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Influence of random phase modulation on the imaging quality of computational ghost imaging*

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In this paper, we investigated phase modulation-based computational ghost imaging. According to the results of numerical simulations, we found that the range of the random phase affects the quality of the reconstructed image. Besides, compared with those amplitude modulation-based computational ghost imaging schemes, introducing random phase modulation into the computational ghost imaging scheme could significantly improve the spatial resolution of the reconstructed image, and also extend the field of view.

Keywords: computational ghost imaging, random phase modulation, imaging quality

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1. Introduction

Ghost imaging is a kind of active illumination-based computational imaging scheme that was first proposed and realized by using entangled sources in 1995.[1] Later in 2002, it was proved that ghost imaging can be realized by using a classical source,[2] which extended the application of ghost imaging. Comparing with conventional imaging techniques, ghost imaging has many advantages, such as high lateral resolution,[3] and robustness against turbulence.[4] Due to these advantages, ghost imaging has become a hot topic in recent years.[5–14] Fundamentally, ghost imaging is based on intensity fluctuation correlations, and therefore, any light sources with a spatially fluctuating intensity distribution is theoretically suitable to be applied as the light source in ghost imaging. There are many ways to obtain an appropriate light source for ghost imaging. One is to use a pseudo-thermal light, which is generated by a laser and a rotating ground glass.[15] Ghost imaging based on pseudo-thermal light was carried out in 2004.[16] In 2008, Shapiro introduced a computational ghost imaging scheme.[17] Different from the conventional ghost imaging scheme, the computational ghost imaging technique applies a programmable light source, and the experimental setup can be simplified. The programmable light source can be considered as a combination of an illumination light source and a light modulation device, such as a laser and spatial light modulator (SLM), LED and digital micromirror device (DMD), a laser and DMD, *etc*. These methods can be roughly divided into three different types according to the means of modulation: phase-only, amplitude-only, and phase–amplitude modulation. Both amplitude modulation and phase modulation can change the intensity distribution of the output light. In the present article, we focus mainly on the phase modulation-based computational ghost imaging, and make a comparison between the amplitude-only schemes. We found that, for a phase-only modulation-based computational ghost imaging scheme, the range of random phase modulation affects the quality of the reconstructed image. Furthermore, compared with amplitude-only schemes, introducing random phase modulation into the computational ghost imaging scheme will significantly improve the spatial resolution of the reconstructed image, and extend the field of view. We believe that these features will be helpful for the practical application of ghost imaging techniques. The rest of this article is arranged as follows. In Section 2, we introduce the physical model of phase modulation-based computational ghost imaging. In Section 3, we carry out numerical simulations and discuss the results. Finally, conclusions are made in Section 4.

2. Physical model

The schematic diagram of a standard computational ghost imaging scheme is shown in Fig. 1. The light source is a 632.8-nm He–Ne laser, and an LCoS SLM is applied to modulate the phase distribution of the light source. The masks loaded on the SLM are pre-generated by the computer, with massive individual frames. The output light (with intensity distribution $I_n(x,y)$, where the subscript "n"

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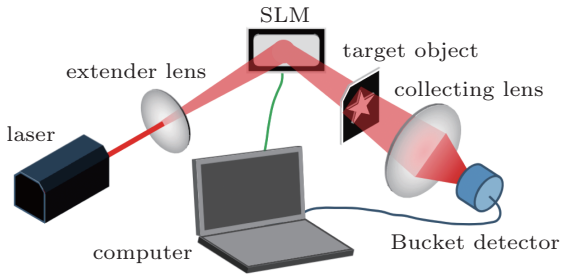


Fig. 1. Schematic diagram for computational ghost imaging. We apply a laser as the light source, and the light emitted by the light source is modulated by an SLM that is controlled by a computer. After modulation, the beam illuminates the object, and the transmitted light is collected by a bucket detector that is connected to a computer.

represents that this is the n-th modulated pattern) illuminates the target object, and the transmitted light is collected by a bucket detector. The corresponding bucket signal B_n is recorded by a computer. By calculating the second-order correlation function,[18] the image of the object can be revived:

$$g^{(2)}(x,y) = \frac{\langle I_n(x,y)B_n\rangle}{\langle I_n(x,y)\rangle\langle B_n\rangle}, \tag{1}$$

where $\langle\cdots\rangle$ represents the statical average, and x,y denote the transverse coordinates on the object plane.

It has been proved that the intensity distribution of the illuminating light on the object plane is a relevant factor in ghost imaging schemes; it significantly impacts the quality of the reconstructed image.[19] Thus, we study the intensity distribution of the illuminating light. The distribution of the field of the light source on the SLM plane is

$$u_s(x_s,y_s) = A(x_s,y_s)\,\mathrm{e}^{\mathrm{i}\theta(x_s,y_s)}, \tag{2}$$

where $A(x_s,y_s)$ and $\theta(x_s,y_s)$ represent the amplitude and phase distribution of the light field, respectively. After modulation, the distribution of the light field reads

$$u_0(x_s,y_s) = A(x_s,y_s)\,\mathrm{e}^{\mathrm{i}[\theta'(x_s,y_s)+\theta(x_s,y_s)]}, \tag{3}$$

where $\theta'(x_s,y_s)$ is the phase delay due to the modulation. After modulation, the light propagates a distance of z, reaches the object plane, and illuminates the object. According to the Fresnel principle, the distribution of the light field on the object plane is

$$u(x,y) = \frac{\mathrm{e}^{\mathrm{i}kz}}{\mathrm{i}\lambda z}\iint u_0(x_s,y_s)\exp\left\{\frac{\mathrm{i}k}{2z}[(x-x_s)^2+(y-y_s)^2]\right\}\mathrm{d}x_s\mathrm{d}y_s. \tag{4}$$

We can obtain the intensity distribution

$$I(x,y) = \langle u^*(x,y)u(x,y)\rangle. \tag{5}$$

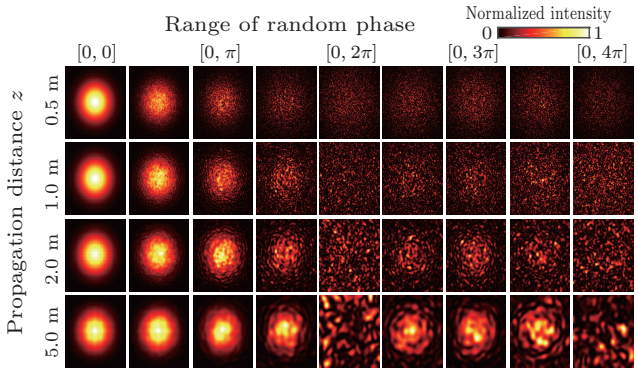


Fig. 2. The numerical results of the intensity distribution on planes different distances away from the SLM plane. Different ranges of random phase modulation are taken.

The analytic solutions of Eq. (5) are very complicated, and thus the numerical results are calculated based on different phase distributions. The light beam that illuminates the SLM is a Gaussian beam with a waist radius of 2.56 mm, and the size of the pixels on the SLM is taken to be 40 μm. The SLM provides a phase modulation at every pixel, and the phase delay caused by the modulation is randomly distributed in a determined interval $\theta' \in [0,\Delta\phi]$. We calculated the intensity distribution of the light beam that propagated z distance after being modulated. Figure 2 shows the numerical results of different propagation distances and different ranges of phase modulation.

From the numerical results, it is found that, when the range of phase modulation increases, the fluctuation of the intensity distribution appears stronger. The authors in Ref. [19] proved that using a light beam with strong fluctuation as the illuminating light will significantly improve the quality of ghost imaging. In order to find out the impact of the phase modulation on the fluctuation of the illuminating light, we define the relative intensity of fluctuation (RIF) as follows:

$$\mathrm{RIF} = \frac{\sum\limits_{x,y}[I_n(x,y) - \langle I_n(x,y)\rangle_n]^2}{[\sum\limits_{x,y}\langle I_n(x,y)\rangle_n]^2}, \tag{6}$$

where $I_n(x,y)$ is the intensity distribution after the n-th modulation, and $\langle\cdots\rangle$ denotes the statical mean. The numerator of the RIF judges the average level of fluctuation of every pixel on the whole plane, and the denominator normalizes the value of the RIF. The RIF depends on a large number of samples to ensure that it gives the closest approximation of the fluctuation. In practice, we generated 1000 different masks to modulate the light beam and calculate the RIF. We investigated the

RIF when we change the range of the random phase modulation, and the results are shown in Fig. 3.

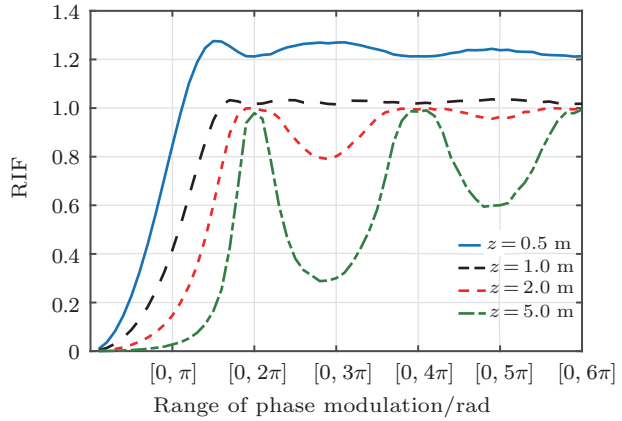


Fig. 3. The RIF of the illuminating light under different ranges of phase modulations and different propagation distances after modulation. For every single data, we take 1000 independent samples (modulation masks) to ensure that the RIF gives the best approximation of the fluctuation of the modulated light beam.

The results in Fig. 3 show that, when the range of phase modulation increases, the RIF is a damping oscillation-like curve with a period of 2π. The oscillation becomes stronger when the propagation distance is longer, but finally becomes stable around its peak value when we keep increasing the range of the random phase. Basically, the RIF will always reach its peak value when the random phase modulation is in the interval $[0, 2m\pi]$ (m is a positive integer); in other words, the intensity fluctuation is strong in this case. The visibility of the image obtained via ghost imaging will be higher when the phase modulation range is taken to be $[0, 2m\pi]$; the visibility is lower in other cases.

With further study, we found that, compared with ghost imaging schemes without phase modulations (such as DMD-based CGI), schemes with appropriate phase modulations have improved visibility and spatial resolution of the reconstructed image. Furthermore, these schemes have the possibility to provide a larger field of view. We investigated the situation when we modulate both the amplitude and the phase. The amplitude modulation progress can be considered as a partly transmissive mask placed on the SLM plane (or simply use an amplitude phase SLM), with a transmission function of $A'(x, y)$. The amplitude modulation masks are independent, and the elements of the transmission function are randomly distributed in the interval $[0, 1]$. We calculated the intensity distributions of the output light beams, and the numerical results are shown in Fig. 4.

The first column in Fig. 4 is the case without phase modulation. When the propagation distance increases, the beam rapidly losses its spatial fluctuation, and becomes concentrated in the center part of the plane. As a computational imaging scheme based on intensity fluctuation correlation, ghost imaging will fail to reconstruct the image of the object when the illuminating light does not have independent spatial intensity fluctuations. The spatial resolution of ghost imaging is related with the transverse coherent size of the illuminating pattern, namely, the size of the "speckles", and an illuminating beam with larger transverse coherence size will decrease the resolution of the image. Due to the affect of diffraction, the transverse coherent size increases when propagation distance increases. However, figure 4 shows that, with appropriate phase modulation, the increase in transverse coherent size can be slowed. This means that under the same conditions, the ghost imaging schemes with phase modulations can reconstruct an image with higher resolution than those schemes without phase modulations. Moreover, the long range of phase modulation also extends the intensity distribution, especially the intervals near $[0, 2m\pi]$. The speckles in the patterns are uniformly distributed, and they occupy a larger region of the plane, in this case, ghost imaging will have a larger field of view.

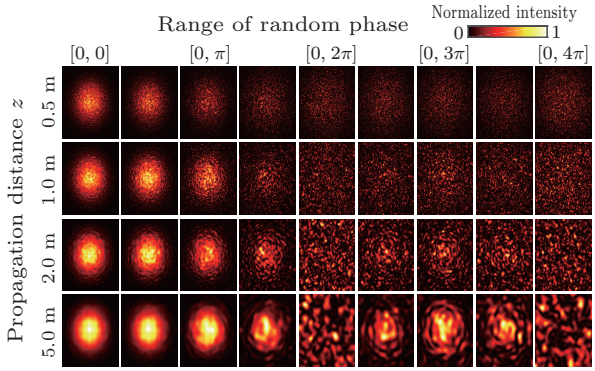


Fig. 4. The numerical results of the intensity distribution on planes at different distances away from the SLM plane. Both the amplitude and the phase of the beam is modulated, different ranges of random phase modulation is taken, the amplitude modulation masks are independent, and the elements in the masks are randomly distributed in the interval $[0, 1]$.

3. Numerical simulations and discussions

In order to verify our theoretical prediction, we carried out numerical simulations. In our simulations, we apply a 632.8-nm laser as the light source, and the pixel size of the SLM is 40 μm. A schematic diagram is shown in Fig. 1. We separate this section into two parts to investigate the influence of the phase modulation on the imaging visibility, and on the spatial resolution and field of view, respectively.

3.1. The influence of random phase modulation on the visibility of the ghost image

In this part, only the phase of the light beam is modulated. Four different distances (0.5 m, 1.0 m, 2.0 m, and 5.0 m) between the SLM and the object, and 20 different ranges of random phase are taken (from $[0, 0.05\pi]$ to $[0, 2\pi]$, steps of

0.05π). The target object is a binary, transmitting star with a size of 2.60 mm × 2.60 mm, and is placed in the central part of the object plane. For every simulation, we take 1.2×10^5 measurements. We show several reconstructed images in Fig. 5.

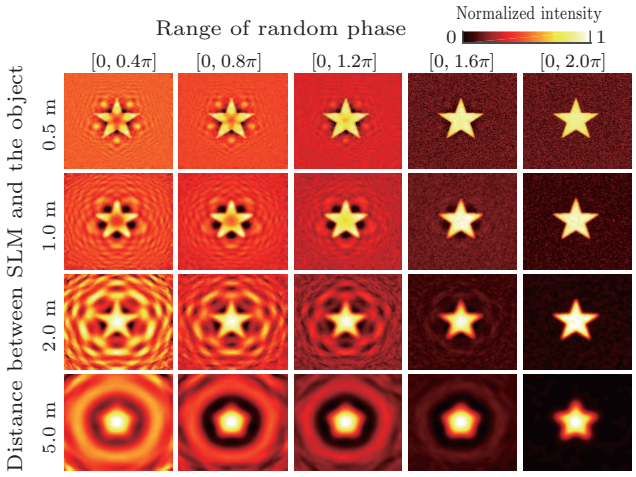


Fig. 5. Reconstructed images using light beams with different ranges of random phase modulations. The distance between the object and the SLM is taken to be 0.5 m, 1.0 m, 2.0 m, and 5.0 m, respectively.

Visually, the results in Fig. 5 show that when we increase the range of random phase modulation, the imaging quality is significantly improved. We use visibility to quantitatively judge the quality of the reconstructed image. For a binary object, visibility is defined as[20]

$$V = \frac{\bar{I}_{\text{in}} - \bar{I}_{\text{out}}}{\bar{I}_{\text{in}} + \bar{I}_{\text{out}}}, \tag{7}$$

where $\bar{I}_{\text{in}}$ ($\bar{I}_{\text{out}}$) stands for the average intensity of the region on the image corresponding to the transparent (nontransparent) part of the object. We calculated the visibility of the reconstruct images, and present the results in Fig. 6

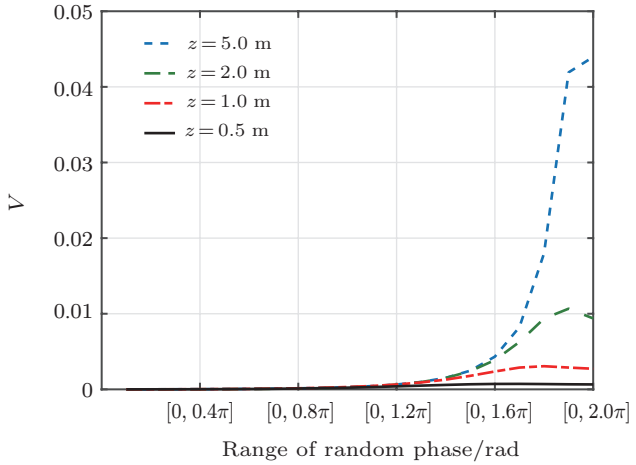


Fig. 6. The influence of the range of random phase modulation on the visibility of the reconstructed image. The distance between the object and the SLM is taken to be 0.5 m (blue dots), 1.0 m (green dashes), 2.0 m (red dot-dashes), and 5.0 m (black line), respectively.

Obviously, due to the increasing intensity fluctuation, the imaging quality is improved when we increase the range of the random phase modulation.

3.2. The influence of random phase modulation on the spatial resolution and the field of view of ghost imaging

In this part, in order to judge the resolution, we made a target object with multiple different sizes of details on it, as shown in Fig. 7. The size of the target object is 192 × 192 pixels, and the size of pixels is equal to those on the SLM (40 μm × 40 μm).



Fig. 7. The target object contains details of multiple sizes. The size of the object is 192 × 192 pixels and the size of the pixels are 40 μm × 40 μm.

Besides, for convenience when comparing with schemes without phase modulation but only amplitude modulations, we modulate the amplitude of the light field as well. The elements in amplitude modulation masks are randomly distributed in the interval $[0, 1]$. The other conditions are the same as mentioned above, and we obtain reconstructed images under different ranges of phase modulations. The results are shown in Fig. 8.

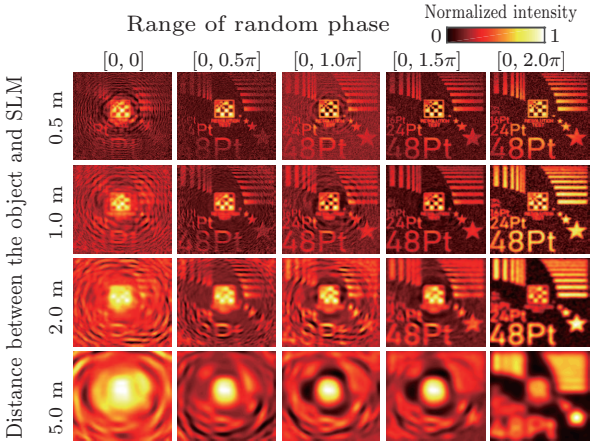


Fig. 8. Reconstructed images, with different ranges of phase modulations and different distances between the object and SLM.

The results in Fig. 8 agree well with our theoretical prediction. The images in the first column correspond to the situation without phase modulation. As objects are placed farther away from the SLM, the schemes without random phase modulation rapidly lose spatial resolution; meanwhile, schemes with random phase modulation seem to be more robust to the loss of spatial resolution caused by diffraction. It is also clear

that with the increasing ranges of random phase modulation, the resolution improves and a larger field of view is obtained.

Comparing with schemes using thermal light as the light source and only modulating the amplitude, schemes with appropriate phase modulation show some advantages in practical applications. The results above illustrate that under the condition in which the light source is coherent, introducing random phase modulation into computational ghost imaging can improve the spatial resolution and the field of view. However, it needs to be pointed out that amplitude modulation-based computational ghost imaging schemes (*i.e.* DMD-based CGI or LCD-based CGI) can also apply a thermal light as the light source. The directionality of thermal light is not as good as that of lasers, and the divergence angle of thermal light is much more bigger than that of lasers. When the thermal light is used as the illuminating light, as the propagation distance is farther and farther, the illuminating light's energy will rapidly diverge. This is relevant because computational ghost imaging is a kind of imaging scheme based on active illumination. Usually, these schemes will add a lens to project the illumination patterns on the object plane. For objects placed at different distances, the lens needs to be adjusted to ensure that the images of the illuminating patterns are projected clearly on the object plane; this complicates setup and operation. Moreover, due to the big divergence angle, if the distance between the bucket detector and the object plane is far, the bucket detector will collect less effective signals, which will usually cause the imaging quality to be more easily affected by external noise. In summary, laser as the light source has more advantages than thermal light, but compared with phase modulation schemes, amplitude-only schemes are not able to take maximum advantage of the laser.

4. Conclusions

We have investigated the influence of random phase modulation on the imaging quality of computational ghost imaging. Random phase modulation will cause changes in the illuminating beam's intensity fluctuation. A beam with strong intensity fluctuation can increase the visibility of the reconstructed image. We defined the RIF to describe the fluctuation of the beam's intensity distribution. Basically, the RIF will reach its peak value when the range of the random phase is taken in the interval $[0, 2m\pi]$. In this case, the visibility of the reconstructed image is improved. Additionally, the random phase modulation also partly destroys the beam's coherence, and as a result, the beam is relatively extended in the transverse direction, and the field of view of computational ghost imaging can be extended. Furthermore, compared with schemes without phase modulations, under the same conditions, schemes with random phase modulation have a better spatial resolution ability. These advantages may be helpful for practical applications of ghost imaging techniques.

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