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4D Imaging Using Accelerating Airy Beams and Nonlinear Reconstruction

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ABSTRACT

A 4D computational incoherent imaging technique using accelerating Airy beams (A^2-beams) and nonlinear reconstruction (NLR) has been developed. The phase mask was designed as a binary version for the generation of a sparse random array of A^2-beams. The imaging process consist of three steps. In the first step a 4D point spread function (PSF) was recorded at different wavelengths and depths. In the next step, a multicolor, multiplane object was loaded and a single camera shot was recorded. Finally, the 4D information of the object was reconstructed by processing the object intensity distribution and 4D PSFs. The simulation results for the imaging concept are presented.
Keywords: Airy beams; computational imaging; 3D imaging; spectral imaging; holography; diffractive optics.

1. INTRODUCTION

Indirect digital imaging generally comprises of two steps: recording of an intensity pattern from an object followed by digital reconstruction via computer algorithms [1]. Incoherent digital holography (IDH) techniques have begun to emerge with advanced capabilities to record 3D information for astronomical and biomedical imaging applications [2,3]. IDH techniques, in general, require a self-interference hologram recorded between object waves with different modulations [2]. Fresnel incoherent correlation holography (FINCH) [4] and coded aperture correlation holography (COACH) [5] are two notable IDH techniques among an extensive library of IDH technologies [6]. In 2017, it was discovered that the 3D information was present in the scattered object wave, which led to the development of interferenceless COACH (I-COACH) [7]. The interferenceless property of I-COACH comes with multiple advantages such as low experimental complexity, high light throughput, high resilience to external vibrations and a high SNR. The first version of I-COACH required at least three camera shots recorded using three uncorrelated quasi-random phase masks for both the object and the point object followed by a computational reconstruction with a matched filter [8]. For 3D imaging using I-COACH, it is necessary to record the point spread function (PSF) library for the entire depth resulting in a time-consuming one-time procedure. The quasi-random phase masks used for beam modulation were lossy resulting in a large photon budget and resulted in a low SNR. Besides, the conventional matched filter used for image reconstruction demanded a large number of camera recordings to average out the noise and achieve a reasonable SNR [9].

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I-COACH technique began to evolve with advancements in optical configuration, computational reconstruction and phase mask design. The simplest optical configuration of I-COACH is its' lensless version called lensless I-COACH (LI-COACH) consisting of only a quasi-random phase mask between the object and the sensor [10]. The computational reconstruction method was modified from matched filter to phase only filter and the number of camera shots was changed from three to two [10, 11]. The latest advancement in the computational reconstruction was the development of the non-linear reconstruction (NLR) method which required only a single camera recording and has a high SNR in comparison to matched filter, phase-only filter and Weiner filter [12]. The latest advancement in phase mask design came with a focus to improve the SNR. So, the engineering approach was modified to focus light into randomly spaced focal spots instead of the scattering light within a predefined area on the sensor [13]. One of the drawbacks in the above phase mask design is the need to multiplex multiple phase masks in order to image at multiple planes resulting in additional noise. Besides, the above approach cannot withstand chromatic aberrations. Recently, a technique to extend the above idea to all axial planes was reported using sparse random array of Bessel beams [14] and Airy beams [15]. The chronology of developments in I-COACH been reviewed thoroughly in literature [2]. The above two methods adapted the latest models of optical configuration and computational reconstruction and only modified the phase mask design. In this study, the LI-COACH technique with sparse random array of Airy beams is investigated for 4D imaging along 3D space and spectrum.

2. METHODS

The optical configuration of LI-COACH with sparse random array of Airy beams is shown in Figure 1. An object is located at a distance of z_s from the Mask with a diameter D and the sensor is located at a distance of z_h from the Mask. The intensity recorded for a single point by the image sensor is given as $I_{PSF}(\bar{r}_0;\bar{r}_s,z_s,\lambda) = \left|\sqrt{I_s}CL\left(\frac{\bar{r}_s}{z_s}\right)Q\left(\frac{1}{z_s}\right)Rect\left(\frac{x}{D},\frac{y}{D}\right)\exp(j\Phi) * Q\left(\frac{1}{z_h}\right)\right|^2$, where $\sqrt{I_s}$ is the amplitude of the point object located at $(\bar{r}_s,z_s) = (x_s,y_s,z_s)$, $Rect\left(\frac{x}{D},\frac{y}{D}\right)\exp(j\Phi)$ is the complex amplitude of the Mask, C is a complex constant, L and Q are the linear and quadratic phase functions given as $L\left(\frac{\bar{s}}{z}\right) = exp\left[i2\pi(\lambda z)^{-1}\left(s_x x + s_y y\right)\right]$ and $Q(b) = exp[i\pi b\lambda^{-1}(x^2+y^2)]$, respectively. The object intensity distribution I_O recorded for an object O can be expressed as $I_O = O \otimes I_{PSF}$, where '⊗' is a 2D convolutional operator. The image of the object is reconstructed using NLR as $I_R = \mathcal{F}^{-1}\left\{\left|\tilde{I}_{PSF}\right|^{\alpha}\exp[j\cdot\arg(\tilde{I}_{PSF})]\left|\tilde{I}_O\right|^{\beta}\exp[-j\cdot\arg(\tilde{I}_O)]\right\}$, where $\mathcal{F}^{-1}$ is the inverse Fourier transform, ~ indicates Fourier transformed version of a matrix. The parameters α and β are tuned from -1 to +1 until a minimum entropy is obtained.

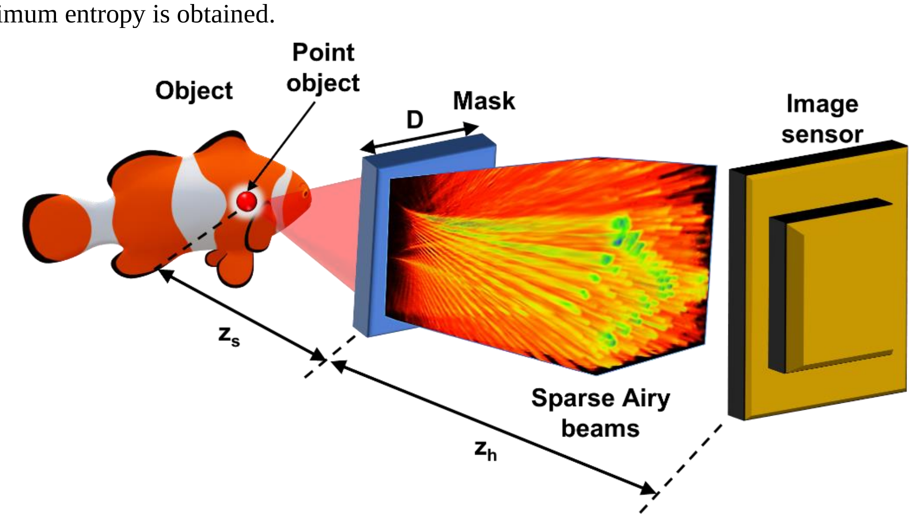

Figure 1 Optical configuration of LI-COACH with a PSF formed by sparse random array of Airy beams. z_s and z_h are the distances of the object and the sensor from the Mask respectively and D is the diameter of the Mask.

Since only the simulation study has been reported, the mask design has been achieved by the summation of cubic phase masks [16] resulting in a complex matrix which is challenging to realize in practical applications. For experimental study, a random multiplexing approach as demonstrated in [15] can be used. A matrix size of 500 × 500 pixels along x and y directions, pixel size of 10 μm, λ = 650 nm, z_s = 20 cm, z_h = 30 cm and diameter of the Mask is D = 5 mm. The Mask is designed as $\Phi = \sum_{k=1}^{N} exp\left[-j\frac{2\pi}{\lambda}\{\xi_k(x_k+\Delta x_k)^3+\eta_k(y_k+\Delta y_k)^3\}\right]$, where $x_k = x_0 cos\theta_k + y_0 sin\theta_k$, $y_k = y_0 cos\theta_k - x_0 sin\theta_k$, Δx_k, and Δy_k are the shifts, ξ_k, and η_k are the scaling factors along the *x* and *y* directions, respectively. The shifting and scaling factors of the Airy beams were varied randomly with respect to one another to create a random set of Airy beams. The amplitude and phase images of a typical Mask for $N = 4$ is shown in Figures 2(a) and 2(b) respectively.

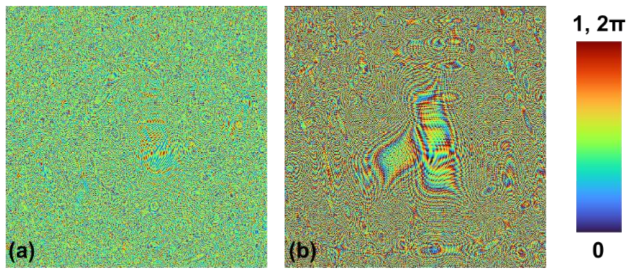

Figure 2 (a) Amplitude and (b) phase image of a typical complex Mask for generating four uncorrelated Airy beams.

Two test objects, namely 'Airy beams' and 'I-COACH' were mounted at z_s and illuminated by two different wavelengths λ_1 = 650 nm and λ_2 = 550 nm respectively. Since the spatial variation has been already investigated, in this simulation the spectral variations are studied. The images of the PSFs for λ_1 = 650 nm and λ_2 = 550 nm are shown in Figures 3(a) and 3(b) respectively. The object intensity distribution obtained by the summation of the intensity pattern obtained for test object – 1 illuminated by λ_1 = 650 nm and intensity pattern obtained for test object – 2 illuminated by λ_2 = 550 nm is shown in Figure 3(c). The reconstructed images using PSF(λ_1) and PSF(λ_2) are shown in Figures 3(d) and 3(e) respectively. As it is seen from the results shown in Figs. 3(d) and 3(e), the spectral discrimination capability is verified.

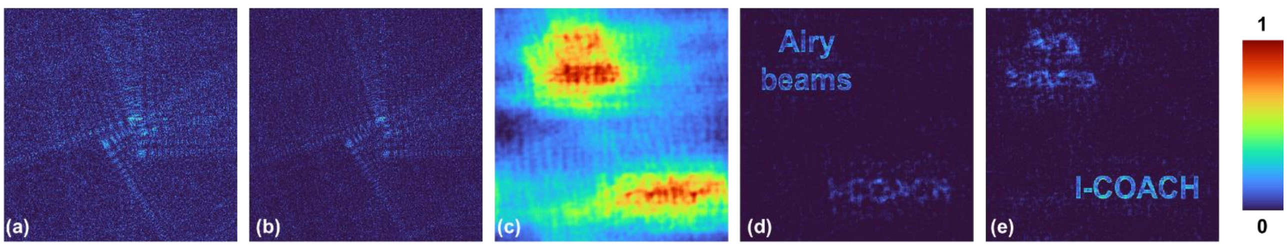

Figure 3 Images of (a) PSF(λ_1), (b) PSF(λ_2), (c) object intensity, reconstructed images obtained for (d) test object – 1 and (e) test object – 2 using (a) and (b) respectively.

3. CONCLUSION AND FUTURE PERSPECTIVES

The I-COACH technique has been investigated using a sparse random array of Airy beams for 4D imaging applications. Since the 3D imaging capabilities have already been verified in [15], with the simulation studies, the 4D imaging capabilities are revealed. Further studies are needed to understand the relation among spectral resolution, number of Airy beams and SNR. Advanced mask design approaches are needed in order to realize the exotic intensity distribution in experiments. We believe that the proposed 4D technique will be useful for fluorescence imaging and astronomical imaging applications.

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