Using a Dual-wavelength Source for Depth Resolution Enhancement in Optical Scanning Holography

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Abstract: We use a wavelength selectable source to demonstrate depth resolution enhancement in an optical scanning holography (OSH) system. Sectional objects separated by 2.5 µm along the axial direction are reconstructed with a Fourier-domain conjugate gradient algorithm.

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1. Depth resolution in OSH with a single wavelength source

Optical Scanning Holography (OSH) is a 3D imaging system using optical heterodyning for complex wavefront recording. It collects an object’s 3D information with a single 2D optical scanning. Its applications include optical scanning microscopy, 3D image recognition, and 3D holography display [1]. Because OSH system does not require spatial coherence in an object, it can also be used for imaging fluorescent samples [2]. Theoretically, OSH system has better transverse resolution than a scanning confocal microscope (SCM) [1]. A recently reported OSH system reaches a transverse resolution about 1 µm and an axial resolution 10 µm [2]. To enhance the OSH system axial or depth resolution, here we propose to use a wavelength-selectable laser as the illumination source. Below, we first analyze the resolution with two point sources in two axial planes when the illumination source only works in a single wavelength.

Figure 1(a) presents the schematic of an OSH system. The measurement in an OSH system is represented as

\[ g(x, y) = \int_{-\infty}^{\infty} |f(x, y; z)|^2 \ast h(x, y; z) \, dz, \]

where \( g(x, y) \) is the 2D measurement of an object, \( h(x, y; z) = -j \frac{h_{2\pi}}{\lambda} \exp\{j \frac{2\pi}{\lambda}(x^2 + y^2)\} \) is the system impulse function, and \( |f(x, y; z)|^2 \) is the object intensity at the \( z \) plane along the axial direction [1]. The object with two point sources located at \( z_1 \) and \( z_2 \) planes is defined as \( |f(x, y; z)|^2 = \delta(x, y)\delta(z - z_1) + \delta(x, y)\delta(z - z_2) \). Based on Equation 1, the system measurement is \( g(x, y) = h(x, y; z_1) + h(x, y; z_2) \). To reconstruct object in an OSH system back, multiple methods have been studied and summarized in [3]. We employ the conventional method because it is fast and using this method does not change our observation and conclusion for the depth resolution analysis. Figure 1(b), (c), and (d) present the reconstruction results at \( (x, y) = (0, 0) \) versus \( z \) for three specific sets of \( z_1, z_2 \), and \( \lambda \). It can be observed that while the two points in Figure 1(b) are barely resolved, they become two distinguishable peaks in (c) and (d) as either \( z \) or the light source wavelength \( \lambda \) decreases.

To understand this observation, note that the OSH system impulse function \( h(x, y; z) \) has the formulation of a complex Fersnel zone plate (FZP). As the \( z \) value or the wavelength \( \lambda \) decreases, the zones switch between opaque and transparent zones faster, therefore the FZP has shorter focus length and smaller depth of focus. In an OSH system, it means the system has an improved depth resolution because the object in an axial plane different from the FZP focal plane is easier to be out of focus. Therefore, employing a shorter wavelength source or moving the object towards the system improves the OSH system depth resolution. However, the former idea is restricted by the availability of a suitable light source, while the latter is constrained by the minimum distance between the object and the system [2]. To overcome these restrictions, new strategies are required for resolution enhancement. Note that an OSH system can be considered a set of FZPs while each FZP images object in one \( z \) plane for measurement. By changing the system source wavelength, we can have distinctive sets of FZPs for 3D object imaging. Using these multiple sets of imaging measurements, we expect to have better system reconstruction performance. This motivates us to use a dual wavelength source for system depth resolution enhancement.
2. Depth resolution enhancement with a dual wavelength source

The system schematic for a dual wavelength OSH (DW-OSH) system will be almost the same as in Figure 1, except that the laser source works at two distinct wavelengths, namely \( \lambda_1 \) and \( \lambda_2 \). Options for such laser sources include multi-line tuning laser such as Krypton or Argon laser emitting at several wavelengths through the visible and ultraviolet spectrums, and wavelength switchable laser which we will discuss more in following section. The measurements in a DW-OSH system are collected sequentially. Note that, if the time for collecting individual measurement is kept fixed, the total data acquisition time in a DW-OSH system will be doubled compared to an OSH system with single wavelength. This will restrict OSH system from in-vivo imaging applications or applications in which samples can be easily overexposed to the source. To deal with this issue, we can increase the data acquisition rate to keep the total measurement collecting time unchanged. The challenging is to have high speed AOFS for source temporal modulation, scanning mirror, and data acquisition instrument after the detector as shown in Figure 1. Because of this faster data acquisition process, the time for collecting individual measurement will reduce hence the detector needs to work in a larger bandwidth. Thus, more detector noise will present in the DW-OSH system measurement.

Note that the OSH system measurement in Fourier domain can be represented as the summation of multiplications between impulse function \( H_i(k_x,k_y;z_n) = \mathcal{F}\{h_i(x,y;z_n)\} \) where \( n = 1,2,\ldots,N \), for source wavelength \( \lambda_n \) and object \( \mathcal{F}\{|f(x,y;z_n)|^2\} \) over all \( z_n \) planes. Therefore, in Fourier domain the DW-OSH system measurement can be represented as

\[
g = \begin{bmatrix} g_1 \\ g_2 \end{bmatrix} = \begin{bmatrix} H_1(z_1) & H_1(z_2) & \cdots & H_1(z_N) \\ H_2(z_1) & H_2(z_2) & \cdots & H_2(z_N) \\ \vdots & \vdots & \ddots & \vdots \\ H_N(z_1) & H_N(z_2) & \cdots & H_N(z_N) \end{bmatrix} \begin{bmatrix} f(z_1) \\ f(z_2) \\ \vdots \\ f(z_N) \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} = Hf + n,
\]

where \( g_i \) (with \( i = 1,2 \)) of size \( M \times 1 \), \( f(z_n) \) of size \( M \times 1 \), and \( n_i \) (with \( i = 1,2 \)) of size \( M \times 1 \) are the measurement, the object, and the detector noise vectors in Fourier domain, respectively. The detector noise is assumed additive white Gaussian with standard deviation \( \sigma \). Measurement matrix \( H_i(z_n) \) of size \( (M \times M) \) is a diagonal matrix with diagonal elements \( H_i(k_x,k_y;z_n) \). We focus on the sectioning problem in Fourier domain instead of in spatial domain in this work because fast converging algorithms have been designed to solve linear equation system such as Equation 2 when the coefficient matrix \( H \) is sparse. Another advantage of solving the sectioning problem in the Fourier domain is that the memory requirement for the fast algorithms is low because of the sparsity in \( H_i(z_n) \), hence solving a large dimensional object sectioning problem is feasible. To reconstruct the object \( f(z_n) \) at \( z_n \) plane, we use a preconditioned CG algorithm referred to as block Jocobi restrictively preconditioned conjugate gradient (BJ-RPCG) algorithm [4].
3. Experiment and conclusion

Two objects of size $401 \times 401$ with dynamic range $[0, 255]$ as shown in Figure 2(a) and (e) located at $z_1 = 60\text{mm}$ and $z_2 = 60.0025\text{mm}$ planes are used for simulation. The two wavelengths of the laser source used in the simulation are $\lambda_1 = 543\text{nm}$ and $\lambda_2 = 633\text{nm}$, which are achievable with a wavelength-selectable Helium-Neon laser [5]. The detector noise variance $\sigma^2$ is assumed to be 52, which means the signal-to-noise ratio (SNR), defined as the average object pixel intensity over all $z$ planes divided by the noise variance, is 20dB. Conventional and BJ-RPCG sectioning methods using single wavelength measurement $g_1$ is also studied for comparison.

The sectioning results using the conventional method and the BJ-RPCG method after $m = 15$ iterations are presented in Figure 2. Figure 2 (a), (b), (c) and (d) present the object, the sectioning results using conventional and BJ-RPCG methods with single and dual wavelength measurements at $z_1$ plane, respectively. Similarly Figure 2 (e), (f), (g), and (h) present the object, the sectioning results using conventional and BJ-RPCG methods with single and dual wavelength measurements at $z_2$ plane, respectively. It can be observed that the reconstructed results using conventional method with measurement $g_1$ at $z_1$ and $z_2$ planes are about same. Even using the BJ-RPCG algorithm with the single wavelength source measurement $g_1$, the reconstructed objects at $z_1$ and $z_2$ planes are not close to the original two object sections. However, with dual-wavelength laser source, the two sectioning results presented in Figure 2 (d) and (h) estimate the original object properly. As a conclusion, we demonstrate the idea to enhance an OSH system depth resolution with a dual-wavelength source in this work. With our theoretical study, the DW-OSH system with source wavelengths 543nm and 633nm can reach depth resolution $2.5\mu\text{m}$ when the two object sections are located about 60mm away from the system.

References