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Single-pixel spatial frequency domain imaging with integrating detection

Armin J. M. Lenz,[a,*] **Pere Clemente,**[b] **Vicent Climent,**[a] **Jesús Lancis,**[a] **and Enrique Tajahuerce**[a]
[a] *GROC-UJI, Institute of New Imaging Technologies (INIT), Universitat Jaume I, 12071, Castelló, Spain*
[b] *Servei Central d'Instrumentació Científica (SCIC), Universitat Jaume I, 12071, Castelló, Spain*
[*] *Corresponding author: maxemili@uji.es*

Abstract: We present a spatial frequency domain imaging (SFDI) system based on single-pixel imaging (SPI) techniques with a single digital micromirror device (DMD) modulating simultaneously the sinusoidal pattern and the spatial sampling masks. © 2021 The Author(s)

1. Introduction

Spatial frequency domain imaging (SFDI) is a diffuse optical imaging (DOI) modality where the turbid media sample's optical properties (absorption and scattering parameters) are characterized by measurements in the spatial frequency domain [1, 2]. The general procedure in this modality is to project spatially structured light patterns at multiple spatial frequencies onto the sample and to capture diffuse reflected light distribution with a camera. These measurements of diffuse reflectance are processed to obtain information about the spatial modulation transfer function (s-MTF) in order to spatially map sample absorption and reduced scattering coefficients, μ_a ans μ_s', respectively.

The simplest implementation requires the projection of sinusoidal patterns at different spatial frequencies (at least 2) each one with three different spatial phase offsets (0, $\frac{2\pi}{3}$ and $\frac{4\pi}{3}$). Multiple scattering and absorption will result in a decrease in the amplitude of the sinewave. For each spatial frequency (f_i) of the sinusoidal wave, the reflectance images ($I(x;f_i,0)$, $I(x;f_i,2\pi/3)$ and $I(x;f_i,4\pi/3)$) captured by the camera are further digitally processed to obtain the AC and DC amplitude modulation for every pixel via demodulation:

$$\begin{aligned} M_{\mathrm{AC}}(x;f_i) = \frac{\sqrt{2}}{3}\Big\{&[I(x;f_i,0)-I(x;f_i,2\pi/3)]^2 \\ &+[I(x;f_i,2\pi/3)-I(x;f_i,4\pi/3)]^2 \\ &+[I(x;f_i,4\pi/3)-I(x;f_i,0)]^2\Big\}^{1/2}. \end{aligned} \tag{1}$$

$$M_{\mathrm{DC}}(x) = M_{\mathrm{AC}}(x;f=0) = \frac{1}{3}\left[I(x;f_i,0)+I(x;f_i,2\pi/3)+I(x;f_i,4\pi/3)\right]. \tag{2}$$

The amplitude modulations are related to the sample spatial modulation transfer function (MTF) through a calibration step that involves the measurement of the amplitude modulation of a reference phantom with known optical properties. The expected $\mathrm{MTF}_{\mathrm{ref}}$ for the known optical properties of the reference sample is predicted using a light propagation model. The calibration step is then expressed as:

$$\mathrm{MTF}(x;f_i) = \frac{M_{\mathrm{AC}}(x;f_i)}{M_{\mathrm{AC,ref}}(x;f_i)}\cdot \mathrm{MTF}_{\mathrm{ref}}(f_i). \tag{3}$$

In a final step, optical properties are extracted for all pixels in the image by using an inversion method based on a light propagation model. The most common inversion methods in SFDI are multi-frequency fitting to a model extracted from diffusion theory or interpolation with lookup tables (LUT) calculated with the Monte Carlo method.

On the other hand, computational imaging based on structured light (usually referred to as single-pixel imaging, SPI) permits to use light sensors without pixelated structure [3]. The method is based on sampling the scene with a set of microstructured light patterns while a simple bucket detector, for instance a photodiode, records the light intensity transmitted, reflected or diffused by the object. Images are then computed numerically from the photocurrent signal by using different mathematical algorithms. A common approach is to use light patterns codifying functions of a basis, such as Hadamard or Fourier components. Images are retrieved by a simple basis transformation. The technique is also well adapted to apply compressive sensing algorithms by using different basis of functions to sample the object and to reconstruct the image [4–6].

The main advantage of SPI techniques relies on the simplicity of the detection system. This allows to use specific detectors to work efficiently in low light level conditions, to record the spatial distribution of multiple optical properties of the light (such as the polarization state and the spectral content [5] or phase [6]), or even to image in presence of diffusers between the object to be imaged and the bucket detector [7]. The latter property allows to retrieve images by using integrating spheres with photodiodes as bucket detectors [8].

Although SPI techniques have been previously applied to SFDI, they require to replace the detection optics by a single-pixel detector and a digital micromirror device (DMD) to display the spatial sampling patterns [1, 9–11]. This results in need to use 2 DMDs (one for projecting the sinusoidal pattern and another one for sampling the space) [10] or to use a single DMD in the detection system while using a pre-printed sinusoidal patterned mask [11]. The first case results in a more expensive hardware configuration and the latter in a less flexible setup as only a single frequency sinusoidal pattern can be displayed.

In this contribution, we present a single-pixel spatial frequency domain imaging (SP-SFDI) system where a single DMD is used to modulate simultaneously the sinusoidal pattern for the spatial frequency sampling and the spatial sampling patterns in order to achieve spatial resolution. The detection system is therefore simplified to the point where it is replaced by an integrating sphere (IS) with a photodiode as a bucket detector. The characterization capabilities of this system are verified by imaging the absorption and reduced scattering coefficient of an inhomogeneous turbid media slab.

2. Experimental system

The experimental setup is shown schematically in Fig. 1. A broad beam from a collimated deep red (660nm) LED light source impinges onto a DMD. The DMD displays simultaneously the sinusoidal pattern while sampling the space with the set of sampling patterns. The spatial sampling patterns implemented on the DMD are the circular 2-D scrambled Walsh-Hadamard basis functions. The scrambled Walsh-Hadamard (scr-WH) functions are generated by randomly permuting the columns of the Hadamard matrix. And the circular functions are achieved by assuming the scr-WH functions to be represented in (ρ^2, ϕ) space and by casting them to the (x, y) space. This results in circular sampling functions that are ortogonal with a constant pixel area. This approach resembles imaging with random patterns but with a deterministic base and with the advantages of a fast transform algorithm (e.g. fwht in MATLAB). The doubly modulated patterns are proyected by a 4-f optical system into the turbid media sample located at the exit port of an integrating sphere (Thorlabs IS236A). A wide core multimode fiber attached to the IS carries the light to an avalanche photodetector (Thorlabs APD440A) which measures an intensity signal for the set of sampling patterns. The digital processing step consists in the reconstruction of the intensity images, demodulation, reference sample calibration and interpolation using a LUT calculated with a hybrid model of Monte Carlo Method and diffusion theory as described in Ref. [12].

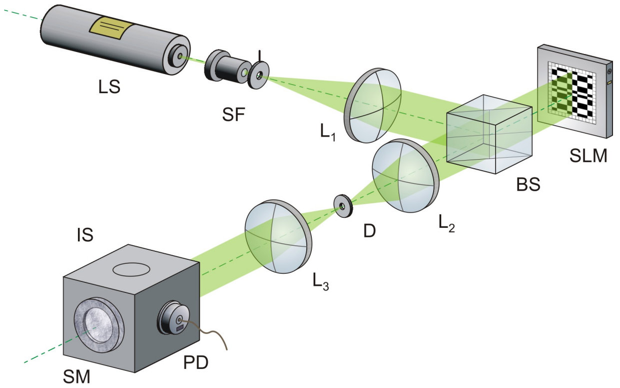

Fig. 1. Schematic of the experimental setup. A light source illuminates the spatial light modulator (a DMD in our case). This single DMD modulates both, the sinusoidal spatial frequency sampling pattern and the set of spatial sampling patterns. The doubly modulated light is projected by means of a 4-f relay system onto the sample located at the exit port of the integrating sphere. For each pattern a bucket detector attached to the integrating sphere measures a signal proportional to the diffuse reflected light.

3. Results and conclusions

In order to validate the system, we characterized a slab of epoxy resin with TiO_2 nanoparticles (Titanium(IV) oxide, rutile nanopowder, $< 100\,\text{nm}$, Sigma-Aldrich) as scattering agent. The optical properties of this sample were previously characterized with a DOI system based on the Kubelka-Munk model as reported in Ref. [8]. The bulk optical properties of the background of the sample are μ_a of about $0.4\,\text{cm}^{-1}$ and μ_s' of about $2.6\,\text{cm}^{-1}$. The high scattering heterogeneity presents values of $0.1\,\text{cm}^{-1}$ for μ_a and $10.1\,\text{cm}^{-1}$ for μ_s'. The absorption inclusion has a μ_a value of about $0.65\,\text{cm}^{-1}$. The imaged optical property maps shown in Fig. 2 show good agreement with the measured values in Ref. [8].

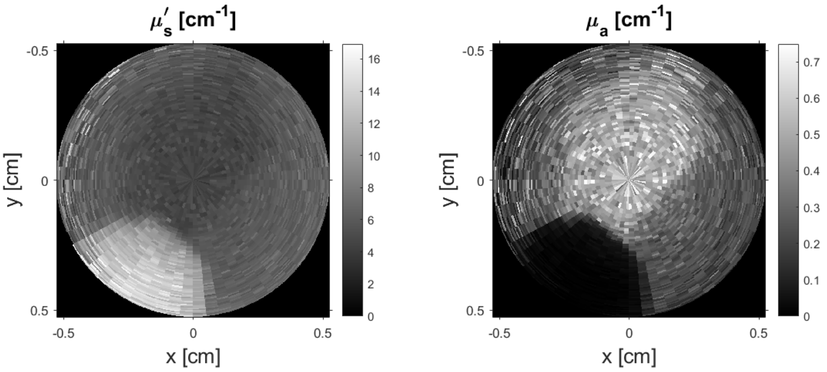

Fig. 2. Maps of the reduced scattering coefficient (left) and the absorption coefficient (right) of the heterogeneous turbid media sample described in Ref. [8].

In conclusion, we have presented a single-pixel spatial frequency domain imaging (SP-SFDI) setup where a single DMD modulates both the sinusoidal pattern and the set of spatial sampling patterns, thus reducing hardware requirements (such as a camera or a second DMD). The data acquisition process can be speed up by the application of compressive sensing. The simplicity of the detection system makes it possible to choose more complex sensors attached to the integrating spheres, such as fiber spectrometers for performing hyperspectral imaging.

References

1. J. P. Angelo, S. J. K. Chen, M. Ochoa, U. Sunar, S. Gioux, and X. Intes. Review of structured light in diffuse optical imaging. *Journal of Biomedical Optics*, 24(07):071602, 2018.
2. S. Gioux, A. Mazhar, and D. J. Cuccia. Spatial frequency domain imaging in 2019: principles, applications, and perspectives. *Journal of Biomedical Optics*, 27(7):071613, 2019.
3. M. P. Edgar, G. M. Gibson, and M. J. Padgett. Principles and prospects for single-pixel imaging. *Nature Photonics*, 13(1):13–20, 2019.
4. V. Durán, F. Soldevila, E. Irles, P. Clemente, E. Tajahuerce, P. Andrés, and J. Lancis. Compressive imaging in scattering media. *Optics Express*, 23(11):14424, 2015.
5. F. Soldevila, E. Irles, V. Durán, P. Clemente, Mercedes Fernández-Alonso, Enrique Tajahuerce, and Jesús Lancis. Single-pixel polarimetric imaging spectrometer by compressive sensing. *Applied Physics B: Lasers and Optics*, 113(4):551–558, 2013.
6. F. Soldevila, V. Durán, P. Clemente, J. Lancis, and E. Tajahuerce. Phase imaging by spatial wavefront sampling. *Optica*, 5(2):164, 2018.
7. E. Tajahuerce, V. Durán, P. Clemente, E. Irles, F. Soldevila, P. Andrés, and J. Lancis. Image transmission through dynamic scattering media by single-pixel photodetection. *Optics Express*, 22(14):16945–16955, 2014.
8. A. J. M. Lenz, P. Clemente, V. Climent, J. Lancis, and E. Tajahuerce. Imaging the optical properties of turbid media with single-pixel detection based on the Kubelka–Munk model. *Optics Letters*, 44(19):4797, 2019.
9. B. O. L. Mellors, A. Bentley, A. M. Spear, C. R. Howle, and H. Dehghani. Applications of compressive sensing in spatial frequency domain imaging. *Journal of Biomedical Optics*, 25(11):112904, 2020.
10. S. Bélanger, M. Abran, X. Intes, C. Casanova, and F. Lesage. Real-time diffuse optical tomography based on structured illumination. *Journal of Biomedical Optics*, 15(1):016006, 2010.
11. M. Torabzadeh, I. Y. Park, R. A. Bartels, A. J. Durkin, and B. J. Tromberg. Compressed single pixel imaging in the spatial frequency domain. *Journal of Biomedical Optics*, 22(3):030501, 2017.
12. L. V. Wang and H. I. Wu. *Biomedical Optics. Principles and Imaging*. Wiley-Interscience, 2007.

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