Optics Communications 381 (2016) 63–71

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Thermal light ghost imaging based on morphology

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ARTICLE INFO

Article history:
Received 10 May 2016
Received in revised form
23 June 2016
Accepted 25 June 2016

Keywords:
Ghost imaging
Morphology
Undersampling noise
Peak signal-to-noise ratio

ABSTRACT

The quality of thermal light ghost imaging could be degraded by undersampling noise. This kind of noise is generated because of finite sampling, which could reduce the signal-to-noise ratio (SNR) of ghost imaging and submerge object information. In order to reduce the undersampling noise, we propose a thermal light ghost imaging scheme based on the morphology (GIM). In this scheme, the average size of the undersampling noise can be obtained by computing the second-order correlation function of the ghost imaging system. According to the average size of the undersampling noise, the corresponding structure element can be designed and used in the morphological filter; then, the GIM reconstructed image can be obtained. The experiment results show that the peak signal-to-noise ratio of the GIM reconstructed image can increased by 80% than that of conventional ghost imaging for the same number of measurements.

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1. Introduction

Quantum imaging has been a very popular research topic in recent years, and ghost imaging is an important research field of quantum imaging. Since the earliest ghost-imaging experiment was carried out by Pittman et al. [1], people have studied this domain for twenty years. Many researchers have recently paid more attention to the practical applications of ghost imaging and have attempted to enhance the imaging quality, including the resolution and signal-to-noise ratio (SNR) [2–15]. In order to achieve this goal, people have proposed many methods such as *N*-order ghost imaging [16,17], compressive ghost imaging [18], and differential ghost imaging [19]. Although these ghost-imaging technologies can achieve better imaging quality than the conventional ghost imaging (CGI), there still is a factor that prevents them from obtaining higher SNR. This factor is the undersampling noise [20,21], which could submerge the object information and reduce the SNR of ghost imaging.

In this paper, we have carefully investigated the cause of undersampling noise in a thermal light ghost-imaging system. According to our investigation, the undersampling noise is caused by the finite sampling of the ghost-imaging system, and it is independent of environmental factors. In order to reduce the undersampling noise, we propose a thermal light ghost imaging scheme based on morphology (GIM). In this scheme, we used a morphological filter [22,23] as a denoising tool, including a dilate operator and an erode operator, and so on. In order to utilize the morphological filter, the average size of the undersampling noise needs to be estimated by computing the second-order correlation function of the ghost-imaging system. According to the average size of the undersampling noise, the corresponding structure element can be designed and used in the morphological filter. After a series of signal-processing steps, the GIM reconstructed image can be finally obtained. The experimental results show that the peak signal-to-noise ratio (PSNR) of the GIM reconstructed image is increase by 80% than that of CGI for the same number of measurements. In the future, this technology may find applications in thermal light ghost-imaging systems.

This paper is organized as follows. In Section 2, we establish the theoretical model of CGI and analyze the undersampling noise. In Section 3, we propose the GIM scheme, which is based on the morphology. In Section 4, we present two experiments that demonstrate the effectiveness of the proposed scheme. Finally, we briefly summarize the work in Section 5.

2. Conventional ghost imaging

Ghost imaging mainly uses two kinds of light sources: entangled light and thermal light [24,25]. In practice, researchers usually use thermal light as a light source because entangled light is difficult to prepare. In this paper, CGI refers to noncomputational ghost imaging that uses thermal light as the light source, which

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http://dx.doi.org/10.1016/j.optcom.2016.06.070
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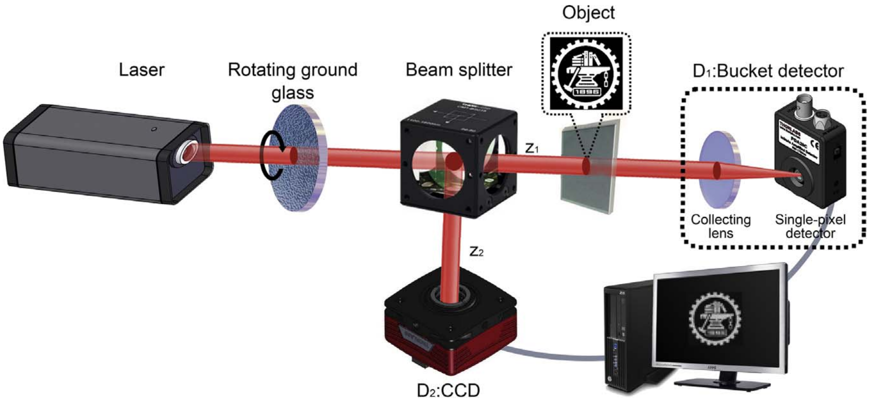

Fig. 1. The setup of conventional ghost imaging.

has two optical paths.

2.1. The setup of CGI

The essence of CGI is correlation imaging, which usually utilizes the second-order correlation characteristic [26]. Assuming thermal light with a Gaussian distribution, the second-order correlation function (in other words, the intensity correlation function) of this thermal light can be described as follows [27]:

$$G^{(2)}(\boldsymbol{\rho}) = \langle I(\boldsymbol{\rho} + \boldsymbol{\rho}_0) I(\boldsymbol{\rho}_0) \rangle = I_0^2 + |\Gamma(\boldsymbol{\rho})|^2, \tag{1}$$

where $\boldsymbol{\rho}$ is 2D plane coordinates perpendicular to the direction of propagation, I_0 is the average intensity, and $\Gamma(\boldsymbol{\rho}) = \langle E(\boldsymbol{\rho} + \boldsymbol{\rho}_0) E(\boldsymbol{\rho}_0) \rangle$, which is a first-order correlation function.

The setup of CGI is shown in Fig. 1. When a laser beam irradiates a rotating ground glass, the output light is pseudo thermal light. Then, the pseudo thermal light is divided into two beams by a beam splitter (BS); one beam is called the signal light, and other beam is called the reference light. The signal light illuminates an object whose aperture function is $O(\boldsymbol{\rho})$, and the light intensity before the object is $I_s(\boldsymbol{\rho})$. Then, all of the light transmitted through the object is sent to a bucket detector D_1, contains a collecting lens and a single-pixel detector, and the measuring result of the bucket detector D_1 is B. The reference light is directly sent to CCD detector D_2 after a certain distance of free-space propagation. The measuring result of D_2 is $I_r(\boldsymbol{\rho})$. In order to generate the correlation in this experimental setup, we must let $z_1 = z_2$, where z_1 is the distance between the light source and the object to be imaged, and z_2 is the distance between the light source and D_2.

According to the principles of ghost imaging, the object information can be recovered from the joint measurement between two detectors. Of course, there are various recovery algorithms including the CGI algorithm, background-subtracted CGI algorithm, high-order ghost-imaging algorithm [16,17], compressive ghost-imaging algorithm [18], differential ghost-imaging algorithm [19], and so on. In the following analysis, the recovery algorithm is the CGI algorithm.

In the CGI algorithm, the reconstructed imaging result is $O_{cgi}(\boldsymbol{\rho})$, which can be calculated as follows:

$$O_{cgi}(\boldsymbol{\rho}) = \langle B I_r(\boldsymbol{\rho}) \rangle, \tag{2}$$

where B is the total light intensity recorded by D_1, and $I_r(\boldsymbol{\rho})$ is the spatial distribution of the light intensity recorded by D_2.

In fact, B is correlated with $I_r(\boldsymbol{\rho})$ because B and $I_r(\boldsymbol{\rho})$ are from the same thermal light source. The relationship between these two variables is as follows:

$$B = \int_\Omega O(\boldsymbol{\rho}) I_r(\boldsymbol{\rho}) d\boldsymbol{\rho}, \tag{3}$$

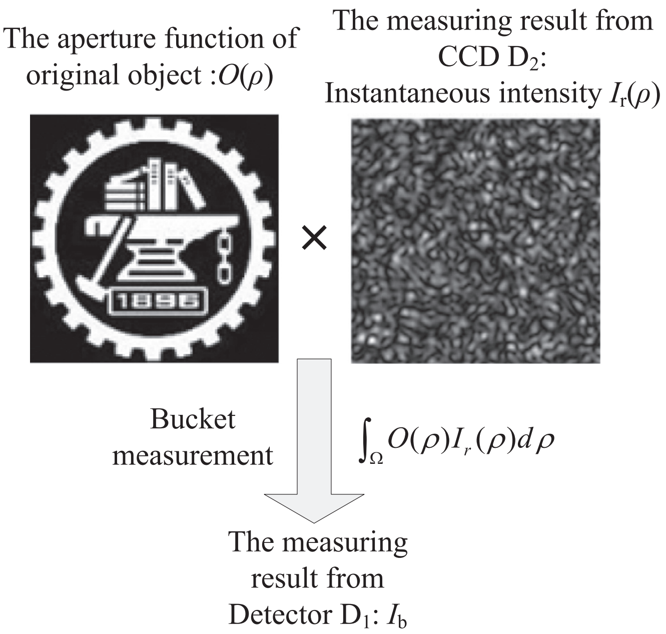

Fig. 2. The schematic of the relationship between B and $I_r(\boldsymbol{\rho})$.

where Ω is the irradiated area of the object. A schematic of this formula is shown in Fig. 2. Eq. (3) can be easily understood as follows; first, a beam of light is split into two beams by the BS, and these two beams of light are copies of the original light. Then, they freely propagate over the same distance ($z_1 = z_2$); thus, their diffraction spectra are the same ($I_s(\rho) = I_r(\rho)$), where $I_s(\rho)$ is the light intensity before the object. Then, the light intensity through the object is $O(\boldsymbol{\rho})I_s(\boldsymbol{\rho}) = O(\boldsymbol{\rho})I_r(\boldsymbol{\rho})$. Finally, bucket detector D_1 collects the total light intensity through the object; therefore, we use integration and obtain Eq. (3).

By substituting Eq. (3) into Eq. (2), we obtain

$$O_{cgi}(\boldsymbol{\rho}) = O(\boldsymbol{\rho}) \otimes G^{(2)}(\boldsymbol{\rho}), \tag{4}$$

where $\otimes$ denotes two-dimension convolution, and a detailed proof is presented in Appendix. Eq. (4) shows that the CGI result is two-dimension convolution of the object aperture function $O(\boldsymbol{\rho})$ and the correlation function $G^{(2)}(\boldsymbol{\rho})$. In other words, $G^{(2)}(\boldsymbol{\rho})$ is just the impulse response [or point spread function (PSF)] of the ghost-imaging system, which can determine the imaging resolution.

2.2. The undersampling noise

The quality of CGI is mainly determined by two factors. The first factor is the second-order autocorrelation function $G^{(2)}(\boldsymbol{\rho})$, which

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