600.446 CIS II Paper Critical Summary

Group 1: Ultrasound Imaging of Brain Shunts

Yang Hong

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M. Fink, "Time reversal of ultrasonic fields-Part I: Basic principles". *IEEE Trans. Sonics Ultrason.* 39(5), 555–566 (1992).

J.-L. Robert, M. Burcher, C. Cohen-Bacrie, and M.Fink, "Time reversal operator decomposition with focused transmission and robustness to speckle noise: Application to microcalcification detection". *J. Acoust. Soc. Am.*, 119:3848-3859 (2006).

Reasons for selecting the papers

Our project is to image the occlusion together with the brain shunts using photoacoustic and ultrasound imaging. Photoelectric excitation on the occlusion material induced by laser systems will generate acoustic waves to propagate to all the directions, which can be further collected by an external ultrasound probe, making the occlusion and the shunts visible.

One major challenge of our project is the reflection and attenuation of the acoustic waves caused by the skull, which makes the image vague and indistinct. The nature of the problem is that, the variation of the time delays incurred by the inhomogeneities of the medium finally leads to poor special focusing. The first selected paper introduces a method called time reversal process to solve this problem. Furthermore, associated time reversal operators are discussed in the second paper to achieve dynamic focusing.

Paper I: Time reversal of ultrasonic fields-Part I: Basic principles

Summary

In classical techniques (adaptive time-delay techniques), the speed of sound is assumed to be constant through the medium, so we can calculate the propagation time from each transducer, and the required time delay to focus on the focal location can be further obtained by maximizing the cross-correlation of the received signals. However, the variation of the sound speed and the attenuation in the medium, which cause the received signal varying in shape and size, rarely lead to the optimized delay for each transducer element.

The time reversal process suffers from none of the above problems. A simplistic example with the propagation of acoustic waves through the interface between two mediums has been adopted to show how time-reversal works. To expand it to complex 3D situations with multiple scatters, a time reversal cavity is formed. The efficiency of time-reversal is analyzed from closed cavities.

Unfortunately, such a time-reversal cavity is considered difficult to realize, which is replaced by an array of transducers. By utilizing piezoelectric transducer arrays, a time-reversal mirror (TRM) has been developed, which has the same constrictions as the classical focusing techniques while implementation: the diffraction effects, the limited dimension of the TRM, the introduced grating lobes and a maximum sampling rate of T/8.

The reciprocity theorem states that the observed pressure stays the same while reversing the position of the point source with the observer, which is shown in the Green function $G(r_0, t_0|r, t) = G(r, t_0|r_0, t)$. The time reversal process is demonstrated with a single scatterer in 3 steps: first, acoustic wave signal to location r_0 is sent; second, each transducer element receives an impulse response: $h_i^{ac}(t) \otimes h_i(r_0, t)$; third, the received signals are time-reversed and re-emitted: $h_i^{ac}(T-t) \otimes h_i(r_0, T-t)$. This allows the signals propagate through the medium to reach the scatterer at the same time, which maximize the energy of the signal at r_0. Finally, element j will receive the signal:

$$\left[\sum_{i=1}^{M} h_i^{ac}(T-t) \otimes h_i(r_0, T-t) \otimes h_i^{ac}(t)\right] \otimes h_j(r_0, t)$$

In multiple scatterer cases, the most reflective target will be left and the weak targets will be eliminated after some iterations.

A closed time-reversal cavity and a long enough recording time are required to form a complete time-reversal process. Therefore, the practice process suffers from loss of information due to a finite spatial aperture and short temporal windows, chosen by TRM. But this actually helps the iterative mode to have the capability to select its target.

At last, the possibility of automatic selection and excitation of vibration modes has been discussed, and a comparison between TRM and phase-conjugated mirrors has been provided.

<u>Analysis</u>

The problems of the traditional adaptive time-delay focusing have been solved by the time reversal process developed by the author. It does not suffer from the cross-correlation related problems, since it does not depend on the transmission signals. Furthermore, no assumptions have been made regarding the medium or the properties of the ultrasound transducer elements, so the inconsistencies of these won’t affect the process, which makesits robustness to be a very remarkable achievement of the time-reversal focusing.

This approach gives an optimal solution for focusing on the location of the scatterer, which maximizes the energy at the selected target location and realizes the spatial-temporal matched filter between the transducer elements and the target through an inhomogeneous propagation transfer function.

The ability of TRM to choose the origin and the duration of the signals to be time reversed is one of its major advantages, that enables the automatic target selection. In multiple scatterer cases, the time reversal process always automatically focuses on the strongest scatterer after some iterations, which, however, isn't desirable all the time. Sometimes, weak scatters need to be focused as well, which is the major weakness of the process.

Paper II: Time reversal operator decomposition with focused transmission and robustness to speckle noise: Application to microcalcification detection

Summary

Decomposition of the time reversal operator (DORT) has been developed to deal with the weakness of TRM we discussed above. The iterative time reversal process is described by the decomposition of the transfer matrix in DORT. DORT inheres the advantages of TRM over traditional cross-correlation based method, that no assumptions have been made on the medium and the transducer elements.

In this paper, the conventional DORT method has been modified to create FDORT by using focused pulses for initial transmission, instead of using a single element. Two limitations of DORT make FDORT more attractive to use, while FDORT preserves all the merits of DORT: most of the ultrasound scanners transmit a focused beam by transducer array with proper time delays, which makes the collection of a full data set impossible; the susceptibility to speckle of DORT makes its eigenvectors too noisy to focus on scatters accurately.

First, DORT is introduced thoroughly in the paper, which is based on a transmit-receive process performed between to arrays. The signal received on the nth transducer is linked by an inter-element impulse response $k_{mn}(t)$ to the signal transmitted from the mth transducer: $r_n(t) = e_m(t) \otimes k_{mn}(t)$, which leads to the following matrix formulation: $R(\omega) = K(\omega)E(\omega)$. After time reversing and re-emitting, the signal received at e is $\mathrm{K^T\overline{KE}}$, conjugate of $\mathrm{(K^H K)E}$, with $\mathrm{K^T}$ denoting the frequency response in reverse direction. Thus, the received signal after nth iteration is $\mathrm{R^n = (K^T\overline{K})^n\overline{E}}$.

Consider two scatters P and Q. Define Green functions $\mathrm{H_{Tx}(P)}$ from e to P, $\mathrm{H_{Rx}(P)}$ from r to P, $\mathrm{H_{Tx}(P)_m}$ the propagation between mth element of e and P, and D(P) the reflectivity of P. the propagation from m to n is $\mathrm{K_{nm} = H_{Tx}(P)_m D(P) H_{Rx}(P)_n + H_{Tx}(Q)_m D(Q) H_{Rx}(Q)_n}$. So finally we have the transfer matrix $\mathrm{K = (H_{Rx})^T D H_{Tx}}$, and the time reversal operator $\mathrm{KK^H = (H_{Rx})^T D H_{Tx} H_{Tx}^H \overline{D H_{Rx}}}$.

$$\mathrm{\overline{H_{Rx}}{H_{Rx}}^T} = \begin{bmatrix} \mathrm{\|H_{Rx}(P)\|^2} & \mathrm{< H_{Rx}(Q), H_{Rx}(P) >} \\ \mathrm{< H_{Rx}(P), H_{Rx}(Q) >} & \mathrm{\|H_{Rx}(Q)\|^2} \end{bmatrix}$$

Since D is diagonal, the time reversal operator needs to be diagonalizable as well:

$< H_{Rx}(Q), H_{Rx}(P) > = 0$, and $< H_{Rx}(P), H_{Rx}(Q) > = 0$, which means the scatters need to be spacially spread to not interfere with each other. The above calculation is based on isotropic scattering, only true for point-like discontinuity in compressibility. Additional complexity is needed for Dipole scattering.

In FDORT, a generalized transfer matrix is defined: $K_{foc} = KB^T$, where B is a $M \times N$ matrix that denotes focusing to M locations by N elements. Using previous result of DORT, we have $K_{foc} = (H_{Rx})^T D H_{Rx} B^T$. Therefore, the focusing locations of multiple scatters can be determined by FDORT.

Then, the author provides a comparison between DORT and FDORT theoretically and practically. The resolution is lower with FDORT and is limited by the size of the transmit aperture. When speckle is presented, both DORT and FDORT are not able to resolve different scatterers. To sample the medium in slices and gate the signal in depth gives a solution to the problem, which is only available in FDORT.

FDORT is proved to adapt for local processing better than DORT. An application of the method to detect small microcalcifications embedded in speckle is presented, and demonstrated to have good properties for clinical use. Manipulating both the ratio of the two first eigenvalues and the location of the window by local FDORT to improve the quality of the focusing is proposed.

Analysis

The contribution of the DORT and FDORT are obvious that adaptively focusing on strongly reflecting targets has been achieved invariant of the medium and the transducer properties. The shortcoming of only focusing on the strongest scatter has been overcome. Speckle will highly affect the quality, but solutions have been proposed to improve the condition.

Some limitations of the methods are inhered from TRM, that not many scatters can be detected after some iterations, and the scatterers need to be point sources. When the scatters are spacially close to each other or to speckles, the overlap of their responses will make FDORT hard to focus on each scatter individually. And because the methods are theoretically depends on the calculation of the eigenvectors and the eigenvalues, which are based on the distance and magnitude of the scatters, scatters with same magnitude are not able to be resolved and focused. The solution to the above problems should be further explored during the future research.