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Iterative normalized correspondence ghost imaging

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ABSTRACT

We propose a technique, which we call iterative normalized correspondence ghost imaging, to remove noise and improve the quality of traditional ghost imaging (GI). An iterative model based on correspondence imaging is established by assuming invariance of the background noise between successive measurements. Numerical simulation is used to determine the optimal parameters of the model, including the number of iterations required. Both simulation and experimental results reveal that the quality of the image reconstructed by this strategy is higher compared to that of traditional correspondence GI and normalized GI, and no more demanding. The signal-to-noise ratio is improved without requiring a priori knowledge of the target object. This approach represents another step forward towards real practical applications.

1. Introduction

The first demonstration of second-order correlation imaging, or "ghost imaging" (GI), was performed with entangled biphoton pairs generated by spontaneous parametric down-conversion[1–6]. Later, theoretical and experimental studies showed that classical light can also be used to produce GI [7–16], and research has now progressed to solving practical engineering problems. Because of its high resolution, ultra-sensitivity, and non-local character, GI has great potential for application in remote sensing, medicine, and microscopic imaging. However, the quality of the reconstructed image is limited, and still cannot meet actual requirements, and how to improve the quality of pseudo-thermal light GI is a key problem that remains to be solved.

It is well known that the second-order correlation algorithm is one of the most important features of GI, and its efficiency directly affects the image quality. A number of scholars have investigated this issue [12–16]. For example, a scheme named correspondence ghost imaging (CI) was demonstrated by Luo et al. [17]. Although CI is performed without direct correlation computation, no full explanation of the underlying physics has as yet been provided. Several articles have presented a theoretical analysis. Yu et al. calculated the Pearson correlation coefficient between the bucket detector intensity and the brightness at a given pixel of the reference detector [18]; Yao et al. also established a statistical optics model to explain the phenomenon [19]. Further experimental and theoretical developments of this positive-negative image concept have been presented in many other papers, such as positive–negative CI [20–22] and time-correspondence differential GI [23,24].

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Although this phenomenon continues to be debated, it has already been used to improve the quality of direct correlation imaging [17,21,22]. Fluctuation correlation imaging is a traditional GI method [25,26] but the time required to reconstruct the image is rather long. Normalized ghost imaging (NGI) has a more appropriate weighting factor applied to the ensemble average of the estimated object [27], and shows remarkable enhancement compared to traditional GI or CI. However, the image quality is only somewhat improved after the number of measurements increases to a certain value. The correlation algorithm still needs to be upgraded for the reconstructed image quality to satisfy the demands of application. In this paper, by incorporating the merits of both positive-negative CI and NGI, we propose a new method to improve the signal-to-noise ratio (SNR) of NGI by employing an iterative algorithm to remove noise.

The validity of our iterative normalized correspondence GI (INCGI) method is first derived theoretically. The differential signal value of NGI is taken as a selection criterion in the reconstruction of the CI image. When the exposure rate is faster than the rate of change of the noise, we can assume that the background noise of the reconstructed image is the same over a given measurement time; we define this as our noise invariance assumption. An iterative model based on CI is established by using this background noise assumption, and its parameters are optimized by simulation experiments. It is shown that the contrast of the reconstructed image can be greatly improved compared with NGI and CI, and that the influence of background noise can be minimized.

2. Theoretical derivation and numerical simulation

The theory and numerical simulation are based on the experimental setup shown in Fig. 1, a conventional GI system. A thermal light beam is separated by a beam splitter (BS) into two arms. In the signal arm, the light passes through an object (Obj) and the total intensity I_B is collected by a bucket detector (BD). In the reference arm, the light intensity distribution $I_R(x_R)$ is received by a charge-coupled device (CCD) detector, where x is the spatial coordinate of the latter. The target image is then recovered by computing the second-order correlation of the output signals from the two arms. In the CI experiment [6], all the reference frames are divided into two subsets:

$$\{I_R(x)|I_B(x) - \langle I_B(x)\rangle > 0\}\,,\{I_R(x)|I_B(x) - \langle I_B(x)\rangle < 0\} \tag{1}$$

where $\langle\ldots\rangle$ represents the ensemble average of K exposure measurements, x is the spatial coordinate of the target object. As can be seen from Eq. (1), the mean $\left\langle I_B\right\rangle$ of the signal light detection value is used as the threshold in the CI. The bucket intensities of the signal light are divided into two parts, in one of which all the measured values are greater than $\left\langle I_B\right\rangle$, and in the other, less than $\left\langle I_B\right\rangle$. At the same time, the values of the reference beam distribution $I_R(x)$ are also synchronously divided $I_R^+(x_R)$ and $I_R^-(x_R)$. $I_R^+(x_R)$ are divided on the condition of $I_B - \left\langle I_B\right\rangle > 0$ while $I_R^-(x_R)$ are divided on the condition of $\left|I_B - \left\langle I_B\right\rangle < 0\right.$. CI can be achieved by simply averaging the reference light distributions separately, where $\left\langle I_R^+(x)\right\rangle$ gives a positive image and $\left\langle I_R^-(x)\right\rangle$ a negative image [23]

$$\begin{cases} \left\langle I_R^+(x)\right\rangle \simeq \left\langle I_R(x)\right\rangle + C_0T(x)/\left\langle\left|\varDelta I_B\right|\right\rangle \\ \left\langle I_R^-(x)\right\rangle \simeq \left\langle I_R(x)\right\rangle - C_0T(x)/\left\langle\left|\varDelta I_B\right|\right\rangle \end{cases}, \tag{2}$$

where C_0 is a constant, $T(x)$ is the transmittance function, and $\varDelta I_B = I_B - \left\langle I_B\right\rangle$.

However, CI is susceptible to environmental noise, and the quality of the image cannot meet application requirements. We therefore adopt a normalization procedure, which has been shown to reduce the influence of noise in traditional GI, and can thus obtain a higher SNR.

To implement NGI we need to define the sum of the reference detector signal $S_R = \sum_{x=1}^{U\times V} I_R(x)$, where U and V are the height and width of the reference detector array. The normalized GI can be written in an operative form as [27]

$$O_{NGI}(x) = S_N\left(I_R(x) - \left\langle I_R(x)\right\rangle\right), \tag{3}$$

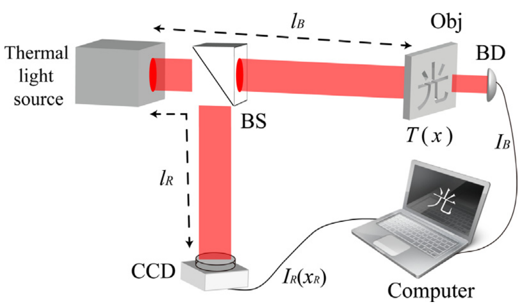

Fig. 1. Schematic of experimental setup. BS, beam splitter; $T(x)$, transmission function of the object Obj; BD, bucket detector; CCD, camera.