SYNTHETIC PHASED ARRAY IMAGE FORMATION AND RESTORATION

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ABSTRACT

A coherent array imaging method is described that uses small groups of adjacent array elements called *subarrays*. For each firing event, only one subarray is used for transmit and receive, and all elements of the subarray transmit and receive in parallel. Phased array processing is used to focus and steer the subarray beam in transmit and receive. A sufficient number of beams are acquired such that the Nyquist sampling criteria is met for the subarray. The beams acquired from each subarray are upsampled, filtered, and combined with beams from all the other subarrays to form the final high-resolution image. A subarray-dependent reconstruction and restoration filter is applied to the subarray beams. The method significantly reduces the front-end hardware complexity compared to full phased array imaging. Experimental results demonstrate the performance of the proposed method.

1. INTRODUCTION

State-of-the-art ultrasound imaging systems currently use arrays with 128 individual elements. The most common beamforming method is *full phased array* imaging, a method that fires and receives on all elements in order to acquire a single beam line [1-3]. This method requires that received echo signals from all 128 transducer elements be received and processed in parallel. As the number of transducer elements increases, it becomes unreasonable to employ parallel transmit and receive processing channels for every array element [4]. This is especially true for 2D transducer arrays for 3D image acquisition, where a relatively small 16×16-element array would require 256 parallel channels.

As an alternative to implementing parallel processing channels for all array elements, we propose a flexible acquisition scheme that transmits and receives on a small number of adjacent elements called a *subarray*. The number of elements in the subarray, M, is much smaller than the total number of array elements, N. Adjacent subarrays overlap and the centers are spaced P elements from each other. By time multiplexing the acquisition process over all the subarrays, a complete dataset can be constructed for final image reconstruction. We refer to this method of image formation as *phased subarray* imaging [5, 6].

In order for the point-spread function (PSF) of phased subarray imaging to be equivalent to that of full phased array imaging, the coarray—also called the effective aperture—of each method must be equivalent [7, 8]. Although certain choices of the subarray distance, P, result in an equivalent coarray function, most do not. A restoration filter is required for most overlap choices and is applied to the resulting image.

In this study, we explore image formation and restoration using partially overlapping phased subarrays, where the amount of overlap can be arbitrarily chosen. Our approach is based on coherent processing of subarray data using subarray-dependent digital filters to handle both the reconstruction and restoration of the desired cosubarrays for large coarray synthesis.

2. METHODS

2.1 Basic definitions

The aperture function, PSF, and coarray function are used to design and evaluate the performance of a coherent array imaging system, and are all interrelated. The coarray function, or effective aperture function, represents the spatial frequency response of the array in the Fraunhofer region (far field) [7, 8]. The coarray function is given by

$$u[n] = a_t[n] \otimes a_r[n], \tag{1}$$

where $a_t[n]$ and $a_r[n]$ are the aperture functions for transmit and receive, and $\otimes$ is the convolution operator.

The PSF is given by the Fourier transform of the coarray function

$$U[q] = \Im\{u[n]\} = \Im\{a_t[n]\} \cdot \Im\{a_r[n]\}, \tag{2}$$

and represents the lateral imaging response of a coherent array imaging system to a single point source in the far field [9]. The PSF characterizes the performance of the imaging system: the point and contrast resolutions are calculated directly from the main lobe width and side lobe level of the PSF.

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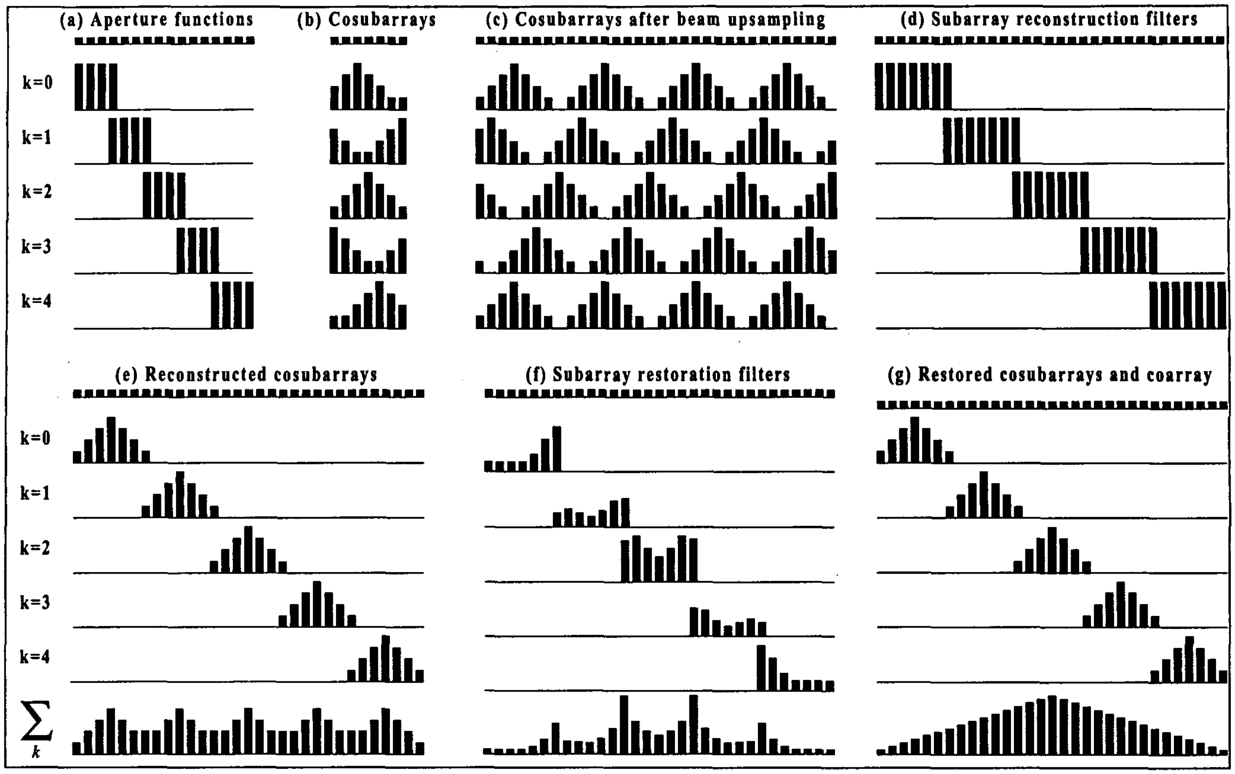

Figure 1. Phased subarray process flow in coarray and cosubarray spaces.

2.2 Subarray representation

For subarray acquisition, each of the K subarrays has a corresponding aperture function. The k^{th} transmit and receive aperture functions are denoted as $a_{tk}[n]$, and $a_{rk}[n]$, respectively. For our purposes, we let the transmit aperture equal the receive aperture, and denote the aperture for the k^{th} firing event as $a_k[n]$. Given a reference subarray at the end of the array, $a_0[n]$, the others can be written in terms of this array and the array spacing, P:

$$a_k[n] = a_0[n - kP],\ k = 0 \ldots K\text{-}1. \tag{3}$$

Likewise, if $u_0[n]$ is the cosubarray of the reference aperture function $a_0[n]$, then the k^{th} cosubarray function is given by

$$u_k[n] = u_0[n - 2kP], \tag{4}$$

and the PSF for a single subarray is

$$U_k[q] = U_0[q] \cdot \exp(-j2kPq). \tag{5}$$

The resultant coarray and system PSF without any restoration is the sum of the individual cosubarrays and PSFs:

$$u[n] = \sum_k u_0[n - 2kP], \text{ and} \tag{6}$$

$$U[q] = U_0[q] \cdot \sum_k \exp(-j2kPq) \tag{7}$$

If $P = M/2$, then the subarray responses can simply be weighted and summed such that the final PSF and coarray function are equivalent to that of a full phased array system. In other words, the subarray restoration filters are all-pass with different gains. For any other choice of P, however, a frequency-shaping restoration filter must be applied on either the subarray beams or the reconstructed beams.

Figure 1a shows the aperture functions corresponding to system with 16-elements and 5 subarrays, each with 4 elements. Figure 1b shows the low-resolution cosubarrays.

2.3 Beamspace sampling

To reconstruct coherent array images without aliasing in the lateral direction, the acquired beam density must be sufficiently high to satisfy the Nyquist sampling criteria. Applied to coherent array imaging, the number of beams, Q, needed is

$$Q \geq 2(2N-1)\frac{d}{\lambda}\sin\left(\frac{\Theta}{2}\right), \tag{8}$$

where d is the array element pitch, λ is the acoustic wavelength, and Θ is the scan angle. Since the number of beams must be an integer, Q is typically chosen to be the next largest integer that satisfies the inequality. In general, $d = \lambda/2$, in which case the sampling criteria simplifies to

$$Q \geq (2N-1)\sin\left(\frac{\Theta}{2}\right). \tag{9}$$

Each subarray acts as an independent phased array, and thus has it's own sampling requirement:

$$Q^S \geq (2M-1)\sin\left(\frac{\Theta}{2}\right) \tag{10}$$

Unlike full phased array imaging where all array elements are used at once for both transmit and receive of each of Q beams, subarray acquisition uses only M elements at a time. Each of the K subarrays acquires $Q^S << Q$ beams. Full phased array imaging requires a total of Q firing events, while phased subarray imaging requires $K \cdot Q^S$ firing events. Once all beams are received from all subarrays, a final image is reconstructed as described in the following sections.

2.4 Upsampling and reconstruction

The final image must have a number of beams that meets the beam sampling criteria for the full array. To do this, the subarray beams are upsampled by inserting an integer number of zero-valued beams between acquired beams. The amount of upsampling can be expressed in terms of the number of subarray beams, Q^S, and the number of final beams, Q:

$$L = \frac{Q}{Q^S} \tag{11}$$

Lateral upsampling in beam space corresponds to periodic replication in cosubarray space (Figure 1c).

Prior to combining the results of each subarray, a reconstruction filter with a pass-band matching the cosubarray functions must be applied across the upsampled subarray beams to avoid aliasing in the final image (Figure 1d and 1e). The final image consists of the coherent sum of each of the upsampled and reconstructed subarray images.

2.5 Restoration filter

After reconstruction, the resulting coarray function will still differ from that of full phased array imaging. A final restoration filter must be applied to the reconstructed image to account for this difference (Figure 1f). If $u^D[n]$ is the desired coarray function—corresponding to that of full phased array imaging—and $u^R[n]$ is the coarray function after reconstruction, then the lateral restoration filter that needs to be applied in coarray space is

$$h[n] = \frac{u^D[n]}{u^R[n]}. \tag{12}$$

The filter kernel to be applied laterally in beam space to the final image is then

$$H[q] = \Im\{h[n]\}. \tag{13}$$

In our approach, this restoration filter is decomposed into subband filters, each applied to the respective subarray data. Furthermore, since the reconstruction and restoration filters for each subarray are cascaded, they can be combined into a single filter. Hence, we apply a different single filter to each subarray dataset to realize both the reconstruction and restoration of the desired cosubarray function that is needed for large array synthesis. The subarray filter in cosubarray space is given by

$$h_k[n] = \frac{u_k^D[n]}{u_k^R[n]} \tag{14}$$

The final image is then formed through coherent summation of the filtered subarray data. The subarray filters thus sum to form the overall filter:

$$h[n] = \sum_k h_k[n] \tag{15}$$

A special case is when the restoration filter becomes an all-pass filter with subarray-dependent gain:

$$h_k[n] = w_k, \tag{16}$$

where w is the gain for the k^{th} subarray data. In this case the image formation simply becomes the weighted coherent sum of the reconstructed subarray beams.

Figure 1f shows the individual filters that would be used in cosubarray space, as well as the total filter given in Eq. 13 that could be applied to the final image. Figure 1g shows the final restored cosubarrays and coarray. Note that the coarray shown here is identical to that achieved by using full phased array imaging with the same array.

3. RESULTS

The proposed image formation and restoration method was tested using archival raw RF data sets acquired from point and contrast resolution phantoms with a 128-element ultrasonic piezoelectric transducer array [www.bul.umich.edu]. The array element spacing was 220 μm, and the transmitted pulse had a center frequency of 3.5 MHz and 40% bandwidth. Image reconstruction was implemented using off-line digital data processing.

Full phased array imaging was performed with $N = 64$ and $Q = 128$ beams. The resulting cyst and wire phantom images are shown in Figure 2a and 2c, respectively. For image formation, a sector angle of 90° with a depth of 120 mm is used.

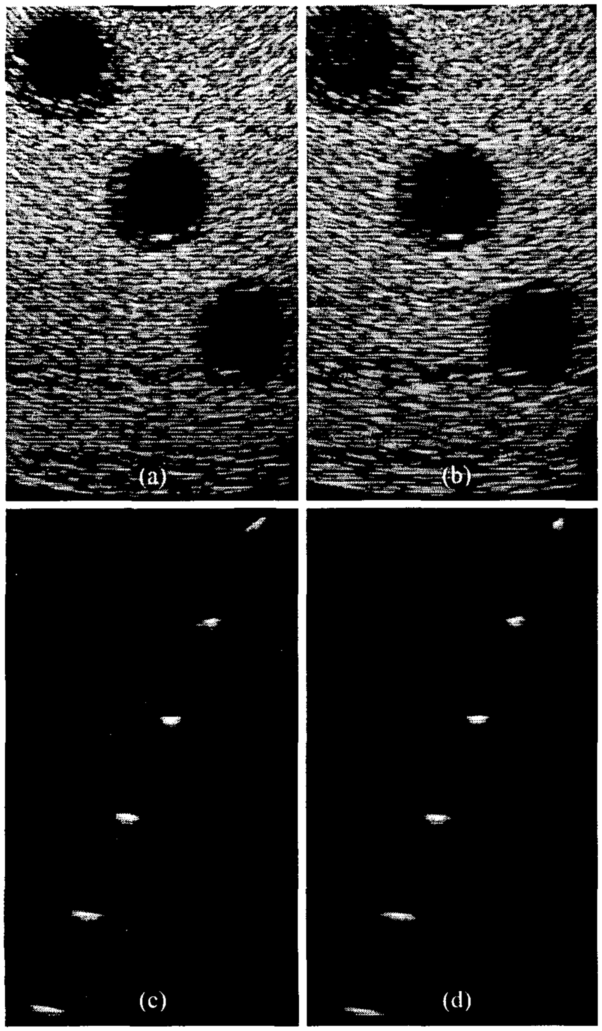

Figure 2. Ultrasound test images of a contrast phantom (top) and point targets (bottom) using full phased array (left) and phased subarray imaging (right).

Phased subarray imaging was performed with $K = 7$ subarrays, each with $M = 16$ elements, and spaced $P = 8$ elements apart. Q^S was chosen to be 32, giving an upsampling rate of $L = 4$. A 17-point reconstruction filter was applied to the subarray images. Because $P = M/2$, the restoration was realized by weighting the subarray beams prior to the coherent summation to form the final high-resolution image. The resulting images are shown in Figure 2b and 2d.

The contrast-to-noise ratio (CNR) was compared between full phased array and phased subarray imaging. The calculations are based on data from the two contrast images. Regions inside the three cysts and a large portion outside the cysts were used for contrast comparison. The reduction in CNR due to using phased subarray processing was only 7%.

The point resolution was also compared near the transmit focal distance. The point resolution is defined to be the width of the PSF main lobe where the level has dropped to 3 dB below the PSF's maximum value. As expected, the resolution of the phased subarray method is larger than that of the full phased array imaging method, but only by 15%. The numbers of transmit/receive firing events for the full phased array and phased subarray methods are 128 and 160, respectively. For this case, only a 25% increase in firing events or 20% reduction in frame rate is caused by using phased subarray imaging. The most important result is that only 16 parallel processing channels are required for phased subarray imaging, only 25% of the number of channels required for full phased array imaging.

4. CONCLUSION

Coherent array imaging using phased subarrays together with coarray reconstruction and restoration is promising for large array system design with reduced front-end complexity. The proposed method provides an image quality comparable to the full phased array while it scales the front-end processing by a factor of the ratio of the subarray size to the full array size.

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