Optics Communications 341 (2015) 188–193

Contents lists available at ScienceDirect

Optics Communications

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

Embedding image into a phase-only hologram

P.W.M. Tsang [a,*], T. -C. Poon [a,b,c,d], Y.-T. Chow [a]

[a] Department of Electronic Engineering, City University of Hong Kong, Hong Kong SAR, PR China
[b] Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, VA 24061, USA
[c] Institute of Information Optics, Zhejiang Normal University, Jinhua, Zhejiang 321004, PR China
[d] Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, P.O. Box 800-211, Shanghai 201800, PR China

ARTICLE INFO

Article history:
Received 15 July 2014
Received in revised form
3 December 2014
Accepted 5 December 2014
Available online 7 December 2014

Keywords:
Digital Fresnel hologram
Phase-only hologram
Data embedded error diffusion hologram
Error diffusion
Image encryption

ABSTRACT

Past research has demonstrated that with error diffusion, a complex Fresnel hologram can be converted into a phase-only hologram, and capable of preserving high fidelity on its reconstructed image. Furthermore, the phase-only hologram can be embedded with an image that is of the same size as the hologram. This is achieved by replacing the least *M* least significant bits (LSB) of each hologram pixel with the *M* most significant bits (MSB) of the embedded image in the error diffusion process. The phase-only hologram obtained in this manner is known as a Data Embedded Error Diffusion (DEED) hologram. Despite the success, the quality of the embedded image is rather poor for small value of *M*. However, if *M* is increased to preserve the quality of the embedded image, the phase-only hologram will be jeopardized. The DEED hologram also has no protection on the access of the embedded image, as it can be retrieved by simply extracting the *M* least significant bits of the hologram pixels. In this paper, a method for overcoming the above problems is reported. Briefly, the image to be embedded is first converted into an *M* bit data with the use of error diffusion. Next, a fixed window is reserved in the binary bit-string of each hologram pixel, within which *M* bits are randomly selected and replaced with the embedded image data. As such, the bit selection configuration in each hologram pixel can be taken as an encryption key for retrieving the embedded image. The image embedded phase-only hologram realized with such means, which is referred to as the Image Encrypted Error Diffusion (IEED) hologram, is capable of preserving high fidelity on the content of the hologram, as well as favorable visual quality on the embedded image if the correct encryption key is presented.

1. Introduction

Digital holography is an effective means of representing a three-dimensional (3-D) object scene into a two-dimensional (2-D) complex hologram. Theoretically, when a digital hologram is fed to an electronic display that is capable of presenting both magnitude and phase information, the 3-D scene can be reconstructed and observed visually. However, in practice, existing devices such as the spatial light modulator (SLM), are only capable of modulating either the amplitude, or the phase of the optical information. Such limitation has imposed difficulty on the presentation of holographic information, as neither the magnitude nor the phase component of the hologram alone can reproduce an acceptable image of the original scene. A straightforward solution to overcome this problem, is through the concatenation of a pair of devices, one for displaying the magnitude, and the other for displaying the phase components of the hologram [1–3]. There are other variations on this fundamental approach, such as the display of the real and the imaginary parts of the hologram with a pair of amplitude SLMs. Alternatively, a complex hologram can be converted into the sum of a pair of phase-only images, so that each can be displayed with a phase-only SLM [4]. Although these methods are effective, they are rather complicated and difficult to realize in practice, as precise alignment of the display devices is required. Over the years, a lot of research works have been conducted with the attempt of displaying a complex hologram with a single device. For example, a complex digital hologram can be converted into an off-axis amplitude hologram by multiplying it with an inclined reference wave, and retaining the real part of the product. It is also possible to display the orthogonal components of a hologram at non-overlapping pixels or partitions on the display, and merged them via a high-resolution grating [5–7]. An even more promising solution, is to convert the complex hologram into a single phase-only hologram (POH). Being different from an

* Corresponding author.
E-mail address: eewmtsan@cityu.edu.hk (P.W.M. Tsang).

http://dx.doi.org/10.1016/j.optcom.2014.12.014
0030-4018/

amplitude hologram, a POH has higher optical efficiency, and inherently free from the zeroth-order diffraction and the twin image. However, as has been reported by numerous literatures, simply retaining the phase component of a complex hologram will lead to severe degradation on the reconstructed image. The tradition means of generating a POH through iteratively means, [8, 9] is computationally intensive. To alleviate this shortcoming, the One-Step-Phase-Retrieval (OSPR) method has been proposed in [10, 11]. Despite the success, such approach requires multiple repetitions of the holograms at high frame rate, resulting in an increase of the bandwidth and the system complexity. Recently, Tsang et al. [12, 13] have proposed to convert a complex Fresnel hologram into a POH with error diffusion [14]. Apart from the computation efficiency, high fidelity on the reconstructed image is preserved in the phase-only hologram derived with such means. Furthermore, it has also been shown that the error diffusion process is also capable of embedded an image, which is similar in size as the hologram, without jeopardizing the quality of the reconstructed image. The POH with the data embedded in it, is known as the Data Embedded Error Diffusion (DEED) hologram [15]. Despite the favorable outcome, the quality of the image embedded in a DEED hologram is rather poor. Besides, there is no control over the access of the embedded data.

In this paper, we propose a new approach for deriving a POH from a Fresnel hologram that is embedded with an encrypted image. The hologram generated is referred to as the Image Encrypted Error Diffusion (IEED) hologram. In comparison with the DEED hologram, the embedded image is superior in quality, and can only be retrieved correctly with the right encryption key. The major objective of our work is to develop a fast, non-iterative framework for converting a complex hologram into a phase-only hologram (POH), and at the same time embedding an encrypted optical image into a POH, in a way that both the reconstructed image of the POH and the embedded image (if decrypted with the correct key) can be preserved with good quality. Being different from a complex hologram that are comprised of a magnitude and a phase components, a POH only has the phase component and the magnitude of all the pixels are constant in value. As such, a POH can be displayed on a single phase-only SLM. Briefly speaking, we intend to provide a framework for the above 2 issues, rather than emphasizing on specific applications like watermarking and holography-based steganography [16]. Having said that we shall discuss briefly, in the conclusion, the possibility of extending our framework to the above mentioned applications. Organization of the paper is given as follows. For the sake of completion, the principles behind the conversion of a complex hologram to a DEED hologram is outlined in Section 2. In Section 3, we shall present our proposed method in deriving the IEED hologram. Results obtained with numerical simulation will be illustrated in Section 4. Subsequently, a conclusion will be provided to summarize the essential findings of the proposed method.

2. Data-embedded-error-diffusion (DEED) phase-only hologram

In this section, we shall briefly describe the method described in [15] for converting a complex Fresnel hologram into a DEED phase-only hologram. To begin with, consider a three-dimensional (3-D) scene that is comprising of a collection of self-illuminating object points, each having an intensity a_j. Based on the Fresnel diffraction formula, a complex Fresnel hologram $H(u, v)$ can be generated to record the diffraction fringe patterns scattered from the object points, and given by

$$H(u, v) = \sum_{k=0}^{N-1} a_k \exp\left(\frac{i2\pi r_k(u, v)}{\lambda}\right), \tag{1}$$

In Eq. (1), u and v are the horizontal and the vertical co-ordinates. The terms N, λ, and $r_k(u, v)$ denote the total number of object points, the wavelength of the optical beam, and the distance between the kth object point to a location (u, v) on the hologram, respectively. The magnitude of the hologram $|H(u, v)|$ is normalized to 1, while its phase component $\angle[H(u, v)]$ is quantized into a P-bit binary number corresponding to a value within the range $[0, 2\pi]$.

The data to be embedded is a 2-D array, denoted by $D(u, v)$, of M-bit (where $M < P$) binary numbers. For simplicity of explanation, and without loss of generality, we assume that the dimension of $D(u, v)$ is the same as the hologram $H(u, v)$. The hologram is scanned sequentially from the top row to the bottom row. In each row, the pixels are evaluated along a left-to-right direction. For each visited hologram pixel, its magnitude is forced to unity, and the M least significant bits (MSB) of its phase quantity is replaced with the corresponding entry in $D(u, v)$. The modified hologram pixel $H_p(u, v)$, is given by

$$|H_p(u, v)| = 1, \text{ and } \angle\left[H_p(u, v)\right] = \{\angle[H(u, v)] \wedge B_M\} \vee D(u, v), \tag{2}$$

where B_M is a P-bit binary number with the M least significant bits set to ‘0’, and the rest of the digit equals to ‘1’. $\wedge$ and $\vee$ are the binary ‘AND’ and the ‘OR’ operators, respectively The change in the hologram pixel from $H(u, v)$ to $H_p(u, v)$, is expressed as an error quantity $E(u_j, v_j)$ given by

$$E(u_j, v_j) = H(u_j, v_j) - H_p(u_j, v_j). \tag{3}$$

The error is distributed proportionally to (4) of its neighborhood pixels with the Floyd–Steinberg error diffusion algorithm [14] as

$$H\left(u_j, v_j + 1\right) = H\left(u_j, v_j + 1\right) + w_1 E(u_j, v_j), \tag{4}$$

$$H\left(u_j + 1, v_j - 1\right) = H\left(u_j + 1, v_j - 1\right) + w_2 E(u_j, v_j), \tag{5}$$

$$H\left(u_j + 1, v_j\right) = H\left(u_j + 1, v_j\right) + w_3 E(u_j, v_j), \tag{6}$$

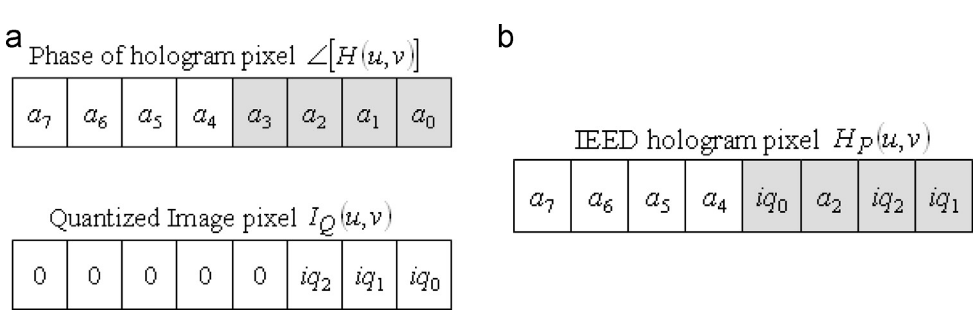

Fig. 1. (a) The bit-strings representing $\angle[H(u, v)]$ and $I_Q(u, v)$, based on $M = 3$, and $P = 8$. (b) Embedding $I_Q(u, v)$ into randomly selected bits in the bit-string of $\angle[H(u, v)]$, resulting in the IEED hologram pixel $H_P(u, v)$.