Software Toolbox and Programming Library for Compressed Sensing and Parallel Imaging

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Introduction: The high complexity of advanced algorithms presents challenges for research and clinical application of new reconstruction methods. While researchers need flexible and interactive tools, clinical evaluation and application require robust and highly efficient implementations. With the aim to fulfill these disparate requirements, we present a framework for image reconstruction, which consists of a programming library and a toolbox of command-line programs. The library provides common operations on multi-dimensional arrays, Fourier and wavelet transforms, as well as generic implementations of selected iterative optimization algorithms. The command-line tools provide direct access to basic operations on multi-dimensional arrays as well as efficient implementations of selected iterative reconstruction algorithms.

Implementation: The library is built for the Linux operating system using the C/C++ programming language and OpenMP. It makes use of the FFTW, the GNU Scientific Library, and optionally CUDA (NVIDIA, San Jose, CA) and the ACML (AMD, Sunnyvale, CA). It offers simple but powerful interfaces for many operations on multi-dimensional arrays, e.g. to access slices of an array or to apply an FFT along selected dimensions. Most operations can be transparently accelerated using GPUs. The use of memory-mapped input/output allows the processing of extremely large data sets and access to the data during long-running computations or debugging stops. The command-line tools operate on files representing multi-dimensional arrays, which is computationally efficient due to the use of memory-mapped input/output. The file format is simple and files can be accessed with Matlab (MathWorks, Natick, NA).

ESPIRiT Reconstruction: ESPIRiT calibration and reconstruction have been implemented as separate tools using the presented library. The implementation highlights several features of the library. First, the use of multi-dimensional arrays and generic algorithms facilitates the extension of SENSE to an ESPIRiT reconstruction basically by adding another index to support multiple images and sets of sensitivity maps. Second, the separation of pre- and post-processing steps, calibration, and reconstruction into separate tools allows rapid prototyping and simple scripting of complete of batches of numerical experiments. Finally, the use of GPU acceleration enables reconstruction times of a 3D volume of a human knee (Figure 1) to be accelerated from 17.5 minutes using a single-threaded CPU implementation to 1.5 minutes using four GTX 580 GPUs (NVIDIA, San Jose, CA).

Summary: The use of command-line tools facilitates the interactive processing of data required during research and development of reconstruction algorithms. Simple experiments can be scripted using any shell language, which allows rapid prototyping and reproducibility of numerical experiments. More complex algorithms can be developed using the functions of the library and added to the toolbox, which has been demonstrated here for the ESPIRiT calibration and reconstruction algorithm. Future work will extend the library with support for more linear algebra routines, iterative algorithms, support for non-Cartesian trajectories, and improved support for multiple GPU systems.

Figure 1: *Sagittal section of a human knee acquired with an 3D-FSE sequence and reconstructed with L1-ESPIRiT. Using the presented framework, the example can be computed with the following script:*

```
#!/bin/sh

# ESPIRiT calibration
calib kspace.cfl maps.cfl

# SENSE/ESPIRiT reconstruction
sense kspace.cfl maps.cfl volume.cfl

# extract section 140 along dimension 2
slice 2 140 volume.cfl section.cfl
```

References:

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