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Display Pixel-based Synthetic Aperture Focusing Method for Intravascular Ultrasound Imaging

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***Abstract*— An intravascular ultrasound image reconstruction technique that combines synthetic aperture focusing and display pixel-based focusing methods is presented. Although the synthetic aperture focusing method can improve intravascular ultrasound image quality, the final displayed images are usually blurry in the angular direction due to the limitations of the digital scan converter. The display pixel-based focusing method can eliminate blurring effects caused by the digital scan converter. Therefore, the image quality can be further improved by applying the display pixel-based focusing method to the synthetic aperture focusing method, especially for intravascular ultrasound images. The experimental studies were performed to evaluate display pixel-based synthetic aperture focusing method. The computational complexity of the display pixel-based synthetic aperture focusing method was discussed in comparison with that of the synthetic aperture focusing method.**

I. Introduction

Intravascular ultrasound (IVUS) imaging, capable of direct assessment of morphological properties of coronary arteries, is widely used in clinics to diagnose coronary atherosclerotic disease. However, the IVUS image quality is reduced, compared to conventional array-based ultrasound images, because of technical limitations of IVUS catheters and geometric problems of IVUS images.

In array-based intravascular catheter systems, size and power constraints permit only one element (or limited set of elements) to be activated at a time. Therefore, the synthetic aperture focusing (SAF) method was introduced to produce focused ultrasound beams in IVUS imaging [1]. As a result, the SAF method can enhance the angular resolution of IVUS images. The superposition of each element data, collected at a different time but considered with appropriate delays, allows two-way focused beams in IVUS imaging. However, since imaging points reconstructed using the SAF method are defined in polar coordinates (r, θ), the digital scan converter (DSC) is needed to display IVUS images on the screen in Cartesian coordinates (x, y). The DSC can cause blurring effects that degrade the angular resolution of final IVUS images. These blurring effects can be reduced by increasing the number of scan-lines within the frame. However, more efficient and cost effective methods are required to eliminate the distortion due to the DSC, especially for IVUS imaging.

Hwang and Song proposed the display pixel-based focusing (DPBF) method to solve DSC problems in conventional ultrasound imaging [2]. In this technique, ultrasound waves are directly focused at display pixels on the monitor. Therefore, the DSC is no longer required.

In this paper, we applied the DPBF method to the SAF method for the purpose of improving the IVUS image quality. In order to efficiently implement the DPBF method in IVUS imaging, a phase rotation beamforming (PRB) method was used. Since only one element (or limited set of elements) can be activated at a time in array-based intravascular catheter systems, only one pair (or limited set of pairs) of demodulation circuits is required for the PRB method. Also, the PRB method uses complex baseband signals so it can directly generate envelope data on display pixels without any other post-processing. The phantom experiments were performed to evaluate the spatial resolution and contrast of IVUS images obtained by using display pixel-based synthetic aperture focusing (DPBSAF) method. To conclude, we discuss the computational complexity of the DPBSAF method.

II. IVUS Image Reconstruction

A. Synthetic Aperture Focusing (SAF)

A transmit-receive scheme for IVUS synthetic aperture imaging, using a 64-element array catheter and a 14-element effective aperture, was originally proposed by O'Donnell and Thomas [1]. By using a total of 896 (i.e., 64 × 14) different transmit-receive data sets, fully focused (i.e., two-way focused) ultrasound beams can be generated. Those beams are placed in polar coordinates (r, θ). Therefore, the DSC has to be performed to display IVUS images on the screen in Cartesian coordinates (x, y).

B. Digital Scan Converter (DSC)

Bilinear interpolation is commonly used in the DSC [3]. For bilinear interpolation, two different linear interpolations are consecutively performed in radial, then angular direction. The reconstructed pixel value, P, is pictorially shown in Fig. 1, and can be calculated by:

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$$P = \frac{\alpha \times I_2 + \beta \times I_1}{\alpha + \beta} \;, \qquad (1)$$

where

$$I_1 = \frac{d_2 \times s_1 + d_1 \times s_2}{d_1 + d_2} \;,\; I_2 = \frac{d_2 \times s_3 + d_1 \times s_4}{d_1 + d_2} \;,$$

α and β are angular differences between P and neighboring scan-lines, and d_1 and d_2 are radial differences between P and neighboring samples on scan-lines.

As shown in Fig. 1, four neighboring data formats are used in order to estimate P value. This procedure can cause image distortions like blurring effects on converted images.

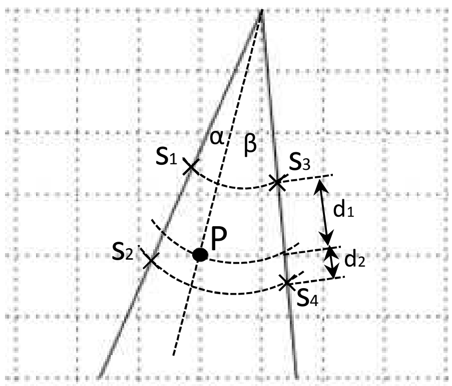


Fig. 1. Graphical representation of bilinear interpolation in the DSC.

C. Display Pixel-based Focusing (DPBF)

In IVUS imaging, the performance of the DSC depends on the number of scan lines. If there are enough scan-lines per one frame, high quality of IVUS images can be displayed on the screen. However, non-uniform sampled data in Cartesian coordinates (x, y) are inefficient. While data are oversampled in the region close to the catheter, there are insufficient data points in the region far from the catheter as shown in Fig. 2.

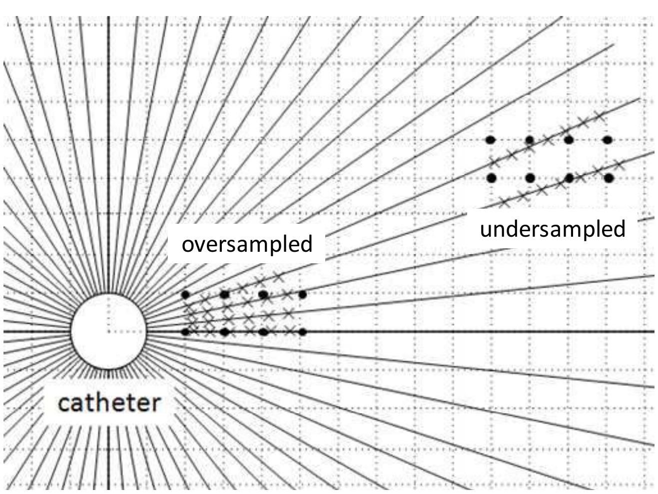


Fig.2. Illustration of IVUS image reconstruction. Crosses represent focused data on scan-lines. Circles represent display pixels on the screen.

The DPBF method, proposed by Hwang and Song [2], can solve the problem of mismatches, in IVUS images, between the focused data positions and the display pixel positions by directly focusing beams on display pixels. However, in this case, certain length of virtual scan-lines that crosses each display pixels are needed for the envelope value of the display pixel.

D. Phase Rotation Beamforming (PRB)

In order to avoid additional signal processing (i.e., envelope detection of focused beams) during the DPBF, a baseband beamforming method was used in this paper. Phase rotation beamforming (PRB) method is one of the baseband beamforming techniques based on the frequency domain approach [4]. The applications of the PRB method are restricted to narrowband signals because only center frequency component can be correctly delayed and focused. However, the performance of the PRB method has been proven high enough for broadband applications because of low sensitivity of phase delay errors in ultrasound signals [5]. Since the PRB method is a baseband approach, envelope data on each display pixel can be directly acquired after the beamforming if the DPBF method is used.

In addition, the PRB method requires high hardware complexity in array-based systems, because each array element has to be connected to different demodulation circuits due to the simultaneous data collection using several elements. However, in the case of IVUS systems, only one element (or limited set of elements) can be activated at a time so the PRB method can be implemented using only one demodulation circuit (or limited set of demodulation circuits). Therefore, the PRB method for IVUS synthetic aperture imaging does not increase hardware complexity compared to other time domain approaches [4].

III. MATERIALS AND METHODS

To investigate the quality of IVUS images obtained using the DPBSAF method and conventional SAF method, experimental studies were performed. The first set of experiments was conducted using point targets to examine the blurring effects caused by the DSC. Three 250-μm diameter nylon strings, representing point targets, were placed at different distances from the catheter. The second set of experiments was performed using polyvinyl alcohol (PVA) phantom and a rabbit artery. The phantom was produced using 8% of PVA solution and 0.4% of 15-μm silica particles. The rabbit artery was used to verify that the DPBSAF method improves the IVUS image quality in real tissues.

In order to collect the single element transmit-receive data sets, an EagleEye, 20 MHz, array-based catheter (Volcano Corporation, CA, USA) was used. This 1.17-mm diameter catheter has 64 acoustic elements.

IV. Results and Discussion

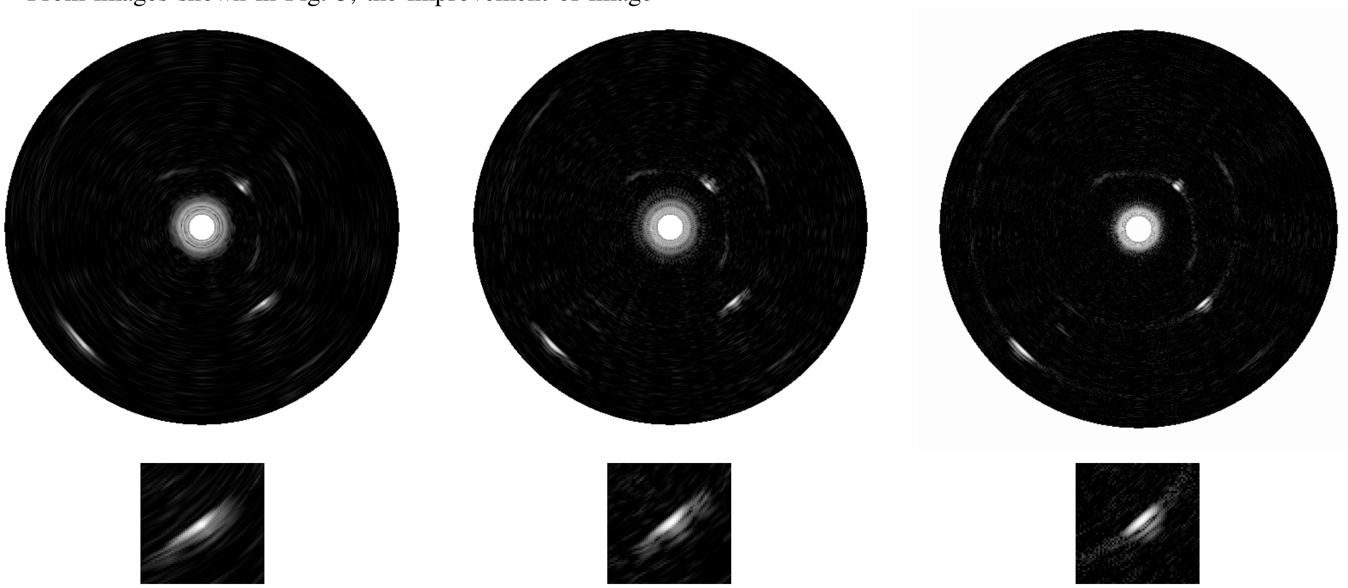
A. Point Spread Function (PSF) and Contrast-to-Noise Ratio (CNR)

From the point target experiment, the PSF and CNR were analyzed. To evaluate the spatial resolution of IUVS images, the PSF was analyzed. The CNR was calculated to quantitatively evaluate the blurring effects caused by the DSC. The CNR was obtained as follows:

$$CNR = 20 \cdot \log_{10}\left(\frac{2(\varepsilon_1 - \varepsilon_2)^2}{\sigma_{\varepsilon_1}^2 + \sigma_{\varepsilon_2}^2}\right), \qquad (2)$$

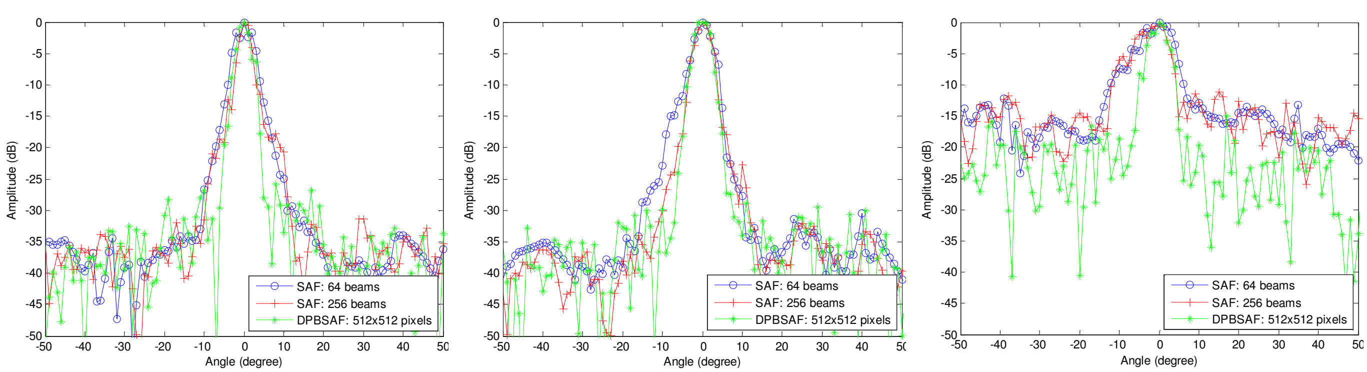
where ε_1 and ε_2 represent the means, and $\sigma_{\varepsilon_1}^2$ and $\sigma_{\varepsilon_2}^2$ denote the signal variances within the region inside and outside the point target, respectively.

From images shown in Fig. 3, the improvement of image quality is evident. Point targets in the image, obtained using the DPBSAF method, are sharper than those obtained only using the SAF method. As expected, the blurring effects were removed in the DPBSAF image. The PSF in Fig. 4 shows that the increase in number of scan-lines from 64 to 256 beams for the SAF method causes narrower beam width. However, it is not as significant as the DPBSAF method. The CNRs of each image of point targets are 98.3 dB for the SAF method with 64 beams, 99.5 dB for the SAF method with 256 beams, and 100.3 dB for the DPBSAF method. Since the background noise of an IVUS image is usually caused by the blurring effects of the DSC, the DPBSAF method can decrease noise and increase the CNR. The improvement of IVUS images using the DPBSAF method, in terms of both spatial resolution and CNR, is clearly shown in the experimental results of the phantom and the rabbit artery (Fig. 5 and Fig. 6).



(a) (b) (c)

Fig. 3. IVUS images of point targets obtained using the SAF method with (a) 64 beams and (b) 256 beams, then converted into 512 by 512 pixels, and (c) using the DPBSAF method with 512 by 512 pixels. The dynamic range of all images is 40 dB. The second row images are zoomed-in point targets positioned at 4.5-mm apart from the center of a catheter. Clearly, the image obtained using the DPBSAF method has better angular resolution compared to images obtained using the SAF method.



(a) (b) (c)

Fig. 4. Angular profile of the point spread function at (a) 2.6, (b) 4.5, and (c) 7.9mm apart from the center of a catheter. In each graph, the DPBSAF method compares with the SAF method. At all positions, the DPBSAF method has better performance, especially for the farther position from the catheter.

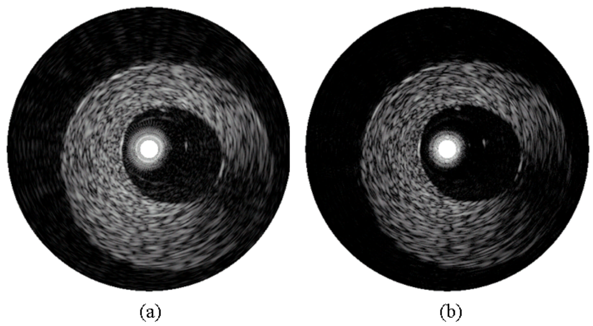


Fig. 5. PVA phantom images obtained using (a) the SAF method with 256 beams, and (b) the DPBSAF method with 300 by 300 pixels. All images are shown using 40 dB display dynamic range.

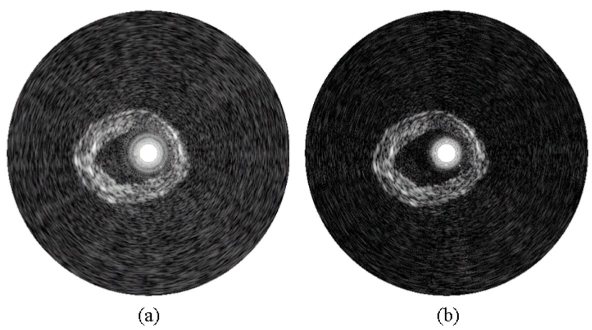


Fig. 6. Rabbit artery images obtained using (a) the SAF method with 256 beams, and (b) the DPBSAF method with 300 by 300 pixels. All images are shown using 40 dB display dynamic range.

B. *Computational Complexity*

The computational complexity of the DPBSAF method was compared with that of the SAF method by counting the number of multiplications per unit time (MPU). In the case of the DPBSAF method, only beamforming computational load was considered while the SAF method took account of not only beamforming but also DSC computational load. Imaging conditions are shown in Table 1.

TABLE I
IVUS IMAGING CONDITIONS

Effective transmit channels	14
Effective receive channels	14
The number of beams	N
The number of samples per beam	256 (for 10mm)
Display pixels	n × n

To generate one focused beam, the SAF method requires 14 × 14 different data sets based on effective transmit and receive aperture sizes. The PRB method requires four multiplications to adjust delays for the channel data because of the complex value multiplication. Also, the DSC requires nine multiplications per one pixel. Based on all of those, computational complexity was compared between the SAF method and the DPBSAF method in Fig. 7. The DPBSAF method with 300 by 300 pixels is comparable to the SAF method with 256 beams in terms of computational complexity.

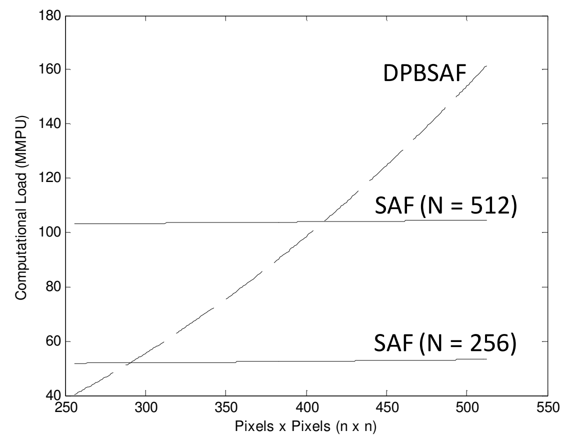


Fig. 7. MPUs for the SAF with 256 and 512 beams, and the DPBSAF method.

V. CONCLUSIONS

In IVUS imaging, the SAF method has played an important role to increase the image quality. However, the DSC degraded IVUS images because of its geometrical problem. The combined method of the SAF and the DPBF methods further improves the IVUS image quality. In addition, the computational complexity of the DPBSAF method can be comparable to the SAF technique.

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