Noninvasive Ghost imaging for objects completely hidden behind turbid media

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Ghost imaging (GI) in principal requires known illumination patterns on an object. The traditional GI fails for objects completely hidden behind turbid media, because the projected patterns on the objects become indeterminable due to scattering. However, we discover that, in Fourier domain, the correlation between the preset patterns of the light source and their corresponding bucket signals yields the Fourier magnitude of the object. With phase retrieval algorithms, the object’s image can be fully recovered. In this letter, we demonstrate noninvasive GI through strong scattering media. Both analytical solution and experimental proof are provided.
INTRODUCTION

Ghost imaging (GI) has a different mechanism than the traditional imaging methods that rely on the first-order interference (typically using lenses). It exploits the second-order correlation that acquires several advantages such as better resistance to turbulence, high detection sensitivity [1, 2], lensless imaging capability [3], and broad adaptability for different scenarios [4–6]. Therefore, GI has drawn a lot of attentions during the past 25 years, invoking a lot potential applications in many fields ranging from optical imaging [7], X-ray imaging [8–10], to atomic sensing [11, 12].

A typical GI setup consists test and reference arms. In test arm, an object is illuminated by light whose intensity fluctuates temporally and spatially. The reflected or transmitted light from the object is collected by a bucket detector with no spatial-resolving capability. In reference arm, the variance of the intensity is measured, and then the correlation between the light fluctuation and the bucket signal is calculated, which recovers the image. Computational ghost imaging is another setup, which removes the reference arm but pre-calculates or pre-determines the light patterns (the temporal and spatial variance) on the object plane. In spite of which type of setups, GI requires that the light patterns on the object must be well determined. If a turbid medium is placed between the source and the object, severely scrambling the incident light and making light patterns entirely changed and indeterminable, GI fails to reveal an image. Previous researches demonstrated that the bucket detection is highly resistant to light scattering [13, 14]. But none of them, under our knowledge, has explored a scenario of an object completely hidden behind a turbid medium. In this paper, we propose a theory to overcome this challenge.

The experimental setup is sketched in Fig. 1. The diffuser (GG1) is placed between the light source and the object, scattering the projecting light into a random speckle-like pattern on the object plane. This patterns is completely indeterminable. When the light source is within the memory effect range with respective to GG1, the point-spread-function (PSF) from the DMD plane to the object plane, $S_{MO}(r - \rho)$, is shift invariant. The speckle-like pattern can be written as the convolution of the source and the PSF, i.e., $P_j(r) = [M_j * S_{MO}](r)$. The correlation of $\{P_j(r)\}$ and its corresponding bucket signals $\{B_j\}$ can be
FIG. 1. Schematic of ghost imaging for an object hidden between two diffusers. A DMD (Digital Micromirror Device) displays a sequence of patterns \( \{M_j(\rho)\} \). A LED bulb and a lens are used to project the patterns towards an object hidden behind a ground glass (GG1). GG1 scatters the illuminating light and generates random speckles \( \{P_j(r)\} \) on the object \( O(r) \). A small aperture with a diameter of \( D \simeq 6 \text{ mm} \) is placed right in front of GG1. A bucket detector measures the transmitted light from the object passing through a ground glass (GG2), giving the bucket signals of \( \{B_j\} \). The focus length of the lens is 25 mm. \( Z_M = 50 \text{ mm} \). \( Z_L = 250 \text{ mm} \). \( Z_O = 300 \text{ mm} \).

expressed as a function of the PSF:

\[
G^{(2)}(r) = \sum_j B_j \cdot P_j(r) = \sum_j B_j \cdot [M_j * S_{MO}](r). \quad (1)
\]

In Fourier domain, \( \tilde{G}^{(2)}(u) = \sum_j B_j \cdot \tilde{M}_j(u) \cdot \tilde{S}_{MO}(u) \), where the tilde denotes the two-dimensional Fourier transform, and \( u \) is the spatial frequency coordinate vector. Its Fourier magnitude is

\[
\left| \tilde{G}^{(2)}(u) \right| = \left| \sum_j B_j \cdot \tilde{M}_j(u) \right| \cdot \left| \tilde{S}_{MO}(u) \right|. \quad (2)
\]

The PSF can be written as the convolution of two successive PSFs: \( S_{MO}(r - \rho) = [S_L(\xi - \rho) * S_S(r - \xi)](r - \rho) \). Here, \( \xi \) is the coordinate vector of an arbitrary transvers plane located between the lens and the object. \( S_L(\xi - \rho) \) is the PSF of the lens system from the DMD plane to \( \xi \)'s plane. \( S_S(r - \xi) \) represents the PSF of the scattering system from \( \xi \)'s plane to the object plane. \( |\tilde{S}_L| \propto T_L^{1/2} T_L^{1/2} \), where \( T_L \) is the squared modulus of the pupil function of the lens system. \( |\tilde{S}_L| \) acts as a spatial frequency filter, defining the diffraction-limit. So does \( |\tilde{S}_S| \). When the scattering system contains sufficient random scatterers to satisfy the ergodic-like condition\[15\],

\[
|\tilde{S}_S(u)| \propto \{[T_S * T_S](u) + \delta_D\}^{1/2}, \quad (3)
\]
where $\delta_D$ is a delta-like peak, representing the zero frequency relating to the background of the illumination. $T_S$ represents the squared modulus of the aperture function right in front of the GG1, determining the average size of the speckles on the object plane, i.e., the resolution of the imaging. With an circular-shape aperture, the system has a best spatial-frequency resolution is $f_{\text{upper}} \sim \frac{D}{\lambda Z_0}$. Here, we assume that the size of $T_S$ is much smaller than $T_L$, and the diffraction-limit of the whole PSF is mainly determined by $T_S$. Within the spatial frequency range of $[-f_{\text{upper}}, f_{\text{upper}}]$, $|\tilde{S}_L|$ and $|\tilde{S}_S|$ are constant. Then,

$$|	ilde{G}^{(2)}(u)| \propto \left| \sum_j B_j \cdot \tilde{M}_j(u) \right|. \quad (4)$$

Thus, $|\tilde{G}^{(2)}(u)|$ is determinable. Moreover, using a phase retrieval algorithm, such as HIO, ER[16], the phase of $\tilde{G}^{(2)}(u)$ can be recovered from its magnitude. Therefore, $\tilde{G}^{(2)}(u)$ can be fully reconstructed. Its inverse Fourier transform reveals the image of the object.

![Figure 2](image)

**FIG. 2.** (a) $G^{(2)}(r)$; (b) $|\tilde{G}^{(2)}(u)|$; (c) The image recovered from $|\tilde{G}^{(2)}(u)|$ after a phase retrieval process; (d) The original object.

Figure 2 shows the experimental results. We measured the bucket signals while we were playing a sequence of pre-set pattern on the DMD. The correlation of the bucket signals and their corresponding patterns, i.e., $\sum_j B_j \cdot P_j(r)$, is shown in Fig. 2(a). Its Fourier magnitude (Fig. 2(b)) exhibits the power spectrum of the object. Using the phase retrieval algorithm combing HIO and ER, the image of the object is recovered, as shown in Fig. 2(c).

The experimental result proves the theory presented above. Therefore, ghost imaging is able to image an object hidden behind media, even the light patterns on the object become completely indeterminable. On the other hand, this method requires that, the light source has to be within the memory effect range. This requirement can be easily met by using a small size of the light source, or placing the light source far away from the turbid medium.
Another practical way is to design a proper lenses system to construct a virtual light source that is equivalently small enough and far away enough from the turbid medium.

The experiment shows that, the present of the diffuser between the light source and the object results in a speckle-like second-order correlation, which

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