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Invited Paper

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Abstract

Imaging systems are foundational to our observation and understanding of the world around us, and biological microscopy is our window to the microscopic world of living things. Ideally, we wish to capture all the spatial, directional, spectral, even statistical information about a specimen with infinite precision; practically, the optics and detector impose significant constraints, forcing us to choose among accepting various tradeoffs depending on the specific applications. In recent years, computational algorithms are effective in pushing these limitations. Specifically, our focus is on holographic microscopy, where the axial information is encoded in the digital holograms. By recording the interferometric patterns created by the interaction of a reference light source and an object, we can achieve volumetric imaging; equivalently, we can reconstruct individual sections of the 3D object computationally. In this work, we will overview two types of computational advances for digital holographic microscopy. First is the development of computational techniques that aim to reduce data capture and increase spatial resolution. This is possible often with appropriate image model, such as sparsity, which becomes part of the constraints in the image reconstruction process. Second relates to the recent popularity of machine learning techniques in many applications of computer vision. We will discuss how such data-driven approach to digital holography is possible, and can be effective tools among different holographic image reconstruction algorithms.

Keywords: computational optical imaging, digital holography, image reconstruction, holographic microscopy

I Introduction

Microscopes are extremely valuable tools enabling a visual understanding of the minuscule world, and have far-ranging significance from microbiology to nanotechnology. Among the many forms of optical microscopes, those built on the principle of digital holography (DH) [1], where the recorded data contain the interferometric patterns of the incident light with the object to be imaged, have the additional capability of capturing the depth information, and consequently making volumetric imaging possible. This comes at a price, however; from the recorded holograms, computational processing is necessary to extract the target information, such as a sectional image of the object [2-5]. Artifacts may also arise during this process, such as the emergence of defocus noise that originates as the unwanted signal from sections other than the target [6].

A further challenge of DH in biological imaging is that the coherent imaging nature is not suitable for detecting fluorescence. One way to circumvent this issue is by using scanning holographic imaging [7]. Scanning, however, is often slow, and a prolonged scanning process may also lead to motion artifacts when imaging living specimens.

In the following, we briefly overview two computational approaches we have developed to tackle the issues mentioned above. First is our strategy to reduce the data capture by harnessing sparsity of the object in the reconstruction algorithm, and second is our

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investigation of model-based and data-driven approaches to enhance focus in holographic imaging.

II Reducing data capture

The most conventional scanning trajectory is raster scanning in the Cartesian coordinates. This does not involve any assumption of the object, and the resulting hologram resolution is determined by the Nyquist frequency in the sampling. To speed up the process, we can improve the scanning hardware, but in addition to cost it also comes at the expense of reducing the photon budget, causing a lower signal-to-noise ratio.

The alternative to achieving a reduction in acquisition time is to capture fewer data points. By assuming that the image is sparse, we design a low-density non-raster trajectory using compressed sensing where the "missing" data can be reconstructed computationally. We further show that spiral is a viable non-raster scanning path. We term the approach "subsampled scanning holographic imaging (SuSHI)". Details of the optical system design and computational algorithms can be found in Ref. [7,8].

III Increasing axial resolution and focus

In reconstructing sectional images from the digital holograms, the content from adjacent sections manifests as defocus noise [9,10]. Thus, various computational optical imaging schemes have been developed to enhance the axial resolution, including inverse imaging [2], using a dual-wavelength laser source [11], double detection [12], configurable pupil [13], and a spiral modulated point spread function [14]. In many applications, it is also very useful to be able to identify the section of interest within the hologram. Techniques for blind identification [15] and autofocus [16,17], as well as extended focused imaging [18], have been developed to tackle this challenge.

All these approaches can be considered model-based, in the sense that the sectional image reconstruction involves optimization that has an *a priori* image model as the constraint [19]. Examples include using L_2 norm for Tikhonov regularization, or L_1 and total variation norm for sparse reconstruction. Recently, a new paradigm emerges, which follow a data-driven approach to learn the image model. This builds on the success of many machine learning and deep learning approaches to various engineering applications [20]. In the case of scanning holographic imaging, we have demonstrated an autofocusing scheme for both amplitude and phase images [21], as well as an end-to-end learning for digital holographic reconstruction [22].

IV Conclusions

Digital holographic imaging allows for the recording of three-dimensional information about an object, and computational imaging algorithms can be used to reconstruct sectional images of interest. In this paper, we overview some of the work we have done in scanning holographic imaging for microscopy applications. This work was supported in part by the Research Grants Council of the Hong Kong Special Administrative Region, China, under Project 17203217, and by the NSFC/RGC under Project N_HKU714/13.

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