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Enhanced Reconstruction of Spatially Incoherent Digital Holograms Using Synthetic Point Spread Holograms †

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Abstract: Coded aperture imaging (CAI) methods offer multidimensional and multispectral imaging capabilities with minimal resources than needed in a lens-based direct imager. In a CAI method, the light diffracted from an object is modulated by a coded mask, and the resulting intensity distribution is recorded. Most of the CAI techniques involve two steps: recording of point spread function (PSF) and object intensity under identical conditions and with the same coded mask. The image of the object is reconstructed by computationally processing the PSF and object intensity. The above recording and reconstruction procedure preclude the introduction of special beam characteristics in imaging like a direct imager. In this study, a post-processing approach has been developed where synthetic PSFs capable of introducing special beam characteristics when processed with the object intensity were generated using an iterative algorithm. The method was applied to generate edge-enhanced images in both CAI as well as Fresnel incoherent correlation holography method.

Keywords: edge enhancement; coded aperture imaging; Fresnel incoherent correlation holography; phase-retrieval algorithm; holography; incoherent imaging; high-speed imaging

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1. Introduction

The coded aperture imaging (CAI) technique is a widely used computational optical method that has efficiently replaced the need for high-quality optical components in direct lens-based imagers with computational methods [1,2]. In direct imaging methods, the image of an object is directly formed on the image sensor. In CAI, two steps are necessary for imaging. In the first step, a point object is mounted in the object plane, and the light from it is modulated by a coded mask (CM), and the resulting intensity distribution—point spread function (I_{PSF}) is recorded. In the next step, an object is mounted at the same location as the point object, and with the same CM and identical conditions, a second intensity distribution is recorded. The two intensity distributions are processed in a computer to reconstruct the object information. In a linear, shift-invariant system, the object intensity (I_O) can be expressed as a convolution of the object function O with the PSF, $I_O = O \otimes I_{PSF}$, where '$\otimes$' is a 2D convolutional operator. The image reconstruction is carried out by a cross-correlation given as $I_R = I_O * I_{PSF}$, where '*' is a 2D correlational operator.

The above principle of recording and reconstruction precludes the introduction of special beam characteristics in the imaging system. In direct imaging methods and well-established holography methods such as Fresnel incoherent correlation holography (FINCH), the introduction of beam characteristics is easy and straightforward. Let us consider the case of edge enhancement which is a useful technique in many applications [3,4]. In direct imaging, the edge enhancement is achieved by modulating light using a vortex filter [5]. In FINCH, the object hologram is usually formed by interfering two object waves with different quadratic phase modulations and reconstructed by numerically propagating the recorded hologram to one of the image planes [6,7]. In FINCH, the edge enhancement was introduced by a modulo-2π phase addition of a vortex filter to one of the quadratic phase masks used to modulate the object wave [8]. The resulting hologram, when propagated to one of the image planes, an edge-enhanced image of the object was obtained. A similar approach was attempted in FINCH with the reconstruction method of CAI in a simulative study, and no edge enhancement was noticed [9,10]. In FINCH, the original reconstruction mechanism is independent of the modulating function, and whether the phase mask is quadratic or quadratic with a vortex filter, the hologram is numerically propagated to one of the image planes. In FINCH, when the CAI reconstruction method was implemented, i.e., instead of numerical backpropagation, a cross-correlation with the PSF was carried out, the scenario becomes different as the reconstructing function, i.e., PSF is dependent upon the modulation function. Consequently, the characteristics of the modulating function are not expressed during reconstruction. In this study, an iterative algorithm is developed which can synthesize special PSFs from the recorded PSFs. The special PSFs, when processed with the recorded object intensity distributions, can produce edge-enhanced images of the object.

2. Materials and Methods

The optical configuration of the generalized imaging system is shown in Figure 1a. The light from a point object is modulated by optical modulators consisting of lenses, and CMs and I_{PSF} are recorded and given as input into an iterative algorithm shown in Figure 1b. The recorded I_{PSF} was Fourier transformed, and the complex conjugate was calculated ($\tilde{I}_{\mathrm{PSF}}{}^{*}$). The Fourier transform of the initial guess synthetic PSF was assumed to be a random phase-only function which was multiplied by $\tilde{I}_{\mathrm{PSF}}{}^{*}$, and the result was Fourier transformed. The resulting complex amplitude's magnitude was replaced by the far-field diffraction pattern of a vortex filter [11], but its phase was retained. The resulting complex amplitude was inverse Fourier transformed, and the result is multiplied by $\tilde{I}_{\mathrm{PSF}}{}^{-1*}$ and I^{-1}. This process was iterated until an optimal solution was obtained [12]. The resulting solution was correlated with the recorded object intensity distribution using a nonlinear filter to reconstruct the edge-enhanced image of the object [13].

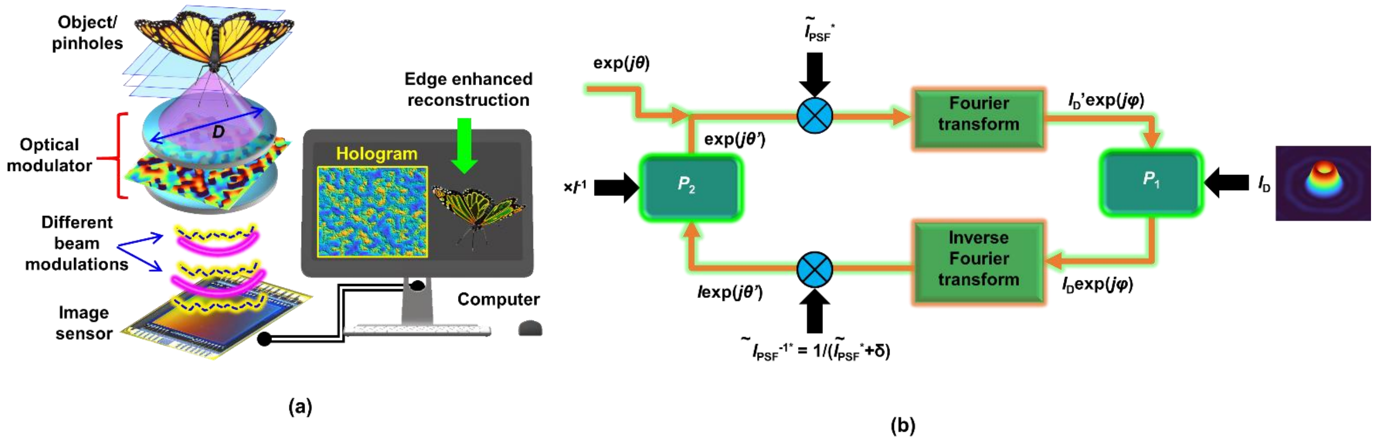

Figure 1. (**a**) Optical configuration of a generalized imaging system. (**b**) Schematic of the iterative algorithm for generating the synthetic PSFs. The symbol~above I_{PSF} represents a Fourier transform operation, ⊗ represents a multiplication operation, and * represents a complex conjugate. The far-field diffraction of a vortex filter input as I_D in P_1.

3. Results

The proposed method, as a matter of fact, is simpler than the conventional method as a vortex filter is not needed for this approach, and the method is completely a post-processing one and therefore will not affect the temporal resolution of the system. The method was applied to two cases: FINCH and CAI.

The FINCH experiment was carried out using randomly multiplexed diffractive lenses mounted between the object and the image sensor [9,10]. Two FINCH holograms were recorded: PSF and object hologram as shown in Figure 2a,b, respectively. The reconstructed image is shown in Figure 2c. The phase of the Fourier transform of the synthesized PSF is shown in Figure 2d, and the edge enhanced reconstruction is shown in Figure 2e. In the CAI experiment, a PSF was recorded (Figure 2f) by modulating the light diffracted from a point object by a mask consisting of a random array of pinholes. In the next step, a spark was generated and recorded, as shown in Figure 2g [2,14,15]. The recorded intensity distribution was processed with the PSF, and the reconstructed image is shown in Figure 2h. The phase of the Fourier transform of the synthesized PSF is shown in Figure 2i, and the enhanced edge reconstruction is shown in Figure 2j.

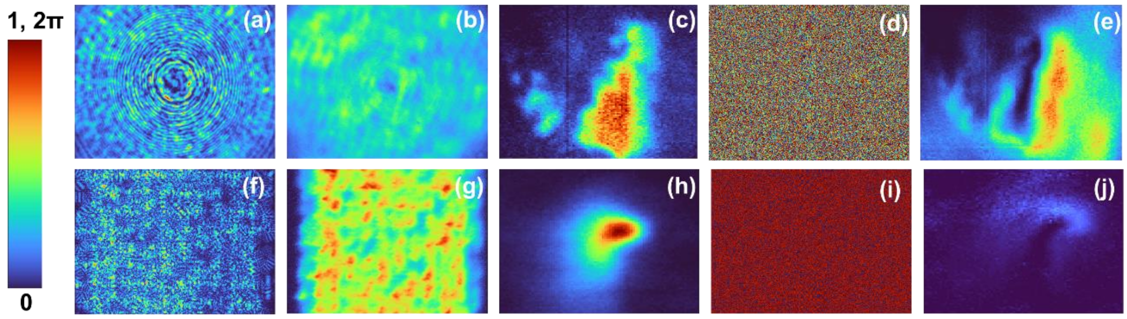

Figure 2. Images of the (**a**) PSF, (**b**) object intensity distributions, (**c**) reconstructed image of Fungi sample with recorded PSF, (**d**) phase of the Fourier transform of synthetic PSF, and (**e**) edge enhanced reconstruction for FINCH system. Images of the (**f**) PSF, (**g**) object intensity distributions, (**h**) reconstructed image of a spark with recorded PSF, (**i**) phase of the Fourier transform of synthetic PSF and (**j**) edge enhanced reconstruction for CAI system.

4. Conclusions

A completely computational edge-enhancement method has been developed for CAI methods. The developed method can be implemented offline, and so it does not affect the temporal resolution of the imaging system. Furthermore, the method does not require any additional optical component such as vortex filters, and so it is low-cost in comparison to existing edge enhancement methods. The preliminary results are promising. The method can be directly extended for implementing any function without the need for additional optical experiments in CAI methods.

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