HomoSENSE: a Filter Design Criterion on Variable Density SENSE Reconstruction

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Introduction: Variable density (vd) parallel imaging provides freedom of optimizing k-space trajectory either to increase reconstruction SNR or reduce low frequency aliasing. The reconstructions using variable density such as SPACE RIP [1], Generalized SMASH [2], and Generalized SENSE [3] consider this problem globally by solving huge matrix equations, which is time consuming. Parallel processing to different acceleration factor regions, such as Madore's method [4], reduces the reconstruction time but can have a ringing artifact at edges. King [5] addressed a smoothing filter to separate variable density high-pass and low-pass data, thus suppressing the ring artifact. The recombination of the two images could still lead to an intensity bias between the high-pass and low-pass components. This paper discusses a filter design strategy in vdSENSE to reduce bias while still filtering out the ring effect, named as homoSENSE.

Methods: A pattern of variable density similar to that used by Madore and King is combined with Nyquist sampled center k-space and outer undersampled k-space of acceleration factor R. The center k-space contains most of the image energy and the direct sum-of-square reconstruction (or Cartesian SENSE with reduction factor equal to one) gives the full field-of-view (FOV) low-resolution image ρ^{LP}. The high-pass image part ρ^{HP}, which contains mostly boundaries and abrupt changes in image space, can be separately reconstructed by Cartesian SENSE with acceleration factor R. Finally the combination of low-pass and high-pass reconstructions gives the final image at each pixel location.

Two key issues exist in vdSENSE. First, the high-pass filter design should provide enough information for the sensitivity map used for SENSE reconstruction in the high-pass part. It can be easily seen that the ideal high-pass filter with the cutoff frequency at the border of the ACS lines fails since no Nyquist sampled center k-space is contained inside high-pass part. The sensitivity map preliminarily estimated from raw ACS lines can't reflect the true coil mapping effect in the high-pass band and thus the high-pass SENSE reconstruction doesn't have a clear unwrapping effect. Therefore, the filtered high-pass part must include at least part of the scaled center full sampled k-space. Second, the two images ρ^{LP} and ρ^{HP} should be combined in a way which does not over-weight either low or high frequency information.

The proposed HomoSENSE, where it is correlated to homomorphic image processing, provides an energy balance criterion to instruct both the filter design and the final combination. The final reconstruction ρ should have energy equal to an estimate of the energy of fully sampled data. The assumption is made that the distribution of energy in k-space is fairly smooth, so that the equally spaced undersampled high-pass spectrum has 1/R energy of the full spectrum. With scaling factors in the IFFT taken into account, energy balance in coil k can be written as $\sum_{i,j} S_k(i,j)^2 (F^{HP}(i,j)^2 + F^{LP}(i,j)^2) = \sum_{i,j} S_k(i,j)^2$, when the energy conserving combination $\rho = \sqrt{(\rho^{HP})^2 + (\rho^{LP})^2}$ is used. Here $S_k(i,j)$ is the full sampled k-space data at the k^{th} coil at 2D k-space coordinates (i,j), F^{HP} and F^{LP} are k-space high-pass and low-pass filter respectively.

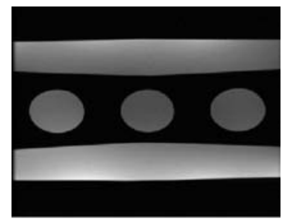

Fig. 1, SoS of Axial phantom data

A natural criterion to meet the energy balance requirement is the point-wise constraint: $F^{HP}(i,j)^2 + F^{LP}(i,j)^2 = 1$. Based on this criterion, the high-pass filter can be designed as $F^{HP} = (1-1/R)F^{HP\_standard} + 1/R$ followed by low-pass filter $F^{LP} = \sqrt{1 - F^{HP^2}}$ where $F^{HP\_standard}$ is a standard high-pass filter in k-space with pass band magnitude one, stop band magnitude zero, cutoff frequency close to ACS boundary and arbitrary filter order.

Results and Discussion: Axial Phantom data was collected by a 1.5T GE system (FOV=480 mm, matrix 256x256, TR=500ms, TE=13.64ms, flip angle=90°, Slice thickness=3mm) with an 8-channel Neurovascular Array coil (Invivo Corporation, Orlando, FL, USA). The reference SoS is shown in Fig. 1. The k-space samples are decimated in outer acceleration factor of four beside the central 64 ACS lines. The high-pass and low-pass filters based on Butterworth filter of order 4 and cutoff frequency at both 107 and 151 are shown in Fig. 2. The central PE line from the reconstructions using SENSE and homoSENSE is demonstrated in Fig. 3. It demonstrates that homoSENSE gives less MSE compared to SENSE with less low frequency bias in the reconstruction. The reconstruction time of both methods is about the same.

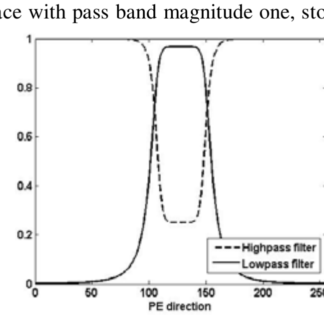

Fig. 2, High-pass and low-pass filter with order 4 and cutoff frequency at 64.

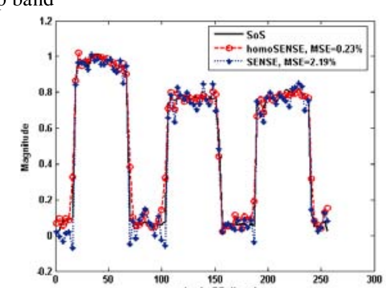

Fig. 3, Central PE line from Reconstructions of homoSENSE of MSE = 0.23%, SENSE of MSE=2.19% compared with SoS.

Conclusions: Variable density reconstruction parallelly processing full sampled and undersampled data is always affected by ring effect and combination bias. A filter design criterion to suppress the bias is discussed in this short paper. This global energy balance criterion approximately solves the scale problem in final combination phase. High and low-pass data are appropriately weighted and ringing is minimal.

References:

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