AAP Contrats doctoraux en Intelligence artificielle

Cofinancé par l'ANR

Machine learning to accelerate acquisition and reconstruction of multi-parametric brain Magnetic Resonance Imaging

1. DESCRIPTION OF THE PHD THESIS PROJECT

1.1 OBJECTIVES OF THE PROJECT BASED ON THE CURRENT STATE OF THE ART

The main objective of this thesis project is to drastically enhance brain magnetic resonance imaging (MRI) by developing specialized machine learning (ML) and deep-learning (DL) approaches. In order to do so, this interdisciplinary project associates machine learning and deep learning specialists (1-3) (Laboratoire d'informatique et systèmes, UMR 7020) with MRI physicists (4-9) (Centre de résonance magnétique biologique et médicale, UMR 7339) and with a direct contact to neuroscientists, neurologists and neuroradiologists who are using MRI in their research and for patient care.

MRI is a major diagnosis tool used in many diseases and it is central for research in biology and medicine as well as for neuroscience. To provide few examples, it is used in oncology to characterize tumor evolution and response to treatments, in neurology to follow up brain lesions such as in multiple sclerosis or epilepsy, or to locate fine structures deep in the brain for treating Parkinson diseases or better understand the development of Alzheimer diseases. All these examples requires too key elements currently not feasible jointly: getting high resolution together with relevant tissue contrasts. Indeed, MRI is extremely versatile in the information it can provide (through a multiplicity of contrast mechanisms), but this is done at a high cost. MRI an expensive technology (a 3T clinical system costs on the order of 3 million €, and an ultra-high field system of 7T between 7 and 10 million €) and there is an increasing number of indications, with a limited availability of MRI systems. Reducing the length of an MRI exam and increasing the information that can be extracted from it would increase its value and broaden its availability. Today, an MRI exam typically lasts between 30 min to 1 hour, during which redundant information is acquired uselessly. In an ideal world, the acquisition process should be optimized to acquire only the necessary information, thus reducing the exam duration and enabling to use this time to obtain finer tissue characterisation.

Deep learning and neural networks have led to dramatic advances in hard application areas. They are extremely efficient on data that have spatial (images), temporal (speech, signals, natural language), or spatio-temporal (video…) structure, via the use of convolutional architectures for image data and recurrent for sequential data. The principle of localization by MRI is based on the sampling of spatial frequencies (called k-space). An MRI acquisition generates structured data in the complex domain with a three-dimensional (k-space) and multimodal (depth corresponding to multiple contrasts), and that are viewed simultaneously by several detectors. Neural networks are therefore establishing themselves as the reference technology for tackling learning problems with raw MRI data.

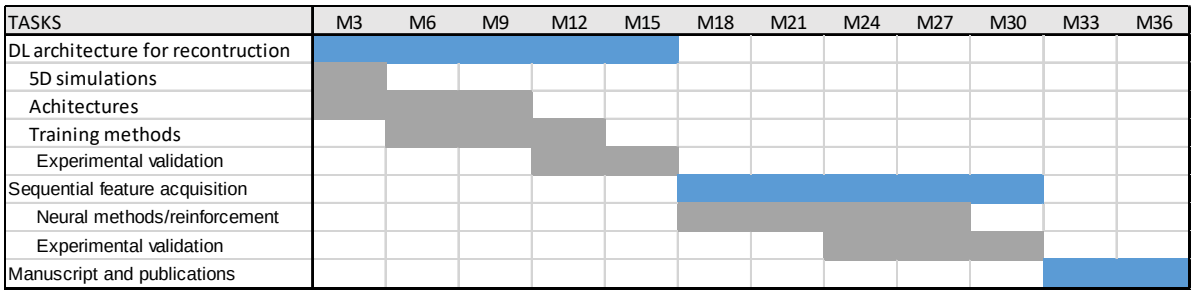
Currently, artificial intelligence in medical imaging mainly relates to image segmentation or classification applications that are intended to provide diagnostic assistance. Nevertheless, the tasks of reconstructing medical images can be carried out with supervised learning (10-12). By a complete modelling of the acquisition process, it is possible to train a neural network to perform specific reconstruction tasks, in particular with a priori (of compressive sensing type (11,13) or MR fingerprinting (10,14)) . However, these approaches do not determine the relevant data to acquire, and do not provide means to reduce acquisition time by determining optimal under-sampling patterns in this high dimensional space.

1.2 METHODOLOGY

In this thesis, we will consider the case of Cartesian sampling of several contrasts in multi-contrast 3D gradient echo type acquisitions (8,9,15), for which we will seek to determine the optimal patterns of subsampling. We propose to accelerate the acquisition by subsampling k-space and contrasts (not necessarily uniformly) and using super-resolution approaches (16,17) to infer the missing data (jointly infer high resolution images from low resolution images). To do this, we propose to formalize the process, including subsampling which is traditionally treated by convolutions (18,19), directly in the form of a neural architecture. This original approach opens ways to rely on most impressive improvements in recent machine learning and deep learning fields.

It turns the problem we want to solve into the optimization of a degradation-restoration architecture that we want to learn end to end, and of comparing its performances with the current techniques of reconstruction of partial data (13,14). Setting up these neural approaches requires studying hard problems, including data management in the complex field (20) calling for suitable architectures. Optimizing such neural architectures will benefit from including structural or algorithmic constraints for the network to respect certain known physical properties of the process (21), for example global linearity or distribution constraints for which adversarial learning seems adapted and can be used, which is not much studied yet. Beyond the super-resolution problem which considers the available input data, it is a second step to consider sampling as a sequential decision problem, i.e., to determine from available data leading to a current estimate the next most informative data to acquire. Different strategies will be considered (reinforcement, neural methods) to treat this process of sequential feature learning (2). From the machine learning point of view the problem consists in designing original neural architectures that allow jointly learning an optimal subsampling of original MRI images and an optimal reconstruction of the original image. To face such a hard problem will require innovative approaches to incorporate prior knowledge as constraints in the learning.

1.3 WORK PLAN



In summary, from the ML and IA point of view, the thesis will cover the adaptation of architectures to complex data specific to MRI and the physical constraints that must respect these models, both in terms of cost functions and in terms of specific architectural design. Finally, it covers sequential feature acquisition applied to the optimization of MRI data sampling, using simulated and acquired data on volunteers and patient, with implementation on an MRI system with in vivo proof of concept experiments.

1.4 SUPERVISOR AND RESEARCH GROUP DESCRIPTION

This thesis will be supervised jointly by Ludovic de Rochefort (CRMBM) and Thierry Artières (LIS). CRMBM has obtained funding linked to this research in the framework of AMIDEX (high field 7T-AMI project), and support from Siemens Healthineers.

*The **Centre for Magnetic Resonance in Biology and Medicine (CRMBM)** is a CNRS-AMU research unit dedicated to the development and validation of new Magnetic Resonance Imaging (MRI) biomarkers. The laboratory has a strong organ-oriented focus associated with applied clinical questions. The **Central Nervous System team** comprises a pluri-disciplinary expertise (with more than 40 people) from MR physics to medical research. The cutting-edge MR technologies developed in the laboratory are validated and applied in diseases such as epilepsy, multiple sclerosis or amyotrophic lateral sclerosis thanks to the close links with the clinical departments of Marseille public hospital structure (neurology, radiology). The laboratory supports a translational research infrastructure involving small animal MRI systems as well as high and ultra-high field clinical systems (1.5, 3 and 7 T) dedicated to researches involving healthy human subjects and patients.*

*The **Computer Science and Systems lab (LIS)** is a CNRS-AMU research unit dedicated to theoretical and applied computer science and systems. The QARMA team is the machine learning team of Aix-Marseille University and gathers about 30 people (including 10 permanent people) working on many aspects of machine learning including statistical learning theory, kernel methods, merging signal processing and machine learning, deep learning, and with a focus on few applicative fields including audio inpainting, computer vision, neurosciences, bioinformatics.*

2. RECENT PUBLICATIONS

1. **Chen M, Denoyer L, Artieres T**. *Multi-View Data Generation Without View Supervision*. ICLR; 2018, https://arxiv.org/abs/1711.00305
2. **Contardo G, Denoyer L, Artieres T**. *Sequential Cost-Sensitive Feature Acquisition*. Advances in Intelligent Data Analysis Xv 2016;9897:284, https://arxiv.org/abs/1607.03691
3. **Sokolovska N, Artieres T**. *A Probabilistic Prior Knowledge Integration Method: Application to Generative and Discriminative Models*. 2016 International Joint Conference on Neural Networks (Ijcnn) 2016:4496, https://integromics.fr/~nsokolovska/WeightedFeaturesFinal.pdf
4. **Leroi L, *et al.*** *Simultaneous multi-parametric mapping of total sodium concentration, T1, T2 and ADC at 7T using a multi-contrast unbalanced SSFP*. Magn Reson Imaging 2018;53:156, http://www.ncbi.nlm.nih.gov/pubmed/30055291
5. **Bödenler M, *et al.*** *Comparison of fast field-cycling magnetic resonance imaging methods and future perspectives*. Molecular Physics 2018:1, https://doi.org/10.1080/00268976.2018.1557349
6. **Bandt SK, *et al.*** *Clinical Integration of Quantitative Susceptibility Mapping (QSM) MRI into Neurosurgical Practice*. World Neurosurg 2018, http://www.ncbi.nlm.nih.gov/pubmed/30201583
7. **Valabregue R, de Rochefort L**. *Fisher Information Matrix for Optimizing the Acquisition Parameters in Multi-Parametric Mapping Based on Fast Steady-State Sequences*. ISMRM; 2016; Singapore. p1569, https://hal.archives-ouvertes.fr/hal-02553615 http://archive.ismrm.org/2016/1569.html
8. **de Rochefort L**. *Encoding with Radiofrequency Spoiling, Equilibrium States and Inverse Problem for Parametric Mapping*. ISMRM; 2015; Toronto, Canada, http://archive.ismrm.org/2015/0445.html
9. **de Rochefort L, *et al.*** *Quantitative susceptibility map reconstruction from MR phase data using bayesian regularization: validation and application to brain imaging*. Magn Reson Med 2010;63:194, https://doi.org/10.1002/mrm.22187
10. **Hoppe E, *et al.*** *Deep Learning for Magnetic Resonance Fingerprinting: A New Approach for Predicting Quantitative Parameter Values from Time Series*. Stud Health Technol Inform 2017;243:202, https://doi.org/10.3233/978-1-61499-808-2-202
11. **Mardani M, *et al.*** *Deep Generative Adversarial Neural Networks for Compressive Sensing (GANCS) MRI*. IEEE Trans Med Imaging 2018, https://arxiv.org/abs/1706.00051
12. **Zhu B, *et al.*** *Image reconstruction by domain-transform manifold learning*. Nature 2018;555:487, https://arxiv.org/abs/1704.08841
13. **Candes EJ, Romberg J, Tao T**. *Robust uncertainty principles: exact signal reconstruction from highly incomplete frequency information*. IEEE Transactions on Information Theory 2006;52:489,
14. **Ma D, *et al.*** *Magnetic resonance fingerprinting*. Nature 2013;495:187, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3602925/
15. **de Rochefort L**; *FR15/54358 Procédé et dispositif d'imagerie par résonance magnétique*. France 2015 13 mai 2015, https://worldwide.espacenet.com/publicationDetails/originalDocument?FT=D&CC=WO&NR=2016180947A1&KC=A1#
16. **Ledig C, *et al.*** *Photo-Realistic Single Image Super-Resolution Using a Generative Adversarial Network*. 2017 IEEE Conference on Computer Vision and Pattern Recognition (CVPR); 2017. p105, https://arxiv.org/abs/1609.04802
17. **Lim B, *et al.*** *Enhanced deep residual networks for single image super-resolution*. arXiv:170702921v1 2017, https://arxiv.org/abs/1707.02921

18. **Griswold MA, *et al.*** *Generalized autocalibrating partially parallel acquisitions (GRAPPA)*. Magn Reson Med 2002;47:1202, https://doi.org/10.1002/mrm.10171
19. **Akçakaya M, *et al.*** *Scan-specific robust artificial-neural-networks for k-space interpolation (RAKI) reconstruction: Database-free deep learning for fast imaging*. Magn Reson Med 2019 81:439, https://doi.org/10.1002/mrm.27420
20. **Trabelsi C, *et al.*** *Deep Complex Networks*. ICLR2017, https://arxiv.org/abs/1705.09792
21. **de Bezenac E, Pajot A, Gallinari P**. *Deep Learning for Physical Processes: Incorporating Prior Scientific Knowledge*. ICLR; 2018, https://arxiv.org/abs/1702.00748

3. EXPECTED PROFILE OF THE CANDIDATE

We are looking for a curious, motivated, team-oriented candidate with a Master degree in signal processing, physics, computer science, machine learning, applied mathematics, biomedical engineering or related topics. Prior knowledge in magnetic resonance parallel imaging acquisition and reconstruction techniques would be advantageous but is not mandatory. Some experiences with machine learning approaches are welcome, although the candidate shall develop corresponding skills during the project.

The successful candidate will work in between the central nervous system team composed of physicists, neuroscientists, clinicians and computational scientists, and in the QARMA team with machine learning and deep learning experts.

ADDITIONAL SKILLS/ABILITIES/COMPETENCIES

Candidates should be enthusiastic about working in an interdisciplinary environment. The successful candidate will be able to work both independently and collaboratively in an academic-industrial partnership environment.

Written and oral English communication skills are expected. French speaking is a plus, although Aix-Marseille University can provide French classes to rapidly acquire the basics for daily life.

Candidates should be familiar with programming languages such as C, Matlab or Python, Linux-based operating systems and optimization algorithms.

APPLICATION

Interested candidates should send a cover letter describing experience, interest, and future career goals, as well as an up-to-date curriculum vitae and contact information for three references to Ludovic de Rochefort and Thierry Artières by email: ludovic.de-rochefort@univ-amu.fr, thierry.artieres@centrale-marseille.fr. Question regarding this position and informal inquiries are welcome. This position is full-time for 36 months with benefits.

4. SUPERVISORS' PROFILE

Ludovic de Rochefort **Researcher ID:** F-8742-2011 / **ORCID**: 0000-0001-7466-6452
Permanent researcher (chargé de recherche CNRS), Central Nervous System team, Centre de Résonance Magnétique Biologique et Médicale CRMBM / UMR 7339 CNRS - Aix Marseille Université.
website: http://crmbm.univ-amu.fr/contact/de-rochefort-ludovic/
Research topic: Measurement methods and instrumentation for magnetic resonance imaging

Education and positions

2014	**Habilitation to conduct research**, Physics, Paris-Sud Univ.
2006	**PhD** in Physics, Paris-Sud Univ. *Dynamic imaging and velocimetry with hyperpolarized gas MRI*
2005	Continuing education on biomedical sciences, IFSBM, Paris-Sud Univ.
2002	**Engineering degree**, Ecole Centrale de Lyon (French 'Grande Ecole'), **master** signal and image
2016 –	**Principal investigator**, Central Nervous System team, Centre de Résonance Magnétique Biologique et Médicale CRMBM / UMR 7339 CNRS - Aix Marseille Université.
2010 – 2016	**Principal investigator**, Imagerie par Résonance Magnétique Médicale et Multi-Modalités, IR4M / UMR 8081 CNRS – Paris-Sud Univ. Leading the 'Structure and function' team, 2012-2106
2008 – 2009	**Researcher-engineer**, Molecular Imaging Research Center (MIRCen), CEA, Fontenay-aux-Roses. Supervisor: Vincent Lebon. *High field preclinical MRI for brain iron quantification.*
2006 – 2008	**Research associate**, Radiology department, Weill Medical College of **Cornell University** (supervisor Y. Wang), New York, USA. *Magnetic source imaging using MRI, brain, cardiovascular, tissue and cellular applications.*

Management, institutional responsibilities, main teaching activities, other

2006 – 2018	supervision of 6 master students and 7 PhD thesis, physics and engineering, neuroimaging.
2010 – 2016	Animation of the lab journal club
2012 – 2016	Team leader, 'Structure and Function' (10 people): research strategy, budget, reporting, member of the laboratory board and direction board, contract management, communication.
2012 – 2014	Member of recruitment boards for university personnel (CNU 63, Paris-Sud Univ.)
2017	Organization of a workshop on quantitative susceptibility mapping, Marseille, 80 participants.
2010 – 2016	Teaching MRI, NMR (30 hours/year) in French 'Grandes Ecoles' and Paris-Sud Masters (ESPCI, ENSEA, IFSBM, medical physics master)
2010 – 2012	Teaching to first year medical students (biophysics, 48 hours/year)
2007 – 2019	Reviewer for scientific journals (MRI, inverse problems)
2012 – 2019	Evaluation of research projects for ANR, ANRT, IDEX, regional funding agencies
2013 –	Member of PhD thesis juries (2) and HDR juries (1), Paris-Sud Univ.
2017 –	Member of the European Ultrahigh-Field Imaging Network in Neurodegenerative Diseases QSM/R2* workgroup (EU joint programme on neurodegenerative disease research)
2016 –	Substitute Member of the European Network on NMR Relaxometry (COST CA 15209), co-leader "instrumental development" workgroup.
2004 –	Member of scientific societies on MRI: ISMRM, ESMRMB, SFRMBM

Projects

Since 2010, participation to ANR projects (ANR blanche SAMOVAR 2010, ANR Tecsan Oxyhelease 2011, ANR Suprasense 2014), Scientific responsibilities (ANR Tecsan ABYSS 2011, Fondation pour la recherche médicale on total lung ventilation), Leader (France Life Imaging funded grants on quantitative MRI, 2015-2016, 2017 and 2018-2019), Participant to H2020 FET Open M-CUBE and to AMIDEX Emergence and Innovation project Imetionic-7.

Publications

In peer-reviewed journals: 38, book chapters: 2. Patents: 3. Conference proceedings: 118. Invitations: international workshops / conferences : 11, seminars since 2010: 7.

Thierry Artières

Full Professor, Ecole Centrale Marseille (High level Engineer School, ECM)
Member of the Computer Science and Systems lab (LIS - AMU, CNRS), Machine Learning team (QARMA)
Web page : *https://pageperso.lis-lab.fr/thierry.artieres/* Publications : https://pageperso.lis-lab.fr/thierry.artieres/?page_id=51
Research Topics: Machine learning, Learning representations, Deep Learning, extreme classification, structured data

Career

2014 -	Full Professor – Computer Science and Artificial Intelligence - Ecole Centrale Marseille Member of the QARMA team of the Computer Science and Systems lab (LIS, UMR 7020)
2007 - 2014	Full professor in Computer Science at Pierre et Marie Curie Universisty, Paris, Member of LIP6 lab (UPMC, CNRS)
2001 -	PEDR bonus for Ph.D. supervision since 2001
2006	Habilitation to conduct research (Pierre et Marie Curie University): Machine Learning for sequences
1995	Ph.D. Computer Science (Paris XI university): Speaker recognition with neural networks and markovian models

Animation, responsibilities, and boards…

- Head of QARMA team at LIS (~20 people including 10 permanent people) (2014-2018)
- Head of Data Science department at LIS (~50 permanent people) (2018-)
- Member of Scientific boards: at ECM (2016-), LIS (2018-), Convergence institute ILCB (2017-), member of scientific board of INS2I CNRS institute (2018-). Member of the Committee on A.I. created by AMU in 2018 to define the policy of AMU on A.I.
- Head of master program on Artificial Intelligence and Machine Learning at Aix Marseille University (AMU) (2018-), head of master program on Fundamental Computer Science at AMU (2015-2018), head of master program on Learning, Datas and Knowledge et l'UPMC (2014).

Research management

- Regular reviewer for most of major (ranked A*) Artificial Intelligence, Machine Learning and Neural Networks conferences for years: ICML (2015-), NIPS (2014-), AISTAT (2016-), ICLR (2016-), AAAI (2017-), *IJCAI* 2018…
- Reviewer for 30 Ph.D. defenses (2 in Spain, 1 in Italy) and examiner in many other Ph.D. defense.
- PC chair of a French speaking international conference (CAP 2016), co-organizer to a workshops aside major ML conferences de ECML/PKDD, WSDM, ICML, NIPS, ECML., co-organizer of a series of international challenges (LSHTC, BioAsQ)

Supervision

He supervised or cosupervised 17 Ph.D. students. He supervised 2 research engineers and 2 post doc since 2009, and many master students. He is currently supervising 4 Ph.D students (at a 50% rate each), with starting dates 2016, 2017, 2019 and 2019. Two of these four current Ph.D. will defend before the end of the year, one in July 2020, the other one in November 2020.

Projects

Member of 2 ANR funded projects , Deep in France (2017-2021) on deep learning, and LIVES (2015-2019) on multiview data, and of ANR convergence institute ILCB (Language Communication and the Brain) where he drives the Machine Learning and Deep Learning topic. He was PI of ANR funded projectClass-Y (ANR blanc 2011-2015) on extreme classification and WP leader for many ANRs funded projects before, like Geopeuple (2011-2013), SAIMSI (2010-2012)... He participated to few European projects including BioAsQ (2012-2014), ITEA UsiXML (2009-2013).

Publications

He published 13 articles in international journals (BMC BioInformatics, JMLR, WWW, Pattern Recognition) and more than 60 papers in international conferences (including more than 30 papers in top ranked, A and A*) related to Machine Learning, Artificial Intelligence and Deep Learning (NIPS, ICML, ECML, ICLR, IJCNN…) and to various application fields ranging from signal processing, speech recognition, motion synthesis… (ICASSP, Interspeech, ICIP, AAMAS, ICDM).

VISA DU RESPONSABLE DE L'INSTITUT ET DU DIRECTEUR DE LABORATOIRE CONCERNÉS

Visa du responsable de l'institut,
NOM Prénom

Fait à Marseille, le 15 mai 2020

Signature

Visa du directeur du laboratoire,
NOM Prénom

BERNARD Monique

Fait à Marseille, le 14 mai 2020

Signature