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 what is needed in a lens-based direct imager. In the 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: the recording of the 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 precludes the introduction of special beam characteristics in imaging, such as a direct imager. In this study, a postprocessing approach is developed, where synthetic PSFs capable of introducing special beam characteristics when processed with the object intensity are generated using an iterative algorithm. The method is applied to generate edge-enhanced images in both CAI as well as Fresnel incoherent correlation holography methods.

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

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 (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 (Io) can be expressed as a convolution of the object function O with the PSF, Io = O ⊗ I PSF, where ‘⊗’ is a 2D convolutional operator. The image reconstruction is carried out by a cross-correlation given as IR = Io* 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, 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, edge enhancement is 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, yields an edge-enhanced image of the object. 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 is implemented, i.e., instead of numerical backpropagation, a cross-correlation with the PSF is carried out, and the scenario becomes different as the reconstructing function, i.e., PSF, is dependent upon the modulating function. The PSF and the object holograms are recorded under identical conditions and using the same modulation function of the vortex filter. Therefore, in this case, during reconstruction by cross-correlation, the edge-enhancing characteristics of the vortex filter are not expressed. 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 enhanced images of the object. While the proposed approach can be used for many applications, in this manuscript, the edge enhancement is demonstrated.

2. Materials and Methods

The optical configuration of the generalized imaging system is shown in Figure 1a. The light from a point object was modulated by optical modulators consisting of lenses, and CMs and I_{PSF} were recorded and provided as input into an iterative algorithm shown in Figure 1b. In this case, the only requirement was that the imaging system had to be a linear shift-invariant system and, therefore, the optical configuration could either be as simple with a single optical modulator or multiple optical elements and components. The iteration occurred between two planes of interest P_1 and P_2 as shown in Figure 1a. The ground truth image was the required output I_D by cross-correlation between the recorded I_{PSF} and synthetic I_{PSF}. This output was transferred to every recorded object point when the synthetic I_{PSF} was cross-correlated with the object intensity distribution. The recorded I_{PSF} was Fourier transformed, and the complex conjugate was calculated (\hat{I}_{PSF}). The Fourier transform of the initial guess synthetic PSF was assumed to be a random phase-only function, which was multiplied by \hat{I}_{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 was multiplied by I_{PSF}^{-1} and I^{-1}. This process was iterated until an optimal solution was obtained [12]. Similar to most iterative algorithms, the optimal solution was achieved using an error function that could be the root mean square error between the ground truth and the result obtained from the algorithm. 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].
3. Results

The proposed method, being a completely postprocessing one, neither required a vortex filter as in the conventional method, nor did it 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 edge-enhanced reconstruction is shown in Figure 2j.

![Image](image-url)

**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. The red scale bar is 150 µm, and the green scale bar is 1 mm.

### 4. Conclusions

A completely computational enhancement method was developed for CAI methods utilizing the indirect reconstruction method of the cross-correlation of the object intensity distribution with the PSF. The developed method could be implemented offline, and so it did not affect the temporal resolution of the imaging system. Furthermore, the method did not require any additional optical component such as vortex filters, and so it is low-cost in comparison to existing edge-enhancement methods. Secondly, the edge enhancement in FINCH required at least three camera shots for every object, i.e., for the m objects, 3m camera shots were needed. The proposed method required only a single camera shot, and the PSF recording was conducted only once and did not need to be repeated for every new object. Therefore, for the m objects, the number of camera shots needed was only m + 1. Therefore, when m was large, the impact was clear. The preliminary results were promising when implemented for the fungi sample with well-defined boundaries and a spark event involving a gradual variation in intensity. A strong edge-enhancement was seen in the regions with rapid changes in intensity while a mild edge enhancement is noticed in the regions with a slow variation in intensity in the case of the spark image as expected. The method could be directly extended for implementing many operations such as blurring, sharpening, etc., of reconstructed images without the need for additional optical experiments in CAI methods. Future studies will involve applying the developed method for different image enhancement tasks and quantitative comparison studies with existing methods.

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