Hyperspectral Single-pixel Image Reconstruction using Nonnegative Matrix Factorization and Deep Learning

Master II Project, CREATIS, Lyon, France

The CREATIS laboratory announce the opening of a six-month internship position, starting in March 2023. An ANR-funded PhD position will be opened in October 2023 to continue on the same topic.

Fluorescence-guided surgery (FGS) refers to surgical guidance in brain tumor resection, where fluorescence imaging has proven to be efficient for glioma resection, with improved survival rates without recurrence [1]. This technique consists of administration of 5-aminolevulinic acid to the patient, which is a molecule that is absorbed by the tumor cells and metabolized into protoporphyrin IX (PpIX). The PpIX fluorescence signal can be visualized using an intraoperative microscope equipped with a fluorescence module (excitation, 405 nm; emission, 630 nm). While initial studies have shown that only high-grade glioma resection can benefit from FGS, several recent studies have indicated that FGS is also of interest for low-grade gliomas, provided that the full-spectrum information is measured by point probes [2] or multispectral cameras [3]. While this work paves the way to a better determination of the tumor margin during surgery, the latter studies considered point measurements with an external measurement device. It will be highly desirable to perform hyperspectral measurement with the surgery microscope itself, providing the surgeon with real-time imaging rather than a few point measurements. However, a high spectral resolution is needed to distinguish the two states of PpIX.

Problem definition In a previous project[1], we developed a computational imager that can acquire a linear transformation of hypercubes $X \in \mathbb{R}^{N\times\Lambda}$ at high spectral resolution (e.g., $\Lambda = 2,048$). More precisely, our system measures sequentially a set of M spectra, each of them being the spectrum of the light selected from a portion of the pixels using a spatial light modulator. Repeating the experiment for M spatial light patterns yields the raw measurements that can be modelled for a given wavelength λ as

$$y_\lambda \sim \mathcal{P}(\alpha A x_\lambda), \quad 1 \le \lambda \le 2048,$$

where $y_\lambda \in \mathbb{R}^M$ are the raw measurements, $\mathcal{P}$ is the Poisson distribution, α is the image intensity, $A \in \mathbb{R}^{M\times N}$ is a matrix containing the spatial light patterns (e.g., a subsampled Hadamard matrix) and $x_\lambda \in \mathbb{R}^N$ is a slice of the hypercube X. Our acquisition device being computational, it requires a reconstruction algorithm to recover the hypercube X from the raw data Y.

Challenge In a series of works, we have proposed deep-learning reconstruction methods that can be interpreted in a Bayesian framework [4, 5]. These algorithms reconstruct the images x_λ for each wavelength λ independently, for simplicity. Here, we would like to estimate X from all the measurements Y in a joint manner, in order to enforce the consistency of the solution along the spectral dimension.

A promising direction is hypothesize that hyperspectral images are low-rank and model X as a product of two small nonnegative matrices W and H, where H represents the spectra of the image components (e.g., PpIX) and W their concentration. Combining this prior knowledge with the previously developed methods leads to the optimization problem:

$$\min_{W\ge 0, H\ge 0} KL(Y|\alpha AWH) + g_\theta(W,H), \tag{1}$$

where g_θ is a regularization related to the action of a deep neural network, promoting realistic images, and KL is the Kullback-Leibler divergence. This problem is an extension of Nonnegative Matrix Factorization [6], a well-studied unsupervised machine learning problem.

[1] ANR JCJC ARMONI (2018–2022)

CREATIS | institut universitaire de France | UNIVERSITÉ DE LYON

Work plan This internship will include the following tasks:

- Literature review on Nonnegative Matrix Factorization and unrolled networks for reconstruction.
- Validation of the low-rank hypothesis on hypercubes X acquired in our lab.
- Understand, and possibly modify, the proposed cost function (1).
- Suggestion of an optimization algorithm to solve (1).
- Implementation of the proposed algorithm and evaluation of the reconstruction performance on simulated and experimental data.

Skills We are looking for an enthusiastic and autonomous candidate with a strong background in applied mathematics, image processing, or deep learning. The applicant can be enrolled in either a Master or Engineering degree program. The following skills will be acquired during the internship, although prior knowledge on these topics are appreciated:

- Programming in Python (numpy/pytorch in particular), collaborative development (git and github)
- Convex and non-convex numerical optimization (projected/proximal gradient descent)
- Linear algebra and inverse problems (ill-posed problems, regularization)
- Deep learning (neural network design and optimization, automatic differentiation)
- Hyperspectral imaging

The intern will be part of a dynamic team composed of several permanent researchers and engineers and other interns recruited simultaneously on related topics.

How to apply? Send CV, motivation letter, and academic records to nicolas.ducros@creatis.insa-lyon.fr and jeremy.cohen@cnrs.fr.

Salary The gratification of the internship corresponds to 1/3 of the hourly minimum wage (∼€550 net monthly).

References

[1] W. Stummer, U. Pichlmeier, T. Meinel, O. D. Wiestler, F. Zanella, H.-J. Reulen, and ALA-Glioma Study Group, "Fluorescence-guided surgery with 5-aminolevulinic acid for resection of malignant glioma: a randomised controlled multicentre phase III trial," *Lancet Oncol.*, vol. 7, pp. 392–401, May 2006.

[2] L. Alston, L. Mahieu-Williame, M. Hebert, P. Kantapareddy, D. Meyronet, D. Rousseau, J. Guyotat, and B. Montcel, "Spectral complexity of 5-ALA induced PpIX fluorescence in guided surgery: A clinical study towards the discrimination of healthy tissue and margin boundaries in high and low grade gliomas," vol. 10, no. 5, pp. 2478–2492.

[3] J. J. Bravo, J. D. Olson, S. C. Davis, D. W. Roberts, K. D. Paulsen, and S. C. Kanick, "Hyperspectral data processing improves PpIX contrast during fluorescence guided surgery of human brain tumors," *Sci. Rep.*, vol. 7, pp. 1–13, Aug 2017.

[4] A. Lorente Mur, P. Leclerc, F. Peyrin, N. Ducros, and N. Ducros, "Single-pixel image reconstruction from experimental data using neural networks," *Optics Express*, vol. 29, pp. 17097–17110, May 2021.

[5] A. Lorente Mur, P. Bataille, F. Peyrin, and N. Ducros, "Deep Expectation-Maximization For Image Reconstruction From Under-Sampled Poisson Data," in *2021 IEEE 18th International Symposium on Biomedical Imaging (ISBI)*, (Nice, France), pp. 1535–1539, IEEE, Apr. 2021.

[6] N. Gillis, "The why and how of nonnegative matrix factorization," *Connections*, vol. 12, no. 2, 2014.