Optics and Lasers in Engineering 73 (2015) 123–127

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

Optical authentication via photon-synthesized ghost imaging using optical nonlinear correlation

Wen Chen*, Xudong Chen

Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore 117583, Singapore

ARTICLE INFO

Article history:
Received 16 December 2014
Received in revised form
5 February 2015
Accepted 21 April 2015

Keywords:
Ghost imaging
Photon synthesis
Correlated photon
Optical signal processing

ABSTRACT

We present a method for optical authentication via photon-synthesized ghost imaging using optical nonlinear correlation. In ghost imaging, multiple series of photons recorded at the object beam arm can be arbitrarily controlled for the generation of synthesized objects. Ghost imaging with sparse reference intensity patterns provides a channel to effectively modulate the noise-like synthesized objects during the recovery, and the reconstructed (noise-like) objects, i.e., added or subtracted information, can be further authenticated by optical nonlinear correlation algorithm. It is expected that the proposed method can provide an effective and promising alternative for ghost-imaging-based optical processing.

1. Introduction

Optical technologies [1–12] have been attracting more and more attention for encoding information, especially during optical storage and communications. Significant advantages of optical technologies have been illustrated, such as parallel processing and multiple degrees of freedom [2–12]. In one typical optical system [1], the signals can be converted into stationary white noise by using two statistically-independent phase-only masks respectively placed in the input plane and spatial frequency domain. During the past decade, some optical systems [2–14], such as holography [13] and diffractive imaging [14], have been developed and successfully applied. However, it is concerned that attack algorithms [15,16], such as known-plaintext attack, may be used to extract experimental parameters. Hence, new optical systems are always desirable, and much current effort has been made to develop different imaging configurations.

Recently, ghost imaging [17–23] has become a promising alternative due to the complexity of its optical parameters. In ghost imaging systems [22,23], a series of reference intensity patterns can be considered as principal parameters, and a series of photons recorded at the object beam arm are applied as encoded data. However, conventional configurations with ghost imaging are developed with single layer, and multiple-layer data or synthesized-data authentication has not been investigated.

In this paper, we present a method for optical authentication via photon-synthesized ghost imaging using optical nonlinear correlation algorithm. In ghost imaging, multiple series of photons recorded at the object beam arm can be arbitrarily controlled for the generation of synthesized objects. Ghost imaging with sparse reference intensity patterns can provide a channel to effectively modulate the recovered objects, and the reconstructed (noise-like) objects, i.e., added or subtracted information, can be further authenticated.

2. Optical setup and analysis

Fig. 1 shows a schematic arrangement for the proposed ghost-authenticated imaging with photon synthesis. When random phase-only profiles are sequentially embedded into spatial light modulator (SLM), a series of intensity points (i.e., photons) are recorded by single-pixel bucket detector (without spatial resolution) at the object beam arm. Computational ghost imaging [17–19] is applied, and a series of 2D reference intensity patterns (i.e., 20,000) can be virtually calculated at the reference beam arm.

Here, three different objects $[t_k(\xi,\eta) \quad k=1,2,3]$ are sequentially encoded for illustrating the validity of the proposed method, however in practice it could be straightforward to encode more or fewer objects. A series of intensity points (i.e., photons) can be recorded by single-pixel bucket detector at the object beam arm for encoding each object, and symbols $\{A_i\}$, $\{B_i\}$ and $\{C_i\}(i=1,2,3,\ldots N)$ are used to denote the three different series of recorded photons. At the reference arm a series of reference intensity patterns $\{I_i(\xi,\eta)\}$ are virtually calculated, and here only

---

* Corresponding author. Tel.: +65 65166855; fax: +65 67791103.
E-mail address: elechenw@nus.edu.sg (W. Chen).

http://dx.doi.org/10.1016/j.optlaseng.2015.04.012
0143-8166/

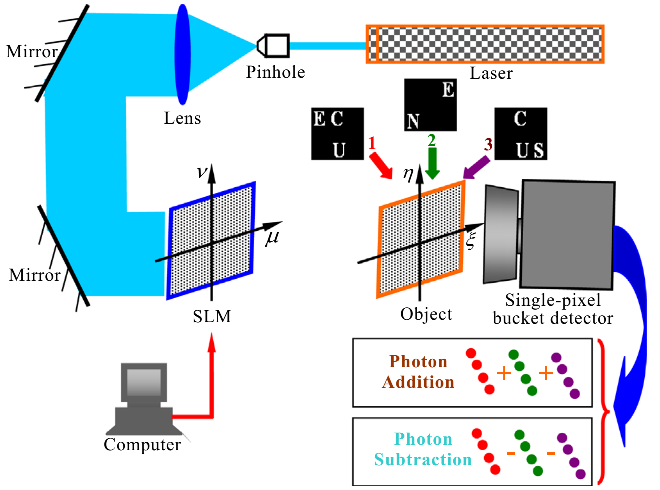

Fig. 1. A schematic arrangement for the proposed optical system: SLM, spatial light modulator. In computational ghost imaging, wave propagation process at the reference beam arm can be virtually calculated and is not shown here. The digits “1, 2, 3” denote the first, second and third object which is sequentially encoded. The object is placed just before the bucket detector.

one series of random phase-only profiles is repeatedly used and embedded into the SLM. These reference intensity patterns are correlated with the photons recorded at the object beam arm for the reconstruction. In this study, the three series of photons are arbitrarily controlled for the recovery of synthesized objects, and typical addition and subtraction operations are respectively described by

$$X_i = A_i + B_i + C_i \Rightarrow \begin{cases} X_i - B_i - C_i & \Rightarrow \{A_i\} \\ X_i - A_i - C_i & \Rightarrow \{B_i\} \\ X_i - A_i - B_i & \Rightarrow \{C_i\} \end{cases}, \tag{1}$$

$$Y_i = A_i - B_i - C_i \Rightarrow \begin{cases} Y_i + B_i + C_i & \Rightarrow \{A_i\} \\ -(Y_i - A_i + C_i) & \Rightarrow \{B_i\} \\ -(Y_i - A_i + B_i) & \Rightarrow \{C_i\} \end{cases}, \tag{2}$$

where $\{X_i\}$ and $\{Y_i\}$ denote the series of added and subtracted photons, respectively. Note that in Eqs. (1) and (2) only simple addition and subtraction operations are illustrated, and complex synthesis cases can be arbitrarily designed when more objects are encoded. After the encoding, the series $\{X_i\}$ or $\{Y_i\}$ should be stored or transmitted to the receivers. However, when one receiver tries to recover each independent object, additional series of photons (such as $\{B_i\}$ and $\{C_i\}$) will be requested as shown in Eqs. (1) and (2). For the recovery, the series of reference intensity patterns $\{I_i(\xi,\eta)\}$ are correlated with added or subtracted photons, i.e., $\{X_i\}$ or $\{Y_i\}$.

$$G_a(\xi,\eta) = \frac{1}{N}\sum_{i=1}^{N}\left(X_i - (\langle\{A\}\rangle + \langle\{B\}\rangle + \langle\{C\}\rangle)\right)\left[I_i(\xi,\eta) - \left\langle\left\{I(\xi,\eta)\right\}\right\rangle\right], \tag{3}$$

$$G_s(\xi,\eta) = \frac{1}{N}\sum_{i=1}^{N}\left(Y_i - (\langle\{A\}\rangle + \langle\{B\}\rangle + \langle\{C\}\rangle)\right)\left[I_i(\xi,\eta) - \left\langle\left\{I(\xi,\eta)\right\}\right\rangle\right], \tag{4}$$

where $\langle . \rangle$ denotes ensemble average, N is the total number of measurements, and $G_a(\xi,\eta)$ and $G_s(\xi,\eta)$ denote the reconstructed objects corresponding to addition and subtraction cases, respectively.

In this study, the main objective is to conduct the authentication of synthesized objects by using sparse concept. When each reference intensity pattern $\{I_i(\xi,\eta)\}$ is sparse, the recovery process with data authentication can be implemented. In this case, synthesized objects (i.e., addition and subtraction) can be respectively recovered by

$$\hat{G}_a(\xi,\eta) = \frac{1}{N}\sum_{i=1}^{N}\left(X_i - (\langle\{A\}\rangle + \langle\{B\}\rangle + \langle\{C\}\rangle)\right)\left[\hat{I}_i(\xi,\eta) - \left\langle\left\{\hat{I}(\xi,\eta)\right\}\right\rangle\right], \tag{5}$$

$$\hat{G}_s(\xi,\eta) = \frac{1}{N}\sum_{i=1}^{N}\left(Y_i - (\langle\{A\}\rangle + \langle\{B\}\rangle + \langle\{C\}\rangle)\right)\left[\hat{I}_i(\xi,\eta) - \left\langle\left\{\hat{I}(\xi,\eta)\right\}\right\rangle\right], \tag{6}$$

where $\left\{\hat{I}_i(\xi,\eta)\right\}$ denotes the series of sparse reference intensity patterns, and $\hat{G}_a(\xi,\eta)$ and $\hat{G}_s(\xi,\eta)$ denote the recovered objects corresponding to addition and subtraction cases, respectively. Since sparse reference intensity patterns are applied, the reconstructed objects [i.e., $\hat{G}_a(\xi,\eta)$ and $\hat{G}_s(\xi,\eta)$] cannot clearly render the visual information. Nonlinear correlation algorithm [24–32] is applied to compare the reconstructed objects with the original image (used as reference). The optical authentication methods corresponding to addition and subtraction cases are respectively described by

$$N_a(\xi,\eta) = \left|\mathrm{IFT}\left(\left|\left\{\mathrm{FT}\left[\hat{G}_a(\xi,\eta)\right]\right\}\left\{\mathrm{FT}[ta(\xi,\eta)]\right\}^*\right|^{p-1}\left\{\mathrm{FT}\left[\hat{G}_a(\xi,\eta)\right]\right\}\left\{\mathrm{FT}[ta(\xi,\eta)]\right\}^*\right)\right|^2, \tag{7}$$

$$N_s(\xi,\eta) = \left|\mathrm{IFT}\left(\left|\left\{FT\left[\hat{G}_s(\xi,\eta)\right]\right\}\left\{\mathrm{FT}[ts(\xi,\eta)]\right\}^*\right|^{p-1}\left\{\mathrm{FT}\left[\hat{G}_s(\xi,\eta)\right]\right\}\left\{\mathrm{FT}[ts(\xi,\eta)]\right\}^*\right)\right|^2, \tag{8}$$

where $N_a(\xi,\eta)$ and $N_s(\xi,\eta)$ denote nonlinear correlation distributions respectively corresponding to addition and subtraction cases, asterisk denotes complex conjugate, FT and IFT respectively denote 2D Fourier transform and inverse Fourier transform, $ta(\xi,\eta)$ denotes the originally added image $[ta(\xi,\eta) = t_1(\xi,\eta) + t_2(\xi,\eta) + t_3(\xi,\eta)]$, $ts(\xi,\eta)$ denotes the originally subtracted image $[ts(\xi,\eta) = t_1(\xi,\eta) - t_2(\xi,\eta) - t_3(\xi,\eta)]$, and p denotes the strength of applied nonlinearity [24–32]. To illustrate the proposed method aforementioned, a flow chart is given in Fig. 2.

3. Results and discussion

As shown in Fig. 1, collimated plane wave, with a waist of 740 μm and wavelength of 632.8 nm, is generated by the combination of pinhole and a lens for the illumination. A series of random phase-only profiles, distributed in the range of $[0, 2\pi]$, can be generated by the computer and sequentially embedded into phase-only SLM (pixel pitch of 18 μm and pixel number of 64 × 64). Axial distance of 7.4 cm [i.e., between the SLM and detector (at reference or object beam arm)] is used. Due to resource limitation, we choose to conduct a proof-of-concept study with numerical simulation based on Matlab platform.

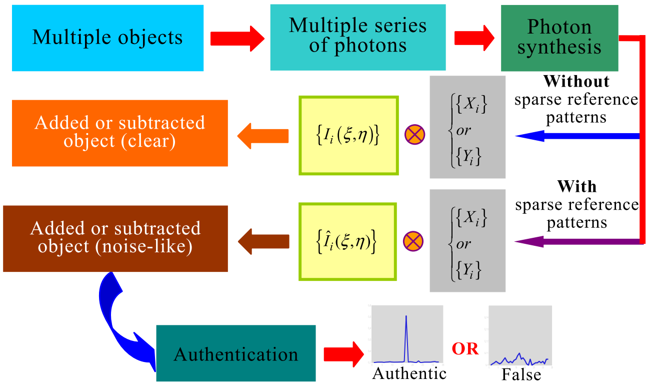

Fig. 2. Flow chart for the proposed method: symbol ⊗ denotes the correlation. In practical applications both non-compression or compression strategy can be applied, and in this study we focus on designing the ghost imaging system for optical synthesized-data authentication rather than optical encryption.