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Single-pixel correlated imaging with high-quality reconstruction using iterative phase retrieval algorithm

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ABSTRACT

A single-pixel correlated imaging scheme based on iterative phase retrieval algorithm, which can encode an original object into a series of measured intensities, is proposed in this paper. Initially, a plenty of intensity patterns are derived from the Hadamard matrix with the certain order, and a pair of noisy phase profiles can be obtained by decomposing an intensity pattern via an iterative phase retrieval algorithm. When a pair of phase profiles is cascaded and sequentially embedded into two spatial light modulators in the proposed optical configuration, a measured intensity can be recorded by the bucket detector without spatial resolution. By only making the use of second-order correlation algorithm, the object with high quality can be reconstructed with measured intensities. Meanwhile, the number of recording the measured intensities can be reduced greatly in the process of imaging, which results in high efficiency. The reported approach provides an effective alternative for enriching the related research on single-pixel correlated imaging systems.

1. Introduction

Also known as ghost imaging, single-pixel correlated imaging has been one of the most intriguing optical technologies, and gained more and more attention owing to its remarkable physical characteristics [1]. In the conventional pseudo-thermal ghost imaging configuration [2], the reconstruction of an object can be implemented by means of intensity correlation between two optical beams, where the signal beam scattered at the object arm is detected by a single-pixel bucket detector and the reference beam diffracted by a rotating diffuser is collected by a spatially resolving detector such as charge-coupled device (CCD). Although the object is not placed at the reference beam, it can be decoded by correlating the signals recorded in two detectors. Shapiro [3] described a computational ghost-imaging arrangement to pre-compute the intensity fluctuation pattern that has been recorded by the detector with high spatial resolution, which can afford background-free imagery in the narrow-band limit. Bromberg et al. [4] experimentally demonstrated that the pseudo-thermal ghost imaging does not rely on nonlocal quantum correlations, and can be implemented with only a single detector by replacing the high-resolution detector in the reference path with a computation of the propagating field. Katz et al. [5] proposed an advanced reconstruction algorithm based on compressed sensing to recover original object, where the number of measurements can be reduced by an order of magnitude.

Until now, the application based on single-pixel imaging has been extensively developed such as remote sensing [6], pattern recognition [7] and object identification [8]. With the development of optical information encryption techniques [9–14], the research on applying single-pixel imaging techniques in this field has attracted more and more attention [15–18]. Most importantly, a large amount of new configurations and algorithms on single-pixel imaging has been explored such as high-order [19], differential [20] and normalized [21] ghost imaging. Liu et al. [22] demonstrated lensless ghost imaging with pure filtered sunlight and promoted its practical application with ordinary daylight. Yu et al. [23] proposed adaptive compressive ghost imaging not only to reduce the number of measurements and stringent hardware restrictions but also to improve the robustness against noise. Li et al. [24] investigated the influence of axial relative motion on ghost imaging and solved the degradation of imaging resolution based on speckle-resizing and speed retrieval. Gong [25] presented a pseudo-inverse ghost imaging to enhance spatial transverse resolution and implement the imaging of gray scale objects with high-resolution. Zhang et al. [26] applied the sinusoidal patterns instead of random speckle patterns to illuminate objects and achieved high-quality images by using Fourier transform. Chen

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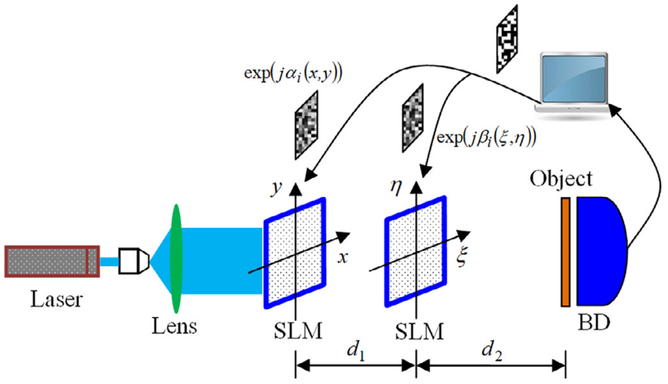

Fig. 1. Schematic setup for the single-pixel correlated imaging system: SLM, spatial light modulator; BD, bucket detector; $\exp(j\alpha_i(x,y))$ and $\exp(j\beta_i(\xi,\eta))$, phase-only Masks; d_1 and d_2, axial distance.

[27] proposed a single-pixel imaging via phase extraction to implement encryption of objects, where a series of random intensity patterns are pre-generated as principal security keys. Wang and Zhao [28] designed a ghost imaging scheme to realize fast reconstruction, where the Walsh–Hadamard pattern pairs are used to illuminate an object to record pairs of measured intensities, and the differential results between each pair of intensities are considered as measurements. Liu et al. [29] employed the superbunching pseudothermal light to make image quality with high visibility in ghost imaging applications. Shi et al. [30] used polarization-division multiplexing speckles to illuminate objects so as to simultaneously obtain polarimetric information by a single detector.

In this paper, a single-pixel correlated imaging scheme is presented to realize high-quality imaging. In this scheme, a plenty of intensity patterns are pre-generated based on the Hadamard matrix with the certain order, which are decomposed into pairs of noisy phase profiles using an iterative phase retrieval algorithm. These pairs of phase profiles are cascaded and sequentially embedded into two spatial light modulators located in the optical configuration, and then a series of measured intensities can be recorded by using the bucket detector. Similar to conventional computational ghost imaging, the intensity patterns in the reference arm are calculated virtually, which are used for correlating with measurement intensities to reconstruct the original object. Because the pairs of phase profiles are derived from spatially orthogonal Hadamard matrix, the redundancy between them can be decreased sharply, which makes it possible that the reconstruction result with high-quality can be obtained with much less measured intensities. Meanwhile, a significantly small number of pairs of phase profiles can be employed to verify the presence of original object by using the nonlinear correlation algorithm.

The rest of this paper is organized as follows. In Section 2, the proposed single-pixel correlated imaging scheme is introduced in detail. Meanwhile, the iterative phase retrieval algorithm to decompose an intensity pattern into a pair of phase profiles is discussed. In Section 3, the analysis on the reconstruction results are performed. Finally, a brief conclusion is described in Section 4.

2. Scheme description

As we all know, a large amount of measured intensities are usually recorded by the single-pixel bucket detector at the object arm to reconstruct the object with high quality in the conventional computational ghost imaging, which will lead to the increase of acquisition time and the inability to make effective use of photons in many low-light imaging conditions. To improve the quality of the object reconstructed with much less measured intensities, a mechanism of single-pixel correlated imaging by using an iterative phase retrieval algorithm is presented. The corresponding schematic setup is depicted in Fig. 1, where an optical cascaded sensing infrastructure is used. A series of intensity patterns $I_i(\mu,\upsilon)$ $[i=1,2,3,\ldots,K]$, K is the total number of patterns, are pre-generated based on a Hadamard matrix with the certain order, and an iterative phase retrieval algorithm is applied to decompose each intensity pattern into a pair of noisy phase profiles denoted as $\alpha_i(x,y)$ and $\beta_i(\xi,\eta)$, where (x,y) and (ξ,η) represent the coordinates of two phase planes, respectively. During the process of object imaging, the laser beam is collimated for the illumination, and each pair of phase profiles is sequentially embedded into two phase-only spatial light modulators. The wave is modulated by two phase-only masks, namely $\exp(j\alpha_i(x,y))$ and $\exp(j\beta_i(\xi,\eta))$, $j=\sqrt{-1}$, and the resultant speckle pattern passes through the object. The measured intensity B_i is recorded by the bucket detector without spatial resolution located behind the object, which is mathematically described as

$$B_i = \iint \left| FWP_{\lambda,d_2}\left\{ FWP_{\lambda,d_1}\{\exp(j\alpha(x,y))\}\exp(j\beta(\xi,\eta))\right\}\right|^2 T(\mu,\upsilon)d\mu d\upsilon. \tag{1}$$

Here, $T(\mu,\upsilon)$ is the transmission function of the object, (μ,υ) denotes the transversal coordinates of object plane, and $FWP_{\lambda,\,d}$ denotes the free-space wave propagation with the light wavelength λ and the axial distance d. The free-space propagation field passing through the first phase-only plane is conducted by using the Fresnel diffraction as

$$E_i(\xi,\eta) = FWP_{\lambda,d_1}\left\{\exp\left(j\alpha_i(x,y)\right)\right\} = \exp\left(j\alpha_i(x,y)\right) \quad * h\left(x,y,d_1\right). \tag{2}$$

Here, * denotes the convolution calculation and $h(x,y,d_1)$ is the point pulse function of the Fresnel propagation, which is defined as

$$h\left(x,y,d_1\right) = \frac{\exp\left(j2\pi d_1/\lambda\right)}{jd_1\lambda}\exp\left(\frac{j\pi}{d_1\lambda}\left(x^2+y^2\right)\right). \tag{3}$$

Similarly, the free-space propagation field passing through the second phase-only plane is described as

$$\begin{aligned} E_i'(\mu,\upsilon) &= FWP_{\lambda,d_2}\left\{E_i(\xi,\eta)\exp\left(j\beta_i(\xi,\eta)\right)\right\} \\ &= \left(E_i(\xi,\eta)\exp\left(j\beta_i(\xi,\eta)\right)\right) \quad * h\left(\xi,\eta,d_2\right). \end{aligned} \tag{4}$$

The corresponding point pulse function is expressed as

$$h\left(\xi,\eta,d_2\right) = \frac{\exp\left(j2\pi d_2/\lambda\right)}{jd_2\lambda}\exp\left(\frac{j\pi}{d_2\lambda}\left(\xi^2+\eta^2\right)\right). \tag{5}$$

To reconstruct the object, the measured intensities recorded by the bucket detector will be cross-correlated with a series of intensity patterns denoted as $I_i'(\mu,\upsilon)$ $[i=1,2,3,\ldots,K]$, which are generated using the same cascaded infrastructure and calculated as $|FWP_{\lambda,d_2}\{FWP_{\lambda,d_1}\{\exp(j\alpha_i(x,y))\}\exp(j\beta_i(\xi,\eta))\}|^2$. Finally, the calculated reference intensity patterns are correlated with the measured intensities to decode the object using correlation function, which is mathematically expressed as

$$\begin{aligned} G(\mu,\upsilon) &= \left\langle BI'(\mu,\upsilon)\right\rangle - \langle B\rangle\left\langle I'(\mu,\upsilon)\right\rangle \\ &= \frac{1}{N}\sum_{i=1}^{K}\left(B_i - \langle B_i\rangle\right)\left(I'_i(\mu,\upsilon) - \left\langle I'_i(\mu,\upsilon)\right\rangle\right). \end{aligned} \tag{6}$$

Here, $\langle\cdot\rangle$ is the ensemble average calculation.

As described in the aforementioned imaging process, a series of intensity pattern is firstly pre-generated based on the Hadamard matrix, where each pattern are decomposed into two phase profiles. The basic block with the order 2 is usually applied to build the Hadamard matrix with any order, which is mathematically defined as

$$H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}. \tag{7}$$

Then, the Hadamard matrix with order 2^k (k is any integer) is obtained with the following recursive formula as

$$H_{2^k} = \begin{bmatrix} H_{2^{k-1}} & H_{2^{k-1}} \\ H_{2^{k-1}} & -H_{2^{k-1}} \end{bmatrix}. \tag{8}$$