Multifrequency illumination patterns in single snapshot tissue optical properties imaging

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Motivation

- Spatial Frequency Domain Imaging (**SFDI**) is a **non-invasive wide-field** blood oxygenation measurement technique based on structured light illumination.
- Illumination patterns are simple 2D sinusoids, **one spatial frequency at a time**.
- Multiple spatial frequencies improves accuracy of optical properties extraction.

Goal:
Sample tissue at multiple spatial frequencies in one snapshot by optimizing the illumination pattern.

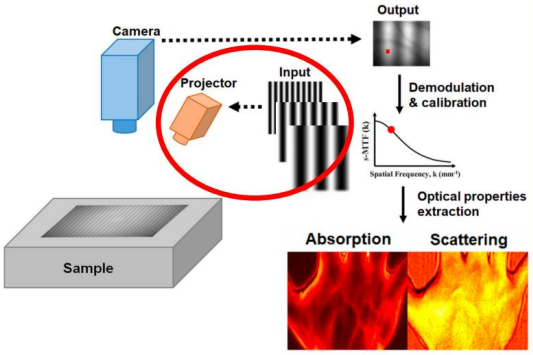

Figure 1: Typical SFDI setup. Adapted from [1].

New Technique

Improved single-snapshot SFDI illumination patterns.
- Multiplexing spatial frequencies in a layered pattern (**SSOP**).
- Superimposing spatial frequencies in an angled pattern (**SSMD**).

New demodulation algorithms for better separation of DC/AC signals.
- Vertical deblurring in multiplexing
- Multifrequency angle optimization

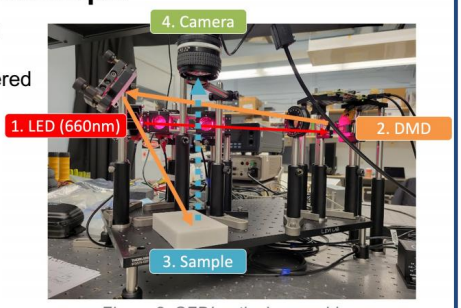

Figure 2: SFDI optical assembly.

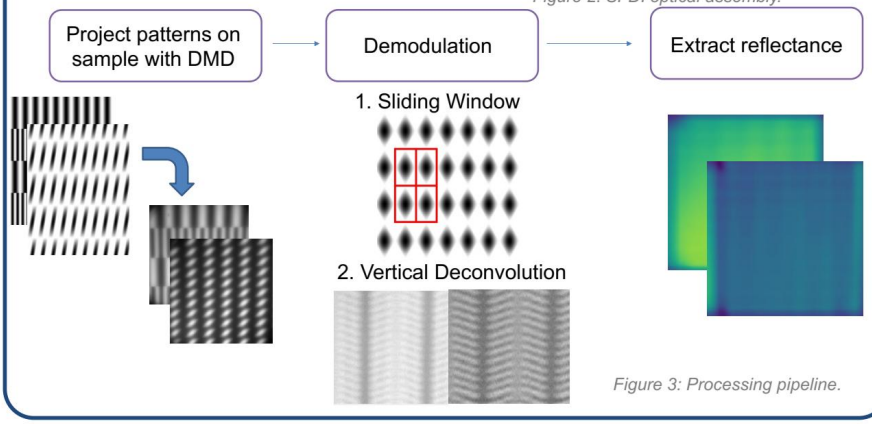

Figure 3: Processing pipeline.

Related Work

Spatial Frequency Domain Imaging (SFDI) [1]:
- **Illumination:** Multiple spatial frequencies and phases of single sinusoid patterns.
- **Processing:** Average over phase-shifted images to extract DC/AC reflectance.
- **# Images:** 3+ (2 frequencies/3 images)
- **Image Quality:** Low noise, minimal artifacts.

Single Snapshot Optical Properties (SSOP) [2]:
- **Illumination:** 1 2D sinusoidal spatial frequency.
- **Processing:** Line-by-line low/high-pass filter to separate DC/AC reflectance respectively.
- **# Images:** 1 (2 frequencies/image)
- **Image Quality:** High noise, significant depth variation artifacts.

Single Snapshot Multiple frequency Demodulation (SSMD) [3]:
- **Illumination:** 2 superimposed sinusoid patterns.
- **Processing:** Average over sliding window to extract DC/AC reflectance.
- **# Images:** 1 (3 frequencies/image)
- **Image Quality:** Better than SFDI and SSOP in noisy images.

Future Work

SSOP
- More sophisticated 1D deconvolution methods to eliminate vertical diffusion blurring

SSMD
- Overlay more spatial frequencies in a single snapshot
- Construct polygon shaped unit cell for demodulation

References

[1] D. Cuccia et al., "Quantitaion and mapping of tissue optical properties using modulated imaging", Journal of Biomedical Optics, 2009.
[2] J. Vervandier et al., "Single snapshot imaging of optical properties", Biomedical Optics Express 4, 2013.
[3] M. Xu et al., "Single snapshot multiple frequency modulated imaging of subsurface optical properties of turbid media with structured light", AIP Advances 6, 2016.

Experimental Results

Angled pattern SSMD:
45° is the optimum angle. Smaller angles lead to larger window size and lower resolution. Larger angles causes more severe aliasing.

Multiplex SSOP:
Higher multiplexing frequency decreases accuracy due to diffusion but is somewhat recoverable with vertical deblurring.

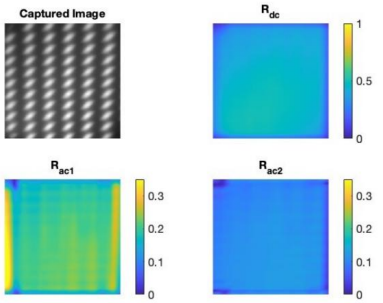

Figure 4: SSMD results (60°, 0.1/0.2mm⁻¹).

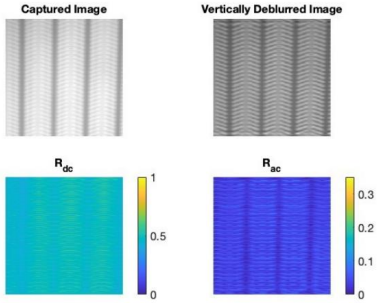

Figure 5: Multiplexed SSOP results (64 regions per frequency, 0.1/0.2/0.3/0.4mm⁻¹).

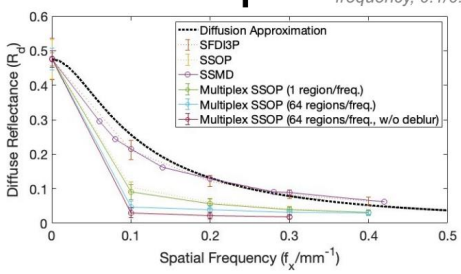

Figure 6: Diffuse reflectance of tissue phantom by spatial frequency with various SFDI methods.

Methods	Efficiency (Frequencies/Image)	Accuracy
SFDI	2/3 = 0.67	High
SSOP	2/1 = 2.00	Moderate
SSMD	3/1 = 3.00	High
Multiplex SSOP	5/1 = 5.00	Moderate