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One-step reconstruction of assembled 3D holographic scenes

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ABSTRACT

We present a new experimental approach for reconstructing in one step 3D scenes otherwise not feasible in a single snapshot from standard off-axis digital hologram architecture, due to a lack of illuminating resources or a limited setup size. Consequently, whenever a scene could not be wholly illuminated or the size of the scene surpasses the available setup disposition, this protocol can be implemented to solve these issues. We need neither to alter the original setup in every step nor to cover the whole scene by the illuminating source, thus saving resources. With this technique we multiplex the processed holograms of actual diffuse objects composing a scene using a two-beam off-axis holographic setup in a Fresnel approach. By registering individually the holograms of several objects and applying a spatial filtering technique, the filtered Fresnel holograms can then be added to produce a compound hologram. The simultaneous reconstruction of all objects is performed in one step using the same recovering procedure employed for single holograms. Using this technique, we were able to reconstruct, for the first time to our knowledge, a scene by multiplexing off-axis holograms of the 3D objects without cross talk. This technique is important for quantitative visualization of optically packaged multiple images and is useful for a wide range of applications. We present experimental results to support the method.

1. Introduction

We found an astonishing development over the area of optical and digital information processing during the last years [1–21]. The possibility of optically or digitally processing the light coming from an object or from optical systems allows both studying the properties of the object itself or the developing of areas such as three-dimensional (3D) surface optical imaging [2], pattern recognition [3], and optical security [4], to mention just few of them. Optical processing systems can be divided into two categories: experimental [5–14] and virtual [15–17]. One of the main tools for such development of experimental systems is digital holography, where the light scattered or transmitted from the object or from an optical system is recorded in a sensor and then digitally or optically processed [18–20]. By using digital holography is possible to record and to process information of bidimensional (2D) [18,19] or 3D objects [18,20]. Recent advances show that digital holographic techniques can be further applied to imaging live humans through smoke and flames [9], or to obtain a full color natural light holographic camera [10].

Powerful tools have been developed for processing optical holograms [6–21]. In the context of experimental optical encryption of 2D objects a filtering and positioning process were successfully applied for security purposes. The joint power spectrum (JPS) in a joint transform correlator (JTC) encrypting architecture is filtered to remove the undesired terms of the JPS and to position the relevant term containing the encrypted information. This processing allows obtaining only the decrypted object in a desired position in the output plane. This procedure was applied for the first experimental implementation of the multiplexing of optically encrypted 2D movies [8], and also for the experimental demonstration of the noise-free recovering of optical encrypted 2D data [11]. In this context, another fundamental tool in optical and digital processing is multiplexing [5–12,16]. In multiplexing protocols, several processed data is added in order to manage multiple data in an efficient way. These protocols have been applied for adding multiple bi-dimensional encrypted data [5,6,8,11], the angular multiplexing and de-multiplexing of digital holograms recorded in microscope configuration [7], the fast reconstruction of off-axis digital holograms based on digital spatial multiplexing

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[12], and multiple images encryption based on Fourier transform hologram [16]. On the other hand, the efficient handling of information requires the inclusion of compression techniques [13–15]. Compression methods were successfully applied to interference patterns with application to phase-shifting digital holography [13], encrypted 3D objects [14] or to encrypted color videos [15].

One of the main advantages of digital holography is that the information coming from 2D or 3D objects can be digitally stored, and then the objects can be remotely reconstructed using an optical setup or a virtual optical system. As we live in a 3D world and 3D objects provide several degrees of freedom to perform imaging and optical information processing, 3D display and imaging are important topics because they allow performing natural views.

In a recent paper of Girshovitz et al. [21] we found a proposal of a simple method for real-time reconstruction of off-axis digital holograms based on a kind of digital angular multiplexing algorithm. This method realizes the quick synchronous reconstruction of two holograms recorded at different time, thus greatly increases the reconstructing speed, which makes it possible to realize real-time holographic reconstruction with a simple personal computer system.

Nevertheless, we face a problem when trying to record a hologram of a scene composed by several elements occupying a large area compared with the setup distribution. Problems may vary from the visualization through the recording device to the illuminating source used to cover the entire scene. On the other hand, multiplexing is the option when multi-3D images are taken into account. In this framework, proposals rely in applying a basic scheme to every single 3D object and then multiplexing the entire set of images into a single package. In this way, we achieve a more compact information-carrying unit.

In this paper, we present a novel off-axis experimental approach to 3D holographic recording of a scene otherwise not possible to be covered by a single snapshot. We accomplish the task by a multiplexing procedure based on a filtering and a repositioning protocol previously employed in the optical encryption of 2D data, without complex algorithms, avoiding complicated optical architectures, and at the same time allowing noise reduction in the reconstruction, thus regaining the advantages mentioned above for off-axis holograms. This proposed and experimentally implemented method allows simultaneously reconstruct several holograms with acceptable resolution and quality of the retrieved images, so that efficiency with respect to other proposals could be improved, thus opening a new avenue of research.

2. General procedure behind recording and filtering

In our experiment, we chose the Fresnel optical architecture depicted in Fig. 1. This scheme is denominated off-axis holography as originally proposed by Leith and Upatnieks [22]. We control the reference beam orientation by tilting the mirror M_1.

A CCD camera records the Fresnel hologram of the object

$$H(v,w) = |O(v,w)|^2 + |P(v,w)|^2 + O(v,w)P^*(v,w) + O^*(v,w)P(v,w) \tag{1}$$

where $O(v,w)$ is the object field, $P(v,w)$ is the reference tilted plane wave and * means complex conjugate. In this experimental setup, the reference wave can be described as

$$P(v,w) = \exp(-i2\pi z(v\sin\alpha + w\sin\beta)) \quad v = \frac{x}{\lambda z} \;\; w = \frac{y}{\lambda z} \tag{2}$$

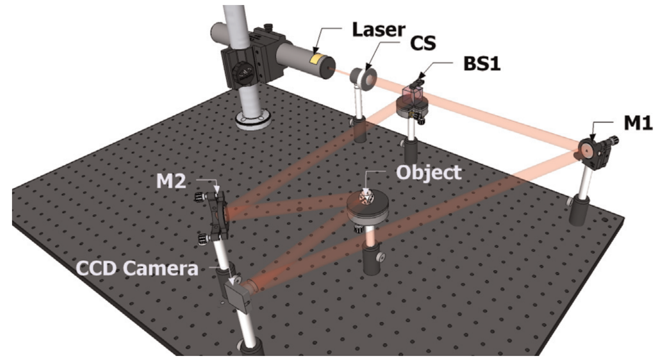

Fig. 1. Experimental scheme used for the capture of Fresnel holograms (BS1: beam splitter, M1, M2 mirrors, CS: collimation system).

and the angles α and β determine the tilt of the reference wave, z is the propagation distance, λ is the wavelength, and (x,y) are the object plane coordinates.

In the proposed method, we isolate the last two terms of Eq. (1) by performing its Fourier transform (FT), obtaining

$$H`(\xi,\eta) = O'(\xi,\eta) \otimes O'^*(\xi,\eta) + P'(\xi,\eta) \otimes P'^*(\xi,\eta) + O'(\xi,\eta) \otimes \delta(\xi - z\sin\alpha,\ \eta - z\sin\beta) + O'^*(\xi,\eta) \otimes \delta(\xi + z\sin\alpha,\ \eta + z\sin\beta) \tag{3}$$

In Eq. (3), $O'(\xi,\eta)$ and $P'(\xi,\eta)$ represent the FT of $O(v,w)$ and $P(v,w)$ respectively. The first two terms are the autocorrelations of the FT of the object and the reference beams, corresponding to the central order shown in Fig. 2. The last two terms are the FT of the object field and its complex conjugate spatially separated due to the convolution with the Dirac delta function resulting from the FT of the plane wave given by Eq. (2), and these two terms can be seen in Fig. 2 as two distinct patterns.

Since the last two terms contain the object information necessary for hologram reconstruction, and are separated spatially, we can digitally retain the third term and discard the remaining terms of Eq. (3). The filtered term can then be positioned in any spatial coordinate, depending on the desired application, and can be described as

$$E'(\xi,\eta) = O'(\xi,\eta) \otimes \delta(\xi - x', \eta - y') \tag{4}$$

where (x', y') are freely assigned coordinates. Now in order to recover the filtered hologram, we perform the inverse Fourier transform (IFT) of Eq. (4)

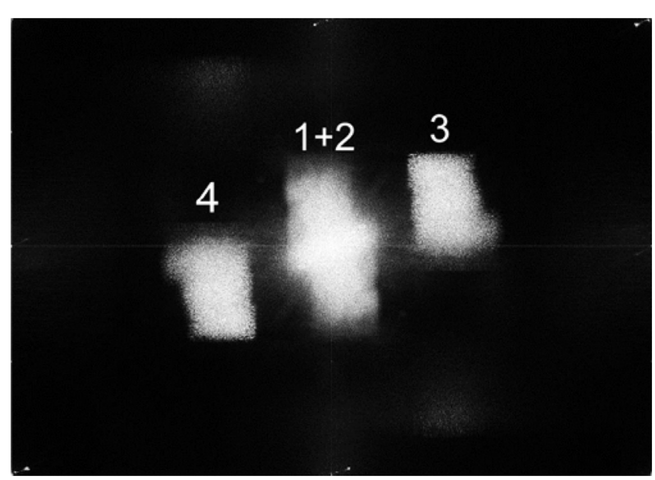

Fig. 2. Intensity pattern corresponding to Eq. (3): (1+2) first two terms, (3) third term, and (4) fourth term.

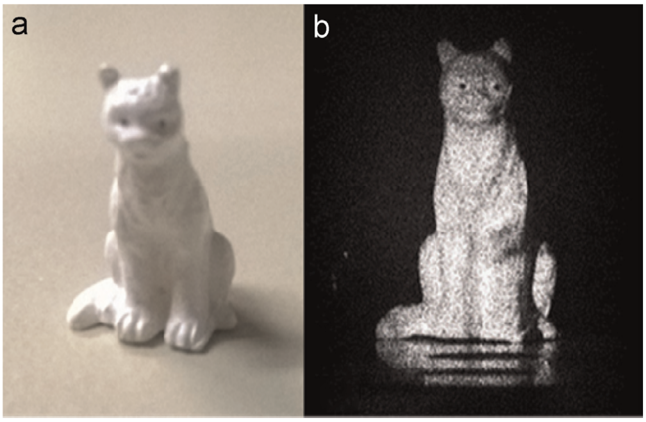

Fig. 3. (a) Original object and (b) reconstructed object (Eq. (6)) from the filtered hologram (Eq. (5)).

$$E(v, w) = O(v, w)\exp[2\pi i(vx' + wy')] \tag{5}$$

From this filtered hologram, the reconstruction of the object is performed by applying the inverse Fresnel transform corresponding to the propagation from the camera to the object plane, obtaining [6]

$$e(x, y) = o(x, y) \otimes \delta(x - x', y - y') \tag{6}$$

Eq. (6) represents the reconstructed object $o(x, y)$ centered at coordinates (x', y').

This procedure renders the recovered 3D object without the undesired orders. The example shown in Fig. 3, comparing the original object and its filtered hologram reconstruction, represents an experimental proof of this assertion.

If we now try to record a large scene, it is possible that the available illuminating source is not enough to cover the whole scene, perhaps some elements have strong reflecting differences to each other, or even the bandwidth of the light reflected by the object surpasses the resolution limit of the optical system, to name three usual problems found in this context.

We propose the following protocol to overcome these issues. The idea is to detach the elements composing the scene, and then make single holograms of each one positioned in a more convenient place, thus ensuring that they can be adequately processed by the optical system. Next, we apply the concept of hologram multiplexing to get a single digital hologram containing the whole scene. When propagating this hologram the adequate distance, we obtain the assembled 3D scene with adequate reconstruction quality.

Once all holograms are registered and filtered using the previously discussed method, they can be added to form a multiplexed hologram. The coordinates (x_i, y_i) of each filtered hologram to be multiplexed are carefully selected in order to preserve the desired positions during reconstruction.

When the individual holograms have the form of Eq. (5), they can be added to get the multiplexed hologram,

$$M(v, w) = \sum_{i=1}^{N} O_i(v, w)\exp\left[2\pi i(vx_i + wy_i)\right] \tag{7}$$

where $O_i(v, w)$ is the filtered Fresnel hologram of the 3D object $o_i(x, y)$. Applying the appropriate inverse Fresnel Transform to Eq. (7), a scene containing all objects is obtained. In particular for our example, as individual holograms have the same reconstruction plane, they will all appear in focus at the same time, [21]

$$m(x, y) = \sum_{i=1}^{N} o_i(x, y) \otimes \delta(x - x_i, y - y_i) \tag{8}$$

Eq. (8) reveals the fact that the holographic data of the entire scene is contained in a single assembled package. The recovered objects $o_i(x, y)$ will all appear centered at their respective coordinates (x_i, y_i),and even though we partitioned the scene elements, we recover the complete information in one step.

3. Reconstruction of the 3D holographic scene

In order to illustrate the method, we build a scene with the three objects in a row shown in Fig. 4a. We show in Fig. 4b the result of capturing the scene using a single hologram. Due to the limitations of the recording optical system, the scene is not satisfactorily reproduced. In Fig. 4c we see the case when the single-shot hologram of the scene is filtered. Although the objects are now shifted to the center, they are not recognizable, except for the object in the center.

In our proposal, the Fresnel hologram of each object is individually captured and processed, and then all processed holograms are multiplexed. In this approach, all Fresnel holograms are recorded with the same object-camera distance. After recovering with the appropriate propagation length, the whole scene is successfully displayed as shown in Fig. 5, where all figurines are perfectly recognized with nearly equalized intensity. Certainly, this intensity always depends on the diffusing properties each single object possesses. Nevertheless, in no way could equalization be reached when the objects or part of them lie closer to the edges of the area covered by the illuminating source.

Media 1 shows the hologram reconstruction, were each frame represents a propagation of 0.5 mm, starting from 175 mm to 225 mm. Since all objects were registered with the same object-camera distance, and individually all have nearly the same depth extent (Fig. 4a), they all appear in focus in the same plane. The proposed method allows properly recording and processing scenes that would be impossible to adequately process due to the

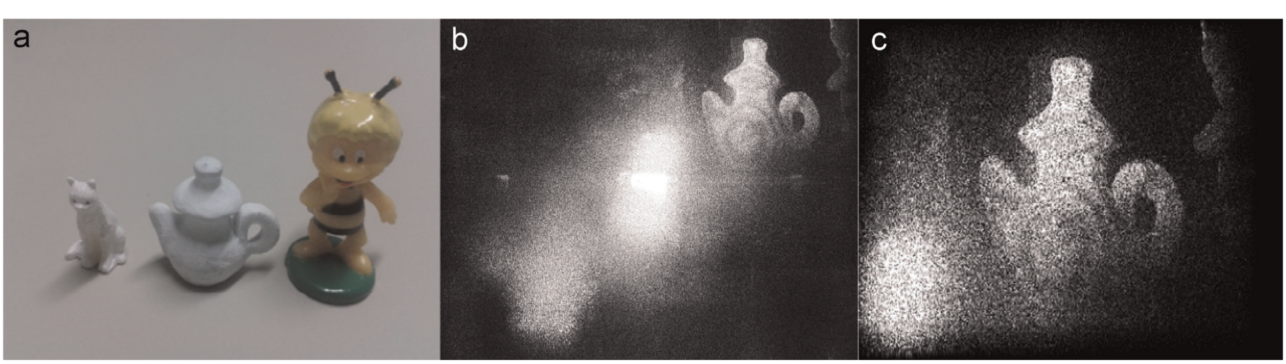

Fig. 4. (a) Original 3D scene, reconstructed scenes from a single hologram: (b) without filtering, and (c) after filtering.

Fig. 5. Reconstructed scene of three objects from the multiplexing of three filtered holograms in the focusing plane (see Media 1).

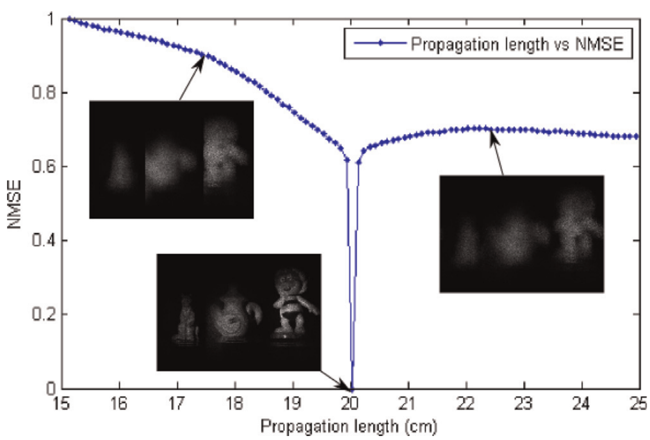

Fig. 6. NMSE curve for different propagation lengths.

inherent limitations of the experimental optical system. Among the advantages of the proposal we mention the use of exactly the same optical setup for each and every holographic record.

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In order to evaluate the recovering of the 3D scene, above mentioned in Fig. 5, in terms of the reconstruction plane we calculate the normalized mean square error (NMSE) for different propagation lengths. The NMSE between the 3D scenes recovered after propagating the adequate distance $ws(n, m)$ (Fig. 5) and the case when the propagation length does not correspond with the object–camera distance used during recording of the holograms *w'(n,m)*.

$$NMSE = \frac{\sum_{n,m}^{N} |ws(n, m) - w`(n, m)|^2}{\sum_{n,m}^{N} |ws(n, m) - ws_w(n, m)|^2} \quad (9)$$

where (n, m) are the pixels coordinates, $N{\times}N$ is the number of pixels of the recovered message, and $ws_w(n, m)$ is the worst expected case.

Fig. 6 shows the NMSE curve obtained from a comparison between the retrieved scene after propagating the adequate distance and the recovered scenes for different propagation lengths. The NMSE curve shows the evident degradation of the reconstructed scene when modifying the adequate propagation lenght (see Media 1). This behavior corresponds to a single shot Fresnel hologram, demonstrating that the assembly process does not cause any alteration on the reconstruction process. As expected, the scene is successfully recovered when the propagation distance match with the distance employed to store the holograms of the objects that compound the scene.

The amount of objects that can be multiplexed depend on the size of the space were the filtered holograms are positioned and by the bandwidth of each hologram. As long as the space is enough to accommodate all the multiplexed objects, the method can be used without loss of fidelity in the reconstructed objects.

All experimental results in this paper were carried out in the scheme of Fig. 1. We use a CMOS EO-10012M camera, with a pixel size of 1.67 µm × 1.67 µm and a resolution of 3480 × 2748 pixels, and a Laserglow Technologies DPSS laser with 542 nm of wavelength and 50 mW of output power. The objects used had maximum dimensions of 15 mm × 28 mm × 14 mm. The object–camera distance was 200 mm.

4. Conclusions

In summary, we present a method for displaying in one-step the Fresnel hologram of a 3D scene that cannot be recorded and recovered satisfactorily as a whole in a single shot, while not altering the recording setup in any step. The digital processing of the Fresnel holograms is performed with little computational cost. This method uses a previously developed filtering process over single Fresnel holograms of 3D objects, which also allows controlling the spatial coordinates of every reconstructed single object to compose the desired scene. The experimental results demonstrated that several filtered holograms can be added in a new multiplexed hologram and then all single holograms can be reconstructed simultaneously, allowing batch reconstruction of several objects. Although the procedure to obtain the multiplexing of processed Fresnel holograms involves several optical and digital steps, the reconstruction of the scene is performed in only one-step. The simplicity and versatility of the proposed method allow its implementation in many fields that employ off-axis Fresnel holography of 3D objects, like metrology, optical encryption, holographic interferometry, and holographic microscopy, amongst others.

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