CSC2529 Project Proposal: Evaluating Custom Illumination Patterns for Single-Snapshot Optical Tissue Properties Imaging

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Motivation

Biological tissue is a heterogeneous and dynamic mixture of different chromophores that exhibit different optical properties. By measuring and processing the optical response of tissue, it becomes possible to safely and non-invasively extract important physiological information such as tissue oxygenation and hemodynamic structures.

One such technique is Spatial Frequency Domain Imaging (SFDI), which has been of particular interest since its inception[1] due to its large field-of-view and rapid imaging capabilities[2]. This technique involves illuminating a tissue with spatially modulated intensity patterns to sample the tissue modulation transfer function (MTF), from which absorption/scattering maps can be extracted to discriminate between different tissue chromophores. However, this method requires sequentially sampling the tissue MTF at various spatial frequencies and phases, limiting the temporal resolution of the technique.

Due to recent advances in spatial light modulator (SLM) and digital micromirror device (DMD) technologies, we can arbitrarily modulate light intensities with high spatial and temporal resolutions. Furthermore, it has been shown that wide-field tissue properties can be extracted from single-snapshot derivatives of SFDI techniques at the cost of increased noise and artefacts. Here, we aim to exploit the capability of custom illumination patterns to optimize the accuracy and spatial resolution of single-snapshot-derived wide-field optical tissue measurement techniques.

Related Work

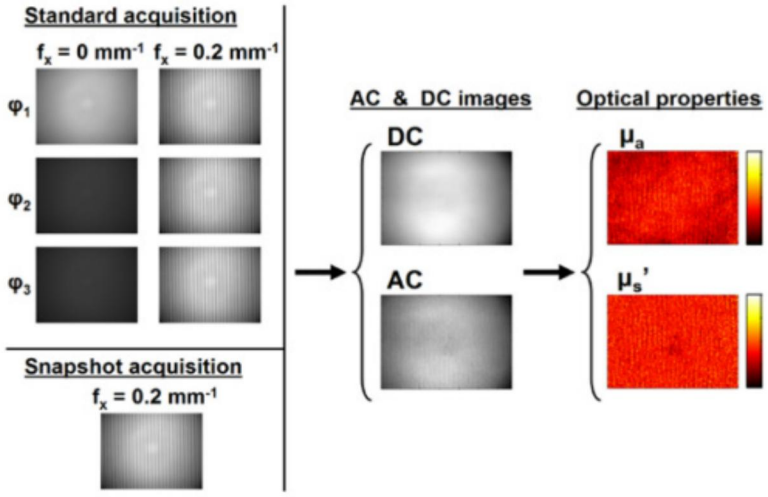

Figure 1: SFDI (Standard acquisition) and SSOP (Snapshot acquisition) illumination patterns can both be used to develop tissue optical property maps. Taken from [3].

The original SFDI was introduced in 2009 by Cuccia et al.[1]. Since then, there have been a wide variety of attempts to produce tissue optical property maps from a reduced number of images.

Nadeau et al. modifies this approach by exploiting the multiple spatial frequencies in binary square waves[4]. They report strong agreement with 3-phase SFDI using two images (square wave and DC).

Vervandier et al. developed the single snapshot optical properties (SSOP) technique[3], which illuminates with a single 0.2mm^{-1} spatial pattern and applies digital line-by-line filtering to separate DC and AC components of the tissue MTF. However, SSOP images are noisy and have depth variation artefacts since only one spatial frequency of the tissue MTF is sampled.

Cao et al. increases the number of sampled frequencies with the multiple frequency demodulation (SSMD) method[5] by superimposing two spatial frequencies rotated 45° with respect to each other such that there are two spatial frequencies in a single illumination pattern. Compared to SSOP, it is shown to improve the reduce noise and motion artefacts.

Based on these previous works, we suspect that the illumination pattern can be optimized jointly with the image processing technique to improve single-snapshot optical property map fidelity.

Project Overview

The goal of this project is to exploit the full illumination pattern generation capabilities of a DMD to explore the benefits of custom illumination patterns for sampling tissue MTF in SSOP. We shall collect both simulated and experimental SFDI/SSOP data using an optical setup and LightTools simulations previous developed in our lab by Lindsay Kuramoto.

First, we shall explore permutations of simple patterns with standard SFDI/SSOP processing flows to explore their effects. These include:

- ***Angle between two spatial frequencies patterns:*** Cao et al. reports on a spatial frequency pattern consisting of two harmonics aligned 45° to each other[5]. Giessen illuminates with a grid pattern and uses the warping on one axis to correct for sample depth changes[6]. What effect do different angles between overlapping spatial patterns have on SSOP results?
- ***Multiplexing spatial frequencies:*** Vervandier et al.'s original SSOP method take a line-by-line Fourier transform of each image to extract the MTF[3]. What if we alternated the illumination pattern every several lines? What happens at the interface between patterns due to photon diffusion? Would we be able to sample the MTF using multiplexed frequencies?

Provided the above investigations are promising, we aim to apply/develop complementary computational methods for extracting tissue properties. These include:

- **Complementary processing:** The SFDI/SSOP MTF sampling methods are optimized for sampling single spatial frequencies. Modifications will likely be necessary to exploit custom illumination patterns.
- **Edge smoothing**: Vervandier et. al's SSOP method results in edge artefacts arising from illumination patterns distorting with depth variations[3]. Would edge sharpening techniques (bilateral filtering, NLM, etc.) correct edges while maintaining medical accuracy?

Learned approach: del Hougne et al. showed that tunable surfaces such as DMDs can be used as physical network layers[7]. Is it possible to learn an optimized illumination pattern using ADMM?

Milestones/Timeline/Goals

Week 1: Nov 17 – Nov 23

- Familiarize ourselves with the SFDI/SSOP setup and LightTools simulations using standard illumination patterns.
- Replicate two spatial frequency pattern results from Cao et. al's method[5].
- Characterize optical property maps generated from changing the angle between the spatial patterns.
- Characterize the effects of multiplexing spatial patterns in line-by-line SSOP.

Week 2: Nov 24 – Nov 30

- Modify SSOP processing flow to exploit experimentation results from Week 1 to develop new computational methods optimized for different illumination patterns.
- Compare SSOP + Edge Smoothing algorithms against SFDI images to characterize accuracy.
- Time permitting, learn an optimized DMD pattern with ADMM trained with SFDI results.

Week 3: Dec 1 – Dec 8

- Three days (Dec 1 – 3) to complete remaining work or any new tasks arising from investigations.
- Write report.
- Design and print poster.

References

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Appendix: Notes on Tissue Optical Properties Imaging

- Spatial Frequency Domain Imaging (SFDI) reveals optical properties of tissue by projecting a spatially modulated wave pattern.
    - Light source needs to be incoherent to avoid speckle patterns
    - Modulation of light is done by software controlled DMD, to project sinusoidal pattern on tissue
    - Raw SFDI data is collected as diffuse reflectance, which consists of an AC signal overlaying on DC signal
    - Usually more than three snapshots are captured (with a phase difference between the illumination patterns), to separate AC from DC
    - Separating two streams of signal helps to calculate the optical properties of tissue (absorption and scattering coefficients)
    - A look-up-table is generated for easier matching of data.
- Single Snapshot Optical Properties (SSOP) is an advanced version of SFDI that only takes one snapshot (rather than > 3)
    - Approach #1: Separate signals in Fourier domain
    - Artefacts near contours are significant, where signals in Fourier domain have low frequency
    - Approach #2: Overlapping tilted patterns with the same spatial frequency
    - Noise level on the recovered optical properties becomes lower
    - Original work by Cao et al. used 45 degrees between two patterns, different angles may optimize extraction of optical properties
    - Approach #3: Multiplexing spatial frequencies in one snapshot
    - Utilize the fact that Fourier transform of image is calculated line-by-line to extract MTF
    - The output may contain more information with graded spatial frequency