Interactive Adjustment of Regularization in SENSE and k-t SENSE using Commodity Graphics Hardware

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Background

Parallel imaging techniques such as SENSE and GRAPPA have provided significant speed-ups for MRI. The parallel imaging reconstruction algorithms are, however, more computationally intensive than straightforward Fourier inversion. Consequently, the reconstruction is not always able to keep up with the acquisition when a large number of receiver coils are used. Extensions of the SENSE technique, such as *k-t* SENSE provide a further speed-up of the acquisition but again with increased reconstruction complexity. The more complicated reconstruction algorithms often have a number of tuneable parameters (e.g. regularization) that have a significant impact on image fidelity and because the reconstruction is relatively time-consuming it has not previously been feasible to adjust these parameters interactively. Here we present a SENSE and *k-t* SENSE reconstruction algorithm implemented on commodity graphics hardware (GPU). Using this algorithm, we demonstrate that it is feasible to adjust regularization parameters for *k-t* SENSE in a real-time, interactive manner.

Theory and Methods

A SENSE or *k-t* SENSE algorithm generally consists of a loop over several sets of aliased pixels. For each set of pixels a system matrix must be inverted to unalias the pixels. This inversion is normally the most time consuming step of the reconstruction. To accelerate this inversion step, it was implemented it on a graphics processor (GPU). The GPU used was a GeForce 8800 Ultra (NVIDIA, USA), which has 16 multi processors each with 8 so-called stream processors available. We chose to implement an algorithm in which there are as many threads working on each inversion problem, as there are aliased pixels. This provided a good balance between the usage of fast on-chip memory and the number of threads running concurrently on the GPU. The reconstruction speed was compared to a single threaded CPU implementation using simulated datasets with varying matrix sizes, acceleration factors, and number of receiver coils.

We also investigated the use of the fast GPU reconstruction algorithm for interactive adjustment of regularization parameters in *k-t* SENSE. For this purpose, a fully sampled 2D short axis SSFP cine dataset was acquired using a Siemens Avanto 1.5T clinical scanner (Siemens Medical Solutions, Erlangen, Germany). Six receive coils were employed for data reception and sequence parameters were: matrix size 192x165, FOV 340x276 mm^2, TR/TE 2.86/1.43 ms, 17 cardiac phases. The fully sampled dataset was then sub-sampled five-fold using an optimized sheared grid *k-t* sampling pattern to simulate accelerated acquisition. For training data, the 11 central profiles in *k*-space were used and the *k-t* SENSE reconstruction result was compared to the fully sampled acquisition for different settings of key regularization parameters.

Results

The reconstruction performance for the CPU and GPU implementation is shown in Table 1. The GPU reconstruction performed faster than the CPU reconstruction for all tested configurations and the speed-up (SU) increased with matrix size and the number of coils. For the CPU reconstruction, the SENSE inversion is the most time consuming part of the reconstruction but for the GPU implementation it is now the FFT, which dominates the reconstruction times. Figure 1 shows example images for real-time adjustment of the regularization parameters of the *k*-t SENSE reconstruction. The *k-t* SENSE inversion time (excluding FFT) for the entire dataset was 29ms. Notice in Fig. 1 how it is possible to find a setting of the reconstruction parameters that gives a reconstruction result, which is close to the fully sampled reconstruction.

	2D, 256x256 matrix, 16 coils, 4 aliases, time [ms]			2D, 512x512 matrix, 32 coils, 2 aliases, time [ms]			3D, 128x128x128 matrix, 12 coils, 4 aliases, time [ms]		
	CPU	GPU	SU	CPU	GPU	SU	CPU	GPU	SU
Data Transfer	-	4.7	-	-	67.3	-	-	207.5	-
Noise decorrelation	96.0	2.6	36.6	1588.3	56.3	28.2	2845.46	50.1	56.8
FFT	58.6	19.2	3.1	1137.4	78.3	14.5	2516.0	740.7	3.4
SENSE Inversion	**467.7**	**4.3**	**108.3**	**2926.2**	**20.0**	**146.0**	**13234.9**	**149.2**	**88.7**
Total	622.3	26.1	23.8	5651.9	155.1	36.4	18596.4	939.9	19.8

Discussion

We have shown that Cartesian SENSE and *k-t* SENSE reconstructions can be performed efficiently on commodity graphics hardware. Our comparison with a CPU implementation showed that speed-ups of 50-150 times (or more) could be achieved for typical configurations. This could potentially be utilized in real-time, interactive imaging with large coil arrays. The GPU implementation performed best at the larger matrix sizes since at lower matrix sizes a relatively low number of threads are active and the GPU architecture is consequently not fully utilized. As an example of an application of the fast reconstruction for non-real-time imaging, we have illustrated that it is possible to reconstruct *k-t* SENSE images with an update-rate, which is fast enough to allow real-time adjustment of regularization parameters. This provides an interesting new way of optimizing reconstruction algorithms because the optimal setting of regularization parameters depends not only on things that we can measure (e.g. noise level) but also on patient specific conditions such as the exact geometry of the imaged anatomy and the configuration of the receive coils. Moreover, the setting of the tuneable parameters may depend on the context in which the images are to be interpreted.

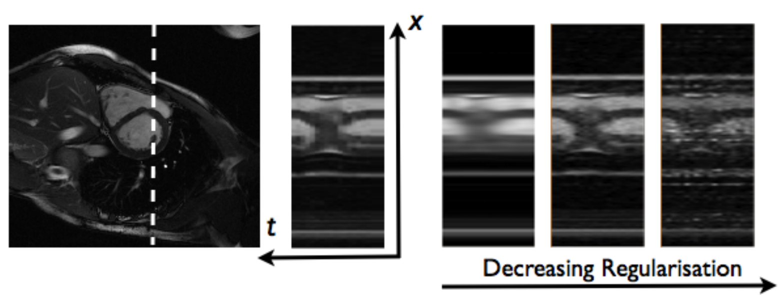

Figure 1. Interactive adjustment of reconstruction parameters. Left most *x-t* plot is from a fully sampled dataset. The 3 plots on the right show 3 different reconstructions of a 5-fold undersampled dataset. The user can choose the appropriate reconstruction interactively. Total reconstruction time is 29ms for all frames.