Fast High-Resolution In-line Phase Retrieval of Sparse Off-Axis Holograms

László Orzó[1,*], Márton Zsolt Kiss[1], Daniel Terbe[1] and Ákos Zarándy[1]

[1] *Institute for Computer Science and Control. H-1111, Kende street. 13-17. Budapest, Hungary*

[*] *orzo@sztaki.hu*

Abstract: A modified version of the well-known Gerchberg-Saxton algorithm is introduced that in the case of sparse samples provides an extremely fast and accurate phase reconstruction utilizing the whole bandwidth of an off-axis hologram.

1. Introduction

Digital Holographic Microscopy [1,2] allows the numerical reconstruction of the complex wave field of the measured sample objects. A Gabor type [1] in-line (IL) holographic configuration exploits the whole hologram surface for the reconstruction. However, the recovery of the exact phase distribution is usually not possible, as the diffraction of the different overlapping terms distort the reconstruction of the objects. In the case of sparse samples, phase retrieval can be achieved, utilizing the finite support properties of the objects using the Gerchberg-Saxton (GS) type of algorithms [3, 4]. However, these algorithms frequently show very slow convergence. In off-axis (OA) digital holographic microscope configurations [5] the object term can be separated in the frequency space from the zero-order and conjugated object terms. This way the phase retrieval is straightforward, but the applied filtering considerably confines the available space-bandwidth product of the hologram reconstruction. There were attempts to alleviate this inherent restriction [6, 7], but the achievable resolution is still significantly smaller than that of an in-line hologram. Earlier we were able to speed up the phase retrieval of an in-line hologram using the reconstruction of an additional off-axis measurement [8]. Similarly, using two different in-line holograms of the same object, we can considerably speed up the phase retrieval [9]. Furthermore, an imaginative new method [10] shows, that from two acquired off-axis holograms with different shifted phase references, it is possible to remove the zero-order term and this way, high-resolution phase reconstruction is achievable. Nonetheless, these methods require the recording of two holograms. We introduce here a simple, straightforward modification of the conventional modified GS algorithm, to become applicable for off-axis holograms too. It can be employed only if the sample is sparse and the object support constraint is applicable. This way, fast, accurate, high-resolution, and large field of view phase reconstruction can be achieved from a single off-axis hologram.

2. Method

The steps of the proposed algorithm are detailed below.

1. Use a zero image or the off-axis reconstruction as the initial object wave field estimation.
2. Propagate the complex object wave field to the hologram plane.
3. Add a proper off-axis reference to the propagated object wave field. This way we can estimate the wave field of an off-axis hologram.
4. Apply the hologram amplitude constraint to compensate the errors of the off-axis wave field estimation.
5. Subtract the earlier added complex off-axis reference from the compensated complex off-axis wave field estimation. Thus, we can derive the improved object wave field estimation.
6. Propagate the object wave field estimation in the sample image plane. This way we get the reconstructed object wave field.
7. Apply the object support constraint to the reconstructed wave field and this way we get an improved object wave field estimation.

Steps 2-7 are to be iterated, till the change becomes small enough. We show the performance of the introduced algorithm on simulated holograms. We can compare the efficiency of the introduced algorithm, the result of the conventional off-axis and in-line phase retrieval (see in Fig. 1)

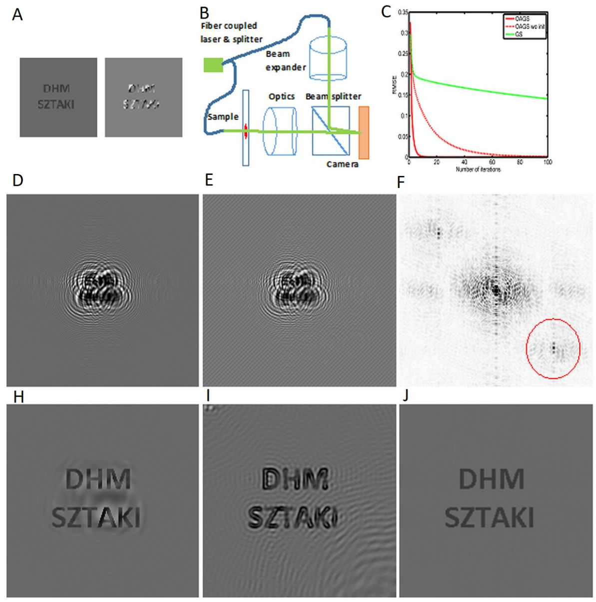

Fig. 1. Simulated in-line (D) and off-axis (E) hologram of a complex test object (A). In the Fourier transform of the off-axis hologram (F), the red circle delimits the object term. We can compare the In-line reconstruction after 400 steps of Gerchberg-Saxton iteration (H), the reconstruction based on the off-axis hologram object term (I) and the reconstruction after 10 steps of iteration using the proposed off-axis Gercnhberg-Saxton algorithm (J). The comparison of the speed of convergences of the conventional GS algorithm with the OA GS algorithm using OA term initialization or not (C).

3. Conclusion

Using the proposed modified GS algorithm, we can utilize the whole hologram surface area for the reconstruction. Although we use an off-axis configuration, the resolution of the phase reconstruction is determined primarily by the in-line component of the recorded hologram. This way extremely fast, high-resolution phase retrieval is achievable. This method can overcome the limitation of both the off-axis and the in-line numerical phase reconstruction processes. Contrary to the conventional off-axis setups, where the size of the object term determines the quality of the phase retrieval, here we can use a more simplified measuring configuration, where this term has to be adjusted to the actual Fresnel number of the recording to optimize the speed of the phase retrieval. (Supported by the MIT NRDI Office Hungary, within the framework of the Artificial Intelligence National Laboratory Program.)

References

1. D. Gabor, "A new microscopic principle," Nature **161**, 777–778 (1948).
2. O. Mudanyali, D. Tseng, C. Oh, S. Isikman, I. Sencan, W. Bishara, C. Oztoprak, S. Seo, B. Khademhosseini, and A. Ozcan, "Compact, light-weight and cost-effective microscope based on lensless incoherent holography for telemedicine applications," Lab on a Chip **10**, 1417 (2010).
3. R. Gerchberg and W. Saxton, "A practical algorithm for the determination of phase from image and diffraction plane pictures," OPTIK **35**, 237–246 (1972).
4. J. Fienup, "Phase retrieval algorithms: a comparison," Appl. Opt. **21**, 2758–2769 (1982).
5. E. N. Leith and J. Upatnieks, "Reconstructed wavefronts and communication theory," J. Opt. Soc. Am. **52**, 1123–1128 (1962).
6. I. Frenklach, P. Girshovitz, and N. T. Shaked, "Off-axis interferometric phase microscopy with tripled imaging area," Opt. Lett. **39**, 1525–1528 (2014).
7. G.-L. Chen, C.-Y. Lin, M.-K. Kuo, and C.-C. Chang, "Numerical suppression of zero-order image in digital holography," Opt. Express **15**, 8851–8856 (2007).
8. L. Orzó, "High speed phase retrieval of in-line holograms by the assistance of corresponding off-axis holograms," Opt. Express **23**, 16638–16649 (2015).
9. L. R. Orzó, M. Z. Kiss, and Ákos Zarándy, "Improving speed and accuracy of phase retrieval applying two in-line hologram recordings," in *Holography: Advances and Modern Trends VI,* , vol. 11030 A. Fimia, M. Hrabovský, and J. T. Sheridan, eds., International Society for Optics and Photonics (SPIE, 2019), pp. 209 – 217.
10. N. Shaked, Y. Zhu, M. Rinehart, and A. Wax, "Two-step-only phase-shifting interferometry with optimized detector bandwidth for microscopy of live cells," Opt. Express **17**, 15585–15591 (2009).