Dgital Beam Forming in the MRI

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Introduction

In phased array radar, the element antennas are excited with different phases to point the array beam in a particular direction and this is termed analog beam forming, and varying the phases causes beam to scan. Various techniques have been used for staring beams which have the antenna beams point in particular directions, including the Butler [1] and Blass [2] matrices, which vary both the phase and magnitude of excitation. The beam forming may also be performed with the receive signals from a broad side array, in which the magnitude and phase of excitation of every element is identical. These receive signals are down-converted to an intermediate frequency (IF) and digitized with the in-phase and quadrature channels. In this case, the digital beam forming is performed by inserting weights, magnitude and phase, on the receive signals to point receive beams in different directions, also null the receive signals from a particular direction as necessary. This paper discusses the extension of these ideas to the MRI system signals. The analog beam forming in the MRI corresponds to the RF shimming, in which the multi-channel coil elements are excited with different magnitudes and phases, in addition to the usual phase delay to obtain the circular polarized RF magnetic field in the subject [3, 4]. The early papers on digital beam forming using the receive signals by Roemer et al [5] has focused on using the correlation matrix to improve the signal to noise ratio. Walsh et al [6] has used the correlation matrix with matched filters again to improve the signal to noise ratio. The whole repertoire of techniques used in radar digital beam forming have not been exploited to the present time and this paper illustrates some of these.

Application to MRI

Following the formulation of Roemer [5] and Walsh [6], the matrix operators representing the signal and noise correlation, $\mathbf{R_s}$, and $\mathbf{R_n}$, are formed from the receiver image data. These matrices serve as weighting operators for the spatial beamforming array vectors from the transmit (or receive) array elements to a set of observation points in the image space. For example, for an *N*-element array and a set of *M* observation points, we can design a propagation operator, **H**, with elements $H(n,m)$ obtained from the complex directivity of the *n*th array element at the *m*th observation point. In practice, these directivities can be computed using an appropriate simulation model or measured directly. For simplicity, we assume that the array elements operate in transmit-receive mode. In this case, the backpropagation operator is + assumed to be the Hermitian transpose for a uniform featureless phantom). An optimum minimum-norm least-squares solution to the beam synthesis problem can be obtained through the *pseudoinverse operator*, $\mathbf{H}^{+}$, which can be computed through *singular-value decomposition.* However, more insight into the workings of the operator can be gained by examining the either the minimum-norm or the least-squares solution depending on whether $M<N$ or $M>N$, respectively. The weighted minimum-norm solution to the synthesis problem gives the complex array excitation vector in terms of specified complex field values at the observation points [7]:

$$\mathbf{u} = \mathbf{W}\mathbf{H}^{*t}\left(\mathbf{H}\mathbf{W}\mathbf{H}^{*t} + \gamma\mathbf{I}\right)^{-1}\mathbf{f} \qquad (1)$$

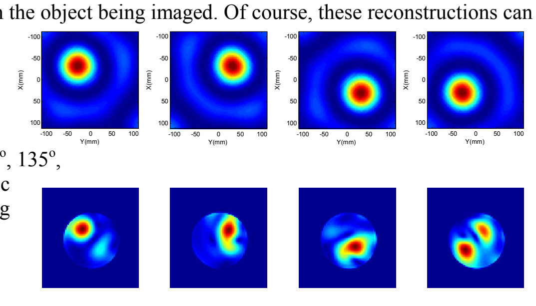
where **W** is a weighting matrix, **f** is an $M\times 1$ vector of the complex field values at the observation points, and γ is a regularization parameter, which can be determined using the Lagrange multipliers method for specific choice of **W**. Assuming **W=I** and $\gamma=0$ for the moment, Equation 1 shows that the synthesis problem involves a spatial inverse filtering followed by a back propagation operator when $\mathbf{H}\mathbf{H}^{*t}$ is invertible. Reciprocity of the wave equation allows for the use of equation 1 for finding the array steering vectors on transmit and receive. The preliminary results shown below were obtained under the assumptions **W=I** and $\gamma=0$ and using image data from an 8-element transmit-receive array. For the case when the transmit and receive arrays employ separate elements with different geometry, equation 1 may be used with different propagation operators describing the array directivity at the observation points in each case. The propagation operator may be used to capture and compensate for the coupling between the array elements. In addition, the weighting matrix may be used to minimize the energy at selected locations in the field (as opposed to nulling) while meeting the constraints specified at the observation points. For example, one can use a spatial correlation matrix associated with a set of pixels in the image to form the weighting matrix $\mathbf{W}=\mathbf{R}^{-1}$, where **R** is defined as follows:

$$R(j,k) = \int_{VoI} I_j(x,y,z) I_k^*(x,y,z)\,dx\,dy\,dz \qquad (2)$$

where $I_j(x,y,z)$ is the complex image due to the *j*th receiver value at a voxel and *VoI* is a volume of interest and j,k=1,2,…, number of receivers. The volume of interest can be determined based on knowledge of regions within the image with artifacts, e.g. the use of instruments in the field of view (FoV). This formulation may also be used in improving the dynamic range by suppressing dominant sources without the use of harsh nulling. The formulation in equation 1 can also be used to address SNR improvements when the spatial noise matrix is characterized for the receiver array, e.g. receive when all transmitters are off. It is also possible to suppress signal components from regions where the SNR is very poor within the FoV.

Results

MR data was collected from an 8-coil transmit-receive array with a diameter of 265 mm with the elements uniformly distributed (45^o angular spacing). The object imaged was a plastic 8 liter bottle, diameter 18 cm, filled with sucrose, salt and water to have ε_r of 58.1 and s of 0.54 S/m. Three sets of *k*-space data include: **Set 1:** All 8 elements were used on simultaneously on transmit (phase angles 0, 45^o, 90^o, … , 315^o) with one data set for each receiving elements**; Set 2:** All 8 elements were off on transmit with one data set for each receiving element; **Set 3:** All eight elements were excited individually on transmit with one data set for each receiving element, a total of 64 data sets. The figure below illustrates the potential benefits of beamforming with arrays of transmit-receive coils. The panels on top illustrate the capability of the 8-element prototype to concentrate the focusing gain for a large range of steering angles off the center of the cylindrical array. The focal spot in every case is largely the same as the geometric spot shown in the figure, top row. The reconstructions below (one two-way focus pattern and the corresponding reconstruction directly below) demonstrate the improved SNR in a region largely defined by the focal region, but also depends on the object being imaged. Of course, these reconstructions can be compounded (as is currently being done with root square sum) to produce a more complete reconstruction. With sufficient computing power, this two-way synthetic aperture imaging can be performed for every pixel of the reconstructed image as is currently being done in the field of ultrasound imaging [8]. Furthermore, the array steering vectors can be computed based on multiple optimality criteria to guard against artifacts or other spatially inhomogeneous noise patterns. The figure shows two-way steered-focus patterns using the 8-coil transmit-receive profile (left to right -45^o, 45^o, 135^o, 225^o) on the top row, and the bottom row the corresponding beamforming reconstructions (synthetic aperture beamforming). Image data from anatomically significant targets (e.g. brain) are currently being analyzed and will be presented at the Meeting.



References

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