Project Proposal

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1. Motivation

Working in the field of interferometric imaging for biomedical applications, there are many challenges with regard to image processing. I work with optical coherence tomography (OCT), which uses low-coherence interferometry to provide tomographic visualization of internal tissue micro-structures. Adopting the structure of the Michelson interferometer, we use a line-field spectral domain OCT to image rat retina and try to measure the distance between different retinal layers using the phase information encoded in the OCT image. Layer spacing will change in response to different stimulus, e.g., photoreceptor cell mechanical deformation during the process of phototranduction, thermo-mechanical expansion of retina pigmentation epithelium due to heating. These layer movements are on the order of nanometer scale but the OCT achieves only micrometer resolution. Therefore, even though there are layer movements, we would not able to observe them on the OCT intensity scan. Pictorially,

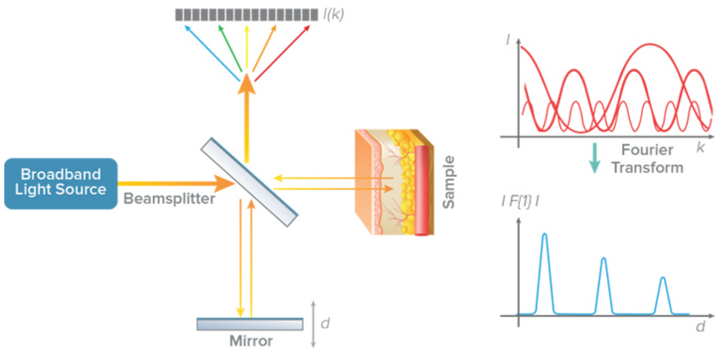

Figure 1: OCT: Michelson Interferometer

the peaks will be stationary because the layer movements are subpixel scale. However, the complex spectrum obtained from the Fourier transform of the real-valued interferogram contains extra phase information. The phase difference between two peaks can actually be converted to absolute distances. To utilize the phase, we must make sure that we have good signal-to-noise ratio in the intensity OCT image. Despite the optical methods, e.g., using adaptive optics to reduce system abberations, there are various kinds of software based techniques. **One crucial factor** that blurs or broadens the peaks shown in Figure 1 is the dispersion mismatch between the two arms. Dispersion compensation algorithms have been extensively explored in the literature (please see the next section for more details). They all come with different flavors, pros and cons.

In this project, I will evaluate some of the algorithms, potentially with real OCT data. I will also formulate the problem based on some contrast-based metric and solve the optimization problem with some techniques learned in class.

Another crucial factor that plays an important role in our phase analysis is the image registration. When imaging real animals, even though we anesthetize the animal and use contact lens to fixate their eyes, movements are observed in the OCT retina scans. Image registration algorithms under rigid deformation or nonrigid deformation assumptions are also explored extensively in the literature (please see the next section for more details). I think it might be also good to investigate more in this area.

2. Related Works

- Maciej Wojtkowski, Vivek J. Srinivasan, Tony H. Ko, James G. Fujimoto, Andrzej Kowalczyk, and Jay S. Duker, "**Ultrahigh-resolution, high-speed, Fourier domain optical coherence tomography and methods for dispersion compensation**," Opt. Express 12, 2404-2422 (2004)

  The dispersion compensation algorithm proposed in this paper is an iterative method to find two coefficients, i.e., a_2 and a_3. The flow is showing below:

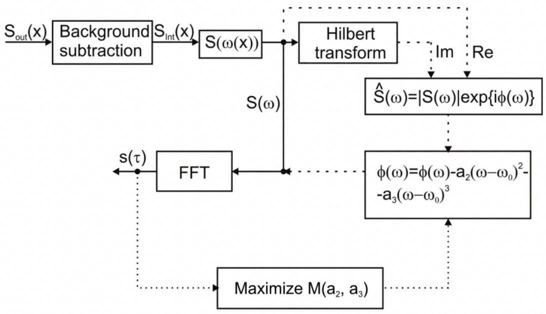

Figure 2: Dispersion algorithm 1

  $S_{\text{out}}(x)$ denotes the camera spectrum reading. After background subtraction and wavenumber resampling, the resultant interferogram is Hilbert transformed so the complex analytic signal of the real interferogram is found. The phase is corrected simply by adding two terms, where the second order term tries to cancel the group velocity dispersion imbalance and the third order term is to cancel third-order dispersion imbalance. The algorithm tries to iteratively maximize a sharpness metric $M(a_2, a_3)$, which is defined as the one over the total number of pixels if the pixel value is above a threshold. This metric basically measures the concentration of the energy within the image, as mentioned in the paper. To my knowledge, the paper didn't mention explicitly about the iterative solver they use to solve this optimization problem.

- Shangbang Luo, Guy Holland, Eric Mikula, Samantha Bradford, Reza Khazaeinezhad, James V Jester, Tibor Juhasz, "**Systematic dispersion compensation for spectral domain optical coherence tomography using time-frequency analysis and iterative optimization for iridocorneal angle imaging**," arXiv:2112.15302 (2021)

  This paper uses time-frequency analysis (TFA) for dispersion compensation. As shown below: for

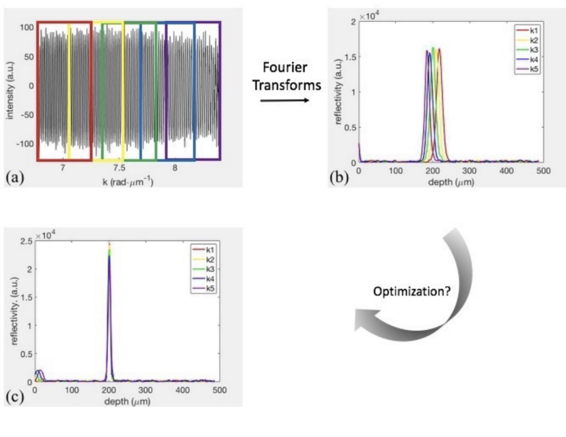

Figure 3: Dispersion algorithm 2

  a simple mirror sample, taking the short-time Fourier transform (STFT) of the interferogram, the layer profiles were not overlapping on each other due to dispersion. They basically iterative solving for the same two coefficients as shown in the previous paper, namely, a_2 and a_3, to minimize a cost function (custom function defined in the paper) after ridge detection. They used the Simplex search method, 'fminsearch', off-the-shelf function written in MATLAB for the iterative optimization.

Comments: There are many more papers on dispersion compensation but most of them are based off the same principle of solving for the best phase compensating coefficients.

- Xu J, Ishikawa H, Wollstein G, Kagemann L, Schuman JS. **Alignment of 3-D optical coherence tomography scans to correct eye movement using a particle filtering**. IEEE Trans Med Imaging. 2012 Jul;31(7):1337-45. doi: 10.1109/TMI.2011.2182618. Epub 2012 Jan 4. PMID: 22231171; PMCID: PMC3417150.

I also want to look into image registration of OCT images. Even though I have not yet fully grasped the working principle of the algorithm of particle filtering yet, I am very interested in this state-space and probabilistic approach of tracking motions of images.

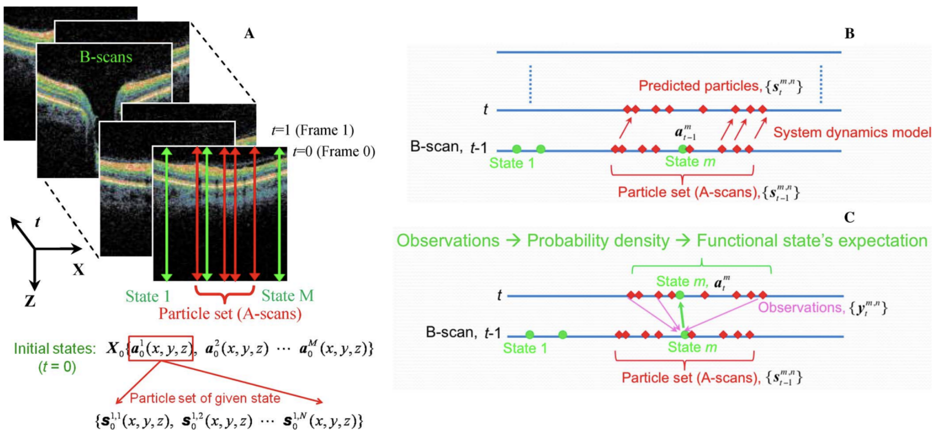

Figure 4: OCT image registration algorithm 1

The class of image registration is huge. They are mainly classified as intensity-based and feature-based approaches. Intensity-based approach tends to use correlation ratio, Shannon's entropy or other metrics to evaluate the spatial correlations between images. Feature-based approaches often extract layers structures first using either graph theory or deep learning (image segmentation), and then compute the shifts between layers. There are also review papers on comparing various kinds of image registration algorithms. I think it would be worth to explore some of these algorithms if dispersion compensation is easily done.

3. Milestones

- Feb 25th: formulate the (dispersion compensation) optimization problem using various kinds of contrast-based metrics or other kinds of metric that could describe the sharpness of an image. David's brainstorm ideas: spectral density estimation (MUSIC), multi-scale representation or image pyramid (speckle noise reduction), simulation considerations (how to simulate OCT interferogram? how sophisticated it should be?).
- Feb 28th: finish at least one algorithm exploration.
- Mar 4th: finish at least three algorithm exploration.
- Mar 9th: project presentation

The final goal of this project is to study various kinds of image processing algorithms (especially, coherent imaging) and compare their performances, so I could later use in my research. I have talked with David in depth about OCT and he has agreed to be my mentor.