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Influence of detector response speed on the contrast-to-noise ratio of reflective ghost imaging

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ABSTRACT

The influence of detector response speed on the contrast-to-noise ratio (CNR) of reflective ghost imaging (RGI) is studied. To mimic the situation of a slow response detector, the illuminating speckle patterns are replaced with the sum of uncorrelated speckle patterns for each measurement. An expression for the CNR of RGI with added speckle patterns is derived. By employing a light projector to provide spatially incoherent structured illumination in a computational ghost imaging system, we perform computational RGI based on added speckle patterns. The experimental results show that when up to 40 uncorrelated speckle patterns are added together in each measurement, the CNR of computational RGI obtained from 5000 effective measurements remains almost the same as the conventional computational ghost imaging. The reason for this is that the image quality of RGI depends on the kurtosis of intensity fluctuation of speckle field instead of the contrast ratio of speckle pattern. The experimental results agree with the theoretical prediction.

1. Introduction

Ghost imaging (GI) is an imaging method to extract the object information by means of spatial intensity correlation measurement, which is different from conventional imaging. In a typical GI system, the source beam is divided into two correlated beams by a beam-splitter, one of which interacts with an object and then is detected by a bucket detector without spatial resolution, whereas the other never interacts with the object and is measured by a spatially resolving detector. The object image can be reconstructed by correlating the output signals from these two detectors. The first GI experiment was performed by using two-photon entangled light generated in spontaneous parametric down-conversion [1]. Later GI was also realized with thermal light [2–8]. Subsequently computational ghost imaging was presented theoretically by Shapiro [9] and demonstrated experimentally by Bromberg et al. [10]. The extension of reflective ghost imaging (RGI) to this computational framework has opened the door for a variety of applications, including remote sensing and laser radar [11–13]. Recently, by employing a digital light projector in a computational ghost imaging system with several single-pixel detectors, Sun et al. performed three-dimensional (3D) reconstruction of an object [14].

Ever since GI was proposed, the image quality of this new technique has become a hot issue in view of practical applications. Some important factors which influence the image quality of GI have been considered, such as illumination levels, the number of speckles transmitted through the mask in the object channel, the number of spatio-temporal modes detected by the reference detector, and the response speed of detector [15–18]. It is well known that a slow response detector used in conventional imager based on speckles would produce blurred images of object. However, in performing transmissive ghost imaging with intensity-averaged (or blurred) speckle patterns, Brida et al. [15] and Zerom et al. [18] showed that the image quality of transmissive ghost imaging can remain high, even though the response speed of detectors is much slower than the correlation time of the illuminating speckle field, as long as the fluctuation of the detected signal is mainly caused by the illuminating speckle field rather than noise of the detection system. This result implies that using slow detectors for true thermal light GI is possible. This is why Wu's group can carry out GI experiment with true thermal light whose coherence time (0.2 ns) is shorter than the time resolution (0.45 ns) of the detection system [19–21]. Because computational RGI is more feasible in applications, in this paper, we will discuss the influence of detector response speed on the contrast-to-noise ratio (CNR) of computational RGI both theoretically and experimentally. The paper is organized as follows. In Section 2, the CNR of RGI with added speckle patterns is derived. In Section 3, we

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present the experimental results. And in Section 4, the conclusion is made.

2. Theoretical analysis

The scheme of computational GI for a reflective object is depicted in Fig. 1. The computer is used to generate the random speckle patterns and perform the intensity correlation measurement. The computer-generated speckle patterns follow negative exponential intensity statistics, which are projected using a light projector. The light projector is composed of a high-pressure mercury lamp, dichroic mirrors and three liquid crystal display (3LCD) panels. The speckle patterns projected by the light projector illuminate the reflective object and the reflected light is measured by a single-pixel (bucket) detector. The output signal from the bucket detector is sent to the computer through a data acquisition (DAQ) card.

With the model introduced by Chan et al. [16,17] and Brida et al. [15], an analysis of image quality of transmissive ghost imaging with averaged speckle patterns was presented by Zerom et al. [18]. Here we discuss the CNR of RGI following this model. We now assume that the noise in detection system can be neglected so that the measured signal variation of the detector is mainly caused by the intensity fluctuation of the incident speckle patterns. The ghost image of the object can be reconstructed by correlating the bucket signal with the intensity distribution of the incident speckle pattern projected onto the object, averaging over many measurements. The second-order correlation of RGI can be expressed as [16–18]

$$G(\vec{x}) = \frac{1}{K}\sum_{k=1}^{K} I_o^{(k)} I^{(k)}(\vec{x}) - \frac{1}{K^2}\sum_{k=1}^{K} I_o^{(k)} \sum_{k=1}^{K} I^{(k)}(\vec{x}), \tag{1}$$

where K is the number of measurements, k denotes the k-th measurement, and $I^{(k)}(\vec{x})$ is the intensity distribution measured by the spatially resolving detector for the k-th measurement. $I_o^{(k)}$ is the reflected intensity measured by the single-pixel (bucket) detector for the k-th measurement, which can be expressed as

$$I_o^{(k)} = \sum_{\vec{x}} I^{(k)}(\vec{x}) O(\vec{x}), \tag{2}$$

where $O(\vec{x})$ is the object reflectivity function. For simplicity, we assume that the object is a black-and-white reflective object with its size much larger than the speckle size of illumination pattern. Thus the reflectivity function of the black-and-white reflective object can be expressed as

$$O(\vec{x}) = \begin{cases} R_1 & \text{white area}, \\ R_2 & \text{black area}. \end{cases} \tag{3}$$

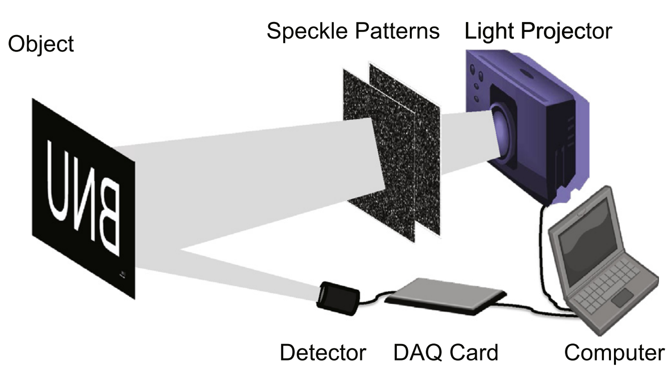

Fig. 1. Setup for computational reflective ghost imaging.

The image quality of RGI can be evaluated by the CNR. Here we adopt the definition of the CNR given in Refs. [16,17]:

$$CNR = \frac{\langle G(\vec{x}_{R1})\rangle - \langle G(\vec{x}_{R2})\rangle}{\sqrt{\Delta^2 G(\vec{x}_{R1}) + \Delta^2 G(\vec{x}_{R2})}}, \tag{4}$$

where $\langle\cdots\rangle$ stands for the ensemble average, $\vec{x}_{R1}$ and $\vec{x}_{R2}$ correspond to the pixels of the white area and black area of the object, respectively; and $\Delta^2 G(\vec{x}) = \langle G^2(\vec{x})\rangle - \langle G(\vec{x})\rangle^2$ is the variance of the correlation.

Following the model built by Chan et al. [16,17] and Zerom et al. [18], we obtain the expression for the CNR of reflective ghost image:

$$CNR = (R_1 - R_2) \left[\frac{K-1}{2(M_1R_1^2 + M_2R_2^2) + (R_1^2 + R_2^2)[(1 - 1/K)(\gamma_I/\sigma_I)^4 - 2 + 3/K]}\right]^{1/2}, \tag{5}$$

where M_1 and M_2 are defined as the ratios of the white area and black area of the object to the speckle size, respectively; $\sigma_I^2 = \langle I^2(\vec{x})\rangle - \langle I(\vec{x})\rangle^2$ and $\gamma_I^4 = \langle [I(\vec{x}) - \langle I(\vec{x})\rangle]^4\rangle$ are the variance and fourth moment of the intensity fluctuation of each illumination speckle pattern, respectively. It can be seen from Eq. (5) that the CNR of reflective ghost image depends on the number of measurements, the object reflectivity, the object size relative to the speckle size and the fourth standardized moment γ_I^4/σ_I^4 (also known as the kurtosis) of the intensity fluctuation of the illumination speckle pattern. When M_1 and M_2 are large ($M_1 \gg 1$, $M_2 \gg 1$), the CNR is almost independent of the kurtosis of intensity fluctuation of illumination speckle pattern.

Now we discuss the effect of detector response speed on the CNR of RGI in two cases: fast response detector and slow response detector.

First we consider the case of fast response detector. If the response time of the detector is shorter than the correlation time of the illuminating speckle field, the fast detector can register individual speckle patterns. According to the probability density function of the speckle pattern following a negative exponential form in this case, we can obtain that $\sigma_I^2 = \langle I(\vec{x})\rangle^2$ and $\gamma_I^4 = 9\langle I(\vec{x})\rangle^4$. Therefore, the CNR of RGI in this case is expressed as

$$CNR = (R_1 - R_2)\left[\frac{K-1}{2(M_1R_1^2 + M_2R_2^2) + (R_1^2 + R_2^2)(7 - 6/K)}\right]^{1/2}. \tag{6}$$

Then we consider the case of slow response detector. When the response time of the detector is longer than the correlation time of illuminating speckle field, the detector measures the intensity-averaged speckle pattern. In order to mimic slow detector in RGI, we replace the illuminating speckle pattern with the sum of N uncorrelated speckle patterns for each measurement. The larger the value that N takes, the slower the response speed of the detector is. Therefore the expressions for the k-th bucket signal and illumination speckle pattern at the object plane should be modified respectively as

$$I_{o,N}^{(k)} = \sum_{n=1}^{N} I_o^{(k,n)}, \tag{7}$$

$$I_N^{(k)}(\vec{x}) = \sum_{n=1}^{N} I^{(k,n)}(\vec{x}). \tag{8}$$

The probability density function for the sum of N uncorrelated speckle patterns with negative exponential intensity statistics reduces to a Gamma distribution [22], that is

$$p(I) = \frac{1}{\langle I\rangle^N \Gamma(N)} I^{(N-1)} \exp(-I/\langle I\rangle), \tag{9}$$