SMD2.pdf

Image Reconstruction from Nonuniform Samples in Spectral Domain Optical Coherence Tomography

Jun Ke*, **Rui Zhu, Edmund Y. Lam**

Department of Electrical and Electronic Engineering, University of Hong Kong, Hong Kong

**Corresponding author: junke@hku.hk*

Abstract: We cast the signal reconstruction in spectral domain optical coherence tomography (SD-OCT) as a minimization problem with total variation regularization. A cross-sectional image in SD-OCT is estimated directly from non-uniformly spaced frequency samples.

OCIS codes: 110.4500, 100.3190, 100.3010.

1. Introduction

Spectral Domain Optical Coherence Tomography (SD-OCT) is an imaging modality providing cross-sectional images with micrometer resolution by using a broadband source and measuring fringe patterns with a spectrometer. As one of the major system parameters, the A-line scanning speed of SD-OCT reaches around 30,000 lines per second [1, 2]. To increase the scanning speed, various kinds of line detector array and signal processing instruments such as graphic processing units (GPU) have been studied [2–4]. Besides the scanning speed, another important concern to OCT systems is to improve signal reconstruction quality, such as improving depth resolution, reducing dispersion effect, and suppressing speckle noise [5]. In this paper, we employ total variation (TV) minimization [6] for 2D signal reconstruction with non-uniformly distributed frequency samples of SD-OCT.

SD-OCT system uses a spectrometer to collect measurements which are uniformly distributed in wavelength. However, the conventional signal reconstruction in OCT employs a fast Fourier transform to samples in wave number space or K-space [7]. To deal with the nonlinear correspondence between a wave number and a wavelength, we need signal resampling before the transform. The drawback caused by the resampling process has been studied by several groups [1–4]. Alternatively, different versions of non-uniform discrete Fourier transform (NUDFT) are employed to avoid this process [1, 3, 4]. In this work, we not only avoid the resampling process, but also reconstruct the 2D cross-sectional image directly from SD-OCT measurements, instead of processing each A-line data separately. Beyond both advantages, because TV regularization is based on signal 2D information, we expect the reconstructed image to have better visual quality.

2. TV method for 2D signal reconstruction in FD-OCT

Figure 1 presents a SD-OCT system [7]. In such a system, the interfered wavefronts reflect from a reference mirror and a sample is measured by a spectrometer. The obtained measurements can be represented as [7]

$$I(\lambda_m) = G(\lambda_m)\left(p_r^2 + \sum_{n=0}^{N-1} p_s(z_n) p_r e^{j2k_m z_n}\right) + n(\lambda_m), \quad m = 0, 1, \cdots, M-1 \tag{1}$$

where λ_m is the mth wavelength detected by the spectrometer, $k_m = 2\pi/\lambda_m$ is the corresponding wave number, $I(\lambda_m)$ and $G(\lambda_m)$ are the system measurement and the source power spectrum at λ_m, $p_s(z_n)$ is the sample reflective ratio at depth z_n, p_r is the reference mirror reflective ratio, and $n(\lambda_m)$ represents the noise or error through the measurement process as a function of λ_m. We normalize Equation (1) with the reference mirror reflective ratio p_r and subtract the measured source spectrum $G(\lambda_m)$. Then the measurement process for L set of spectrometer measurements can be written as $\mathbf{Y} = \mathbf{HX} + \mathbf{N}$, where $\mathbf{Y}$ $(M \times L)$ is the measurement matrix with each column representing one set of the

SMD2.pdf

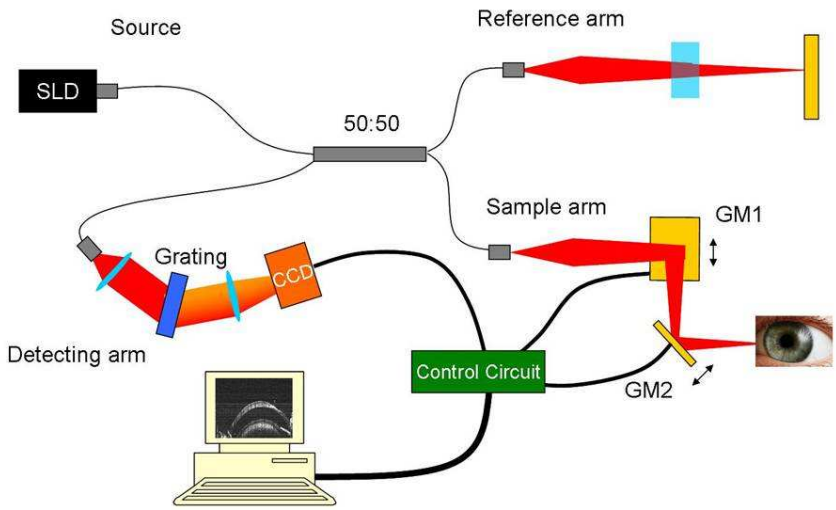


Fig. 1. Diagram for a SD-OCT system.

spectrometer measurements for one A-line, $\mathbf{H}$ $(M \times N)$ is the projection matrix with the $(i, j)^{th}$ element defined as

$$\mathbf{H}_{ij} = \exp\left\{ j2\pi \cdot \frac{k_i - \min_i\{k_i\}}{\max_i\{k_i\} - \min_i\{k_i\}} \cdot \frac{z_j}{\max_j\{z_j\}} \cdot N \right\}, \quad \begin{array}{l} 0 \le i \le M-1 \\ 0 \le j \le N-1 \end{array} \tag{2}$$

and matrix $\mathbf{X}$ $(N \times L)$represents a sample with L A-lines where each A-line contains N depth levels. Similar to the term $n(\lambda_m)$ in Equation (1), matrix $\mathbf{N}$ $(M \times L)$ represents the noise or error in SD-OCT system measurement process.

As discussed in the introduction section, we aim to reconstruct 2D cross-sectional signal using L sets of spectrometer measurements simultaneously. We solve the following minimization problem to search the signal estimation [8],

$$\underset{\mathbf{X},\mathbf{U}}{\text{minimize}} \;\; ||\mathbf{HX} - \mathbf{Y}||_2^2 + \alpha_1 ||\mathbf{X} - \mathbf{U}||_2^2 + \alpha_2 ||\mathbf{U}||_{TV} \;\; , \tag{3}$$

where $\alpha_1 > 0$ and $\alpha_2 > 0$ are two penalty parameters, $||\mathbf{U}||_{TV}$ is the total variation of matrix $\mathbf{U}$ $(N \times L)$,

$$||\mathbf{U}||_{TV} = \sum_{1 \le i \le N, 1 \le j \le L} \sqrt{|(\nabla U)^x_{i,j})|^2 + |(\nabla U)^y_{i,j})|^2} \tag{4}$$

with

$$(\nabla U)^x_{i,j} = \begin{cases} U_{i+1,j} - U_{i,j} & \text{if } i < N \\ 0 & \text{if } i = N \end{cases}, \quad (\nabla U)^y_{i,j} = \begin{cases} U_{i,j+1} - U_{i,j} & \text{if } j < L \\ 0 & \text{if } j = L \end{cases}.$$

To solve Equation (3), we use the following alternating minimization algorithm where

$$\begin{cases} \mathbf{X}^{(i)} = \arg\min_{\mathbf{X}} \;\; ||\mathbf{HX} - \mathbf{Y}||_2^2 + \alpha_1 ||\mathbf{X} - \mathbf{U}^{(i-1)}||_2^2 \\ \mathbf{U}^{(i)} = \arg\min_{\mathbf{U}} \;\; \alpha_1 ||\mathbf{X}^{(i)} - \mathbf{U}||_2^2 + \alpha_2 ||\mathbf{U}||_{TV} \;\; . \end{cases} \tag{5}$$

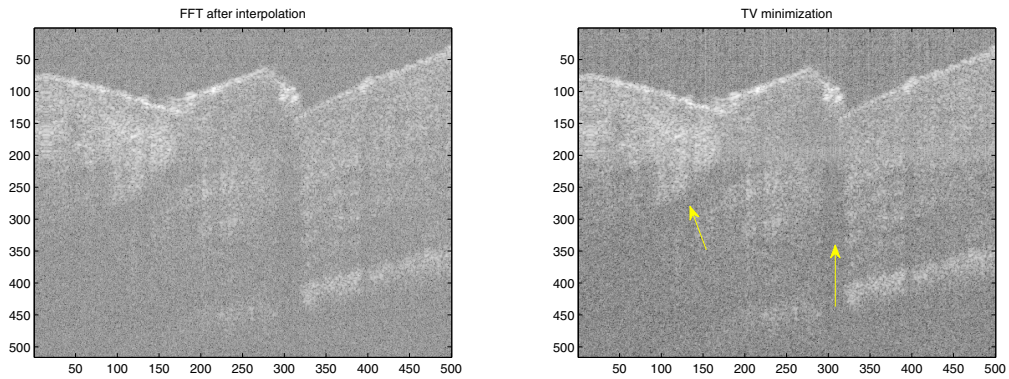
CG method and Chambolle's projection algorithm [8] are used to search the solutions to the first and the second minimization problems in Equation (5), respectively.

3. Result

In the experiment, a Superluminescent Diode (SLD) light is used as the illumination source for the SD-OCT system. The center wavelength of the source is 830nm with a bandwidth of 35nm. We scan the back of a human finger including nail and skin parts to collect the system measurements. A silver coated mirror with 2 inches diameter is

SMD2.pdf

used in the reference arm for reference beam reflection. The measurements are collected by a customized spectrometer consisting of an Edmund Optics 1 inch VPH grating and a line array camera. Using this set-up, 500 A-lines with each A-line including 2048 samples are collected for one cross-sectional image of the sample. To reconstruct the signal, we employ two methods. One is the conventional method where each set of the measurements for one A-line is interpolated onto an uniformly spaced K-space grid, then a fast Fourier transform is used with these samples to reconstruct one A-line signal. The other is to use the TV minimization method for signal reconstruction directly with system measurements without interpolation. Fig. 2 (a) and (b) present a close view of the reconstructed cross-sectional



(a) (b)

Fig. 2. Reconstructed image using (a) interpolation followed by FFT; (b) TV minimization method.

images with conventional and TV minimization methods, respectively. From this Figure, we can observe that the latter is able to reconstruct the 2D signal better, with better contrast and edge sharpness compared with the reconstruction using the conventional method, such as in the area pointed with the two arrows. This is consistent with other group's observation that TV can preserve edges due to the piecewise smooth regularization property of the TV norm [8]. Finally, although we use the TV minimization method for signal reconstruction in SD-OCT system, it can also be used for reconstruction in Swept-Source OCT (SS-OCT) system.

References

1. Kai Wang, Zhihua Ding, Tong Wu, Chuan Wang, Jie Meng, Minghui Chen, and Lei Xu. Development of a non-uniform discrete Fourier transform based high speed spectral domain optical coherence tomography system. *Optics Express*, 17(14):12121–12131, 2009.
2. Yuuki Watanabe, Seiya Maeno, Kenji Aoshima, Haruyuki Hasegawa, and Hitoshi Koseki. Real-time processing for full-range Fourier-domain optical-coherence tomography with zero-filling interpolation using multiple graphic processing units. *Applied Optics*, 49(25):4756–4762, 2010.
3. Henny K.H. Chan and Shuo Tang. High-speed spectral domain optical coherence tomography using non-uniform fast Fourier transform. *Biomedical Optics Express*, 1(5):1309–1319, 2010.
4. Kang Zhang and Jin U. Kang. Graphic processing unit accelerated non-uniform fast Fourier transform for ultrahigh-speed, real-time Fourier-domain oct. *Optics Express*, 18(22):23472–23487, 2010.
5. Wolfgang Drexler. Ultrahigh-resolution optical coherence tomography. *Journal of Biomedical Optics*, 9(1), 2004.
6. Leonid I. Rudin, Stanley Osher, and Emad Fatemi. Nonlinear total variation based noise removal algorithms. *Physica D: Nonlinear Phenomena*, 60(1-4):259–268, 1992.
7. Mark Brezinski. *Optical Coherence Tomography-Principles and Applications*. Elsevier Inc., 2006.
8. Yumei Huang, Michael K. Ng, and You wei Wen. A fast total variation minimization method for image restoration. *Multiscale Modeling & Simulation*, 7(2):774–795, 2008.