with each target being monitored in a window of 6° width with a 0.1° resolution, we need to form 60 beams for each target and 480 beams for all the eight targets.

The input vectors are the same for all the targets, only the weights are changed depending on the look directions. Hence this again offers a chance to execute in parallel the tracking operations for all eight targets. This parallelism is exploited in the implementation scheme for both the CSM computation and inversion processing as well as beam-

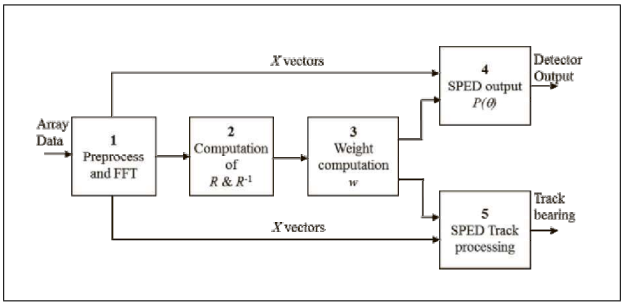

Figure 7. Hardware Implementation Scheme.

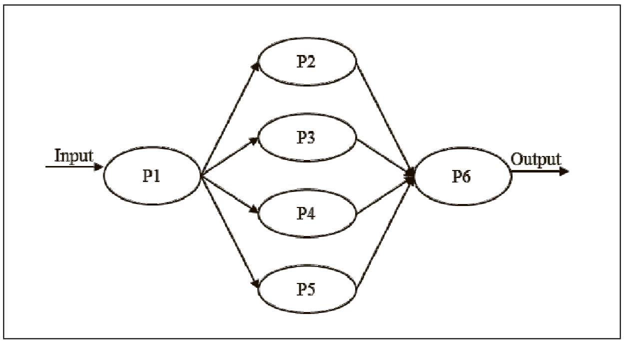

Figure 8. Data Flow through DSP cluster.

forming and SPED processing. So identical code running on parallel processors will minimize the system software overheads. Block diagram of the hardware implementation scheme is given in Figure 7. Each rectangular block in the figure represents an embedded Digital Signal Processor (DSP) board which houses a cluster of six SHARC processors. Total five such boards (5×6=30 SHARC processors) are required for real-time processing of the data from a linear array of 32 sensors. Each DSP board is designed for parallel data processing applications.

The typical parallel dataflow through a DSP board is schematically shown in Figure 8. Each bubble indicates one SHARC processor. The first processor P1 receives the input data, distributes it to four processing nodes P2−P5 and finally the processed data is collected and send to next stage by the sixth processing node P6. Input and output data transfer is done through Ethernet and the data transfer between SHARC processors within a cluster is through custom link port interface provided with the SHARC processors.

Prototype processing system developed using DSP boards for processing the data from the experimental array described in section 3 was successfully tested during sea trials. Real-time processed output is presented in display as shown in Figure 3 by display processor after normalization and quantization by the display processor.

6. Conclusion

An algorithm using broadband adaptive MVDR beamformer with SPED for torpedo detection and tracking using towed array has been successfully implemented and tested. The scheme is suitable for torpedo detection in cluttered acoustic environments. The new tracking scheme was evaluated using a simulator set- up for different signal to noise ratio levels. Targets at various speeds and under different ranges were successfully tracked and the track was consistently holding for high-speed maneuvers. It was found to perform better than the conventional split-beam based tracking methods. Efficient methods are suggested and implemented for making the adaptive beamformer more robust to array perturbations. The various computational aspects of MVDR beamformer with SPED are looked at and an efficient and parallel implementation strategy is proposed. Prototype system was successfully implemented for data processing using ADSP 21062 based signal processing cards. Kalman filter based smoothing and prediction algorithm along with MVDR-SPED for tracking under extremely low SNRs and for tracking while target crossing are the areas for future research.

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