Digital Holographic Adaptive Optics Techniques with Coherent or Incoherent Sources

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Abstract: We have recently proposed two distinct digital holographic adaptive optics techniques, one involving holography of coherent sources and the other incoherent digital holography. Progress on development of the two systems is described and compared.
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Adaptive optics (AO), originally developed for astronomical telescopes, reduces the effect of atmospheric turbulence by measuring the distortion of the wavefront arriving from a point source (guide star) and using the information to compensate for the distortions in the full-field objects to be imaged. When applied to ocular imaging, the "guide star" is provided by a narrow laser beam focused on a spot on the retina. Most commonly a Shack-Hartmann wavefront sensor is used to measure the wavefront of the reflected light [1]. The wavefront distortion is then compensated for using a wavefront corrector, such as deformable mirror. The sensor and corrector typically have a few hundred elements, allowing for adjustment of a similar number of coefficients in the Zernike aberration polynomials. Several iterations of sensing, computation, and corrections are carried out in a feedback loop to reach a stable state. Digital holography, with its inherent capacity to quantify and manipulate phase profile of optical fields [4], offers potentially powerful alternative to the hardware-based compensation of aberration.

We have recently proposed two distinct AO systems that dispense with the wavefront sensor and corrector [2,3]. One of the systems, Fig. 1, is based on digital holography of coherent sources, using Mach-Zehnder type interferometer, as is conventionally done. The other system, Fig. 2, takes advantage of a recent breakthrough in incoherent digital holography, using a variation of FINCH interferometer [5]. Here we describe and compare our recent progress on the development of these two types of holographic adaptive optics system, one with envisioned applications in ophthalmic imaging and the other in astronomical imaging.

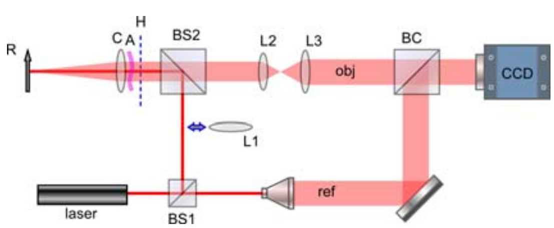

Fig. 1. DHAO apparatus. The CCD camera plane is conjugate to the hologram plane H. R: retinal plane; C: corneal lens; A: aberrator.

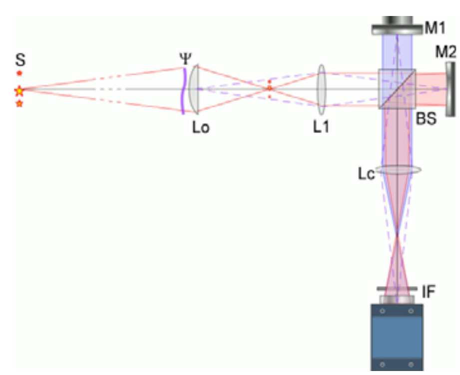

Fig. 2. Optical schematic of IDHAO system. S: object plane, including a guide star; L: lenses; M1: piezo-mounted plane mirror; M2: curved mirror; Ψ : aberrator; IF: interference filter.

In both systems, the DHAO is a two-step process, consisting of acquisition of holograms with full-field and guide-star illuminations. The two complex holograms, containing the amplitude and phase profiles of the corresponding optical fields, are numerically combined to determine and compensate for the effect of aberration in the optical path. A main difference between the two systems is the manner in which the complex holograms are extracted. With a coherent source, the holographic interference between the object and reference automatically contain the necessary complex field information. On the other hand, with the incoherent source, the self-interference between two copies of spherical wavefronts from each source point results in Fresnel zone pattern, which in turn is combined with phase shifting technique for extraction of the complex field.

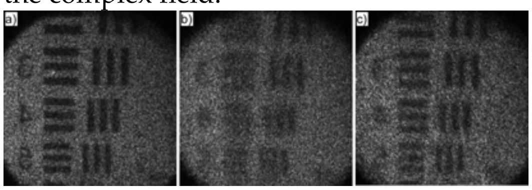

Fig. 3. Reconstructed images of retinal plane: a) in the absence of aberrator; b) with aberrator in place but without aberration correction; c) with aberrator in place and after aberration correction. Field of view is $1121 \times 1121 \mu m^2$.

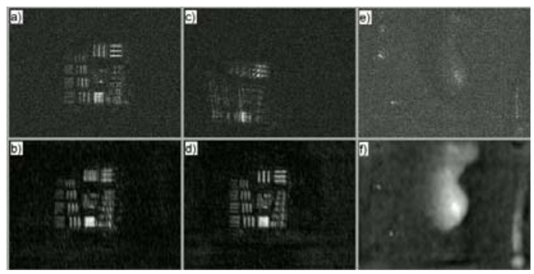

Fig. 4: Experimental demonstration of IDHAO of extended objects. Upper row: reconstructed images from uncorrected hologram; lower row: from corrected hologram. Left: resolution target without aberrator; middle: resolution target with an aberrator; right: chess pawn, no aberrator but low fringe contrast.

An example of experimental demonstration of coherent DHAO is given in Fig.3. For this proof-of-principle experiment, the eye is modeled by a combination of a simple lens (f = 25 mm), C, and a printed-on-paper resolution target, R, placed at the focal plane of the lens. The aberration of the eye is imitated by placing an irregular piece of glass, A, in front of the lens C. The complex optical field of the emergent light is captured by the CCD camera, which is focused at the plane H through the relay lenses L2 and L3. The reference for the holographic imaging is provided by beam-splitter BS1, the beam expander, and the beam combiner BC. The two holograms thus obtained are then used to reconstruct the retinal image. First, in Fig. 3a), the image reconstructed from a hologram without the phase aberrator in place is shown, as a base line. Then, Fig. 3b) is the image reconstructed from the complex hologram with the aberrator in place but without its compensation, showing significant degradation of the resolution. Finally in Fig. 3c), the complex conjugate of the guide star hologram is multiplied to the uncorrected hologram before reconstruction. Compensation of the effect of the aberration and improvement of the resolution is quite evident, thus demonstrating the validity of the DHAO principle.

For DHAO of incoherent sources (IDHAO), an apparatus similar to Fig. 2 is set up using lenses of focal length 100 mm and a concave mirror (M2) of focal length 600 mm. The object plane is approx. 700 mm from the objective lens Lo, and its image is near the front focus of L1. For aberrator, clear plastic piece with irregular surface or astigmatic eyeglass lens were used. A 600 nm interference filter was used to narrow the linewidth to about 10 nm for halogen-lamp illumination. Hologram acquisition, reconstruction, and aberration compensation are carried out by LabVIEW-based programs, the entire cycle taking a few seconds, including file write/read and without any attempt at optimizing the speed. An example of experimental results is shown in Fig. 4, where the object is a resolution target illuminated from behind with a halogen lamp through a piece of frosted glass, while the guide star is provided by an LED placed close in front of the resolution target. First, the IDHAO is carried out without an aberrator. The reconstructed image a) from uncorrected hologram is clear enough, though it required some adjustment of contrast for presentation. There is no aberrator and therefore no aberrations to correct, but application of the IDHAO process results in some loss of resolution but improvement in noise and contrast in the final image b). When an aberrator – an astigmatic eyeglass lens – is introduced, the difference between the uncorrected c) and corrected d) images is more pronounced. The process simultaneously removes distortion, displacement due to tilt, and noise. The fringe contrast in the raw holograms was quite low and the extracted complex hologram had significant noise in the form of a background haze. The IDHAO process substantially suppressed such noise in the final image d). The effect of noise reduction by IDHAO is most evident in Fig. 4e,f), where a chess pawn is imaged with a high-brightness red LED illumination. A separate LED is used as a guide star. No aberrator was in place. Again, the application of the IDHAO process significantly improved the final image quality.

References

[1] K. M. Hampson, J. Mod. Opt. 55, 3425-3467 (2008).
[2] C. G. Liu, and M. K. Kim, Optics Letters 36, 2710-2712 (2011).
[3] M.K. Kim, Optics Letters, in review.
[4] M. K. Kim, *Digital Holographic Microscopy: Principles, Techniques, and Applications* (Springer, 2011).
[5] J. Rosen, and G. Brooker, Nat. Photonics 2, 190-195 (2008).