Rapid non-Cartesian Parallel Imaging Reconstruction on Commodity Graphics Hardware

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Introduction

In this abstract we advocate the concept of real-time non-Cartesian magnetic resonance imaging with minimal reconstruction delay. We focus on cardiac imaging although the presented techniques are generally applicable. Parallel imaging techniques such as SENSE [1] and *k-t* SENSE [2] have been available for years for real-time acquisition. Until now however, available reconstruction implementations have been slower than the speed of the acquisition by at least an order of magnitude, adding a significant delay between the acquisition and the subsequent display of images. In this work we have overcome this problem. We present a parallel algorithm implementing iterative reconstruction and display of two-dimensional non-Cartesian SENSE and *k-t* SENSE in less than the acquisition time on inexpensive commodity graphics hardware (GPUs).

Theory and Methods

Iterative SENSE and k-t SENSE. A non-Cartesian SENSE or *k-t* SENSE reconstruction is formulated as the solution to a set of linear equations [1-3]. The conjugate gradient algorithm (CG) is the usual choice for solving this system as a very good estimate of the solution is obtained after just a few iterations. A matrix-vector multiplication dominates the computational effort in each CG iteration. This matrix encodes Fourier coefficients corresponding to an inverse followed by a forward Fourier transform. As such it corresponds to two discrete Fourier transforms and can with advantage be replaced with fast Fourier transforms (FFTs). In the case of non-Cartesian sampling this will be non-equispaced fast Fourier transforms (NFFTs), i.e. forward and inverse gridding operations. Each gridding operation contains a convolution, an FFT, and a deapodization step. The convolution has previously been the main performance bottleneck on the CPU. It has recently been shown however that the convolution can be effectively implemented on GPUs [4].

GPU reconstruction. The reconstruction was implemented on the new parallel computing architecture, Cuda, available on the G8x series of GPUs (and newer) from the hardware vendor Nvidia. Specifically, the reconstruction was implemented on a Geforce 8800 Ultra graphics card containing 128 processors using vendor supplied libraries for linear algebra (cublas) and fast Fourier transforms (cufft). These libraries combined with the fast GPU convolution algorithm for the gridding operations [4] deliver the required building blocks for an efficient GPU implementation of the *entire* iterative SENSE/*k-t* SENSE algorithms. For the convolution operation we used an oversampling factor of 1.25 and a Kaiser-Bessel kernel width of 4.5.

MRI acquisition. Steady state free precession radial acquisitions with short repetition times were used for real-time acquisition. Each projection was oversampled along the readout direction by a factor of two. On a Philips 1.5T scanner we acquired 32 projections with 5 coils (TR/TE=3/1.5 ms), i.e. 4-fold acceleration for a 10 frames per second (96 ms per frame) real-time SENSE protocol (matrix size 128x128, FOV 320 mm). On a Siemens 1.5T system we acquired 16 projections per frame for each of 26 frames in a cardiac cycle using 4 coils (TR/TE=2.5/1.2 ms), i.e. 8-fold acceleration for a 25 frames per second (40 ms per frame) *k-t* SENSE protocol with reconstruction delayed one cardiac cycle (matrix size 128x128, FOV 300 mm).

Table 1. Sense and kt-Sense GPU reconstruction times in ms.

	Sense (5 coils)	kt-Sense (4 coils)
Once per reconstruction		
Upload samples	<1	1
Noise decorrelation	1	2
Extract training data/regularization	-	30
Estimate coil sensitivity maps	-	52
Compute initial aliased image	4	56
Once per iteration		
Conjugate gradient	1	4
FFT	5	84
Convolution	3	15
Deapodization	1	1
Total for 5 iteration reconstruction	**55**	**661**
Total per frame	**55**	**25**

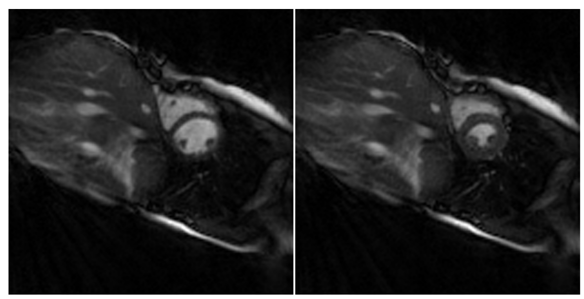

Figure 1. Diastole and systole reconstructed with kt-Sense. Each frame was acquired in 40 ms and reconstructed in 25 ms.

Results

The obtained reconstruction times can be seen in Table 1. Five iterations were used for both reconstructions. For the Sense reconstruction a new frame is reconstructed every 55 ms. The *k-t* SENSE reconstruction took 661 ms but contained 26 frames, i.e. 25 ms per frame. The obtained image quality is shown in Figure 1.

Discussion

For both the SENSE and *k-t* SENSE reconstruction the obtained reconstruction times matched the acquisition times. Thus GPU based reconstruction is sufficiently fast for real-time imaging with a constant reconstruction delay. For the *k-t* SENSE reconstruction the framerate corresponds to 25^{-1} ms^{-1} or 40 frames per second delayed one cardiac cycle, which in this case corresponds to approx. one second.

On CPU-based implementations the convolution operation has traditionally been the bottleneck of the reconstruction. It can be seen from Table 1 however, that the convolution implementation on the GPU [4] is very efficient, putting the majority of the reconstruction time on the FFT. It should be emphasized however that even though the FFT is now our performance bottleneck it still outperforms CPU-based fftw. The expected increase in performance from future-generation GPUs will allow additional full reconstructions within the acquisition duration, meaning that the fixed reconstruction delay can be reduced below one cardiac cycle.

Before reconstruction is initiated the sample trajectories and density compensation weights are extracted once and reused for all imaging planes subsequently acquired. The *k-t* SENSE reconstruction is otherwise fully self-contained as the reconstruction times in Table 1 include noise decorrelation and extraction of training data/coil sensitivity maps. We can hereby avoid acquisition of additional dataset prior to reconstruction. The noise level is estimated from the outermost *k*-space samples, the coil sensitivity maps are estimated from the fully sampled time-averaged *k*-space, while the training data is estimated from the fully sampled central part of *k*-space [3].

In several applications, e.g. paediatric imaging or imaging during exercise, the presented work is likely to have a huge clinical impact considering the spatial and temporal resolution that can now be obtained during real-time imaging. An obvious next step is to integrate the reconstruction with a raw data stream output from the scanner in combination with an interactive tool to define the desired imaging plane online.

References

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