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Computational Complexity Reduction Techniques for High-Contrast and High-Resolution Medical Ultrasound Imaging Using Adaptive Signal Processing

適応型信号処理を用いた高コントラスト高分解能な医用超音波画像化における計算量低減

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1. Background.

Recently, several adaptive beamforming techniques have been proposed to improve the resolution and the contrast of medical ultrasound images. The Capon method is one of the common strategy. The conventional element-space (ES) Capon method requires a large computational complexity because the method calculates the inversion of a large size matrix. The beam-space (BS) Capon method reduces the matrix size and the complexity [1]. However, this method reduces the complexity associated with the calculation of the inversion only. Therefore, the reduction of the complexity is still required. In this study, we propose a method that reduces the complexity assosiated with the time-delay processes to make the focal points and transition processes from the ES signal processing to the BS signal processing.

Additionally, the accurate estimation of the intensity is required for the medical diagnosis. The Capon method assumes that the desired echo has no correlation with the interferences. However, the correlation is large in medical ultrasound imaging. The spatial averaging (SA) technique that suppresses the correlation is widely employed for the stabilization [2]. We propose a method that compensates the estimated intensity using SA technique.

2. Original BS Capon Method

We briefly introduce the original BS Capon method [1]. The method first multiplies the Butler matrix $\mathbf{B}$ with a signal vector after making a focal point $\mathbf{y}(t)$. The method selects a few useful beams that are close to the transmitted beam. In this study, we use an M-element linear array with the element pitch of a half-wavelength at the center frequency. The received signal in BS $\mathbf{y}_{BS}(t)$ is given by:

$$\mathbf{y}_{BS}(t) = \mathbf{B}\mathbf{y}(t) . \quad (1)$$

We set the number of beams as 3 to follow previous studies [1, 2].

The covariance matrix of $\mathbf{y}(t)$ after SA, $\mathbf{R}_A$, is

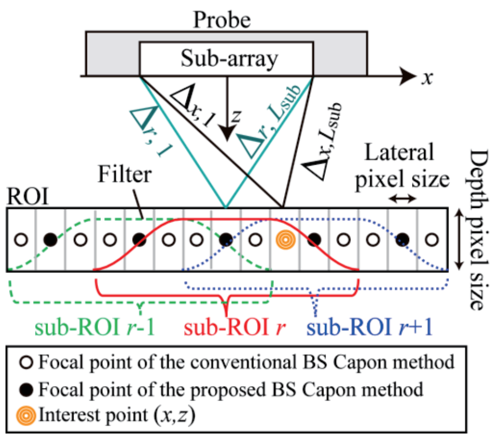

Fig. 1 Schematic presentation of the proposed method.

given by the following formula:

$$[\mathbf{R}_A]_{p,q} = \sum_{n=1}^{L_{ave}} y_{n+p-1}(t) y^*_{n+q-1}(t) / L_{ave} \ , \quad (2)$$

where $y_m(t)$ is the received signal at the m-th element, L_{ave} is the size for SA. The sub-array size L_{sub} is given by $L_{sub} = M - L_{ave} + 1$.

The estimated intensity of the BS Capon is expressed as follows:

$$P_{out}(x,z) = 1/\left[\mathbf{C}^H \left\{\mathbf{R}_{ABS}(x,z)\right\}^{-1} \mathbf{C}\right], \quad (3)$$

$$\mathbf{C} = \mathbf{B}_S[1 \ \cdots \ 1]^T , \quad (4)$$

where P_{out} is the estimated intensity, $\mathbf{C}$ is the BS constraint vector, and $\mathbf{R}_{ABS}$ is the BS covariance matrix.

The method reduces the complexity associated with the calculation of the matrix inversion. However, to make an image, the method requires processes that make the focal points and the transition from the ES signal processing to the BS signal processing at all pixels.

3. Complexity Reduction Using Steering Vector

To reduce the complexity associated with the processes, we replace the time-delay process by the multiplication of a steering vector with a covariance matrix. We first divide the region of interest (ROI) into sub-ROIs, as shown in Fig. 1. The output powers at the points of interest in a sub-ROI are estimated using a covariance matrix at the center of the sub-ROI with steering vectors. The output power at (x, z) $P_{\mathrm{out}r}(x, z)$ estimated by the proposed BS Capon method using the steering vector $\mathbf{C}'(x, z)$ is given by:

$$P_{\mathrm{out}r}(x,z) = 1 / \left[\mathbf{C}'(x,z)^{\mathrm{H}} \left\{ \mathbf{R}_{\mathrm{ABS}}(x_r, z) \right\}^{-1} \mathbf{C}'(x,z) \right], \quad (5)$$

$$\mathbf{C}'(x,z) = \mathbf{B} \left[\exp(\mathrm{j}\theta_1) \cdots \exp(\mathrm{j}\theta_{L_{\mathrm{sub}}}) \right]^{\mathrm{T}}, \quad (6)$$

$$\theta_m = \omega_c (\Delta_{r,m} - \Delta_{x,m}), \quad (7)$$

where $\mathbf{R}_{\mathrm{ABS}}(x_r, z)$ is the covariance matrix when the beam is focused at the center of the sub-ROI (x_r, z), r is the sub-ROI number, and $\Delta_{r,m}$ and $\Delta_{x,m}$ are the time-delay values of the m-th element with foci at (x_r, z) and (x, z), respectively.

Because we consider the center frequency only, the large $\Delta_{r,m} - \Delta_{x,m}$ increases errors caused by replacement of the time-delay process by multiplication of the steering vector with the covariance matrix. Therefore, we use a raised-cosine filter with a roll-off factor of 0.5 to emphasize the output power calculated at the center of the sub-ROI as shown in Fig. 1.

Additionally, we employed a compensation technique using a large SA size to acquire the accurate intensity estimation.

4. Experimental Setting and Results

We investigated the performance of the proposed method in an experimental study. Figs. 2 (a) and (b) show an image and a schematic of the experimental system used in this study, respectively. In this experiment, we positioned copper wire targets at the depth of 20, 30, 40, and 50 mm in a water tank with the lateral intervals of 1.0 mm. We used a 96-element probe with a center frequency of 2.0 MHz and a fractional bandwidth of 50%. The lateral pixel size was 0.050 mm. The sub-array size for imaging L_{sub} was 64. The sub-ROI width was 2.25 mm.

Fig. 3 shows acquired B-mode images using three methods; the conventional delay-and-sum (DAS) technique, the conventional BS Capon with N_{sub} of 64, and the proposed method. The conventional BS Capon method and the proposed method succeeded to depict two targets. The numbers of operations of the conventional BS Capon and the proposed method were 16,744 and 1,179, respectively. As shown in Fig. 2, the image using the proposed method has highest contrast.

5. Conclusion

To reduce the computational complexity of the BS Capon method, we proposed a technique that reduces the number of time-delay processes and the transforms from ES signal processing to BS signal processing using a steering vector. In the experimental study, the conventional BS Capon method and the proposed method depicted two closely positioned targets. Compared to the conventional BS Capon method, the proposed method reduced the number of processes from 16,744 to 1,179 with highest contrast. These results indicate that the proposed method has the potential to implement adaptive signal processing for real-time medical ultrasound imaging.

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References

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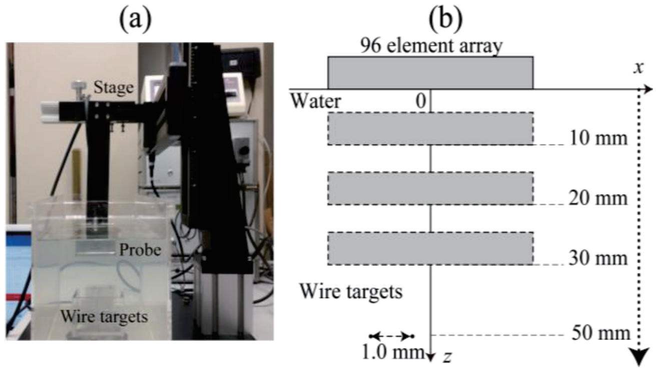

Fig. 2 (a) Experimental setup image, and (b) the schematic of the ultrasound measurement system with two wire targets.

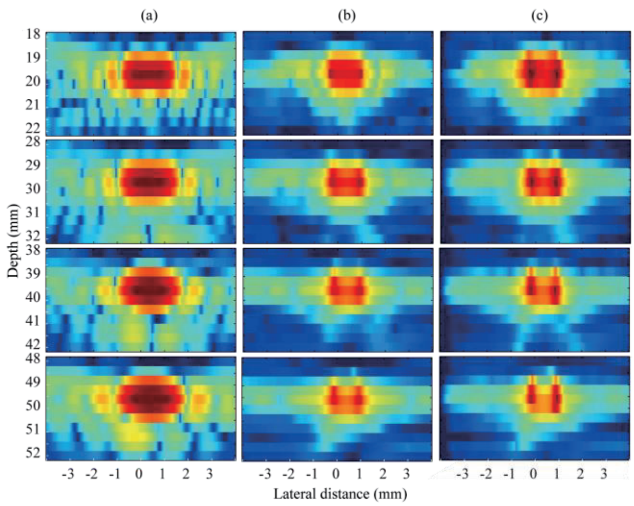

Fig. 3 Experimental results of B-mode images of wire targets using (a) the DAS method, (b) the conventional BS Capon, and (c) the proposed BS Capon method with the compensation technique.