Computational Sectioning and Resolution Enhancement in Optical Scanning Holography

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Abstract: This paper overviews recent computational imaging techniques to increase the axial resolution and sectioning performance of optical scanning holography, including the use of a dual-wavelength source, double scanning, and configurable pupils.

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1. Introduction

Optical scanning holography (OSH) is a specific form of digital holography, making use of optical heterodyning to measure the 3D information of an object with only lateral scanning [1, 2]. It can act as a holographic fluorescence microscope, which is particularly noteworthy because fluorescence is incoherent and holograms normally require a coherent interferometric system [3]. The OSH system diagram is shown in Fig. 1. While its operations are described in more details elsewhere, such as in [4], it suffices to note that we can model the OSH as a linear space-invariant system by fixing the object distance z. With the two pupils $p_1(x,y) = 1$ and $p_2(x,y) = \delta(x,y)$, the optical transfer function (OTF) and the impulse response are

$$\mathscr{H}(k_x,k_y;z) = \exp\left\{-j\frac{z}{2k_0}\left(k_x^2+k_y^2\right)\right\} \text{ and } h(x,y;z) = -j\frac{k_0}{2\pi z}\exp\left\{j\frac{k_0}{2z}(x^2+y^2)\right\}, \tag{1}$$

where k_0 is the wave number proportional to the laser source frequency ω_0, (x,y) are the spatial coordinates, and (k_x,k_y) are the transverse spatial frequency coordinates. The OTF has a quadratic phase factor, while the impulse response is quadratic in x and y, known as a Fresnel-zone-pattern (FZP) impulse response [2].

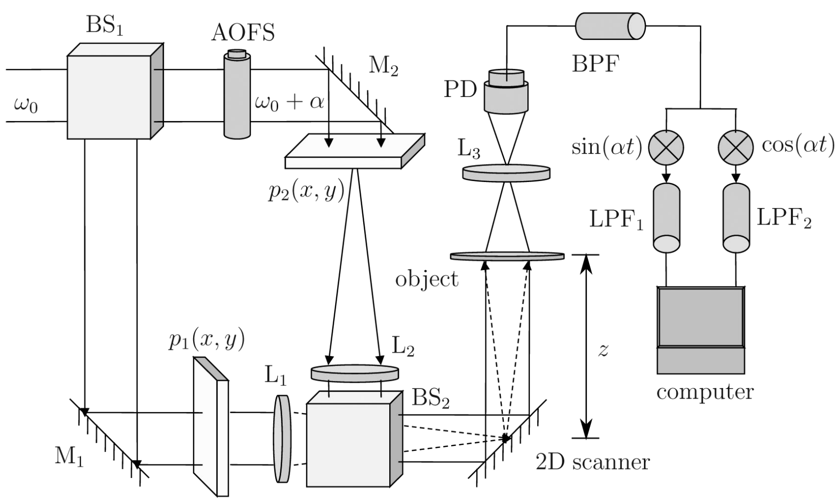

Fig. 1. Schematic diagram of the optical scanning holography system. Reprinted from [5].

The late Prof. Emmett Leith asserted, after four decades of research in holography, that a critical problem in modern imaging was “the imaging of a plane without the image being degraded by defocused light…in biological microscopy, this process has been called optical sectioning." [6] In OSH, the sectioning is achieved digitally, with various computational schemes developed to suppress the defocused light effectively [5]. The ability to filter signals at a nearby axial distance also reflects the axial resolution of the system. In recent years, several efforts have been made to increase the resolution through the capture of an additional hologram of the same object, but under a different imaging condition, and combined carefully in the computational reconstruction algorithms.

2. Computational Imaging Approaches to Resolution Enhancement

The objective for the second capture is to design another impulse response that is sufficiently different from the first one. Considering the expression given in Eq. (1), there are three possibilities:

1. Capture a second set with a different k_0;
2. Capture a second set with a different z;
3. Capture a second set with a different (x,y).

2.1. *Dual-wavelength OSH*

By using a source that works at two different frequencies sequentially, one can achieve what is known as dual-wavelength OSH (DW-OSH) with different values of k_0 for each scan [7]. The object is then scanned once each at the respective frequencies. The doubling of the scan time is a drawback, particularly for dynamic specimen; alternatively, one can scan faster, at the expense of more costly equipment and lower signal-to-noise ratio (SNR) for each scan.

2.2. *Double-detection OSH*

If one is not equipped with a dual-wavelength laser source, it is still possible to acquire two sets of hologram, with the second set shifted axially by Δz, such that the new object distance becomes $z+\Delta z$. This is known as double-detection OSH (DD-OSH). The disadvantage of acquisition time and SNR is similar with DW-OSH, but it appears that with proper configurations, this scheme can lead to better performance. Detailed analyses and results can be found in [8].

2.3. *Configurable pupil OSH*

A third possibility is to change the pupil equation for the second set. In addition to $p_2(x,y)=\delta(x,y)$, we modify it for the second set such that $p_2'(x,y)=\delta(x-x_0,y-y_0)$, where x_0 and y_0 are certain nonzero constants. Consequently,

$$h'(x,y;z) = -j\frac{k_0}{2\pi z}\exp\left\{j\frac{k_0}{2z}\left[(x-x_0)^2+(y-y_0)^2\right]\right\}. \tag{2}$$

This approach is called configurable pupil OSH (CP-OSH). Choosing x_0 and y_0 judiciously allows for more orthogonal information to be present in the two acquisitions, leading to better sectioning performance. Detailed analyses and results can be found in [9].

2.4. *Optimization algorithms*

Complementary to the above schemes, it is also possible to achieve better axial resolution through more sophisticated computational schemes. In the above references, the sectional image reconstruction is computed by inverse imaging, optimizing the computed hologram from an estimate of the object to fit the observation, while constraining on the prior information on the object, such as spectrum smoothness, edge, or object sparsity. For computational efficiency, conjugate gradient with ℓ_2 regularization is often used; however, ℓ_1 or total-variation regularization typically leads to better performance in image reconstruction, and efficient optimization schemes such as the alternating direction method of multiplier (ADMM) [10] is being explored for OSH sectional image reconstruction.

3. Conclusions

In this invited talk we put into perspective the recent development in enhancing the axial resolution and sectional image reconstruction for OSH. This work was supported in part by the Research Grants Council of the Hong Kong Special Administrative Region, China, under Projects HKU 7138/11E and 7131/12E, and by the NSFC/RGC under Project N_HKU714/13.

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