PhD opening 2024–2027
Large-scale reconstruction methods for high-quality 3D photoacoustic imaging

IMT Toulouse France, CNRS, IPAL & A*STAR Singapore

1 Project

Context Photoacoustic tomography (PAT) is a recent imaging modality [12]. Upon a laser excitation of the tissue, the light is absorbed and results in localized pressure increase. An ultrasound wave is thus generated and measured over time (as an electrical signal) by several ultrasound detectors distributed on a surface surrounding the tissue. This modality allows to image tissues at large (centimeter) depths and in high (submillimeter) resolution. The reconstruction of the image is then performed through the resolution of an inverse problem from the observed (measured) signals. PAT is an emerging tool for the evaluation of molecula or nanometric constrast *in vivo*, which is a major challenge of current biomedical imaging, and shows great potential in biological and clinical research.

Scientific challenges and state of the art Reconstructing a PAT image amounts to solving a linear inverse problem with an ill-posed operator A that models the wave propagation and the physics of acquisition of the system. With the perfectly known operator, the resolution of inverse problems is now supported by a rich theory and a set of efficient methods such as proximal algorithms [4] or learned-based algorithms (e.g. plug-and-play [7] or unrolled algorithms [9]). They involve iterative applications of matrix-vector products with A.

The resolution of this inverse problem is however numerically challenging due to the large dimension of the matrix A. Typically, for a 3D experiment with complex acquisition geometries such as the PAT scanner at stake in this project [6], A can be discretized by a sparse matrix of the Terabyte-size in memory. For these reasons, the majority of reconstruction methods proposed in the literature [11] generally assume isotropic detectors and therefore neglect the spatially varying impulse response (SVIR) of real detectors. This leads to the degradation of contrast and resolution of the reconstructed images. Even though their methods cannot be used in practice due to their high memory requirements and long computation times, a few works have emphasized the necessity to incorporate the SVIR of the sensors to reach high-quality reconstruction [2].

Moreover, the physics modeling A involves some parameters (e.g. the electrical impulse response of the sensors) that are unknown and should be properly identified. Describing as faithfully as possible the acquisition system is key to obtain high-quality reconstructions. Finally, the reconstruction algorithms depend on hyper-parameters that are hard to tune for a non-expert to the extent that the most sophisticated algorithms become unusable and must be accompanied by automatic fine-tuning methods.

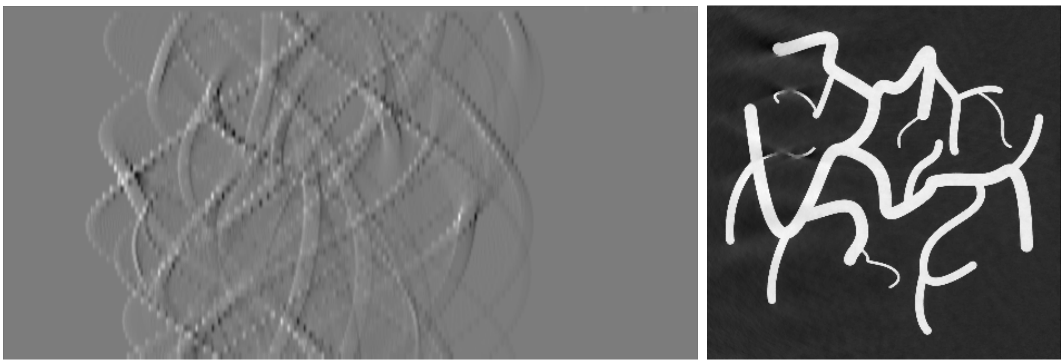

Figure 1: Measured signals (left) and the associated reconstruction (right).

Objectives and outcomes The goal of this PhD thesis is to deploy the 3D PAT scanner designed by Jérôme Gateau at the Laboratoire d'Imagerie Biomédicale (LIB) for a routine use in biomedical studies. This will be achieved by designing fast reconstruction methods that provide high-quality results. Depending on the candidate interests, the following axes would be considered:

- Designing implementations of the forward and adjoint models (modeled by matrix-vector products) that are *fast* and that *incorporate the SVIR* of the detector. During their preliminary works, the partners have identified a promising approximation method of A together with the actual reconstruction algorithms. The method based on the Fourier Integral Operator form of the wave propagation equation [3, 8], should be able to scale high-quality reconstructions to real data. Other types of approximation could also be considered such as Hierarchical matrices [1] or tensor-train decomposition [10].

- Designing reconstruction algorithms based on deep neural networks: such as Plug-and-Play methods [7] or algorithm unrolling [9].

- Implementing an optimized high-parallel (GPU) version of the algorithms to meet with the time requirements of routine use.

- Designing automatic fine-tuning methods of the hyper-parameters involved in these reconstruction algorithms and the calibration of the parameters of A.

One outcome of this PhD project is a photoacoustic scanner that *simultaneously* combine, compared to standard reconstruction methods, (i) shorter acquisition times, (ii) a reconstructed image of higher resolution and contrast, and (iii) shorter computation times. This could have a great impact on the PAT community which in turn will benefit the clinical and biological communities. The candidate will be trained and could develop skills in optimization, image processing, machine learning, high performance computing and approximation theory. These competences are actively being in demand in the industry and the academic research.

2 Information

Supervision The PhD will be supervised by:

Paul Escande	CNRS	Institut de Mathématiques de Toulouse (IMT), France
Caroline Chaux	CNRS	IPAL Singapore
Hwee Kuan Lee	-	A*STAR Singapore and IPAL Singapore

Paul Escande will bring his expertise in operator compression and highly-parallel implementation. Caroline Chaux has developed an expertise in convex optimization, sparse representations and signal processing. She is a member of IPAL in Singapore since 2022. She defended her Habilitation à Diriger les Recherche (HdR) in January 2019. She is the lead principal investigator of WP3 in Descartes project (CNRS@CREATE). Hwee Kuan Lee will bring expertise in Deep Learning and principles of photo acoustics. He is the head of research division and Deputy director in the Bioinformatics Institute, A*STAR.

The project also involves Jérôme Gateau (CR CNRS at Laboratoire d'Imagerie Biomédicale (LIB) in Paris, France) the expert in PAT, who have recently implemented a new photoacoustic 3D scanner similar to [5] and acquired 3D images from the device.

Location, duration and funding The PhD is a three-year project expected to start in October 2024 and will take place between the Institut des mathématiques de Toulouse (IMT) and the IPAL-A*STAR in Singapore with a 50% split between the two. The PhD thesis is **fully funded** by an IPAL-A*STAR fellowship. The applicant will go through the approval of IPAL-A*STAR.

Candidate profile Master of computer science or applied mathematics with strong skills in signal/image processing, optimization, machine learning and numerical computations. Languages: Python/Matlab, C++/CUDA.

Application Applications must be sent to Paul Escande (paul.escande@cnrs.fr), Caroline Chaux (caroline.chaux@cnrs.fr) and Hwee Kuan Lee (leehk@bii.a-star.edu.sg). They should include a resume, a motivation letter, detailed grades at least for Bachelor and Master degrees, recommendation letters and/or contact of referees, possible scientific reports from past projects and any additional useful document.

The timeline is tight, with an application deadline May 15, 2024 (interviews may be conducted before this date, on the fly when application are received). Candidates are invited to contact any of the co-supervisors at any time to obtain more details.

References

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