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Feasibility Study of a Coherent Multi-Transducer US Imaging System

1st Laura Peralta
Dept. of Biomedical Engineering
School of Biomedical Engineering & Imaging Sciences
King's College London, London, UK
laura.peralta_pereira@kcl.ac.uk

2nd Alberto Gomez
Dept. of Biomedical Engineering
School of Biomedical Engineering & Imaging Sciences
King's College London, London, UK
alberto.gomez@kcl.ac.uk

3rd Joseph V Hajnal
Dept. of Biomedical Engineering
School of Biomedical Engineering & Imaging Sciences
King's College London, London, UK
jo.hajnal@kcl.ac.uk

4th Robert J Eckersley
Dept. of Biomedical Engineering
School of Biomedical Engineering & Imaging Sciences
King's College London, London, UK
robert.eckersley@kcl.ac.uk

***Abstract*—Ultrasound images can be difficult to assess, because of the limited resolution and view-dependent artefacts that are inherent to the small aperture transducers used clinically. An extended aperture has the potential to greatly improve imaging performance. This work introduces a fully coherent multi-transducer ultrasound imaging system, formed by two ultrasound transducers that are synchronized, freely located in space with a common field of view and transmit plane waves. Through coherent combination of the different transducers, a larger effective aperture is obtained and then an improved final image. First phantom images produced using this technique are presented here.**

***Index Terms*—Untrasound Imaging, Plane Waves, Large Aperture, Beamforming, Image Resolution**

I. Introduction

The quality of ultrasound images is often limited by the spatial resolution and restricted field of view (FoV), particularly at large depths in abdominal or fetal imaging applications. To increase the FoV, multiple images can be incoherently compounding together in the lateral direction using image registration or mechanically moving the probe [1]. However, the resolution of the resulting image is reduced. Expanding the aperture size is a direct way to improve resolution. Hence, if the different transducers can be coherently combined, significantly increasing the aperture size of the system, an enhanced image is expected.

The improvements of a wider coherent aperture have been already shown in synthetic aperture ultrasound imaging [2], [3], where an extended aperture was obtained by mechanically moving and tracking the ultrasound transducer. The tracking information was used to identify the relative position and orientation of the ultrasound images which were then merged together into a final image. Nevertheless, the use of a motor controlled device requires a calibration procedure that in addition to the tracking inaccuracy may cause image degradation. Resolution will suffer from motion artefacts, tissue deformation or tissue aberration, which worsen with increased effective aperture size and long acquisition times [4].

This work proposes a fully coherent multi-transducer ultrasound imaging system, formed by two linear arrays that are synchronized and freely disposed in space with a common FoV. Through coherent integration of the signals received by both transducers, a larger effective aperture is obtained, leading to an improved final image. Generation of a coherent aperture requires the position of transmitters and receivers to be known to subwavelength accuracy. In this work, no external tracking device is used. The method presented here enables to coherently combining multiple transducers by maximizing the spatial coherence function of the backscattered echoes received by the same transducer and resulting from a targeted scatterer point in the medium isonated by the multiple ultrasound probes of the system.

II. Methods

A. Multi-Transducer Beamforming

Let us consider a multi-transducer system formed by two identical linear arrays which share part of the FoV and lay on the same plane ($y = 0$) but otherwise at an arbitrary angle and position relative to each other (see Fig. 1). The transducers are synchronized and take turns to transmit a plane wave (PW). The resulting echoes scattered from the medium are recorded using all the transducers that form the system (including the transmitting one). A PW transmitted by transducer i at angle α is defined by the line $L_i(\alpha)$. In a sequence in which transducer i transmits and transducer j receives, the RF data received on channel h of transducer j at time t is named $T_iR_j(h, t)$. The resulting image and all transducer coordinates are defined in a world coordinate system arbitrarily located in space $(\hat{x}_0, \hat{z}_0)$. For each transducer, a local coordinate system $(\hat{x}_i, \hat{z}_i)$ is defined at the center of the transducer surface with the $\hat{z}$ direction orthogonal to the transducer surface and directed away from transducer i. The position and orientation of transducer i are then characterized in the world coordinate system with 3 parameters, a translation vector $\mathbf{r}_i$ and a rotation angle θ_i [5].

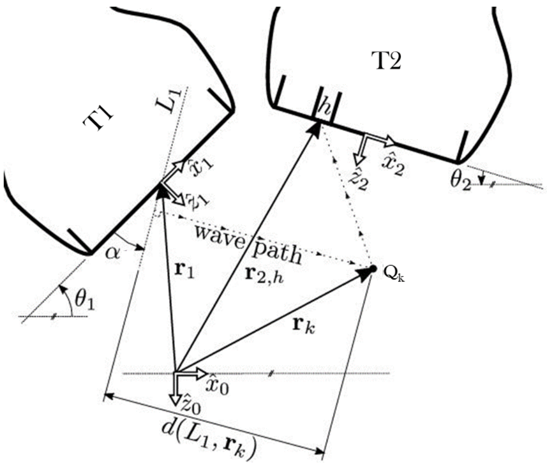

Fig. 1. Multi-transducer beamforming scheme. In this example, transducer T_1 transmits a plane wave at angle α and T_2 receives the echo scattered from Q_k on element h.

Taking into account the full path length between the transmit transducer and the receive elements, PW imaging beamforming [6] can be extended to the present multi-transducer set-up. Assuming that transducer i transmits a plane wave at certain angle α, the image point to be beamformed located at Q_k and described by the vector $\mathbf{r}_k$ can be computed from the echoes received at transducer j as:

$$
\begin{aligned}
s_{i,j}(Q_k;\alpha) &= \sum_{h=1}^{H} T_iR_j\left(h, Q_k;\alpha\right) = \\
&\sum_{h=1}^{H} T_iR_j\left(h, \frac{D_{i,j,h}(Q_k;\alpha)}{c}\right)
\end{aligned} \tag{1}
$$

where H is the total number of elements in the array and c is the speed of sound of the medium. The total distance $\mathrm{D}_{i,j,h}(Q_k)$ between the transmit transducer i, the imaging point Q_k and the receive element h of transducer j is defined by,

$$
\mathrm{D}_{i,j,h}(Q_k;\alpha) = d(\mathbf{r}_k, L_i(\alpha)) + \|\mathbf{r}_{j,h} - \mathbf{r}_k\| \tag{2}
$$

where $d(\mathbf{r}_k, L_i(\alpha))$ is the distance from $\mathbf{r}_k$ to the line $L_i(\alpha)$ that defines the transmitted plane wave, and $\|\mathbf{r}_{j,h} - \mathbf{r}_k\|$ is the Euclidean distance between $\mathbf{r}_k$ and the receive element h of transducer j. These distances are represented in Fig. 1.

Finally, the total beamformed image $S(Q_k;\alpha)$ can be obtained by coherently adding the individually beamformed images acquired in a sequence in which both probes transmit:

$$
\begin{aligned}
&S(Q_k;\alpha) = \\
&s_{1,1}(Q_k;\alpha) + s_{1,2}(Q_k;\alpha) + s_{2,1}(Q_k;\alpha) + s_{2,2}(Q_k;\alpha)
\end{aligned} \tag{3}
$$

B. Calculation of the Relative Position of Two Transducers

This section presents the method to calculate the relative position and orientation of each imaging probe (defined by $\mathbf{r}_i$ and θ_i) that is required to coherently reconstruct images acquired by multiple transducers. The medium is considered homogeneous with constant speed of sound except for K point scatterers located at positions Q_k, $k = 1, \ldots, K$. In the present configuration, of 2 synchronized linear arrays that share part of the FoV, the wavefields resulting from the same point scatterer and received by the same transducer from consecutive transmissions (i.e. $T_1R_1(h, Q_k)$ $T_2R_1(h, Q_k)$ and $T_1R_2(h, Q_k)$ $T_2R_2(h, Q_k)$) must be similar and have spatial covariance [7]. The proposed method consists of finding the optimal parameters for which the similarity across RF datasets sharing the receive transducer is maximum for all common scatterers. Those parameters are the ones that define the total reception time corresponding to each scatterer and are:

$$
\mathcal{P} = \{\alpha, c, \theta_1, \mathbf{r}_1, \theta_2, \mathbf{r}_2, Q_1, \ldots, Q_K\} \tag{4}
$$

In practice the transmit angle α is known and defining the world coordinate system the same as the local coordinate system of one of the transducers reduces the problem to $\mathcal{P} = \{c, \theta_2, \mathbf{r}_2, Q_1, \ldots, Q_K\}$.

The optimal parameters $\bar{\mathcal{P}}$ can be found maximizing the cost function χ by using gradient-based optimization methods,

$$
\bar{\mathcal{P}} = \arg\max_{\mathcal{P}} \chi(\mathcal{P}) \tag{5}
$$

Measuring the coherence by the normalized cross-correlation (NCC), the cost function quantifies the total coherent of the system over all receive transducers,

$$
\begin{aligned}
\chi(\mathcal{P}) = \sum_{k}^{K}\sum_{h}^{H} &\{\mathrm{NCC}(T_1R_1(h, Q_k;\mathcal{P}), T_2R_1(h, Q_k;\mathcal{P}))W_{1,1}W_{2,1} \\
&+\mathrm{NCC}(T_1R_2(h, Q_k;\mathcal{P}), T_2R_2(h, Q_k;\mathcal{P}))W_{1,2}W_{2,2}\}
\end{aligned}
$$

where $W_{i,j}$ is a weighting factor proportional to the degree of coherence between pulses received across the individual elements of a single transducer,

$$
W_{i,j}(\mathcal{P}) = \frac{1}{2} + \frac{1}{2H}\sum_{h_b \neq h}^{H} \mathrm{NCC}(T_iR_j(h;\mathcal{P}), T_iR_j(h_b;\mathcal{P})) \tag{6}
$$

The optimization algorithm can be initialized as follows. Considering the world coordinate system the same as the local coordinate system of transducer T_1 ($\theta_1 = 0$, $\mathbf{r}_1 = [0, 0]$), the parameter $\{\theta_2, \mathbf{r}_2\}$ that define the position of transducer T_2 were calculated using point-based image registration [1], [5]. Two single images, T_1R_1 and T_2R_2, acquired by each of the transducers were used. For the scatterer positions Q_k and speed of sound of the propagation medium c, their initial value was calculated from the RF data T_1R_1 using the best-fit one-way geometric delay for the echoes returning from the targets [8].

III. Experimental Validation

The method was experimentally validated using two 256-channel Ultrasound Advanced Open Platform (ULA-OP 256) systems (MSD Lab, University of Florence, Italy) [9]. The systems were synchronized, i.e. with the same trigger and sampling times in both transmit and receive mode. Each ULA-OP 256 system was used to drive an ultrasonic linear array made of 144 piezoelectric elements with a 6 dB bandwidth ranging from 2 MHz to 7.5 MHz (imaging transducer LA332, Esaote, Firenze, Italy). The two probes were mounted on xyz translation and rotation stage (Thorlabs, USA) and were carefully aligned in the same elevational plane ($y = 0$). For each probe in an alternating sequence, i.e. only one probe transmits at each time while both probes receive, 121 PW were transmitted (-30^o to 30^o, 0.5^o step) at 3 MHz and pulse repetition frequency (PRF) of 4 kHz. RF raw data backscattered up to 77 mm deep were acquired at a sampling frequency of 39 MHz.

A custom-made wire target phantom (200-μm diameter), positioned so that all wires (5 in total) were in the common FoV of the 2 transducers, was used to measure resolution. Spatial resolution was calculated from the point-spread-function (PSF) on a single scatterer and measured as full-width-at-half-maximum (FWHM) using the -6 dB width to describe main lobe resolution. In addition, resolution was described using a k-space representation [10].

IV. Results

Fig. 2 shows a comparison between a conventional PW reconstruction with a single transducer and a coherent multi-transducer image. The multi-transducer image of the wire targets was clearly improved. Lateral resolution (LR) was measured at the transverse cut of the PSF at the scatterer depth indicated by dotted lines and that leads to the best resolution in each case. The resulting performance is summarized in Table I. The coherent multi-transducer acquisition presents the best lateral resolution. Also, larger differences are observed in the behavior of the side lobes, which are higher in the coherent multi-transducer method. When a single PW is used, the biggest difference is between the second side lobes, being raised by 13 dB for the coherent multi-transducer method compared to the single transducer method, while the difference of the first side lobes is 3.5 dB. This suggests that while significant image improvements can be achieved, the image may suffer from the effects of side lobes.

TABLE I

Imaging performance for the different methods

	LR [mm]	1^{st} sidelobe [dB]	2^{nd} sidelobe [dB]
Single Transducer (1 PW)	0.6674	-14.96	-20.79
Multi Coherent (1 PW)	0.1817	-11.46	-7.01
Single Transducer (121 PW)	0.6546	-20.22	-
Multi Coherent (121 PW)	0.1911	-9.94	-9.64

The PSF and the corresponding k-space represenation are shown in Fig. 3. Note that, since the coherent multi-transducer image is obtained by coherently adding four RF data sets (see equation 3), then as a consequence of the linearity of the system, the total k-space of the coherent multi-transducer system shows an extended lateral region that corresponds to the sum of the four individual k-spaces.

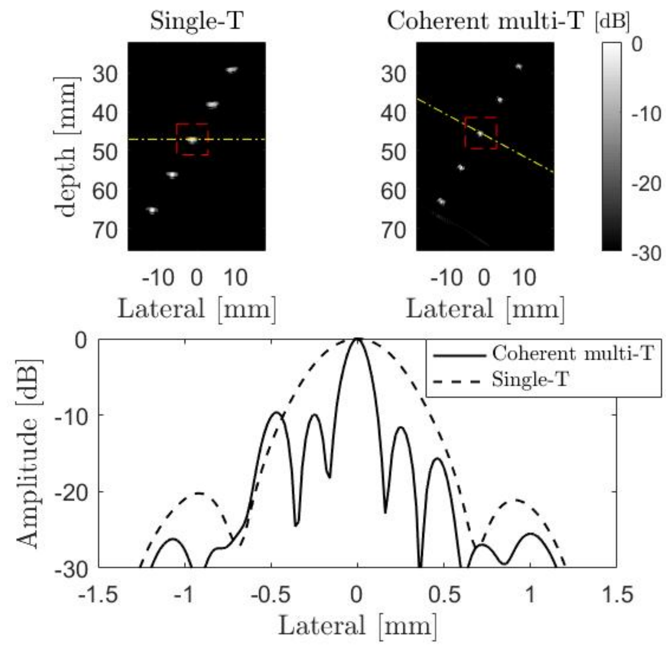

Fig. 2. Experimental images produced with a single transducer and coherently compounding the images acquired by both transducers. Transverse cut of the PSF at the scatterer depth indicated with dashed lines and that leads to the best resolution in each case.

V. Discussion

This study shows the feasibility of increasing the effective aperture by the coherent combination of signals acquired by different synchronized transducers that have a shared FoV and transmit PW. To successfully improve the PSF, the proposed multi-transducer method requires coherent alignment of the backscattered echoes from multiple transmit and receive positions. However, this requirement in practice is not achievable by manual measurements or using electromagnetic or optical trackers on the probes. This study presents a method based on the spatial coherence of the backscattered echoes arising from the same point scatterer and received by the same transducer using sequential transmissions from each of the transducers of the system. The alignment of the backscattered echoes is calculated by optimizing their spatial coherence. The optimization was done by gradient-descent methods, which require an initial estimate of the parameters close enough to the global maximum of the cost function. The distance between maxima, which depends on the NCC and corresponds to the pulse length, dictates this tolerance. This is approximately 1.5 μs (equivalent to 2.19 mm) for the experimental configuration used here. This tolerance value can be realistically achieved through image registration [1], [5].

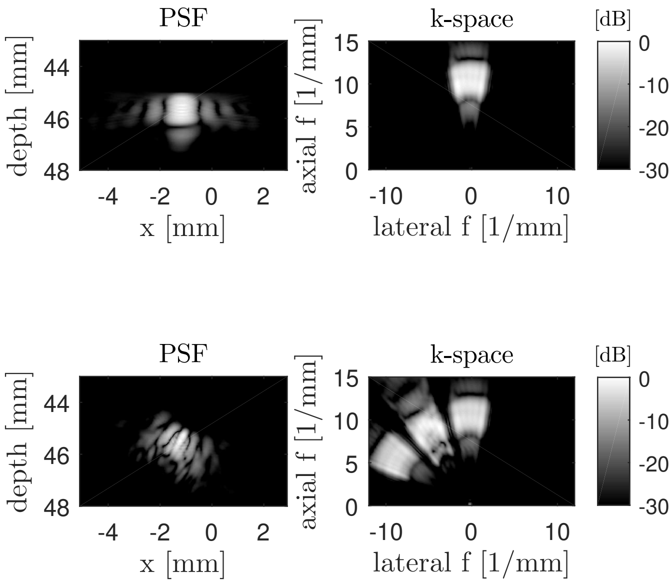

Fig. 3. PSF and k-space representation of a single transducer system (upper graph) and the coherent multi transducer system (bottom graph). Images formed using a single PW at 0^o.

Resolution enhancements related to increasing aperture size are well known [3]. Nevertheless, large-aperture arrays represents ergonomic operator problems and have limited flexibility to adapt to different applications. In this work, the extended aperture is the result of adding multiple freely placed transducers together, which allows more flexibility. Aperture can also be extended by combining synthetic aperture data sets over a range of aperture positions while precisely tracking the position and orientation of the transducer. However, its success relies on the accuracy of the tracking system and ultrasound calibrations. A key feature to consider in the coherent multi-transducer system presented in this paper is that all probes receive simultaneously reducing effect of tissue motion during reception. In addition, since all elements are used in transmission, the use of PW generates a high energy wavefield improving penetration and also enabling high frame rates [6].

Wavefront aberration caused by inhomogeneous medium can significantly limit the quality of medical ultrasound images and is the major barrier to achieve diffraction-limited resolution with large aperture transducers. In the method presented here, the speed of sound is a parameter in the optimization and then, this more accurate speed of sound estimation would improve beamforming and allow higher order phase aberration correction. In addition, the use of multiple transducers allows multiple interrogations from different angles, which might give insight into the aberration problem and help to test new algorithms to remove the clutter.

Finally, different transmit beam profiles such as diverging waves may increase the overlapped FoV, extending the final high resolution image. Further studies are needed to predict the performance of the proposed multi transducer system for in-vivo imaging. Although the theory was presented for punctual scatterers, the approach relies on a measure of spatial coherence which may well allow wider usage.

VI. Conclusions

This study presents a new coherent multi-transducer imaging system. A method to coherently align the different RF data received by the system in order to beamform the final image has been proposed. The method was experimentally validated and improvements in imaging quality in terms of resolution have been shown.

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