Recent advances in acquisition and reconstruction for Compressed Sensing MRI

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Relevance to ISBI audience

This tutorial on recent advances in MRI acquisition and reconstruction fits the ISBI audience very well because MRI is the most represented medical imaging technique in the conference for non-invasively probing soft tissues in Humans.

Tutorial Topic

In the last decade, the application of Compressed Sensing (CS) theory to MRI has received considerable interest and led to major improvements in terms of accelerating data acquisition without degrading image quality. These achievements have mostly relied on (i) massive under-sampling of existing k-space trajectories (either Cartesian lines or non-Cartesian radial and spiral patterns) in 2D and 3D imaging and (ii) nonlinear reconstruction algorithms that promote either sparsity of the reconstructed MR image using a fixed dictionary or transform, or a low-rank representation in an appropriate domain. Two recent complementary research directions are starting to supplant this classical CS setting: first, the design of optimization-based under-sampling schemes and second, the advent of machine learning tools (e.g., deep learning) for MR image reconstruction.

The design of optimized sampling strategies for CS may have a significant impact on the resulting image quality since the Point Spread Function of the sampling schemes acts as a convolution filter in the image domain. In structural MR 2D and 3D imaging, the acquisition in k-space is segmented in multiple shots that must fulfill both hardware constraints on the gradient system and contrast-specification (e.g., short echo time and readout for T1-weighting imaging). Two key aspects for designing such trajectories that are compliant with CS are (i) to perform variable density sampling according to a prescribed distribution and (ii) to maximize sampling efficiency, i.e., the coverage of k-space. The design also must account for other aspects of the MR receive chain.

The conventional regularizers used for CS image reconstruction are total variation (TV) and sparsity of wavelet transforms. These regularizers are designed to encourage certain expected image properties such as piecewise smoothness but they do not exploit information available in existing MR images that were reconstructed from fully sampled data. The growing trend in image reconstruction research is to focus on data-driven (or adaptive) image models. One approach is to learn models (e.g., sparsifying filters or dictionary atoms) from fully sampled training data and then use those models for regularized reconstruction of under-sampled data. Another approach is to learn data-driven models jointly while solving an image reconstruction problem in a patient-specific way. Hybrid approaches are also possible. Another option is to eschew models and define image reconstruction as a recipe consisting of a sequence of operations (filtering steps, nonlinear operations, etc) and then learn the parameters of those operations from training data, as exemplified by deep convolutional neural networks (CNNs). Some CNNs for MRI reconstruction use the k-space repeatedly (“unrolled loops”) whereas others use it only once at the front end of the network.

The course focuses on these new trends in CS MR acquisition and image reconstruction and is split in two parts accordingly. The **first lecture** is dedicated to acquisition strategies: 2D and 3D MR imaging scenarios will be addressed.

The **second lecture** addresses novel reconstruction methods in the machine learning era that are data adaptive. Both model-based, data-driven methods and neural-network approaches will be presented. All the concepts introduced will be illustrated on in vivo Human data.

The course is organized such that the participant acquires knowledge about:

1. mathematical concepts behind adaptation of CS theory to the MRI constraints (sampling density, maximal efficiency, hardware constraints, …),
2. optimization techniques for generating non-Cartesian trajectories in 2D and 3D k-space,
3. cost-function formulations and optimization methods for model-based image reconstruction with data-driven regularizers,
4. CNN approaches to image reconstruction,
5. open-source software for performing both trajectory design and advanced reconstruction.

Tutorial Outline

The course is organized as follows:

- **Part I: Design of optimized sampling trajectories for CS** (Dr. Ciuciu)
- **Part II: Machine Learning for MR image reconstruction** (Prof. Fessler)

Target Audience

It is expected that participants (PhD students, postdocs, senior researchers) have preliminary knowledge of classical MRI acquisition and reconstruction techniques. At the end of the course, attendees should have a broad understanding of recent advances for accelerating both MR acquisition and image reconstruction.

Target Audience Participation

Questions from the audience will be encouraged during the tutorial and there will be planned points in the outline where questions will be especially solicited.

Coursepack

Slides (electronic) and code with demos will be provided to the participants. Many of the image reconstruction methods will be illustrated using Jupyter notebooks based on publicly available data, so that participants can experiment with the methods themselves after the tutorial.