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Enhanced phase imaging based on sampling frequency improvement

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ABSTRACT

High-accurate unwrapped phases are demanded in various research fields such as optical imaging optical holography, optical diffraction tomography, and magnetic resonance imaging. However, the ground-truth phase is not accessible due to 2 ambiguity which arises from phase jumps in the wrapped phase. In this study, we propose to improve the accuracy of unwrapping process by increasing the sampling frequency to reconstruct the unwrapped phase with high accuracy for the application of optical imaging. The simulation results show increasing the optical magnification from 4X to 8X enables improvement of the phase estimation accuracy by 51% for a highly refractive object. Experimental results validate the sensitivity of phase estimation on the sampling size. Our approach demonstrates significant achievement in obtaining ground-truth phases for highly refractive objects.

Keywords: Phase imaging, unwrapping, digital holography

1. INTRODUCTION

Phase unwrapping is a crucial process employed in various research fields such as optical interferometry,[1,2] seismology,[3] signal processing,[4] fringe projection profilometry,[5] magnetic resonance imaging,[6,7] and optical diffraction tomography.[8] Unwrapping a phase is a mandatory process to reach the ground-truth phase from the wrapped (principal) phase. The principal phase is a result of the arctan function experiencing the phase modulo 2π, and that limits the principal phase in the interval $(-\pi, \pi)$. Thus, a continuous phase variation of the ground-truth phase is expressed in terms of the discontinuous phase, and this 2π ambiguity is realized.

To reach the ground-truth phase and mitigate 2π ambiguity, an appropriate integer multiple of 2π has to be added to the principal value; thus, this process yields a true (absolute) phase. However, the true phase may not match the ground-truth phase due to various factors such as various noise mechanisms and a high number of phase jumps in the wrapped phase. There are many algorithms and methods to reach the ground-truth phase from the principal phase.[1,2,4,6,9–15] These algorithms also show great performance in noisy data.[16,17] Due to great advancements in technology, deep learning-based unwrapping operations are also available to attain the ground-truth phase with the principal phase.[5,18]

In this study, we propose the idea of increasing the sampling frequency of a wrapped phase to reconstruct the ground-truth phase. To improve the sampling frequency, we employ a magnifying objective which allows us to fill in missing information between two consecutive wrapped phase points. Therefore, the unwrapping operation becomes less sensitive to 2π ambiguity. As a result of this operation, the true phase becomes less deviated from the ground-truth phase.

2. METHODS

In Fig. 1a, we present a phase object using the specification of a capillary tube immersed in water. The capillary tube has inner and outer diameters of 0.9 mm and 1.6 mm, respectively. As it is seen in Fig. 1a, the refractive index of the tube is constant over the structure and has a value of 1.344. The surrounding medium is water with a refractive index of 1.333. In Fig. 1b, clear sharp RI variation is demonstrated along the line at z=0. The corresponding phase shift on an image plane is computed for lensless imaging case with unity magnification by

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using Eq. 1 and considering the wavelength of a light source λ as 633 nm. $\phi(x, y)$, z, and Δn are the ground-truth phase on the spatial coordinates x and y, the propagation distance of light through the capillary tube along the z-axis, and the refractive index difference between the capillary tube and water, respectively. The ground-truth phase distribution is presented in Fig. 1c where due to the cylindrical symmetry of the capillary tube, along the y-axis, the phase shift is not a function of y-axis. In Fig. 1d, phase variation along x-axis is seen due to the presence of two media: water and the capillary tube.

$$\phi(x, y) = \int \frac{2\pi}{\lambda} \Delta n(x, y, z) dz \tag{1}$$

The electric field that describes a phase object is analytically formulated by Eq. 2, where $U(x, y)$ is the electric field of the light. When this electric field is indirectly recorded by a recording medium such as a CCD camera, its corresponding phase distribution is acquired after computing the argument of the complex electric field by using Eq. 3 where $\phi_p(x, y)$ is the principal phase distribution of the phase object. As a result of this operation, the principal phase of the phase object is realized as seen in Fig. 1e. Unfortunately, due to the arctan operation, the principal phase values are restricted in the interval (-π, π). This is clearly observed in Fig. 1f when we look at the phase variation along the line y=0 mm in Fig. 1e.

$$U(x, y) = \mathrm{e}^{\mathrm{j}\phi(x,y)} \tag{2}$$

$$\phi_p(x, y) = \mathrm{Arg}[U(x, y)] \tag{3}$$

$$\phi_t(x, y) = \phi_p(x, y) + 2\pi m(x, y) \tag{4}$$

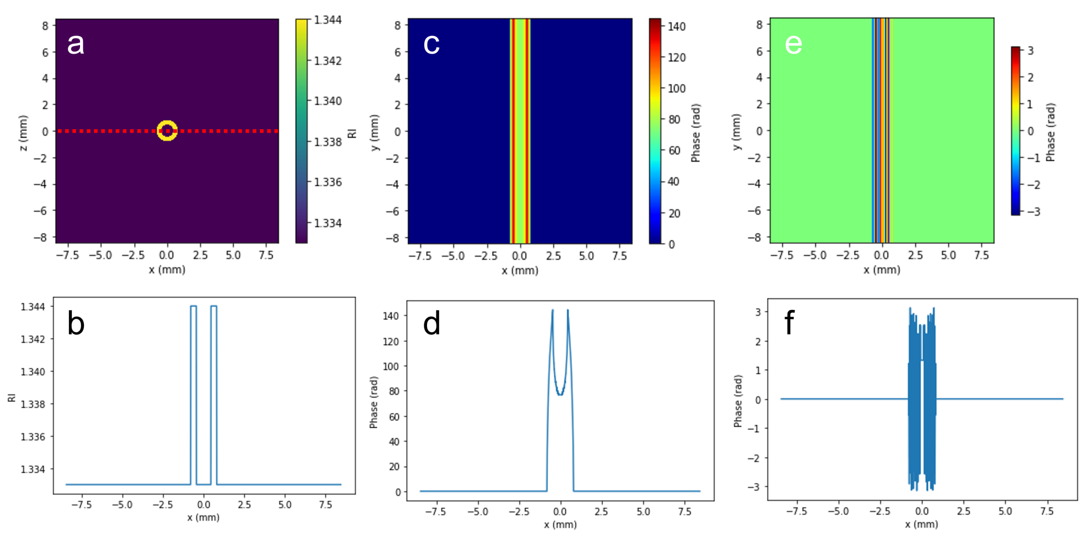

Figure 1. (a) RI distribution of a capillary tube, (b) RI variation along the red line in (a), (c) Ground-truth phase distribution of the capillary tube, (d) Phase distribution of the capillary tube along y = 0 in (c), (e) Principal phase distribution of the capillary tube in (c), (f) Cross-sectional phase variation along y = 0 in (e).

3. CONCLUSION

In this work, we obtain a significant accuracy improvement in retrieving the true phase in the unwrapping operation. Our novel approach, which is based on the lateral magnification of the phase object, increases the sampling frequency and provides highly accurate phase reconstruction. We believe that our idea is benefited from various research fields such as optical holography to obtain 3D object information with better accuracy.

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