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2-D array for 3-D Ultrasound Imaging Using Synthetic Aperture Techniques

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Abstract

A 2-D array of $256 \times 256 = 65,536$ elements, with total area $4 \times 4 = 16 \text{ cm}^2$, serves as a flexible platform for developing acquisition schemes for 3-D rectilinear ultrasound imaging at 10 MHz using synthetic aperture techniques. This innovative system combines a simplified interconnect scheme and synthetic aperture techniques with a 2-D array for 3-D imaging. A row-column addressing scheme is used to access different elements for different transmit events. This addressing scheme is achieved through a simple interconnect, consisting of one top, one bottom single layer flex circuits, which, compared to multi-layer flex circuits, are simpler to design, cheaper to manufacture and thinner so their effect on the acoustic response is minimized. We present three designs that prioritize different design objectives: volume acquisition time, resolution, and sensitivity, while maintaining acceptable figures for the other design objectives. For example, one design overlooks time acquisition requirements, assumes good noise conditions, and optimizes for resolution, achieving -6 dB and -20 dB beamwidths of less than 0.2 and 0.5 millimeters, respectively, for an F/2 aperture. Another design can acquire an entire volume in 256 transmit events, with -6 dB and -20 dB beamwidths in the order of 0.4 and 0.8 millimeters, respectively.

I. Introduction

For breast ultrasound, one-dimensional linear sequential arrays are used because they produce a rectangular scan format useful for imaging targets near the skin, due to the wide field of view close to the transducer. These arrays use a subset of elements, or subaperture, to direct a beam directly ahead for each image line. Through either enabling/disabling elements or through multiplexing, this subaperture “walks” from one end of the array to the other. At each step, a new scan line is produced and the scan lines are placed together to form a rectangular image. Operating in the 7–13 MHz range, such linear sequential arrays typically have 128–256 available elements and a total aperture size of 3–4 cm. A 1-D linear sequential array has transducer elements along the azimuth direction only. Consequently, electronic focusing of the ultrasound beam can only be done in this direction. Figure 1 shows a typical 1-D linear array and its field of view where line A is created using the on-axis or center subaperture, indicated by the gray shading, and line B is created using an off-axis subaperture. An acoustic lens is placed in front of the transducer face to help reduce slice thickness.

Several researchers have explored using 3-D ultrasound imaging by mechanically translating a 1-D array to acquire multiple B-scans. The volume is then reconstructed using offline processing [1]. The mechanical translation may either be done by using motor or freehand methods. In both cases, issues of reliability limit the use of such methods. Such a system has been investigated for diagnostic, biopsy and surgical applications [2–4]. 2-D arrays have several advantages over mechanically scanned 1-D arrays. The acoustic lens of a 1-D array

focuses the beam at a single, predetermined depth. The beam is well focused in elevation at this depth, but diverges at depths away from the focus degrading image quality. Multi-row arrays such as 1.25-D arrays have been proposed to reduce the slice thickness, but elevation focusing remains static [5,6]. 1.5D, 1.75-D and 2-D arrays can produce a thinner slice thickness since dynamic elevation focusing is possible. A 2-D matrix array transducer has square elements in the azimuth and elevation directions so that focusing capability and field of view are equal in both lateral dimensions. We anticipate that a thinner slice thickness from elevation focusing and larger field of view with a 2-D array would improve the early detection of small lesions such as early stage tumors and cysts. Unlike a mechanically translated 1-D array, 2-D arrays do not require moving parts to acquire a 3-D volume. The mechanical components can be slow and unreliable thus limiting their use. Just as mechanically scanned single element transducers were replaced by electronically controlled 1-D arrays for traditional 2-D scans, it is likely that 2-D arrays will completely replace current mechanical scanning methods used in all 3-D imaging applications. Recent commercial 3/4-D systems utilize a 2-D array transducer for echocardiography and obstetric applications. One such system, the Sonos 7500 (Philips Medical Systems, Andover, MA), utilizes a fully sampled 2-D array of about 3,000 elements that produces 3D images at a rate above 20 volumes per second. Its innovative interconnect and integrated electronics allow connecting to approximately 3,000 individual elements separated by a 250 μm pitch before funneling the signals from these elements into 128 system channels via switches and preliminary beam formation within the handle [18].

Synthetic aperture techniques provide an alternative to conventional beamforming methods. Originally developed for sonar and geological applications [21,22], synthetic aperture imaging has been proposed for several applications in ultrasound [7–10]. Some of the advantages of synthetic aperture imaging include a reduction in hardware requirements, transmit and receive focusing capability throughout the entire field of view, and a potentially high frame rate of almost 1000 images/s [7]. However, the disadvantages of synthetic aperture methods include a poor signal-to-noise ratio (SNR), susceptibility to patient motion, and enormous storage and processing requirements. SNR can be increased by using multiple defocused transmit elements [9], and error due to patient motion can be reduced by using cross-correlation methods from subaperture RF data to estimate and account for the motion [8,19,20]. The large hardware and power requirements can be reduced as computing is becoming faster, and more efficient. Researchers have also suggested applying synthetic aperture methods for three-dimensional imaging. While some of this work involves the use a 2-D array [17], most of it is based on the mechanical translation of a 1-D array [7,10]. Thus, investigating various synthetic aperture techniques with 2-D arrays remains largely unexplored. In this paper, we present three acquisition strategies that use synthetic aperture techniques with 2-D arrays, each of which prioritizes volume acquisition time, resolution, or sensitivity.

We first describe our design using a simple 8×8 2-D array (Figure 2). This design utilizes a row-column electrode pattern where the bottom electrodes are a series of vertical electrodes (Fig. 2A). These electrodes serve as the “hot” electrodes which are connected to transmit/receive channels #1–8. The top electrodes are a series of horizontal electrodes which serve as the “ground” electrodes (Fig. 2B). Instead of having a direct connection to the true ground, a switch is placed in between the “ground” electrode and the true ground of our system. With this simplified interconnect scheme, the total number of physical connections for an $N \times N$ array is $2N$, as opposed to N^2 connections in the case of a fully sampled array. In this example, we close all switches (Fig. 2B) and excite transmit channel #4 as indicated by the arrow under channel #4 in Fig. 2A. This column of elements, shown in the gray shading in Fig. 2C, then emits a cylindrical wavefront into the field. In azimuth, the wavefront appears omni-directional since the aperture looks like a single element source. In the elevation direction, the emitted beam is a planar wavefront because all elements fire simultaneously. For receive mode, receive channels #1–8 are active (shown by arrows in Fig. 2D) and the desired receive row is selected

by closing switch S5 (Fig. 2E). In receive mode, the individual elements along one row (gray shading) will be used to record the echoes (Fig 2F). For subsequent transmissions, different combinations of transmit columns and receive rows are used. The echoes recorded from these multiple acquisitions are stored, processed and summed together to interrogate an entire volume. Different sets of elements are used on each transmit event and the results are processed and summed to form high resolution images. Advantages of this design also include a reduced channel count from N^2 (fully sampled case) to N channels and a simplified interconnect scheme. The row-column design can simplify matching the high impedance transducer elements to the electrodes, since entire rows/columns of 256 elements are bussed together, hence reducing the overall impedance. Our design is similar to bathymetric sonars where crossed Tx and Rx 1-D arrays are used. However, using a 2-D array allows for potentially numerous different cross configurations which could be combined to reduce clutter [21,22].

While not all elements are individually connected, this unique interconnect and switching scheme allows access to all elements over multiple transmit events, and could essentially synthesize a fully-sampled 256×256 2-D array through 65,536 transmit/receive events. However, practical considerations of sensitivity, beamwidth and acquisition time call us to develop designs that use various synthetic aperture techniques using groups of elements rather than individual elements. For example, entire rows and columns, or just segments of a row or a column could be used. The system possesses good beamforming capabilities in azimuth, because the ultrasound channels are arranged along the row direction, and can be assigned a different time delay and apodization value. In elevation, elements within one column connect to one channel, and cannot be assigned individual delay or apodization values. Therefore the system does not allow us to readily focus or apodize in elevation. However, these capabilities can be achieved through synthetic aperture techniques. Whether to use these capabilities or not is a tradeoff between three main factors, namely speed, beamwidths, and sensitivity. In this paper, we present three acquisition scheme designs that illustrate these tradeoffs. Each acquisition scheme consists of a synthetic transmit aperture (STA), a synthetic receive aperture (SRA), and their corresponding synthetic delay and apodization 2-D profiles. The idea of having various scheme options is appealing because they can be implemented in software, and the user of the 3-D system will be able to employ these schemes or variations of them.

Design objectives

We design three acquisition schemes while bearing three different design objectives in mind. The first objective is volume acquisition time, which is indicated by the number of transmit events needed for a single volume acquisition. When using synthetic aperture methods, this number corresponds to the number of transmit events needed to synthesize the desired aperture. Requirements for this design objective are dictated by the application, e.g. whether tissue motion is severe, or if real-time imaging (e.g. at 30 volumes/second) is desired. The second set of objectives includes resolution, contrast, and clutter level. These are evaluated using on-axis and off-axis beamplots. The -6 dB beamwidth is an indicator of the resolution of the system and the -20 dB beamwidth is an indicator of contrast [5]. The -40 dB beamwidth and the grating lobe levels can be used as indicators of the clutter level in the image. In breast ultrasound imaging, improved image contrast and resolution would improve differential diagnosis of solid lesions and cysts [11]. The third objective is sensitivity and is estimated by the peak amplitude of the received signal. This figure is of particular importance for sparse synthetic aperture methods since fewer elements are used for each transmit event.

Acquisition Scheme 1: Fully sampled STRA

In this acquisition scheme, individual elements are fired sequentially, emitting spherical acoustic waves in the field. Echoes are received from the same row. Projected onto the elevation axis, this scheme resembles a monostatic acquisition strategy [12], where the same single

element is used to transmit and receive before moving on to the next single element. In azimuth, it resembles a 256-element 1-D linear array, where a single element is fired at one time while beamforming with a subaperture of 128 elements. The linear array is moving in elevation. The sequence of transmit events is illustrated in Figure 3, showing an 8×8 array for illustrative purposes. In Figure 3A, the element in the lower left of the aperture is selected by closing switch S8 and firing channel 1. On receive, switch S8 remains closed and channels 1–8 are active (Fig. 3B). For the second transmit event (Fig. 3C), switch S8 is still closed and channel 2 is the active transmitter. On receive, all elements in the bottom row are used, by only closing switch S8 (Fig. 3D). Subsequent elements are used in transmit by closing the appropriate switch and transmitting with the appropriate channel, and the row containing the transmit element is used on receive. Lastly the element in the top right corner is selected by closing switch S1 and using channel 8 (Fig. 3E), while the top row of elements serves as the receive row (Fig. 3F).

Synthetic Transmit Aperture

The transmit aperture is synthesized element-by-element, which allows for focusing as well as apodization in both azimuth and elevation. The STA beamforming in this case can be formulated as:

$$S_{STA}^l(t) = \sum_{r=M}^n \sum_{c=Q}^R s_{c,r}^l(t - \tau_{c,r}) \quad (1)$$

where $s_{c,r}^l$ is the beamformed signal for A-scan line l , from the individual element on column c and row r ; $\tau_{c,r}$ is the synthetic delay value applied to $s_{c,r}^l$, and obtained from a 2-D profile such as in Figure 5. M , N , Q and R delimit the boundaries of the moving transmit subaperture in use for a particular focal point. Typically, we would use a 128×128 subaperture centered above the point of interest. For example, for the on-axis case of the 256×256 array, $M = 65$, $N = 192$, $Q = 65$ and $R = 192$. Beamformed signals from individual elements can be re-used with different delays to synthesize different subapertures, so that each element is only fired once.

Synthetic Receive Aperture

Taking advantage of the focusing and apodization capabilities readily available in the azimuth direction, the acquisition scheme uses focused, Hanning-weighted 128-element rows which resemble a conventional 1-D linear array. Hanning apodization helps suppress side lobes at the cost of a larger beamwidth. The receive strategy is such that consecutive receive events use 128 adjacent individual 128-element rows, hence synthesizing a 128×128 synthetic receive subaperture row-by-row, as illustrated in Figure 3.

Elevation focusing and apodization are achieved by varying element delays and weighting factors with the row. The synthetic elevation beamforming can be formulated as:

$$S_{SRA}^l(t) = \sum_{r=1}^{128} \sum_{c=1}^{128} w_{c,r}(t) r_{c,r}^l(t - \tau_{c,r}), \quad (2)$$

$l = 1, 2, \dots, L$ (number of scan lines). $c = 1, 2, \dots, 128$ (consecutive columns (or channels)), $r = 1, 2, \dots, 128$ (consecutive rows).

where $w_{c,r}$ is the two-dimensional apodization value for column c and row r , obtained from a 2-D Hanning profile such as those in Figures 4A and 4B, and is time-varying to allow for

aperture expansion in depth. $\tau_{c,r}$ is the synthetic focusing time for column c and row r , and $r_{c,r}^l(t)$ is the received signal from channel c for A-scan line l and row r . The inner summation term in (1) is the laterally beamformed signal for A-scan line l and individual row n , as given by the conventional delay and sum expression. The time delay $\tau_{c,r}$ for an element at location $(x_c, y_r, 0)$ to focus at (x_f, y_f, z_f) is given by:

$$\tau_{c,r} = \sqrt{\frac{(x - x_f)^2 + (y - y_f)^2 + z_f^2}{c_{\text{sound}}}}. \quad (3)$$

Figure 5A shows the 2-D synthetic delay profile for a focus at $(0, 0, 20)$ mm, and Figure 5B the one for an off-axis focus at $(-15, -15, 20)$ mm. Delay values are expressed in microseconds. Negative delay values mean earlier firing and appear dark, while the center of the aperture that lies closest to the focal point has zero delay value and appears white. Through synthetic aperture, this acquisition scheme provides focusing capabilities in transmit as well as in receive in both azimuth and elevation, which yields symmetric beamwidths. A major drawback lies in the acquisition time needed: for a single volume, the number of required Tx/Rx events equals the number of single elements in the aperture, or $256 \times 256 = 65,536$ Tx/Rx events. The number of low-resolution images used to synthesize a particular focal point depends on the subaperture in use, typically $128 \times 128 = 16,384$ images, which implies a large computational effort. Another disadvantage is that transmitting with single elements results in broad, low-power beams, which ultimately yields low sensitivity.

Acquisition Scheme 2: No STA, fully sampled SRA

In this acquisition scheme, all 256×256 elements fire simultaneously. The transmit aperture resembles a single element of dimension $4 \text{ cm} \times 4 \text{ cm}$ emitting a planar wavefront with sound evenly distributed in the rectilinear volume, which means that there is no transmit focusing or apodization, and synthetic aperture techniques are not employed for the transmit aperture. This is similar to an ultrafast imaging technique presented in [13], where all elements in a 1-D array are fired simultaneously, illuminating the field with a plane wave, while receiving with individual channels. The volume is acquired by synthesizing the receive aperture row-by-row. Since there is no transmit focusing, beamforming is achieved exclusively from the sequence of receive events, where every receive row is focused and apodized in azimuth, and the sequence of rows synthesizes an elevation focus and apodization profile. Figure 6 illustrates this scheme with a sequence of firings. All transmit events are similar, with all the channels concurrently active, and all the switches closed (Figs. 6A, 6C, 6E). On the first receive event, the bottom switch S8 is closed, and echoes are recorded from all elements in the bottom row through all the channels (Fig. 6B). On the next receive event, switch S7 is closed to receive with the elements of the next row (Fig. 6D). The scheme is repeated until the top row is selected by closing switch S1 and using all channels (Fig. 6F). Using this scheme, an entire volume can be acquired through 256 firings only for a 256×256 array, one for every receive row, resulting in an improved frame rate. The advantage of speed comes from trading off transmit beamforming, which is expected to reduce resolution, contrast and increase clutter level. Transmitting with all elements should yield an increase in sensitivity over the fully sampled STRA design (acquisition scheme 1), where individual elements are fired.

Acquisition Scheme 3: Sparse STA, fully sampled SRA

This design can be viewed as a hybrid of the previous two designs, which have a fully sampled STA (Design 1) or no STA (Design 2). The motivation behind this design is to achieve better resolution and contrast than with no STA (Design 2), with a shorter acquisition time than the fully sampled STRA (Design 1). Here, several 128-element columns are fired sequentially. In

order to maintain uniform sensitivity and reasonable acquisition time, these columns may be at the top, the center or the bottom of the aperture. Of these three synthetic transmit subapertures, the one that is most centered above a focal point is used in transmit. Delay values are uniform along a column since all elements within a column are connected to the same channel. Every column hence emits a cylindrical wavefront in the field. A sparse transmit subaperture is thus synthesized column-by-column, using N evenly spaced columns $C_1, C_2, \dots, C_N$, which provides focusing capability in azimuth only. Figures 7A, 7C, 7E show the sparse synthetic transmit subaperture. To transmit with the leftmost column, channel 1 is active while switches S3 through S6 are closed. Similarly to transmit with the center or the rightmost column, these switches are closed while channels 4 and 7 are active, respectively. The receive aperture is synthesized row-by-row for every transmit column. As in the previous designs, receive rows are selected by closing the corresponding switch and receiving with all channels (Figs 7B, 7D, 7F).

The transmit subaperture can be formulated as:

$$S_{STA}^l(t) = \sum_{c=C_1, C_2, \dots, C_N} w_c(t) s_c^l(t - \tau_c) \quad (4)$$

where w_c is the apodization value for column c , and is uniform to maximize transmit sensitivity, while a 2-D Hanning apodization profile is used in receive; s_c^l is the beamformed signal for line l from a column of 128 elements connected to channel c ; τ_c is the synthetic delay value applied to s_c^l , and can be calculated, independent of y , for an element at location $(x_c, y_r, 0)$ to focus at (x_f, y_f, z_f) by:

$$\tau_c = \frac{\sqrt{(x - x_f)^2 + z_f^2}}{c_{sound}}. \quad (5)$$

Figure 8 shows the synthetic delay profile for on-axis focus at $(0, 0, 20)$ mm and off-axis focus at $(-15, -15, 20)$ mm, with values expressed in microseconds.

The value of N in (4) determines the sparseness of the transmit aperture. If $N=128$, then all 128 adjacent columns in the 128×128 subaperture are used. Results from [7], however, suggest that much fewer columns can be used, without compromising resolution, contrast, clutter level and sensitivity, while dramatically reducing acquisition time.

III. Methods

We have performed computer simulations using Field II to calculate on-axis and off-axis beamplots obtained through the different acquisition schemes [14]. We simulate a 10 MHz, 2-D array of 256×256 square elements with a pitch of $0.95\lambda = 146 \mu\text{m}$, separated by $25 \mu\text{m}$ kerfs. We use a -6 dB fractional bandwidth of 50 % for the excitation pulse. For rectilinear volumetric imaging, the beamplots were generated in a square area with the lateral dimensions of the transducer, that is $40 \text{ mm} \times 40 \text{ mm}$, and at a focal depth of 20 mm which, for a 128×128 subaperture, corresponds to an $F\#$ close to 1. Sensitivity values are estimated by the peak amplitude of the received signal at the focus then converted to decibels after normalizing to the maximum energy level for the on-axis image line of a fully-sampled, focused 256×256 element 2-D array, which has the highest pulse-echo sensitivity.

IV. Results

We first present the beamplots obtained from a fully sampled, focused 128×128 2-D array using a 2-D Hanning apodization profile. This design serves as the gold standard for 2-D arrays, and is useful in evaluating the different acquisition schemes which are designed to approach the performance of a fully-sampled array. Figures 9A and 9B show the lateral beamplots for on-axis, where $(x, y, z) = (0, 0, 20)$ mm, and Figures 9C and 9D those for off-axis, where $(x, y, z) = (-15, -15, 20)$ mm. Azimuth and elevation beam profiles are identical, since the fully-sampled array and the acquisition scheme are symmetrical. These results show a narrow beam down to at least -70 dB. On-axis -6 , -20 , and -40 dB beamwidths are 0.20, 0.36, and 0.75 mm, respectively. Focusing off-axis at $(-15, -15, 20)$ mm, the beam is slightly broader with -6 , -20 , and -40 dB beamwidths of 0.21, 0.39, and 1.03 mm, respectively. The off-axis beamplots display a grating lobe at a level of -52 dB, due to slight beam steering and a 0.95λ element pitch. Focusing off-axis results in a 2 dB loss in sensitivity relative to on-axis. As an indicator of acquisition time, we calculate the number of transmit events required for a single volume based on the -6 dB beamwidth and the Nyquist criterion: The lateral field of view is equal to the entire aperture, that is $256 \times 0.95 \lambda = 37.4$ mm. The Nyquist sampling interval is $0.20 \text{ mm}/2 = 0.10$ mm, which implies there must be $37.4/0.1 = 374$ lines per plane. There are 374 planes, totaling $374^2 = 139,876$ lines per volume, or as many transmit events. For a 6 cm depth, this corresponds to 0.09 volumes/s. Volume rate could be improved by reducing the field of view, lowering resolution, and using parallel processing [15].

Acquisition Scheme 1: Fully sampled STRA

Figure 10 contains the beamplots for the fully sampled STRA design. On-axis (Fig. 10A) and off-axis (Fig. 10C) azimuth beam profiles show a narrow beam down to at least -70 dB with on-axis -6 dB, -20 dB, and -40 dB beamwidths of 0.20, 0.35, and 0.76 mm respectively, and off-axis -6 dB, -20 dB, and -40 dB beamwidths of 0.21, 0.38, and 1.04 mm, respectively. These figures are very close to those obtained in the fully-sampled case, and the overall beam profiles look similar. As a matter of fact, in azimuth the scheme is similar to a fully sampled array, utilizing focusing and apodization capabilities in transmit and in receive, which explains the similarity. The main lobes in elevation beamplots (Figs. 10B, 10D) are also attractive, with beamwidths close to their azimuth counterparts. There are, however, three main discrepancies relative to the gold standard. First, the use of this scheme results in a -45 dB loss in sensitivity that results primarily from emitting with single $120 \mu\text{m} \times 120 \mu\text{m}$ elements, which by themselves have low sensitivity. Second, elevation suffers from high grating lobe levels of -27 dB and -23 dB at ± 11 mm on and off-axis, respectively. These grating lobes result from the use of a monostatic scheme in elevation with a 0.95λ pitch, instead of the recommended $\lambda/2$ pitch [12]. These grating lobe levels are comparable to those presented in previous work [16], using a sparse 2-D array design with 169 used as transmitters and 256 as receivers.

Acquisition Scheme 2: No STA, fully sampled SRA

We obtain the beamplots shown in Figure 11. Due to the intrinsic symmetry of the transmit aperture and the SRA, azimuth and elevation beam profiles are identical. On-axis beams (Figs. 11A, 11B) are narrow down to -55 dB, with 0.38, 0.69, and 1.44 mm beamwidth for -6 , -20 , and -40 dB, respectively. These numbers are larger than those obtained in the fully-sampled case since the acquisition scheme has no transmit focusing. On-axis beamplots also display grating lobes at ± 17 mm at a -50 dB level. Focusing off-axis at $(-15, -15, 20)$ mm (Figs. 11C, 11D), the main beam broadens, and the aforementioned beamwidths become 0.39, 1.19, and 3.59 mm, respectively. As a result of beam steering, grating lobes raise to a level of -35 dB. The use of a flat, unfocused transmit aperture implies that it insonifies the volume uniformly, so that the energy received at every point is relatively low. Indeed, there is about 40 dB loss in sensitivity relative to the focused fully sampled array. The key advantage of this scheme lies

in the reduced acquisition time: a volume is acquired through 256 firings only, one for every receive row. For a 6 cm depth of view, this corresponds to 50 volumes per second. This advantage comes at the expense of the beam broadening and reduced sensitivity.

To further evaluate the off-axis performance of this scheme, we compute the beamplots at different off-axis foci (Figure 12). On the x-axis, 0 mm represents the on-axis case, and 18.7 mm represents the edge of the transducer. Figure 12 shows that the -6 dB beamwidth remains constant and close to 0.40 mm throughout the field of view. At -20 dB, the beamwidth remains constant around 0.7 mm up to 70 % off-axis, before it widens to about 1.1 mm. These values suggest that resolution and contrast are uniform throughout most of the field of view, with contrast worsening at the edges of the rectilinear volume.

Acquisition scheme 3: Sparse STA, fully sampled SRA

Figure 13 shows the beamplots obtained for the sparse STA, fully sampled SRA design. On-axis beams are narrow down to -60 dB. In azimuth, the beamwidths at -6 , -20 , and -40 dB are 0.20, 0.34, and 0.84 mm, respectively, which closely approach the gold standard fully sampled 2-D array. The absence of elevation focusing in transmit translates into larger elevation beamwidths of 0.35, 0.67, and 1.39 mm for the -6 , -20 , and -40 dB levels, respectively. This matches the beamwidths measured for acquisition scheme 2, where there is also no transmit focusing. The beam slightly broadens off-axis, and azimuth beamwidths of 0.20, 0.37, and 2.65 mm, are measured at -6 , -20 , and -40 dB, respectively. Off-axis elevation beamwidths increase to 0.37, 1.10, and 3.39 mm at -6 , -20 , and -40 dB, respectively. Off-axis, beam steering and a 0.95λ element pitch result in a grating lobe at -40 dB in azimuth. A sensitivity loss of 47 dB on-axis is calculated, which is comparable to the previous designs, and an additional 11 dB loss is incurred by focusing off-axis (Table 1).

In our search for an adequate number of Tx columns to use, we simulate all possibilities, with evenly spaced columns and a fixed subaperture width of 128 columns, or 2 cm. Figure 14 shows the figures of merit obtained from the use of 3, 5, 7, ..., 128 transmit columns. Figure 14A shows that azimuth and elevation beamwidths at -6 , -20 , and -40 dB are independent of the number of columns used in transmit. In Figure 14B, however, sensitivity appears to increase linearly with increasing number of columns, with a 6 dB gain in sensitivity for every two-fold increase in the number of transmit columns. On the other hand, acquisition time increases linearly. With similar beamwidth figures, the tradeoff in the selection of a suitable number of transmit columns is between acquisition time and sensitivity. This tradeoff leads us to use 5 evenly spaced Tx columns, separated by 28 columns, in every 128×128 subaperture; this ensures that sensitivity is above -40 dB relative to the fully-sampled case, while keeping acquisition time moderate at 3,840 required transmit events for a single volume acquisition. The latter number is found as follows: there are 5 evenly spaced columns in a 128×128 subaperture, which corresponds to 10 evenly spaced columns in a 256×128 subaperture. There are also 3 possible subapertures on the top, at the center and at the bottom of the aperture. Every column is fired 128 times, once for every receive row. The total number of transmit events is hence $3 \times 10 \times 128 = 3,840$. For a 6 cm depth of view, this corresponds to a frame rate of 3.4 volumes per second.

V. Discussion and Future Work

We have presented an innovative system that combines a simplified interconnect scheme and synthetic aperture techniques with a 2-D array to achieve 3-D imaging. Three acquisition schemes come to support this design. The figures of merit compiled in Table 1 demonstrate the following: Compared to the fully sampled STRA design (Acquisition scheme 1), the sparse STA, fully sampled SRA design (Acquisition scheme 3) sacrifices elevation focusing for a faster volume acquisition time. This translates into larger elevation beamwidth and a reduced

number of required transmit events. Compared to the design with no STA and a fully sampled SRA (Design 2), the synthetic focus in azimuth of Design 3 improves sensitivity and azimuth beamplots, at the cost of increased acquisition time. In that sense, Design 3 appears as an intermediate between one scheme that seeks to optimize resolution (1), and one that seeks to minimize acquisition time (2). Table 2 summarizes these tradeoffs.

The fully-sampled design has been presented as the reference for 3-D imaging using 2-D arrays. It is appealing because it yields high sensitivity, optimal beamwidths and negligible clutter level. However, the implementation of a 256×256 fully-sampled 2-D array is extremely challenging, with a high number of required channels and extensive wiring. Hence the synthetic aperture alternatives we have presented. The fully sampled synthetic transmit/receive aperture acquisition scheme (Design 1) was presented in order to evaluate the potential of the row-column design in terms of resolution. The beamplots obtained were shown to closely approach the gold standard, with -6 dB and -20 dB beamwidths of less than 0.2 and 0.4 millimeters, respectively. However, a high grating lobe level in elevation affects the general performance of this scheme, and is mainly due the 0.95λ pitch constraint. In addition to a slow frame rate, this contributes to disqualify this design as a practical acquisition scheme. The following two schemes are the main practical alternatives at hand. The scheme with no STA and fully-sampled SRA (Design 2) is suitable for real-time imaging with a frame rate approaching 50 volumes per second, with beamwidths roughly twice as those calculated for the gold standard. An off-axis grating lobe level of -35 dB suggests that the image quality degrades off-axis. If better image quality is desired throughout the field, the user can switch to the sparse STA, fully sampled SRA acquisition scheme (Design 3). Azimuth beamwidths then approach those calculated for the gold standard, clutter level is low, but the frame rate is brought down to 3.4 volumes per second.

In future work, we plan to prototype this transducer using two identical single-layer flex circuits. Implementing this synthetic aperture design would only require two single layer flex circuits: a single layer flex circuit on the bottom and another identical flex circuit on top which has been rotated 90° with respect to the bottom flex circuit. One advantage is that these interconnect circuits would be single layer flex circuits consisting of one metal layer on a polyimide substrate instead of multi-layer flex circuits. Compared to multi-layer flex circuits, single layer flex circuits are simpler to design, cheaper to manufacture and thinner so its effect on the acoustic response is minimized. A thick flex circuit with many intermittent metal layers can cause multiple reverberations thus lengthening the emitted pulse resulting in poor axial resolution.

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Figure 1.
1-D linear array with a rectangular field of view.

Figure 2.
Schematic of synthetic aperture using row-column addressing with a 2-D array

Figure 3.
Sequence of transmit events for fully sampled STA/SRA

Figure 4.
2-D Hanning apodization profile for A) on-axis subaperture and B) off-axis bottom left subaperture

Figure 5. Synthetic delay profile for focus A) on-axis at (0 0 20) mm and B) off-axis at (-15 -15 20) mm

Figure 6.
Sequence of transmit events for no STA, fully sampled SRA

Figure 7.

Sequence of transmit events for Acquisition scheme 3, shown here for the center subaperture

Figure 8. Acquisition Scheme 3- Synthetic delay profile for A) on-axis focus at (0 0 20) mm, and B) off-axis focus at (-15, -15, 20) mm

Figure 9. Fully Sampled 256x256 array, 128x128 subaperture- On-Axis A) Azimuth and B) Elevation Beamplots and Off-Axis C) Azimuth and D) Elevation Beamplots

Figure 10.
Design 1 - On-Axis A) Azimuth and B) Elevation Beamplots and Off-Axis C) Azimuth and D) Elevation Beamplots

Figure 11. Design 2- On-Axis A) Azimuth and B) Elevation Beamplots and Off-Axis C) Azimuth and D) Elevation Beamplots

Figure 12. Design 2- Off Axis -6dB and -20dB beamwidths. 18.7 mm corresponds to the edge of the transducer

Figure 13.
Design 3- On-Axis A) Azimuth and B) Elevation

Figure 14. Design 3- Design curves for selecting number of columns, A) beamwidths and B) Sensitivity and Acquisition time

Table 1

Summary of the three acquisition schemes

		FS (Gold Standard)		FS STA/SRA		No STA/FS SRA		Sparse STA	
		Az	El	Az	El	Az	El	Az	El
On-Axis	6 dB (mm)	0.20	0.20	0.20	0.20	0.38	0.38	0.20	0.35
	20 dB (mm)	0.36	0.36	0.35	0.33	0.69	0.69	0.34	0.67
	40 dB (mm)	0.75	0.75	0.76	0.66	1.44	1.44	0.84	1.39
	60 dB (mm)	1.34	1.34	1.37	2.34	3.05	3.05	2.45	3.47
	GLL (dB)	-72	-72	-65	-27	-50	-50	-65	-82
	Sensitivity (dB)	0		-45		-39		-47	
Off-Axis	6 dB (mm)	0.21	0.21	0.21	0.20	0.39	0.39	0.20	0.37
	20 dB (mm)	0.39	0.39	0.38	0.55	1.19	1.19	0.37	1.10
	40 dB (mm)	1.03	1.03	1.04	1.65	3.59	3.59	2.65	3.39
	60 dB (mm)	2.36	2.36	2.51	3.4	-	-	5.36	6.56
	GLL (dB)	-52	-52	-45	-23	-35	-35	-40	-61
	Sensitivity (dB)	-2		-46		-40		-53	
Acq. Time	# of Tx events	139,876		65,536		256		3,840	
	Volumes/s (6cm depth)	0.09		0.2		50		3.4	

Table 2

Designs evaluation overview

	FS STA/SRA	No STA/FS SRA	Sparse STA
Advantage	Beamwidths	Acquisition time	Az beamwidths
Tx Focusing	AZ/EL	no	AZ only
Main Disadvantages	Acquisition time, El grating lobes	Beamwidths	El Beamwidths Sensitivity