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Optical secure image verification system based on ghost imaging

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ABSTRACT

The ghost imaging can perform Fourier-space filtering by tailoring the configuration. We proposed a novel optical secure image verification system based on this theory with the help of phase matched filtering. In the verification process, the system key and the ID card which contain the information of the correct image and the information to be verified are put in the reference and the test paths, respectively. We demonstrate that the ghost imaging configuration can perform an incoherent correlation between the system key and the ID card. The correct verification manifests itself with a correlation peak in the ghost image. The primary image and the image to be verified are encrypted and encoded into pure phase masks beforehand for security. Multi-image secure verifications can also be implemented in the proposed system.

1. Introduction

Ghost imaging techniques have acquired very fast developments in the last two decades. In 1995, the ghost imaging was first experimentally demonstrated in a quantum fashion by entangled photon pairs [1]. The research afterwards proved that the classical incoherent light can alsomplement ghost imaging [2,3] with a second order correlation of light fields. In the ghost imaging with the classical incoherent light, the light from the source is divided into an object beam and a reference beam. The object beam through the object is detected by a fixed point detector, while the reference beam is detected by a scanning point detector or a CCD camera. The image of object can be obtained through the correlation between the intensities detected by two detectors. In recent years, many research achievements are obtained and promote the development of ghost imaging. For example, the resolution enhancement of ghost imaging [4,5] and the realization of the ghost imaging for a phase object [6–8] have also been investigated.

The ghost imaging technique can also be used in other areas, such as optical image security. Clemente et al. proposed an optical image encryption method based on computational ghost imaging [9]. After that, many image encryption schemes based on ghost imaging were proposed [10–13]. Beside optical image encryption, ghost imaging technique is also used to perform cryptanalysis [14] and image verification [15]. Chen et al. proposed an image verification method by using computational ghost imaging, which can realize verification with less than 5% of the Nyquist limit [15]. They used a nonlinear correlation coefficient between the correct image and the ghost image to realize the image verification. This method can also verify grey images [16]. They also proposed a verification system by using a photon-synthesized ghost imaging [17].

In 2011, Shirai et al. proved that, after some modification, the setup of ghost imaging can perform a Fourier-space filtering with classical incoherent light [7]. Combine this conclusion with the theory of phase matched filtering, we propose an optical secure image verification system based on the ghost imaging. Actually, our proposed image verification system can be regarded as an incoherent matched filtering correlator, which can be applied to optical pattern recognition. Unlike the verification scheme proposed in Ref. [15], in which the correlation was performed outside the ghost imaging, we can implement the image verification by a single ghost imaging. The verification result can be given directly by a correlation peak in the ghost image. If computational ghost imaging [18] is used to simplify the system, then our system can perform image verification only with a point detector.

2. Proposed verification system

Fig. 1 (a) shows the setup of conventional classic incoherent light ghost imaging. The incoherent light from the source is split into object beam and reference beam by the beam splitter. The reference beam is detected by a scanning point detector D_1 after spread distance z_a. The object beam is through the object t after spread distance z_b and detected by a fixed point detector D_2. If the parameters in Fig. 1(a) satisfy $z_a = z_b$, after N times measurements, the correlation between the detected intensities $I_{t,i}(x_t)(i = 1,\ldots,N)$ and $I_{r,i}(x_r)(i = 1,\ldots,N)$ is

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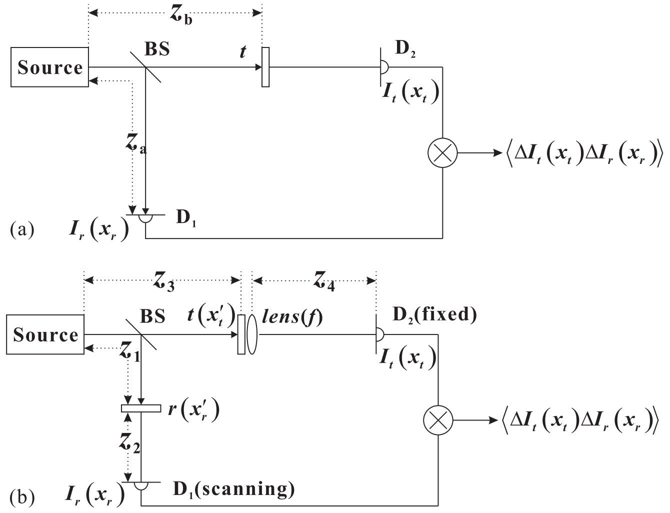

Fig. 1. Schematic diagram of (a) conventional classic incoherent light ghost imaging and (b) proposed verification system, which is the same as the setup for performing Fourier-space filtering in Ref. [7]. The source is classical incoherent light. D_1 and D_2 are point detectors. D_1 is scanned while D_2 is fixed. The focal length of the lens is f.

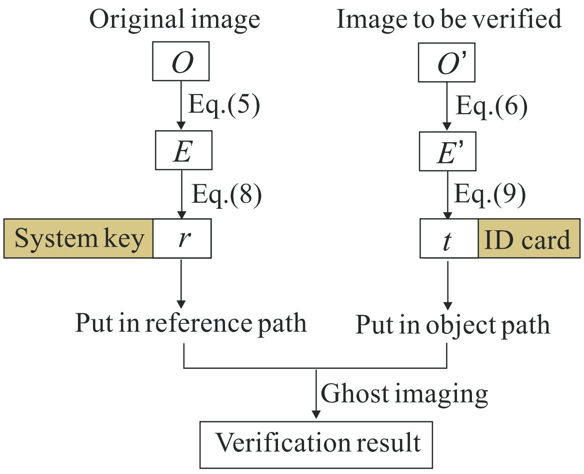

Fig. 2. The flow chart of proposed verification system.

$$\Delta G(x_r, x_t) = \langle \Delta I_t(x_t)\Delta I_r(x_r)\rangle \propto |t(x_r)|^2, \tag{1}$$

in which the square brackets represents the mean value of the N times measurements.

Fig. 1 (b) illustrates the setup of modified ghost imaging proposed in Ref. [7] to performing Fourier-space filtering. It is a ghost imaging version of the 4f system. The filter $r(x'_r)$, which contains the Fourier spectrum information of the primary image, is inserted in the reference path. The distance between the filter and the source is z_1. The distance between the filter and the point detector D_1 is z_2. The object $t(x'_t)$ is put just before a Fourier lens with focal length f in the test path. The distance between the object and the source is z_3 and the distance between the object and the point detector D_2 is z_4. The point detector D_1 is scanned while D_2 is fixed. If the parameters in the setup satisfy

1. $z_1 + z_2 = z_3$,
2. $1/f = 1/z_2 + 1/z_4$,
3. the point detector D_2 is fixed at $x_t = 0$,

then the correlation between the detector results of the test path $I_t(x_t)$ and the detector results of the reference path $I_r(x_r)$ is given as [7]

$$\begin{aligned}\Delta G(x_r, x_t = 0) &= \langle \Delta I_t(x_t)\Delta I_r(x_r)\rangle \\ &= A\left|\int t(x'_t)R^*(x_r - x'_t)d^2x'_t\right|^2,\end{aligned} \tag{2}$$

where $A = (\frac{k}{2\pi})^6\left(\frac{I_0}{z_2^2 z_4}\right)^2$, I_0 is a constant related to the intensity of the light source, and

$$\begin{aligned}R(x_r - x'_t) &= \mathrm{FT}_{z2}\{r(x'_r)\} \\ &= \int r(x'_r)\exp[-jkx'_r(x_r - x'_t)/z_2]d^2x'_r,\end{aligned} \tag{3}$$

where $\mathrm{FT}_{z2}[\cdot]$ indicates the Fourier transform, $k = 2\pi/\lambda$ is the wave vector.

We use this result to perform optical secure image verification. The setup of proposed system is just as the setup shown in Fig. 1(b). The filter $r(x'_r)$ is used as the system key and the object $t(x'_t)$ is used as ID card. We rewrite Eq. (2) into a convolution form as

$$\begin{aligned}\Delta G(x_r) &= A|t(x_r) \otimes R^*(x_r)|^2 \\ &= A|\mathrm{IFT}\{\mathrm{FT}[t(x_r)]\cdot\mathrm{FT}[R^*(x_r)]\}|^2,\end{aligned} \tag{4}$$

where FT[·] and IFT[·] indicate the Fourier transform and inverse Fourier transform respectively. The symbol ⊗means the convolution and * means the complex conjugate. Because $z_1 + z_2 = z_3$, the coordinate of the object plane x'_t is equal to the coordinate of the detector D_1 plane x_r, that is $x'_t = x_r$. Eq. (4) shows that the result of ghost imaging is the intensity of Fourier-space filtered $t(x'_t)$ with the filter of $\mathrm{FT}[R^*(x'_t)]$. Thus Eq. (4) can treated as the correlation between $t(x'_t)$ and $R(x''t)$.

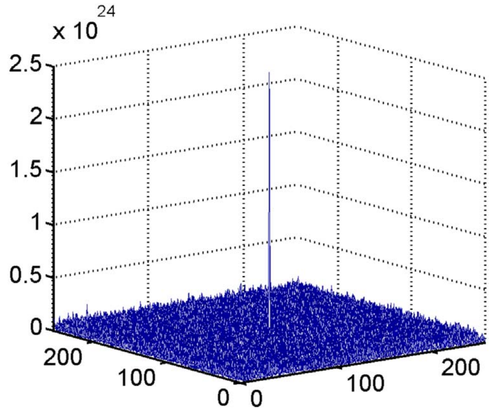

Fig. 4. The resulting ghost image when the input ID card t is correct.

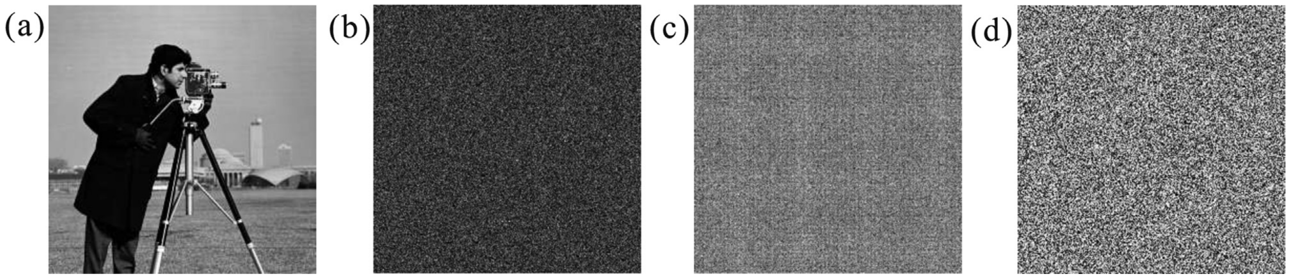

Fig. 3. Pre-processing results of the Cameraman image. (a) The correct image O. (b) The encrypted result E. (c) The amplitude and (d) phase of the obtained system key r.