https://doi.org/10.2352/ISSN.2470-1173.2017.17.COIMG-427

Wavefront Correction using Self-interference Incoherent Digital Holography

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Abstract
Self-interference incoherent digital holography (SIDH) technique allows to capture the complex wavefront information with incoherent light. We suggest a distortion compensation method in an incoherent microscope system using SIDH. To correct the distorted wavefront, we detect the distorted wavefront of a guide-star with SIDH method and modulate the wavefront with a phase-only spatial light modulator (SLM). We present an iterative algorithm that calculates the SLM modulation pattern to correct the wavefront. By the correction, the size of focused spot becomes smaller. It means that the resolution of the image can be improved or even an object covered with a thick aberration layer can be detectable. We verify the feasibility of the wavefront correction method with the simulation and experimental results.

Introduction
Self-interference incoherent digital holography (SIDH) technique made it possible to apply the digital holography techniques to an incoherent optical system. By the virtue of the unique characteristic of SIDH technique that the wavefront of incoherent light can be captured, incoherent holographic microscope and incoherent holographic camera had been proposed [1-12]. Besides, the captured wavefront can be used to compensate the distortion of an incoherent optical imaging system [13-16].

In adaptive optics field, guide-star method is commonly used to reduce the effect of distortion in telescope system [4]. A guide-star means a reference point light source which is a well-known star or artificially induced light emitting source. When the light from a star passes through the atmosphere, it is distorted due to the air turbulence. Since the light from the guide-star also experiences almost the same distortion, by detecting the distorted wavefront of the guide-star, we can acquire the information of the aberration that the light from the star experiences. By modulating the wavefront using the acquired information about the aberration, the image resolution can be improved. In this process, measuring the incoming wavefront is typically done with Shack-Hartmann wavefront sensor, which can detect the localized propagation direction of the light using a lens array and a charge-coupled device (CCD) camera [5].

In this study, we apply the guide-star method into the microscope system. An illuminated pinhole is used as a guide-star. And we apply the SIDH technique as a wavefront detecting method. For the modulation of the wavefront, we use a spatial light modulator (SLM). The purpose of the study is to compensate the effect of distortion and restore the distorted guide-star wavefront with an SLM.

In the following section, we introduce the theory of wavefront detection using SIDH technique and suggest an iterative algorithm that can calculate the SLM modulation pattern to correct the distortion. And we verify the algorithm with the simulation and experimental result.

Theory

Wavefront detection using Self-interference Incoherent Digital Holography
The SIDH method enables capturing the complex wavefront data of incoherent light using the self-interference phenomenon. Assuming an object that emits incoherent light, the object can be thought as a set of multiple incoherent point light sources. The light from each point light source cannot interfere with each other because of its incoherency. However, the light from a single point source can interfere with itself if the optical path length difference is much shorter than the temporal coherence length of the incoherent light source, which is typically several times of wavelength. By capturing the self-interference pattern with a CCD, we can capture the wavefront of incoherent light.

Figure 1 shows the basic concept of the SIDH interferometer system. The light from the object is collimated by an objective lens, and divided into two by a beam splitter. The divided light waves are reflected by two different mirrors with the two different curvatures, respectively. In this paper, one mirror is planar and the other is concave. Here, the distances from the beam splitter to each mirror are precisely controlled to be the same by piezo actuator, so that two light waves can interfere within the short coherence length. Then the reflected light waves are combined into one again by the beam splitter and the interference pattern of the two light waves is captured by a CCD. We can change the phase of light path by controlling the piezo actuator. By changing the phase, we can get the complex hologram of the light wave using 3-step phase shift method.

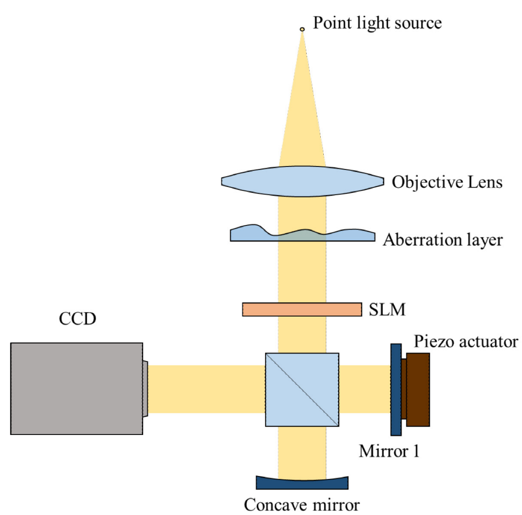

Figure 1. Basic configuration of Self-interference Incoherent Digital Holography (SIDH) interferometer system. A spatial light modulator (SLM) is inserted for wavefront modulation.

For the detailed explanation, let's assume a single point light source at the object plane. Because the incoherent light from the single point light source can interfere with itself, following calculations are the same with those of coherent light case. For convenience, we omit *y* component in this paper and deal with *x* component, since all the calculations about *x* are equal to those about *y*. The light wave from the point light source will be collimated and pass through the aberration layer. Let's call the wavefront U_m at the mirror plane before the reflection. Two split waves are reflected by the mirrors and propagate to the CCD plane, which have the form of

$$U_a(x) = U_m(x) \odot Q_{d_c}(x) , \tag{1}$$

$$U_b(x) = [U_m(x) Q_{-f_m}(x)] \odot Q_{d_c}(x) , \tag{2}$$

where

$$Q_z(x) \equiv \exp\left[\frac{jk}{2z} x^2\right], \tag{3}$$

f_m is the focal length of concave mirror, d_c is the distance between the mirror and CCD plane and $\odot$ stands for 2-dimensional convolution. Then the interference pattern at the CCD plane has the form of

$$I_k = \left|U_a \exp(j\varphi_k) + U_b\right|^2$$

$$= \left|U_a\right|^2 + \left|U_b\right|^2 + U_a U_b^* \exp(j\varphi_k) + U_a^* U_b \exp(-j\varphi_k) , \tag{4}$$

where $k = 1, 2, 3$ and φ_k means the phase shift for 3-step phase shift method. We can get the complex hologram as the result of 3-step phase shift method as follows:

$$C = U_a U_b^*$$

$$= \left[U_m(x) \odot Q_{d_c}(x)\right]\left[[U_m(x) Q_{-f_m}(x)] \odot Q_{d_c}(x)\right]^* . \tag{5}$$

The complex hologram contains the information about U_m, but it is not easy to extract it directly. To extract useful information of U_m from C, we need some additional processes. Let's assume that U_m can be expressed as

$$U_m(x) = \int \mho_m(f_x) \exp(j2\pi f_x x) df_x , \tag{6}$$

where f_x denotes spatial frequency. Substituting Eq. (6) into Eq. (5), the complex hologram can be expressed as

$$C(x) = \iint \mho_m^*(f_x) \mho_m(f_x')$$

$$\times Q_{f_m - d_c}[x - \lambda f_m f_x + \lambda(f_m - d_c) f_x']$$

$$\times \exp[-j\pi\lambda f_m (f_x - f_x')^2] df_x df_x' . \tag{7}$$

If $\mho(f_x)$ is a band-limited function, that is, the wavefront distortion by the aberration layer is not so severe, Eq. (7) can be approximated as

$$C(x) \approx \iint \mho_m^*(f_x) \mho_m(f_x')$$

$$\times Q_{f_m - d_c}[x - \lambda f_m f_x + \lambda(f_m - d_c) f_x'] df_x df_x'$$

$$= \iint \mho_m^*(f_{x0} + \Delta f_x) \mho_m(f_{x0} + \Delta f_x')$$

$$\times Q_{f_m - d_c}[(x - \lambda d_c f_{x0}) - \lambda f_m \Delta f_x + \lambda(f_m - d_c)\Delta f_x'] d\Delta f_x d\Delta f_x' , \tag{8}$$

where

$$\Delta f_x = f_x - f_{x0} , \ \Delta f_x' = f_x' - f_{x0} , \tag{9}$$

and f_{x0} denotes the center spatial frequency of the wavefront. The approximation in Eq. (8) is permitted under the condition that the bandwidth of spatial frequency

$$f_{x,bw} \ll \sqrt{\frac{1}{8\lambda f_m}} . \tag{10}$$

Here, we define a useful parameter T as

$$T(f_x) \equiv \Im\left[C(x + \lambda d_c f_{x0}) \odot Q_{-(f_m - d_c)}(x)\right]$$

$$\approx \left[U_m(x) \exp(-j2\pi f_{x0} x)\right]^*_{x = \lambda f_m f_x}$$

$$\times \left[U_m(x) \exp(-j2\pi f_{x0} x)\right]_{x = \lambda(f_m - d_c) f_x} , \tag{11}$$

where

$$\Im[A(x)] = \int A(x) \exp(-j2\pi f_x x) dx . \tag{12}$$

According to Eq. (11), T is easily expressed by the wavefront $U_m(x)$. In other words, we can easily figure out the information about $U_m(x)$ using T.

Algorithm for wavefront correction

Using the acquired information of the distorted wavefront of a guide-star, we need to decide proper modulation pattern for the SLM. To reduce the approximation error and experimental error, we correct the wavefront gradually in iterative manner. The steps are as follows.

At first, we acquire the distorted wavefront of a guide-star, and calculate T which is described in Eq. (11). In the limit that the distorted wavefront has the narrow bandpass spatial frequency and the distance between the mirror and the SLM is relatively short, the wavefront at the SLM can be approximated as

$$U_s(x) = U_m \odot Q_{-d_m} \approx c_0 U_m \, , \tag{13}$$

where

$$c_0 = \exp(j\pi\lambda d_m f_{x0}{}^2) \tag{14}$$

and d_m is the distance between the mirror and the SLM.

Secondly, we select the modulation pattern to be displayed on the phase-only SLM as

$$S(x) \equiv \frac{T\left(\dfrac{x}{\lambda f_m}\right)}{\left|T\left(\dfrac{x}{\lambda f_m}\right)\right|} \approx T\left(\frac{x}{\lambda f_m}\right)$$

$$\approx \left[U_m(x)\exp(-j2\pi f_{x0}x)\right]^* \left[U_m(x')\exp(-j2\pi f_{x0}x')\right]_{x'=\frac{x}{M}} \, , \tag{15}$$

where

$$M = \frac{f_m}{f_m - d_c} > 1 \, , \tag{16}$$

so that the wavefront at the mirror plane is modulated as

$$U_m{}'(x) = [U_s(x)S(x)] \odot Q_{d_m}(x)$$

$$\approx c_0{}^{-1}[c_0 U_m(x)S(x)]$$

$$\approx \left[U_m(x')\exp(-j2\pi f_{x0}x')\right]_{x'=\frac{x}{M}} \exp(j2\pi f_{x0}x) \, . \tag{17}$$

In spatial frequency domain, the modulated wavefront can be described as

$$\mho'_m(f_{x0} + \Delta f_x) \approx \mho_m(f_{x0} + M\Delta f_x) \, . \tag{18}$$

After one cycle of the modulation, the modulated wavefront has the same center spatial frequency, but $1/M$ times narrower bandwidth. This means that the distorted wavefront becomes more like plane wave.

Lastly, by taking the entire steps again with the modulated wavefront, we can gradually compensate the distortion. Here, the modulation pattern on the SLM in the *n*-th iteration should be selected with the following way.

$$S^{(n)}(x) = LPF\{S^{(n-1)}(x)S(x)\} \, , \tag{19}$$

where LPF means a low pass filter with a heuristically selected cutoff spatial frequency. Because the high frequency component error can be accumulated during the iteration process, applying the band pass filter in every cycle can prevent the error caused by high frequency component. After *n*-th iteration, the wavefront is expected to be corrected as

$$\mho_m{}^{(n)}(f_{x0} + \Delta f_x) \approx \mho_m(f_{x0} + M^n \Delta f_x) \, . \tag{20}$$

All the equations expressed in 1-dimension can be easily expanded to 2-dimension due to the symmetry.

Simulation

To verify the theory, we simulated the correction process using MATLAB software. The geometric parameters such as the distances between the components, the focal length of the concave mirror, the pixel pitch and aperture of the CCD, and the SLM are all set to be equal to the experimental setup.

The aberration is randomly made to have the amplitude transmittance 1 and the low spatial frequency mostly below the 2000 cycle/m, which is equivalent to about 1.1 mrad or 3.78 arcmin in angular sense.

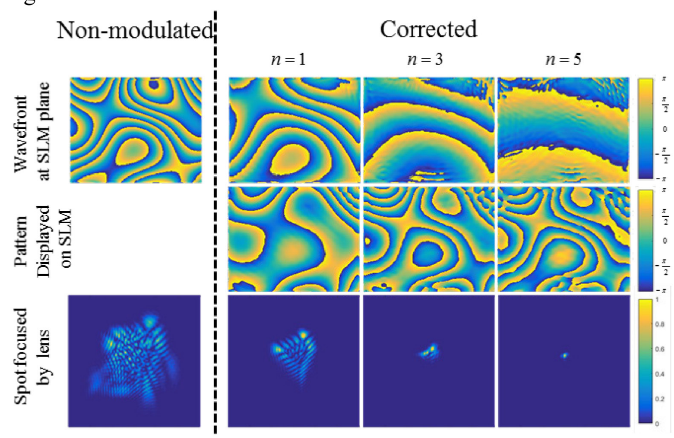

Figure 2. The result of the simulation for the wavefront correction algorithm. (upper) The phase of modulated wavefront at the SLM plane U_m , (middle) the modulation pattern displayed on the phase-only SLM S and (lower) the intensity distribution of a focused spot by a lens. Columns for each case: Non-modulated (normally distorted) and corrected (iteration number = 1, 3, 5).

Figure 2 is the simulation results of the wavefront correction. The wavefront at the SLM plane is originally distorted as shown in upper left side figure. As shown in the upper row of Fig. 2, the wavefront at the SLM plane becomes more like plane wave as the iteration number increases. We can also check in middle row that the modulation pattern gradually becomes like the conjugate of the distorted wavefront. The lower row shows how small the wavefront can be focused by a lens. We selected the lens with the 500 mm focal length in this simulation. We can see that the intensity distribution at the focal plane becomes dramatically sharper as the iteration number increases. In Fig. 3(a), the decreasing tendency of the spot size is described with a graph. The spot size is calculated as the diameter of the area where the intensity is higher than 10% of the maximum intensity. As shown in Figs. 3(b) and (c), by correcting the distorted wavefront, we can theoretically reduce the spot size from 738 μm to 30 μm.

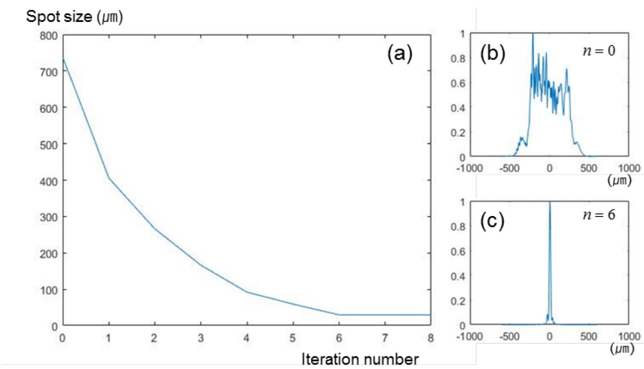

Figure 3. (a) The spot size of the wavefront at the focal plane of a lens whose focal length is 500 mm. It decreases from 738 μm to 30 μm as the time of iteration increases. (b) Normalized intensity distribution of the spot along x-axis in non-modulated (n=0) (c) and corrected case (n=6).

Experiments

System Implementation

To prove the wavefront correction method experimentally, we constructed an SIDH microscope with an SLM. As shown in Fig. 4, the whole system is divided into 3 parts: the microscope part, the wavefront modulation part, and the SIDH interferometer part.

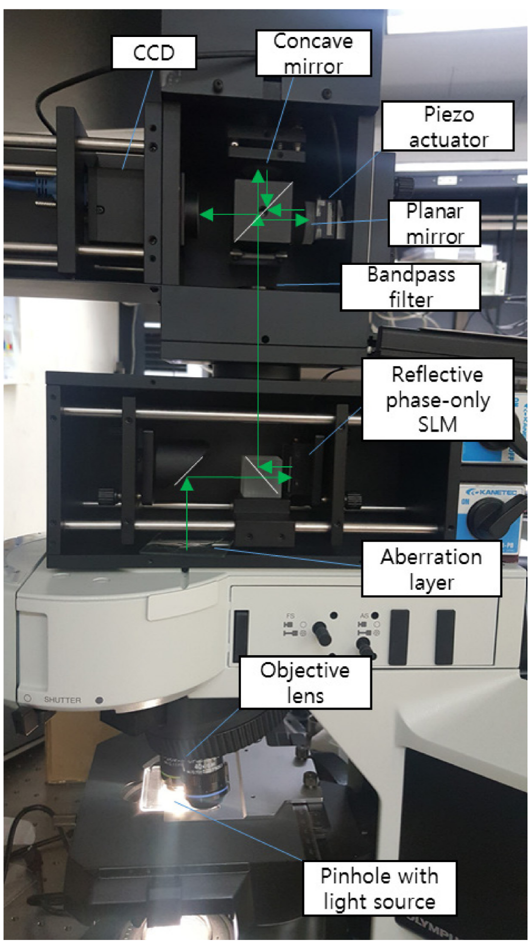

Figure 4. Experimental setup of wavefront correction SIDH microscopy.

The SIDH interferometer part contains a beam splitter, planar and concave mirrors, a piezo actuator, and a CCD. Planar mirror is attached on the piezo actuator for 3-step phase shift method, and focal length of the concave mirror is 500 mm. Interference pattern is captured with a CCD (Point Grey, GS3-U3-91S6C), which has 3.69 μm pixel pitch and 3376×2704 resolution.

In the wavefront modulation part, we used a reflection-type phase-only SLM (HOLOEYE, PLUTO-VIS-014), which has 8 μm pixel pitch and 1920×1080 resolution.

In the microscope part, we used a pinhole of 15 μm diameter as a guide-star. The pinhole is illuminated by focused light from a 100 W halogen lamp whose coherence length is typically 1 μm. To limit the wavelength, we inserted a bandpass filter which has 550 nm center wavelength and 25 nm full-width-at-half-maximum (FWHM). A 20X/0.4NA objective lens (Olympus, RMS20X) is used for the experiment. As an aberration layer, we used a dried glue plate.

Experimental result

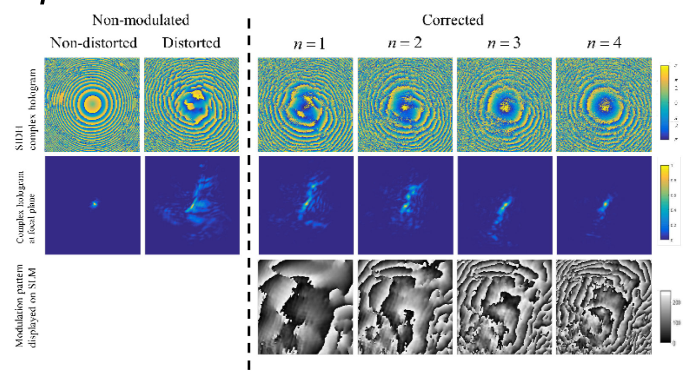

Figure 5. (upper) Experimentally captured complex hologram C, (middle) result of propagation and pattern on SLM for wavefront correction and (lower) the modulation pattern displayed on the SLM S (256 depth). Each column corresponds to each case of: non-distorted, distorted and wavefront-corrected for iteration numbers 1, 2, 3, and 4.

Figure 5 shows the experimental result. The upper row shows the phase of the guide-star complex hologram captured by SIDH interferometer. If the distortion is corrected well, it becomes similar to a simple quadratic phase function, in the shape of perfectly round concentric circles. The result shows that the shape of the complex hologram distorted by the aberration layer can be corrected with the algorithm to have more round shape.

The middle row shows the intensity distribution of the complex hologram propagated to the focal plane. It is closely related with the intensity distribution of the focused wavefront. It also should be a small spot if well corrected. The result verifies that the spot becomes blurred and distorted by the aberration layer and becomes smaller when the wavefront is corrected with the algorithm.

The lower row shows the modulation pattern displayed on the SLM. The pattern gradually converges to a certain pattern that corrects the wavefront.

Conclusion

SIDH technique allows one to capture the wavefront information of incoherent light. We suggested an algorithm that can compensate the distortion of an incoherent microscope system using SIDH technique. With the algorithm, the distorted light wave from a guide-star can be compensated by a phase-only SLM. Then the corrected wavefront creates smaller spot at the focal plane, which leads to better resolution. The algorithm was verified by the simulations and experiments. With this method, we expect that the observation of biological objects covered with thick medium becomes possible with an incoherent microscope system.

Acknowledgement

This work was supported by the Brain Korea 21 Plus Project in 2016.

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