CEA funded NUMERICS program: PhD project

Title: High-performance Simulation for the design of compressed sensing trajectories in high resolution functional neuroimaging at 7 and 11.7 Tesla.

Keywords: non-convex optimization; Fast Multipolar Methods; 4D high resolution imaging ; GPU parallelization ; MRI; 7 Tesla; 11.7 T: compressed sensing;; functional MRI.

Location: The successful PhD candidate will be located at NeuroSpin and affiliated with University of Paris-Saclay in the Physics & Engineering doctoral school. He will get a joint appointment with INRIA Saclay as Philippe Ciuciu is also member of the Parietal team.

Resources: https://cosmic.cosmostat.org/ ; https://sites.google.com/site/philippeciuciu/ https://team.inria.fr/parietal/

Abstract: Magnetic Resonance Imaging (MRI) is the gold-standard medical imaging technique to probe the brain in vivo in a non-invasive manner. MR image resolution improvement in a standard scanning time (e.g. 500µm isotropic in 2 min) is a major challenge to allow doctors to significantly improve their diagnosis. The raise of the new sampling theories like Compressed Sensing (CS) has revolutionized the way of collecting data in numerous scientific fields (e.g., ultrasound imaging, MRI, radio-astronomy) by drastically reducing acquisition times. In this context, NeuroSpin has recently developed new compressive sampling schemes for MRI which are dedicated in MR pulse sequences, called SPARKLING. These sequences allow us a 20- and 70-fold acceleration in T2* weighted 2D and 3D anatomical imaging (500 µm).
The objective of this PhD thesis is to design new compressive sampling schemes for functional MRI (fMRI) allowing us to probe brain activity non-invasively at high spatial resolution. A 3D+time-SPARKLING MR pulse sequence will be developed in order to reach high resolution imaging at 750 µm isotropic in less than 2 sec/volume. The prospective validation will be performed on healthy volunteers first at 7 Tesla during resting-state acquisition and along a visual recognition task. Last, we will envisage to push forward this 3D+t SPARKLING sequence at 11.7 Tesla to reach a resolution of 500 µm isotropic.

Skills:
Medical imaging. Applied maths. Signal processing. Machine learning. High performance computing.

Detailed description of the PhD project

Context

Magnetic resonance imaging (MRI) is the reference medical imaging technique for in vivo and non-invasive probing of soft tissues, particularly the brain. Improving the resolution of MR images in a constant scan time (e.g., 500 µm in 2 min) is a major challenge to enable physicians to significantly improve their diagnosis and patient management. The advent of compressive sampling [1], has revolutionized the way data is collected in several domains by going beyond Shannon-Nyquist's theorem. This breakthrough is based on i) the use of incoherent acquisition schemes, ii) the sparsity or compressibility of images in an adapted representation (e.g., wavelets) and iii) the use of a nonlinear reconstruction algorithm that promotes sparsity. By using these three pillars together, compressive sampling allows massively under-sampling of the data by a factor of R while ensuring conditions for perfect image recovery. Its use in MRI appeared in 2007 [2] and very quickly, a number of studies multiplied (see e.g.,[3-4]). However, the acceleration factors achieved never exceeded R=6.

In-house developments

In this context, NeuroSpin's efforts (PhD theses by Nicolas Chauffert 2012-15 and Carole Lazarus 2015-18) have so far focused on pillar i) to offer new compressed trajectories compatible with the hardware constraints of MR systems [5-7]. Acceleration factors of up to R=20 in 2D imaging and R=70 in T2*-weighted anatomical 3D imaging were achieved on images collected from healthy subjects on the 7 Tesla clinical system (400 µm in plane resolution) [8-9]. Concerning the pillars (ii)-iii), within the framework of the DRF Impulsion COSMIC project (Compressed Sensing for Magnetic Resonance imaging and Cosmology), we have also developed new fast and online image reconstruction algorithms in Loubna El Gueddari's thesis (2016-) allowing to combine parallel imaging and compressed acquisition[10-12]. Still in the COSMIC Also in the context of the COSMIC project, in Zaccharie Ramzi's thesis, we are currently developing new algorithms for reconstructing 3D MRI images based on deep learning and neural networks trained on raw data.

Objectives

The objective of this PhD thesis is now to develop new compressive sampling schemes for functional MRI (fMRI, 3D+time imaging) to probe brain activity at an unprecedented spatial resolution that segregates the activations of the different cortical layers. From a methodological point of view, a major challenge lies in adapting SPARKLING formalism to the context of the trajectories traditionally used in fMRI. The most favourable adaptation context is 3D functional imaging where data is collected in a three-dimensional Fourier space and trajectories are segmented. A first barrier to be lifted will be to successfully simulate segmented 3D trajectories covering the entire Fourier space by solving a *non-convex optimization problem*. Rather than the local strategies considered in [9], all segments will be simulated jointly using fast multipole methods that reduce algorithmic complexity [13]. These simulations will be subject to a specific parallel implementation (multiCPU or GPU) to allow them to be run on high-performance computers because they are generated before the acquisition. Close collaboration with Pierre Kestener (DRF/MdS) is already being carried out on this point but to date it only concerns anatomical imaging.

Care should be taken to optimize the choice of 3D sampling density according to the targeted resolution, the choice of acquisition parameters (TE, TR), the intensity of the magnetic field which impacts the available signal-to-noise ratio and thus the maximal acceleration factor [14]. **Deep learning** will be considered to learn the best target density as suggested recently in the literature [15]. We will first consider homogeneous schemes where the same Fourier space is acquired for each volume of the 3D series + time of volumes before considering inhomogeneous schemes with variable density over time.

Validation & Expected impact

The functional imaging sequence, called SPARKLING 3D+t, will be developed in collaboration with Alexandre Vignaud at NeuroSpin and will be tested first on dynamic phantoms and then on healthy subjects at 7 Tesla as part of resting-state acquisitions, then during a visual recognition task [16] involving several categories of stimuli (words, faces, objects) in collaboration with Professor Stanislas Dehaene (NeuroSpin Director). The averarching objective will be to delineate for the first time the cortical layers that specifically respond to the visual shape of words in a specific region of the ventral pathway of the occipital cortex. Comparisons will be done with the reference fMRI sequence, namely, the 3D Echo Planar Imaging.

In addition, a second version (at slightly degraded spatial resolution) of the sequence will be used to collect functional fMRI data during resting-state scans in premature newborns at 3 Tesla, as part of a collaboration with Prof. Petra Hüppi at the University of Geneva. Here, the goal will be to investigate whether on can identify functional landmarks of prematurity in the intrinsic functional brain networks across the cortical layers.

Finally, the whole image reconstruction pipeline will be carried out using the PySAP software that we are developing in collaboration with the CosmoStat team (DRF/Irfu), led by Jean-Luc Starck, in the context of the DRF Impulsion COSMIC project. Particular attention will be paid to accelerate the 3D+time reconstruction of fMRI images, particularly in the context of multi-channel imaging, following the examples we have recently proposed [17,18] in 2D and 3D imaging.

Candidate profile: We are seeking a PhD student already graduated from top-level engineer schools or with a Master of science in applied mathematics, machine learning, biomedical imaging or data science at large. He/She should have a solid background in optimization, in signal and image processing as well as in scientific computing (Python preferred but skills in C/C++ are welcome too). Preliminary experience in software development for parallel computing architectures (either massively many-core or GPU-based) is welcome. Knowledge in magnetic resonance imaging will be a plus but is not mandatory. The PhD candidate will join a multi-disciplinary international team (INRIA-CEA Parietal) including research scientists in medical imaging, signal/image processing and machine learning for neuroimaging. He/She should demonstrate excellent oral and written communication skills in English.

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