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A COST-EFFECTIVE METHOD FOR ULTRASOUND VOLUMETRIC IMAGING

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ABSTRACT

A synthetic receive aperture technique is explored for cost-effective ultrasound scanners with high frame rates and beam density. The technique provides ultrasound volumetric imaging where beam count is very large with 2-D transducer arrays using subaperture processing. For every beam line, transmit beam is performed with a small subaperture whereas the reflected echo signals are received from non-overlapping subapertures. For every transmit-receive subaperture combination, a small number of beams are acquired and then the number of beam lines is increased through beam space interpolation. A 2-D linear filter with a different spatial frequency band for each subaperture is employed as the interpolation filter. Performance of the technique is analyzed through simulations. The technique reduces the number of firings and therefore allows real-time imaging with very low susceptibility to motion artifacts.

1. INTRODUCTION

Ultrasonic imaging has been an important diagnostic tool in medical applications where 2-5 MHz, 64-128 element phased array systems are used in general. In these systems, transmit and receive signal processing are performed by parallel electronic circuits. The image quality of a conventional phased array (CPA) depends on frequency and transducer array size [1]. A high quality image can be achieved using a large aperture CPA which involves increased system complexity with a high system cost [2]. System complexity is increased with the number of active parallel transmit-receive array channels. For this reason, synthetic aperture (SA) imaging can be considered as an alternate, where a small number of parallel active elements is used. In this approach, signal is sent from a subaperture with small number of elements and echo signals are acquired from small receive subapertures, and therefore electronic hardware and the power consumption is reduced. Synthetic aperture techniques allow design of low cost systems but produce poor image quality [3,4].

Data acquisition time, is critical for real-time synthetic aperture ultrasound imaging. In SA techniques each scan line must be transmitted and received once for each receive subaperture before it is stored in the digital memory. This process reduces the data acquisition rate linearly with the number of subapertures in the full array. Therefore, it is necessary to reduce the number of firings for the data acquisition to achieve real-time imaging [5,6,7].

For real-time pulse-echo imaging, a major constraint is *frames/s x beams/frame x imaging depth/frame* $\leq$ *c/2*. For *20* frames/s, *1540 m/s* acoustic velocity and *20 cm* image depth, at most *Bo*=192 beam lines can be traced. According to the Nyquist sampling criterion, the total number of beams to scan a 90° sector is $\sqrt{2}\,N$, where N is the number of array elements with $\lambda/2$ element spacing.

We propose a subaperture technique in this work. This technique uses different subapertures each consisting of small number of parallel transmit-receive channels. For every subaperture, the number of beam lines is determined to satisfy the Nyquist criterion for that subaperture, and the number of beams are increased to the required beam number of the full synthesized aperture through digital interpolation. This subaperture processing approach allows cost-effective, real-time imaging with image quality almost identical to the phased array.

2. METHOD

In this study, a synthetic receive aperture technique based on beam space interpolation is proposed. To scan the image space, an active subaperture is fired for every beam line and the echo signals are received from elements of an active receive subaperture in parallel. The element count of both transmit and receive subapertures is kept small enough to reduce the system complexity. While the transmit subaperture is at the center of a large transducer array, the active receive subaperture is multiplexed on the array to collect data from non-overlapping receive subapertures. The transmit subaperture is fired to each scan angle as many as the number of receive subapertures. The acquired data are used to synthesize the large aperture.

The beam lines to scan the image space is chosen to satisfy the Nyquist criterion to a single transmit and receive subaperture combination. Following acquisition of two neighbor beams, we perform linear interpolation to increase the beam number by a factor so that the number of overall beam lines should satisfy the Nyquist criterion for the full synthesized array (Fig-1.a).

In this work, using 2-D subapertures with N_t^x x N_t^y parallel elements in transmit and N_r^x x N_r^y parallel active elements in receive, a volumetric synthetic array imager with N_t^x x N_t^y and KN_r^x x KN_r^y elements is investigated, where K is the number of non-overlapping receive subapertures. Using continuous wave and paraxial approximation two-way point spread function (psf) for this system can be written as:

$$h(\sin\theta, \sin\phi) = h_l(\sin\theta) \times h_e(\sin\phi), \quad (1)$$

$$h_l(\sin\theta) = \frac{\sin(\frac{\pi}{\lambda} dN_t^x \sin\theta)}{\sin(\frac{\pi}{\lambda} d \sin\theta)} \times \frac{\sin(\frac{\pi}{\lambda} dKN_r^x \sin\theta)}{\sin(\frac{\pi}{\lambda} d \sin\theta)}, \quad (2)$$

$$h_e(\sin\phi) = \frac{\sin(\frac{\pi}{\lambda} dN_t^y \sin\phi)}{\sin(\frac{\pi}{\lambda} d \sin\phi)} \times \frac{\sin(\frac{\pi}{\lambda} dKN_r^y \sin\phi)}{\sin(\frac{\pi}{\lambda} d \sin\phi)}, \quad (3)$$

where, θ and ϕ are the lateral and elevation angles respectively (Fig-1.a), λ is the wavelength, and d is the inter-element spacing. The last two equations define transmit-receive psf for lateral and elevation responses over KN_r^x x KN_r^y elements 2-D transducer array. For a single transmit-receive 2-D subaperture combination, psf can be written as:

$$h_{k1,k2}(\sin\theta, \sin\phi) = h_{k1}(\sin\theta) e^{j\varphi_{k1}(\theta)} \times h_{k2}(\sin\phi) e^{j\varphi_{k2}(\phi)}, \quad (4)$$

Where, the first and second term represent 1-D responses of the k1 and k2'th subapertures.

In image domain, according to the Nyquist sampling criteria, spatial sampling period must be: $\Delta sin(\theta) \leq 2/(N_t^x+KN_r^x)$, $\Delta sin(\phi) \leq 2/(N_t^y+KN_r^y)$. For SRA, using subaperture consists of N_t^x x N_t^y transmit, N_r^x x N_r^y receive elements, image space is sampled over $-\pi/6 \leq \theta, \phi \leq \pi/6$, resulting the beam lines: $B^\theta \geq (N_t^x+N_r^x)/2$ and $B^\phi \geq (N_t^y+N_r^y)/2$. Then, this sampling count is increased to $B_o^\theta \geq (N_t^x+KN_r^x)/2$ and $B_o^\phi \geq (N_t^y+KN_r^y)/2$ through digital interpolation. Since motion sensitivity necessitates shorter filter length linear interpolation filter is preferred. In order to match the filter spatial frequency band with the associated subaperture function, the phase of the filter for $k1$ and $k2$'th subaperture must be taken same as that of the point spread function (Fig-1.c).

The interpolation filter can be defined for the $k1$ and $k2$'th subaperture as:

$$f_{k1,k2}(\theta,\phi) = \frac{|m-L1|}{L1} e^{-j\Phi_{k1}(\theta)} \times \frac{|n-L2|}{L2} e^{-j\Phi_{k2}(\phi)}, \qquad |m| \leq L1, |n| \leq L2 \quad (5)$$

where, m and n indicate the filter beam numbers along azimuth and elevation directions. High resolution image is finally formed by simply summing the K low resolution images which are composed of beams acquired from K subaperture combinations. Therefore the high resolution system becomes:

$$H_T(\theta,\phi) = \sum_{k1=1}^{K} \sum_{k2=1}^{K} h_{k1,k2}{}^0(\theta,\phi) ** f_{k1,k2}(\theta,\phi), \quad (6)$$

where, ** indicates 2-D convolution. $h_{k1,k2}{}^0(\theta,\phi)$ is the extended form of $h_{k1,k2}(\theta,\phi)$ with $L1$ and $L2$ zeros inserted between two samples (Fig-1.c).

3. SIMULATIONS

To test performance of the proposed technique, psf simulations are performed using a Mills cross array configuration [8] (Fig-1.b). There are one right cross in transmit and a similar four cross oriented at 45 degrees along the diagonals in receive mode [9]. In order to investigate the proposed SRA and compare with CPA, a 3,5 MHz, 128 element ultrasound imaging system is simulated digitally, where the system parameters are given in Table-1.

Table-1: The system parameters used in the simulations.

	CPA	SRA
Effective aperture size (N_e^x, N_e^y)	32 , 32	32 , 32
Active transmit channel count (N_t^x, N_r^x)	16 , 16	16 , 16
Active receive channel count (N_r^x, N_r^y)	32 , 32	16 , 16
Number of firings per each beam line (K)	1	4
Number of acquired beams (B^θ, B^ϕ)	48 , 48	24 , 24
Beam upsampling factor $(L1, L2)$	-	2 , 2
Overall number of beams (B_o^θ, B_o^ϕ)	48 , 48	48 , 48
The size of the linear filter $(2L1+1, 2L2+1)$	-	5 , 5
Relative susceptibility to motion artifacts.	1	4

Signal processing steps of the proposed technique is presented in Fig-2 and Fig-3 via simulations. Fig-2.a shows the zero insertion step of the digital interpolation process. Since the acquired beam number of a subaperture is less than the number of overall beam lines the subapertures seem to be periodic in spatial frequency domain. Their sum is also shown below of the figs. For this SRA model, sampling rate is increased by a factor of $L1=L2=2$. Consequently, four zeros are inserted for each subaperture. Fig-2.b shows, the equivalent subapertures after filtering and their sum. In this step, additional beam lines between two collected neighbor beams are produced by a linear filter for each subaperture in spatial frequency domain. In other words, required subaperture psf is formed in the beam space. The overall psf's of SRA and CPA are given in Fig-3.a and Fig-3.b, respectively. The results show that the point and contrast resolutions of two systems are almost the same.

4. CONCLUSION

In this study, a synthetic receive aperture technique based on spatial interpolation is presented. The technique is examined via simulations and compared to phased array. The proposed technique, uses very small number of active parallel channels and produces image quality identical to that of the phased array. It is suitable for cost-effective systems. It can be efficiently used in volumetric imagers where beam density is a major difficulty.

The SNR of the proposed technique is equivalent to that of the phased array. While imaging of non-stationary organs, the phase distortion may occur during data acquisition and therefore, the imaging quality of SRA may be degraded. Future studies should focus on motion estimation and compensation techniques for the subaperture processing.

5. REFERENCES

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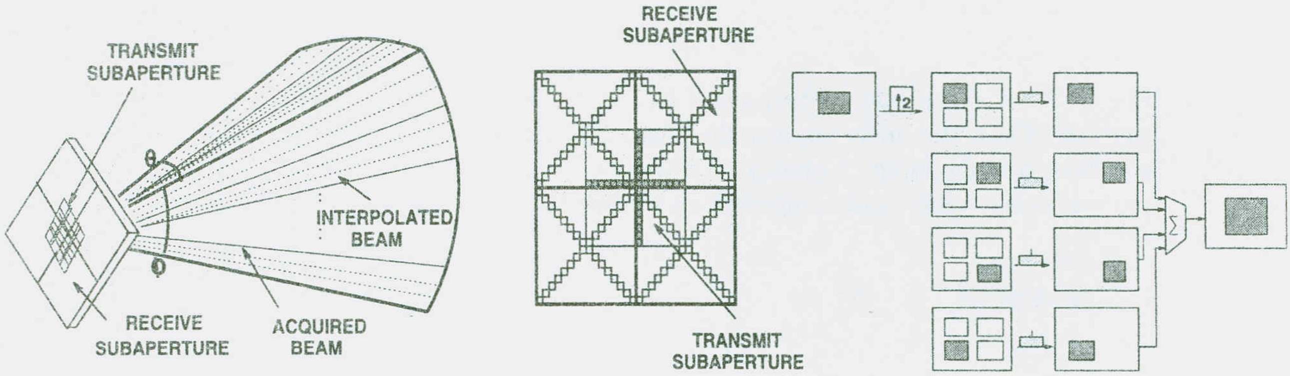
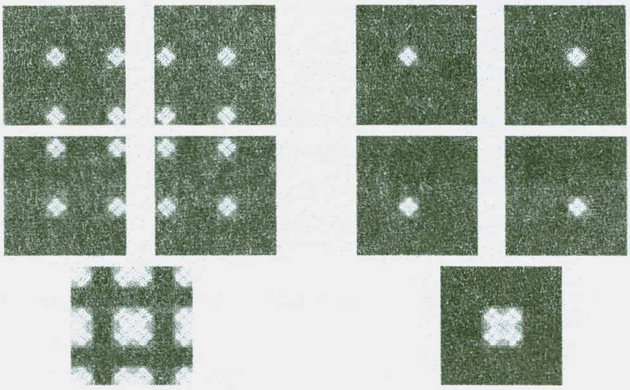


(a) (b) (c)

fig-1

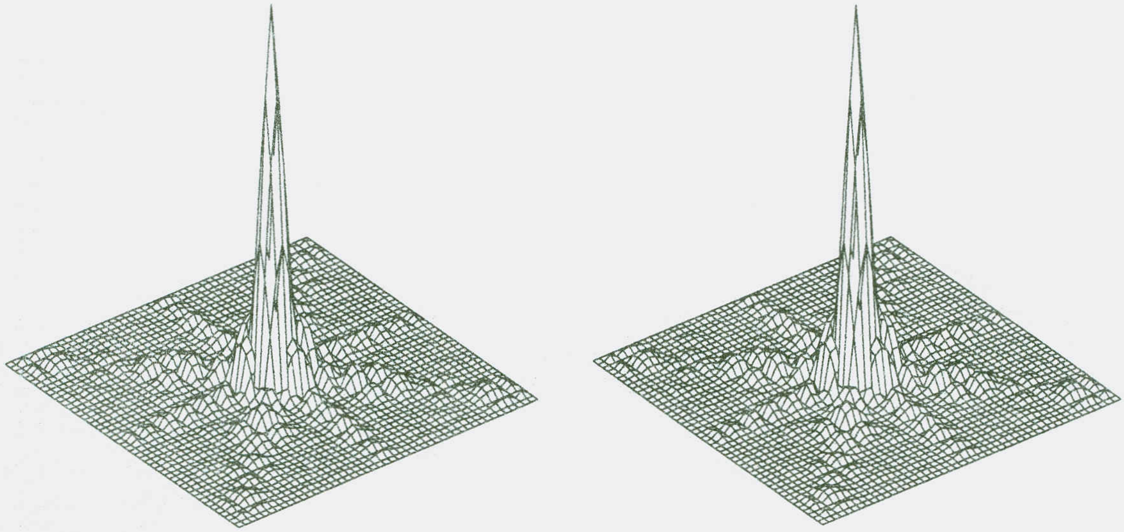
(a) Volumetric imaging. (b) Mills cross array configuation. (c) Aperture space representation of transn receive subapertures (K=2) and their sum.



(a) (b)

fig-2

(a) Equivalent subapertures are viewed periodic and their sum before linear filtering. (b) Equiva subapertures and their sum after linear filtering.



(a) (b)

fig-3

(a) Proposed technique psf and (b) Control psf. (Lateral axis: $sin\theta$, Elevation axis: $sin\phi$, vertical amplitude.) For figure 3: ($K = 2$, $N_t^x = N_t^y = 16$, $N_r^x = N_r^y = 16$, $B^\theta = B^\phi = 24$, $B_o^\theta = B_o^\phi = 48$.)