A New Combination of Compressed Sensing and Data Driven Parallel Imaging

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Introduction

Compressed sensing (CS) can be used with data driven parallel imaging (PI) (1) in an integrated approach, such as L_1 SPIR-iT (2), or a serial approach where CS is the second step (3). Likewise, the combination with model driven PI can be integrated (4,5) or serial (6) but, in the serial case, CS is the first step. A serial approach has the advantage that acceleration can be clearly split between CS and PI, allowing each method to deal with a problem that has better conditioning than if an integrated solution were used with full acceleration. An advantage of using data driven instead of model driven PI is the avoidance of problems that can degrade self-calibrated PI, such as k-space truncation or field of view (FOV) truncation of the coil sensitivity (7,8). Here we explore a new serial combination with data driven PI, where CS is the first step instead of the second. An advantage of using CS as the first step is that any data driven PI method can be used without modification.

Methods

For this study, we chose ARC as the PI method (9) although GRAPPA (10) or SPIRIT (11) is equally suitable. CS requires an incoherently (typically randomly) sampled k-space grid. However, for maximum effectiveness, the final image that CS produces should correspond to a coherently (uniformly) sampled grid. To achieve the k-space sampling pattern that we need, we start with uniformly undersampled k-space points plus auto-calibration signal (ACS) points that would normally be used for ARC (Fig. 1). For clarity of illustration, a small k-space matrix (64x64 fully sampled) is used in this example. In Fig. 1, 2-fold undersampling is used in each direction with an 8x8 ACS region. The subset of these locations that are uniformly undersampled (32x32 samples) is shown in Fig. 2. These locations are then randomly undersampled, but since CS works better with full sampling near the center of k-space, no undersampling is used over an area slightly larger than the ACS region (10x10 in this example), giving the pattern shown in Fig. 3. This pattern, together with the remainder of the ACS locations gives the sampling pattern used to acquire the data (Fig. 4). To reconstruct the image, we give CS the k-space data at the locations in Fig. 3 and ask it to produce an image for each coil that is coherently aliased, corresponding to having k-space data at the uniformly undersampled locations in Fig. 2. After Fourier transforming the images to produce data at these uniformly undersampled k-space locations, the data are combined with the remaining ACS data resulting in data at the locations in Fig. 1. ARC is used to fill in the remaining gaps and produce fully sampled data for each coil, which are then combined using a sum of squares across coils.

A 3T scanner (GE Healthcare, Waukesha, WI) was used to acquire fully sampled data with a receive-only 8-channel head coil on a normal volunteer (3D, T2-weighted fast spin echo, sagittal plane, 256x218x176 (kx by ky by kz)). A 32x32 (ky by kz) full FOV ACS region was used for calibration. The data were undersampled as described above with a Poisson disk pattern (2) used to simulate random undersampling, and with 32x24 uniformly undersampled points near the center of the undersampled space. The ARC synthesis kernel size was 7x7 (ky by kz). Reconstruction code used MATLAB (The Mathworks, Natick, MA). The CS reconstruction used a conjugate gradient (CG) solver with 15 iterations to find an image with the minimum L1 norm of its gradient (total variation) for each coil. Consistency with the acquired data was imposed by substituting the measured k-space data back into the estimated k-space data at the measured locations following each CG iteration. Different splitting of the acceleration between CS and ARC was tested using various total accelerations. The following reconstructions were compared. (1) Fully sampled data, (2) randomly undersampled data with CS plus ARC (3) randomly undersampled data with only ARC, and (4) conventional ARC uniform undersampling and reconstruction with the same acceleration as for cases 2 and 3.

Results

Figure 5 shows the fully sampled reconstruction (case 1) at one x location in the plane of undersampling (y-z plane). Figure 6 shows case 2, the CS plus ARC results. For this image, the total acceleration was 5.3, split into an acceleration of 1.5 for CS along with outer reduction factors of 2 in both ky and kz for ARC. Case 3, using ARC to reconstruct this same undersampled data, is shown in Fig. 7. Case 4, using conventional undersampling and ARC reconstruction to obtain the same acceleration is shown in Fig. 8. Splitting the acceleration by using the combination of random and uniform undersampling and using CS plus ARC (case 2) results in lower noise and better image quality than using ARC alone to reconstruct the same undersampled k-space data or using ARC alone to reconstruct uniformly undersampled k-space data with the same acceleration (case 3 or case 4).

Conclusions

Combining compressed sensing with data driven PI in a serial combination allows splitting the acceleration between the CS and PI steps and gives better image quality than if PI were used to obtain the entire acceleration either with a random or conventional uniform undersampling pattern. This allows better image quality or higher acceleration than could be obtained by PI alone. More work is needed to compare the CS plus ARC approach to other approaches such as L_1 SPIR-iT.

References

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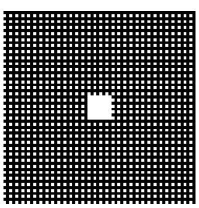

Figure 1. k-space points used for 2D ARC (ky,kz plane)

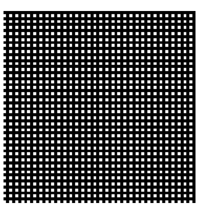

Figure 2. Uniformly undersampled subset of Fig. 1

Figure 5. Full sampling (case 1)

Figure 6. Random undersampling, R = 5.3, CS plus ARC reconstruction (case 2)

Figure 7. Random undersampling, R = 5.3, ARC reconstruction (case 3)

Figure 8. Conventional undersampling, R = 5.3, ARC reconstruction (case 4)

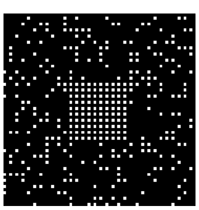

Figure 3. Random undersampling of Fig. 2 with uniform center

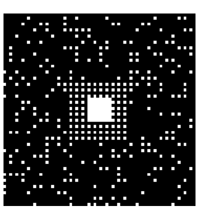

Figure 4. k-space points actually acquired