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CIS II Seminar Presentation

Seminar Presentation Summary

Synthetic Aperture Ultrasound Imaging with Robotic Tracking Technique
600.446 Computer Integrated Surgery II, Spring 2014
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Paper: Synthetic aperture ultrasound imaging, Jensen J., Nikolov S., Gammelmark K., Pedersen M.

Introduction:

History of synthetic aperture imaging:

- Originally conceived for radar systems in the 1950s.
- Monostatic synthetic aperture imaging is implemented in the 1970s and 1980s.
- The first direct attempt to apply synthetic aperture imaging for medical ultrasound imaging: O'Donnell and Thomas published a method intended for intravascular imaging based on synthetic aperture imaging utilizing a circular aperture in 1992.
- The application of multi-element subapertures to increase the SNR using phased array transducers by Karaman et al.
- 3D applications by Lockwood et al.
- Recursive ultrasound imaging by Nikolov et al.
- The definition of synthetic transmit aperture (STA) imaging was introduced by Chiao et al.

The influence of motion in STA is investigated in several publications: Axial motion is the dominant factor causing image quality degradation due to the significantly higher spatial frequency in this dimension, most of the proposed motion estimation methods based on time-domain cross-correlation of reference signals to find the shift in position in the axial dimension.

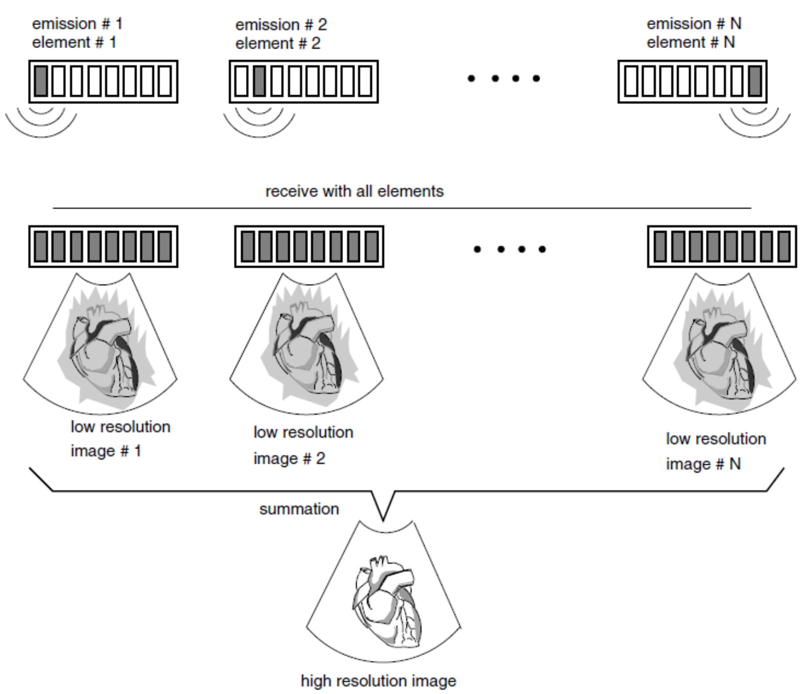
Conventional ultrasound imaging:

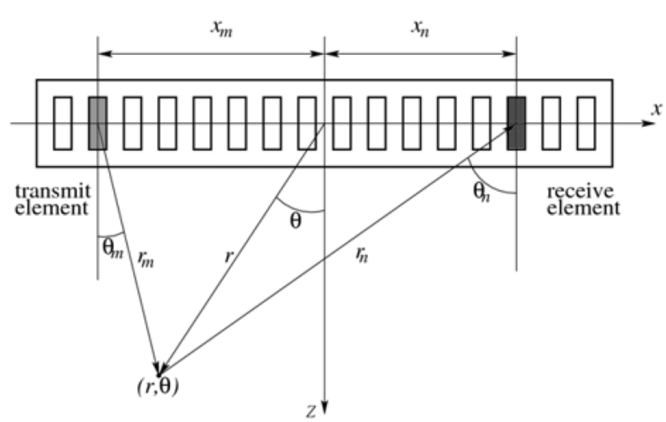
In conventional ultrasound images are acquired sequentially one image line at a time. The acquisition rate is limited by the speed of sound c. The maximum frame rate f_r for an image with N_1 lines to a depth of D is $f_r = \frac{c}{2DN_1}$. The approximate 3-dB resolution of an imaging array consisting of N elements with a pitch of D_p is $b_{3dB} = 0.5\frac{D_i}{ND_p}\frac{c}{f_0}$ where D_i is the focus depth and f_0 is the center frequency. Assuming the image to cover the full size of the array and a pitch $D_p = \lambda/2$ then gives a frame rate of

$N_1 = \frac{2f_0}{D_i c}$, $f_r = \frac{D_i f_0}{DN^2}$. Two problems with the conventional systems is the single transmit focus and the low frame rate for velocity estimation problems. Synthetic aperture imaging can solve both frame rate and focusing problem.

Introduction to synthetic aperture imaging:

A single element in the transducer aperture is used for transmitting a spherical wave covering the full image region. The received signals can be used for making a low resolution image, which is only focused in receive due to the un-focused transmission. Focusing is performed by finding the geometric distance from the transmitting element to the imaging point and back to the receiving element. Dividing this distance by the speed of sound c gives the time instance $t_p(i, j)$ to take out the proper signal value for summation such that $t_p(i,j) = \frac{|r_p - r_e(i)| + |r_p - r_r(j)|}{c}$, r_e: position of transmitting element i, r_r: position of the receiving element j, r_p: image point. (Figure on the left from presented paper, figure on the right from Trots, Nowicki, Lewandowski, Tasinkevych from Institute of Fundamental Technological Research, Poland)





g. 2. Geometric relation between the transmit and receive element combination and the cal point

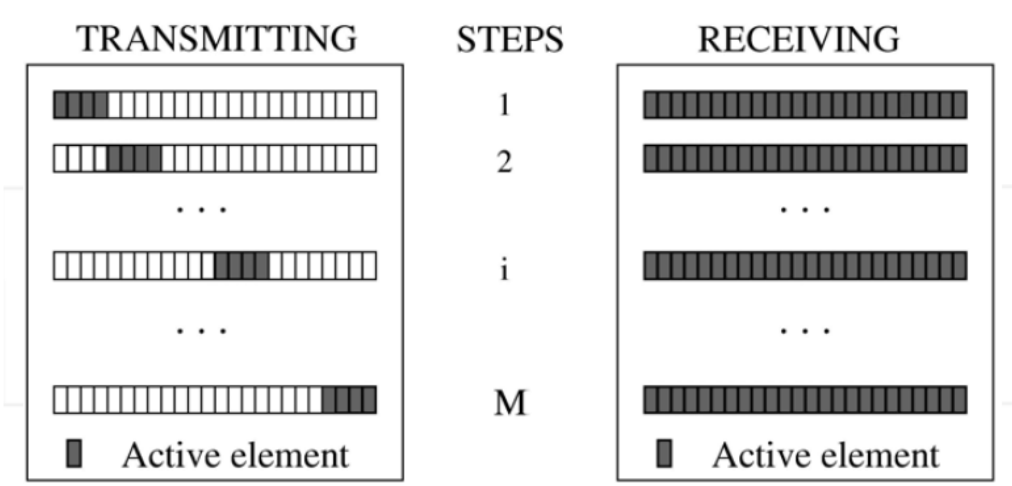
After combining the low resolution images, the final signal is:

$y_f(r_p) = \sum_{j=1}^{N} \sum_{i=1}^{M} a(t_p(i,j),i,j)\, y_r(t_p(i,j),i,j)$ where y_r: the received signal for emission I on element j, a: weighting function applied on the signal, N: number of transducer elements, M: number of emissions. Note that the focused signal is a function of space, and that this can be anywhere in the image. Therefore focusing can be performed in any order and direction. In SA imaging only a sparse set of emissions can be used for creating a full image, so it is possible to decouple frame rate and pulse repetition time. Very fast imaging can, therefore, be made albeit with a lower resolution and higher side-lobes. The resolution is determined by the width of the transmitting and receiving aperture and the side-lobe levels are determined by the apodization and the number of emissions.

On the other hand, fast imaging at the pulse repetition frequency can be attained by using recursive imaging. In this method SA acquisition sequence is repeated, so that emission 1 is performed again after all emissions have been made. A full image can be made by combining all emissions, which can be from 1 to M or from 2 to M and 1. The new emission 1 can, thus, replace the old emission 1, which can be done by subtracting the old and adding the new emission. This can be done recursively, which results in a new image after every emission. Such an approach can yield very high frame rates and can be used for velocity imaging.

Penetration problem

In SA imaging, un-focused wave is used in transmit and only a single element emits energy, so penetration depth is limited. This problem can be solved by combining several elements for transmission and using longer waveforms emitting more energy. Also, to increase the energy, it can be combined with a chirp excitation (for details, see Michaels J.E., Leeb S.J., Croxford A.J., Wilcox P.D., Chirp excitation of ultrasonic guided waves). (Figure from Trots, Nowicki, MLewandowski, Tasinkevych from Institute of Fundamental Technological Research, Poland)



Equipment and implementation

The authors have developed a software (RASMUS) to acquire SA images. All conventional ultrasound imaging methods can be implemented with this system, but real-time SA imaging is not possible. The data is stored in the RAM and later processed on a Linux cluster.

Flow estimation

Velocity estimations in conventional ultrasound is done by finding the shift in position of the scatterers over time. Lines are acquired from the same direction (8-16 times) and then the data is correlated to find the shift in position between lines as either a phase shift or as a time shift. Dividing the spatial shift by the time then gives the velocity. This method can only find the velocity along the ultrasound direction, the standard deviation is often high, and the frame rate is lowered by the number of emissions per direction.

In SA imaging, it is possible to focus the received data in any direction and in any order. It does not have to be along the direction of the emitted beam, since the emission is spherical and illuminates the full region of interest. It is, thus, possible to track motion of objects in any direction. This can be used to devise a full vector velocity imaging system. The received data can be focused along the direction of the flow (Figure from the presented paper).

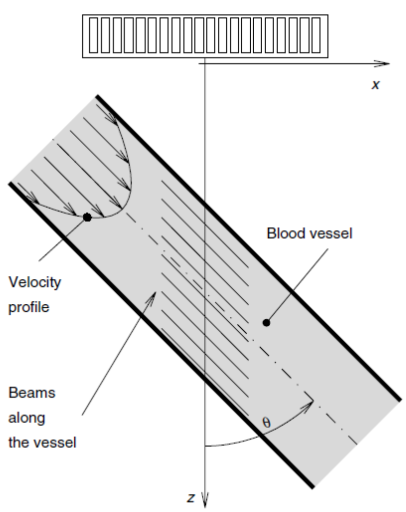


Fig. 7. Beamforming is made along the laminar flow (from [38]).

A sequence of emissions of (M = 4–8) is used and the high resolution image lines y(x') are then focused along the flow direction x'. A velocity v results in a displacement between high resolution images of

$\Delta x' = |v| M T_{prf}$ where T_{prf}: time between emissions. Data for the first image line is $y_1(x')$, and next image line is $y_2(x') = y_1(x' - \Delta x')$. Cross correlation between y_1 and y_2 gives a peak at $\Delta x'$, and dividing by

MT_{prf} gives the magnitude of the velocity. The approach has been investigated using RAMUS. The advantages of the approach is that the velocity can be accurately found in any direction, and that the color flow imaging can be done very fast. Only 128 emissions are needed, where a normal system would need roughly 800 for 100 image directions. The data is also continuously available for all image directions and the velocity can be estimated for as many emissions as the velocity can be assumed constant. The continuous data also makes it easier to perform stationary echo canceling to separate tissue and blood signals, since filters can have any length and initialization can be neglected.

The flow angle must be known before beamforming in the flow direction, and this was in the previous examples estimated from the B-mode image. It can, however, also be estimated from the actual data. At the actual direction the correlation of the data $y_1(x')$ and $y_2(x')$ is highest. For other directions the correlation will drop, since the velocities along that line are different due to the velocity profile of the blood.

Motion compensation

The accurate velocity estimation can also be used for compensating for tissue motion during the SA acquisition process. The B-mode sequence can then be inter-spaced with a flow sequence and the tissue velocity can be estimated from this data. Knowing the velocity is then used for correcting the position of the low resolution images that then can be summed in phase.

Clinical results

Authors acquired in vivo real-time data and then make off-line processing for finding the clinical performance. They programmed the system to acquire both a conventional convex array image and a SA image. The sequences were acquired interleaved to have the same region of interest, transducer, and measurement system at the same time. Seven human volunteers were scanned at two positions for both SA and conventional imaging yielding 28 videos. The sequences were presented to three experienced medical doctors in a double blinded experiment and they were asked to evaluate the images in terms of penetration depth and relative performance between the two images. Penetration depth and image quality showed highly significant improvement in SA images compared to conventional images.

Advanced coded imaging

In the previous approaches, only a single emission center is active at the same time. This limits the emitted energy and the amount of information acquired per emission. It is quite inexpensive to make a transmitter compared to a receiver, and it is, therefore, an advantage to use several emissions simultaneously. This problem was solved in the spread spectrum approach suggested in F. Gran, J.A.

Jensen, Multi element synthetic aperture transmission using a frequency division approach and Spatio-temporal encoding using narrow-band linearly frequency modulated signals in synthetic aperture ultrasound imaging. In this method, each transmitter is assigned a narrow frequency band. The signals for the individual sources can then be separated using matched filters provided that the bands are disjoint. The high resolution image can then be made by repeating the procedure for all frequency bands for all emitters and then combine all the received signals after filtration. The approach can be used for flow estimation, since the separation is not done over a number of emissions.