Simulation and Experiment of Fourier Transform Digital Holographic Adaptive Optics

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Abstract Fourier transform digital holographic adaptive optics imaging system is described. The results from the simulation and experiment are reported that demonstrate the feasibility of this adaptive optics system.

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Incorporation of the adaptive optics(AO) system into vision science has yielded retinal images with unprecedented resolution [1, 2]. The cone mosaics of the retina are obtained at the cellular level. Recently, we presented a new AO retinal imaging system that is based on the principles of digital holography (DH) [3]. Incorporation of DH in an ophthalmic imaging system can lead to versatile imaging capabilities at substantially reduced complexity and cost of the instrument. The presented digital holographic adaptive optics (DHAO) system replaces complex hardware components in conventional AO system with numerical processing through the principles of digital holography [4]. Although this scheme can realize the direct measurement of the pupil function, there are some limitations such as extra spherical curvature and difficulty in determining the correct guidestar hologram. To address these limitations, Fourier Transform DHAO (FTDHAO) system is presented [5]. The CCD is put at the exact FT plane of the eye pupil. There is no spherical curvature induced by the imaging lens, resulting in a more precise measurement of the phase aberration and more compact system. The CCD can directly record the point spread function (PSF) of the system, making it easier to determine the correct guide star hologram. With some modifications, low coherence or even incoherent light source can be incorporated [6-10]. The system will be more flexible and applicable.

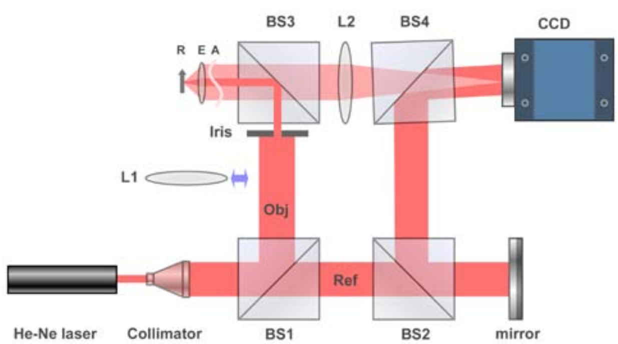

Fig. 1 Schematic of the Fourier Transform digital holographic adaptive optics imaging system. R:Retina, E:eye lens of focal length 25mm, A:aberrator. L1:75mm in focal length. L2:200mm. BS1-4: beamsplitters.

The schematic of FTDHAO setup is illustrated in Fig.1. The eye lens is simulated by the lens E of which the focal length f_1 equals 25mm. R represents retinal plane that is at the back focal plane of eye lens E. A represents the phase aberrator that is at the pupil of the eye lens. The distance between lens E and L2 and that between L2 and the CCD are equal to the focal length f_2 of L2 that is 200mm in our simulation and experiment. In the simulation, we use the group 4 elements 2~5 of USAF1951 resolution target to simulate the amplitude of the retina, as shown by Fig.2 a). The field of view is 906μm×906μm. A random phase noise ranging from $-\pi$ to π simulates the phase distribution of the retina, as illustrated by Fig.2 b). The wavelength of the laser beam is simulated to be 0.633μm. As a baseline, the focused image, without the aberrator in place, is given in Fig.2 c). The phase aberration is shown in Fig.2 d). The pupil size is set to be 5mm in diameter. Fig.2 e) shows the image distorted by the phase aberration. Taking inverse FT of the distorted image field, the optical field at pupil plane can be obtained. The phase map of this field at pupil is represented by Fig.2 f). The measured phase map is shown in Fig.2 g). Subtracting the measured phase aberration by Fig.2 g) from the distorted optical field represented by Fig.2 f), the corrected optical field at pupil can be obtained, as shown by Fig.2 h). Taking FT of this corrected optical field, the corrected image is achieved, as shown in Fig.2 i). The corrected image shows remarkable improvement in resolution.

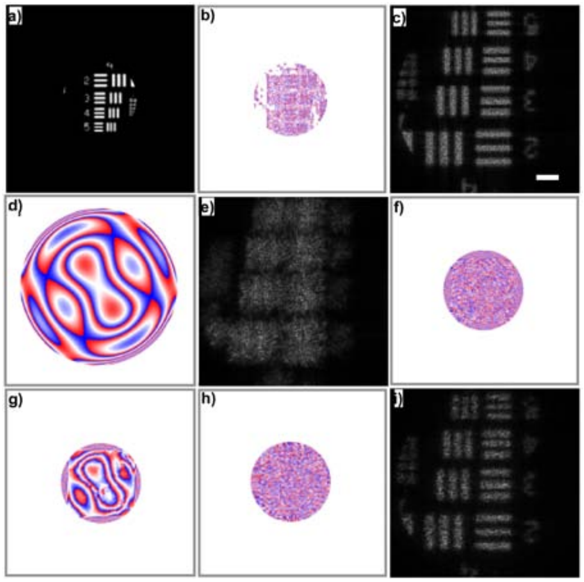

Fig.2 Simulations. a) and b) : simulated amplitude and phase. c): image without aberrator in place. d): simulated phase aberration. e): distorted image. f): the phase map of distorted field at the eye pupil. g):the measured phase aberration at the eye pupil. h): the phase map of the corrected field at pupil. i): the corrected image. scale bar: 100μm.

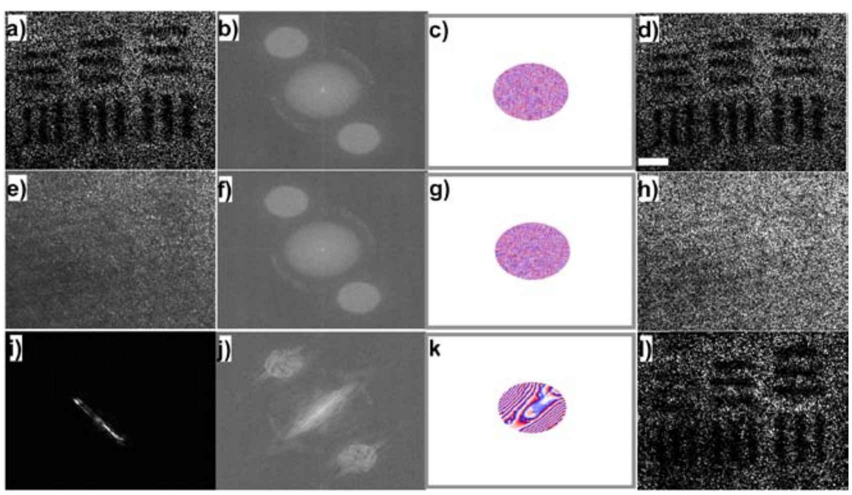

Fig.3 Experimental results on USAF 1951 resolution target. a): undistorted full-field hologram. b): angular spectrum of the a), displayed in logarithmic scale. c): phase map of upper left order in b). d) reconstructed baseline image. e): distorted full-field hologram. f): angular spectrum of e). g): distorted phase map. f): distorted image. i): guide star hologram. j): angular spectrum of part of i) represented by the dashed circle. k): the measured phase aberrations. l): the corrected image. scale bar:100μm.

In the experiment, He-Ne laser is used as light source. The sample under test is a positive USAF 1951 resolution target with a piece of Teflon tape tightly attached behind. The specular reflection is blocked by the pupil whose size is set to be 5mm in diameter. A piece of clear broken glass serves as the phase aberrator. A set of image data is shown in Fig.3.The field of view on the retinal plane is 573μm×430μm. The hologram with full field illumination, without the aberrator in place, is shown in Fig.3 a). The angular spectrum is shown in b). The upper left order in b) is the complex optical field at pupil plane. The phase map of this field is shown in c). Fig.3 d) is the reconstructed image as a baseline. Fig.3 e) shows the full field hologram with aberrator in place. The angular spectrum is shown in f). The phase map of the distorted optical field at pupil is shown in g). h) is the distorted image. The guide star hologram is shown in i). The angular spectrum is shown in j). The measured phase aberration is given by k). Subtracting k) from g) and taking FT, the corrected image is obtained, as illustrated by l) that shows significant improvement in resolution and image quality compared with the distorted image given by h).

In summary, we present a novel DHAO system. The CCD is put at the exact FT plane of the eye pupil and the image plane of the retina, thereby eliminating the spherical curvature from the imaging system and further numerical propagation, compared to the previously proposed setup [3]. Also, because the guidestar hologram directly records the PSF of the system, the signal is stronger. Simulations and experiments of FTDHAO demonstrate the feasibility of this imaging system.

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References

[1] J. Liang, D. R. Williams, and D. Miller, "Supernormal vision and high-resolution retinal imaging through adaptive optics," J. Opt. Soc. Am. A **14**, 2884-2892 (1997).

[2] K. M. Hampson, "Adaptive optics and vision," J. Mod. Opt. **55,** 3425-3467 (2008).

[3] C. Liu , and M. K. Kim, "digital holographic adaptive optics for ocular imaging: proof of principle," Opt. Lett.**36,** 2710-2712 (2011).

[4] M. K. Kim, "Principles and techniques of digital holographic microscopy," SPIE Reviews **1,** 1-50 (2010).

[5] C. Liu, and M. K. Kim, “Fourier transform digital adaptive optics imaging system,” Appl. Opt.**51**,8449-8454(2012).

[6] F. Dubois, L. Joannes, and J. C. Legros, “Improved Three-Dimensional Imaging with Digital Holography Microscope with a Source of Partial Spatial Coherence,” Appl. Opt. **38** ,7085-7094(1999).

[7] G. Pedrini, and H. J. Tiziani, “Short-Coherence Digital Microscopy by Use of Lensless Holographic Imaging System,” Appl. Opt. **41**, 4489-4496(2002).

[8] M. K. Kim, “Adaptive Optics by Incoherent Digital Holography,” Opt. Lett. **37**, 2694-2696(2012).

[9] F. Dubois, and C. Yourassowsky, “Full off-axis Red-Green-Blue Digital Holographic Microscope with LED Illumination,” Opt. Lett. **37**, 2190-2192(2012).

[10] R. Kelner, and J. Rosen, “Spatially Incoherent Single Channel Digital Fourier Holography,” Opt. Lett. **37**, 3723-3725(2012).