MOTION ARTIFACT ELIMINATION ALGORITHM AND ARCHITECTURE WITH EIGEN-BASED CLUTTER FILTER FOR COLOR DOPPLER PROCESSING

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ABSTRACT

Color Doppler imaging is used to visualize the distribution of blood flow in the region of interest. Slight relative motion may cause severe image corruption and incorrect blood velocity estimation. In this work, we propose a velocity bias cancellation algorithm based on the autocorrelation technique widely used in color Doppler and eigen-based clutter filter to eliminate the motion artifact. The proposed algorithm assists clutter filter to suppress tissue noises effectively and compensates the biased velocity. It has more than 5 dB better performance and the error of blood velocity estimation can be reduced by around 77%. Besides, the proposed velocity bias cancellation algorithm is implemented with eigen-based clutter filter by VLSI with TSMC CMOS 90nm technology. The area and maximum operation frequency of the synthesis results are 2.05 mm² and 125 MHz.

Index Terms— Color Doppler, Motion artifact, Ultrasound

1. INTRODUCTION

As shown in Fig. 1(b), slight motion between the probe and subjects caused by tissue motion, respiration, body and probe movements causes severe image corruption and incorrect blood velocity estimation in color Doppler imaging. The image corruption originates from the failure of the suppression of the clutter noises originating from the reverberation of tissue which is originally stationary and slow-moving without motion artifact. And the incorrect blood velocity is biased by the velocity of motion. Therefore, patients are asked to hold their breath to reduce the relative motion. However, requesting children and unconscious patients to suspend their breathing is difficult. Furthermore, motion cannot be avoided in the emergency situation, such as in an ambulance and in battlefield.

To suppress the clutter noises with motion artifact, eigen-based clutter filter has been proposed [1][2] to adapt the passband and stopband with the moving tissue. In order to address the clutter signal accurately, [2] views the mean frequency of dominant eigen-component as the center frequency of clutter noise. Nevertheless, this method is unsuitable when clutter-to-blood ratio (CBR) of eigen-component distribution is low, which may eliminate the blood information instead of clutter noise. In addition to the clutter noise issue, little research takes the biased velocity into consideration. It leads to severe inaccuracy of blood velocity estimation when the motion artifact is large.

In this work, we propose a velocity bias cancellation algorithm based on eigen-based clutter filter. It possesses a biased velocity estimation mechanism utilizing autocorrelation technique [4] of color Doppler to raise the correctness of motion estimation. Moreover, the hardware can be reused without redesign. Besides, the proposed algorithm can effectively suppress clutter noise with more than 5 dB better performance and compensate the biased velocity which reduces the velocity error by around 77%.

This paper is organized as follows. The eigen-based clutter filters are listed in Section 2. The proposed velocity bias cancellation algorithm is shown in Section 3. The simulation results and comparisons are presented in Section 4. The architecture and implementation in VLSI are described in Section 5.

Fig. 1 (a) Normal image and (b) motion-corrupted image.

2. EIGEN-BASED CLUTTER FILTERS

The general filter model can be represented by the matrix-vector multiplication as:

\[ y = Ax, \]

where \( x \) is the input signal vector, \( A \) is the clutter filter matrix, and \( y \) is the filtered signal vector. The eigen-based clutter filter can adapt to the clutter signal characteristics as a regression filter which can be written as
where \( \mathbf{e}_i \) is an orthonormal basis for the clutter signal space, \( K \) is the clutter space order, and \( (\cdot)^H \) indicates the Hermitian operation. By subtracting the signal component contained in the clutter space, the filtered matrix can \( \mathbf{A} \) project the input signal vector \( \mathbf{x} \) into the orthogonal component out of the clutter space.

To attenuate the clutter noise successfully by the regression filter, it is important to determine the clutter space order. Since tissue movement is generally slow compared to blood flow, [2] determines the clutter space \( \Phi_c \) as eigenvectors with low frequency parts by comparing the mean frequency of the eigenvector with a fixed frequency threshold \( f_{th} \), which is called fixed frequency thresholding in this work:

\[
\Phi_c = \{ \mathbf{e}_i | f_i < f_{th} \}, i = 1, ..., N,
\]

where the mean frequency \( f_i \) of each eigenvector \( \mathbf{e}_i \) can be calculated by lag-one autocorrelator \[4\]:

\[
f_i = \frac{1}{2\pi T} \angle \left[ \sum_{n=0}^{N-2} (\mathbf{e}_i(n)\mathbf{e}_i(n+1))^* \right],
\]

where \( T \) is the pulse repetition interval and \( \ast \) denotes the complex conjugate. To handle clutter signals with center frequency \( f_c \), (3) can be revised as a dynamic frequency thresholding form:

\[
\Phi_c = \{ \mathbf{e}_i | f_i < f_{th} \}, i = 1, ..., N,
\]

when the clutter-to-blood ratio (CBR) of eigen-component distribution is high, \( f_i \) can be calculated as the mean frequency of the eigen-component with largest eigenvalue.

**3. Proposed Velocity Bias Cancellation Algorithm**

In this section, we propose a velocity bias cancellation algorithm based on eigen-based clutter filter. In this work, we assume the relative motion is in the same direction. The proposed algorithm includes three steps in the same manner as shown in Fig. 2. First, velocity bias caused by motion artifact is calculated in the biased velocity estimation. Second, the frequency threshold in eigen-based clutter is adjusted with the velocity bias and the variance of the estimated velocity. Finally, the biased blood velocity is compensated by the velocity bias to get the correct velocity in flow parameter estimation. The proposed velocity bias cancellation algorithm can effectively assist eigen-based clutter filter to eliminate moving tissue and compensate the biased blood velocity.

**3.1 Biased Velocity Estimation**

Several motion compensation algorithms utilizing cross correlation of pixels to estimate the value of motion artifact, which is called velocity bias in this work, have been proposed in ultrasound system [5][6]. However, cross correlation is not suitable for color Doppler because of the decimation of RF data. The input data of Doppler processing are baseband signals whose sampling rate is much lower. Therefore, the length each pixel representing increases. As shown in Fig. 3(a), when cross correlation technique is utilized, the displacement of two frames is likely to be computed incorrectly since the displacement is less than the length that a pixel represents.

Fig. 3 (a) Use cross correlation to find the displacement between frames, (b) use autocorrelation technique to compute the phase difference and velocity.

In order to raise the correctness of biased velocity estimation, we propose the weighted autocorrelation method. Autocorrelation technique \[4\] is widely used in color Doppler to calculate the flow parameter, such as velocity, and energy. Since autocorrelation technique computes the phase difference between frames, it is not affected by the length that each pixel represents. The autocorrelation and frequency of slow-time signal \( X \) in pixel \((m,n)\) can be represented respectively as follows:

\[
\hat{R}_{n,m}(T) = \frac{1}{N-1} \sum_{i=1}^{N-1} X((i+1) \cdot T) X^*((i-T)),
\]

\[
f_{n,m} = \frac{\angle \hat{R}_{n,m}(T)}{2\pi T},
\]

where \( T \) is the pulse repetition interval. Moreover, in order to avoid the influence of the blood velocity, we use energy as weight to calculate the average frequency bias because the energy of tissue signal is typically 40-80dB stronger than the one of blood signal. And the center frequency \( f_c \) of tissue in (5), which will be called frequency bias \( f_b \) in this work, is revised and represented as following:

\[
f_b = \frac{1}{M \cdot N} \sum_{m=1}^{M} \sum_{n=1}^{N} E_{m,n} \cdot f_{m,n},
\]

where \( E_{m,n} \) is the energy of slow-time signal \( X \) in pixel \((m,n)\), which is written as
\[ E_{m,n} = \frac{1}{N} \sum_{i=1}^{N} X(i \cdot T) X^*(i \cdot T). \]  

(9)

3.2 Frequency-threshold Adjusting in Clutter Filter

In this step, the frequency threshold in (5) will be adjusted by the distribution of estimated velocity. To observe the distribution of estimated velocity of moving tissue, we use the Field II [7] program to generate synthetic data with different probe velocities. The direction of motion is divided into axial and lateral motion. Axial motion is the motion that the probe moves toward or away from the subject, and the lateral motion is in the direction perpendicular to the axial motion.

With different probe velocities, the mean and standard deviation of velocity estimated by autocorrelation technique for tissue part is computed. As shown in Fig. 4, the blue line represents the data with only axial probe motion from 0.02 m/s to 0.2 m/s, while the red line represents the data with axial probe motion from 0.02 m/s to 0.2 m/s upward and lateral probe motion from 0.01 m/s to 0.1 m/s rightward, which is half the value of corresponding axial motion. We find that the standard deviation increases mainly with the mean of estimated velocity of axial motion. Besides, a proximate linear relationship exists between the mean and the standard deviation of estimated velocity. In other words, a linear function of the green line shown in Fig. 4 could be utilized to describe their relationship. This means that when the mean velocity is obtained, its approximate standard deviation can be calculated.

Moreover, we observe their velocity distribution under different axial velocities as shown in Fig. 5. Their velocity distribution can be mapped into symmetrical exponential distributions. For exponential distribution, more than 95% of values are within 3 standard deviations. That is, the frequency threshold in eigen-based clutter filter can be adjusted with the mean and standard deviation of the estimated velocity bias to eliminate the clutter noise caused by moving tissue. Thus, (5) can be revised and rewritten as

\[ \Phi_e = \left\{ \varepsilon_i \left| \left| f_i - f_b \right| < \left( f_{\text{th}} + 3\sigma_v \right) \right. \right\}, \]  

(10)

where \( \sigma_v \) is the standard deviation of velocity distribution.

Thus, by these two observed phenomena, which might be caused by the estimation error of autocorrelation technique, we can suppress most of the moving tissue by adjusting the frequency threshold.

![Fig. 4 Relationship between the mean and the standard deviation of velocity distribution in tissue.](image)

Fig. 5 Estimated velocity distributions in tissue calculated by autocorrelation technique under (a) probe velocities = 0.02m/s ↑, (b) probe velocities = 0.06m/s ↑, (c) probe velocities = 0.1m/s ↑.

3.3 Velocity Compensation

Since the blood velocity is biased by the motion artifact, it should be compensated with the velocity bias in the flow parameter estimation block to get the correct estimated velocity. The velocity bias \( V_b \) can be calculated from the frequency bias, which is written as

\[ V_b = \frac{c}{2f_0} f_b \]  

(11)

Therefore, the correct estimated velocity \( V_{\text{correct}} \) can be obtained by compensated the original estimated velocity \( V_{\text{origin}} \) with \( V_b \) as follow,

\[ V_{\text{correct}} = V_{\text{origin}} - V_b. \]  

(12)

4. SIMULATION RESULTS AND COMPARISONS

Since the general medical ultrasound images we get are hard to know the velocity bias and the accurate blood velocity they should be, conventional metrics can’t be used to measure the quality after filtering implementation. Therefore, we use the Field II [7] program to generate synthetic data to evaluate the performance. The color Doppler imaging without motion artifact is taken to be the golden pattern. For quantitative evaluation, two parameters are utilized. One is the signal-to-clutter ratio (SCR) [9], which is used to evaluate the effectiveness of clutter rejection. And the other is the Blood Velocity Difference (BVD), which is used to evaluate the accuracy of velocity compensation. Its definition is depicted as

\[ BVD = \frac{\sum_{i=1}^{M \cdot N} \left| V_{\text{NoMotion}} - V_{\text{compensate}} \right|}{M \cdot N}, \]  

(13)

where \( V_{\text{NoMotion}} \) is the estimated velocity of the golden pattern, and \( V_{\text{compensate}} \) is the velocity after compensation under motion environment.

The simulation results are shown in Fig. 6 and Table 1.
As shown in Fig. 6(d), by applying the proposed algorithm, most of the tissue signals can be eliminated effectively and the blood velocity estimation is similar with the one without motion artifact in Fig. 6(a). Besides, the SCR increases more than 5 dB and the error of blood velocity can be reduced by around 77%.

![Fig. 6 Color Doppler image (a) no motion artifact, (b) motion artifact, fixed frequency thresholding [2], (c) motion artifact, dynamic frequency thresholding [2] and (d) motion artifact, proposed velocity bias cancellation algorithm.](image)

Table 1 Performance evaluation when probe velocity is 0.06 m/s upward.

<table>
<thead>
<tr>
<th>Method</th>
<th>SCR (dB)</th>
<th>BVD (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed frequency thresholding [2]</td>
<td>-15.04</td>
<td>0.066</td>
</tr>
<tr>
<td>Dynamic frequency thresholding</td>
<td>1.75</td>
<td>0.094</td>
</tr>
<tr>
<td>Proposed Biased Velocity Cancellation algorithm</td>
<td>7.55</td>
<td>0.015</td>
</tr>
</tbody>
</table>

5. ARCHITECTURE AND IMPLEMENTATION

In this section, we implement the overall color Doppler imaging system in Fig. 3. In this work, [8] is adopted in performing the singular value decomposition (SVD) operation on a 8x8 square matrix in eigen-based clutter filter to accelerate the convergence rate.

Compared to the original operation of eigen-based clutter filter and flow parameter estimation, the main operation cost of the proposed algorithm is in the biased velocity estimation. Since the biased velocity estimation is the extension of autocorrelation technique in flow parameter estimation, the architecture and hardware of biased velocity estimation can be reused for computing velocity and energy in flow parameter estimation, which is depicted in blue in Fig. 7. The overall system is implemented by VLSI with TSMC CMOS 90nm technology. And the area and maximum operation frequency of the synthesis results are 2.05 mm$^2$ and 125 MHz.

6. CONCLUSIONS

In this work, we propose a velocity bias cancellation algorithm based on the autocorrelation technique and eigen-based clutter filter to eliminate the motion artifact. Compared with the reference works, the proposed algorithm has more than 5 dB better performance and the error of blood velocity estimation can be reduced by around 77%.

Besides, we implement proposed velocity bias cancellation algorithm with eigen-based clutter filter by VLSI with TSMC CMOS 90nm technology. The area and maximum operation frequency of the synthesis results are 2.05 mm$^2$ and 125 MHz.

7. ACKNOWLEDGMENT

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8. REFERENCES