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Compression of multiple 3D color scenes with experimental recording and reconstruction

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A R T I C L E I N F O

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A B S T R A C T

We present for the first time a method for compression of 3D color scenes with experimental recording and reconstruction, including scene multiplexing. An experimental setup allows separately registering three off-axis Fourier holograms corresponding to the RGB color channels of a 3D scene. Then, the optical field data contained in each hologram is extracted and their phase is retained. The phases associated to each color channel are spatially arranged to get a single phase-only optical field for the experimental full color reconstruction in another optical setup. This process is then further developed to include different 3D color scenes by multiplying the arranged phase-only optical fields corresponding to each scene by complementary binary masks. Three sampled scenes are multiplexed giving a compression in the data volume up to 97.81% in our experiments. The technique used in the context of multiplexing allows a substantial data volume reduction and the appropriate reconstruction of each color scene without cross-talk and in a single step.

1. Introduction

In a modern realm of networks and multimedia, more and more 3D image information needs to be streamed. Cloud computing and big data processing are two major issues in dealing with the streamed distributions. On the other side, high volume data is intrinsically associated to these procedures. Therefore, compression approaches become imperative to speed up image transmission. In the past decades, various optical systems have been proposed for image compression [1–3]. Optical techniques have many essential and appealing advantages over other tactics, such as high speed and parallelism in processing. A natural optical procedure to store 3D scenes is holography [4–10], preserving both amplitude and phase information. Holography is an indirect method of imaging that provides the ability to record and reconstruct 3D information of a scene. Practical implementation in digital holography and available displays were associated to provide a proper way to record and visualize after transmission these impressive scenes. Evolution of these ideas prompted the field to include color to capture the full realism of actual scenes [11–14]. Aside pseudocoloring methods, reconstruction with at least three RGB coherent sources is the improvement required. Since digital holography records the complex field of scenes, it allows a filtering process which reduces the issues caused by twin image and background noises [15]. Digital holograms can also be multiplexed and encrypted with a large array of techniques [16–19].

On the other hand, when holograms are recorded with multiple wavelengths, problems arise in the size of the reconstructed image and the large data volume that must be processed. The first problem is because for each wavelength an image of different size is generated. This is due to the reconstructed pixel size of image, as they are different for each color channel. P. Ferraro et al. [19] developed and demonstrated a padding method that allows to recover images with equal reconstructed pixel size for the case of information recorded at different wavelengths, thus avoiding this issue. Some data compression techniques have been proposed to compress holographic data [20–23], and increasing data redundancy by padding has also been used to mitigate loss due to the sampling or occlusion [24].

In this contribution we present an alternative experimental procedure to compress holographic data. From a single 3D color scene, we retain the phase information of the optical field´s data separately for each RGB channel. The general idea is to apply this procedure to include several color scenes into a single package. To this end, we applied a sampling and multiplexing procedure by multiplying with binary orthogonal masks each separate processed scene, taking advantage of the

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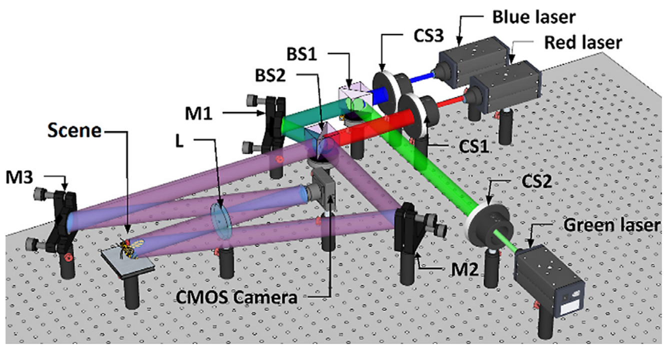

Fig. 1. Scheme of the experimental setup for registering off-axis Fourier holograms of 3D color scenes. (CS: collimation system, BS: beam splitter, M: mirror, L: lens). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

redundancy inherent to holographic data. We present the experimental results corresponding to the recording of three 3D color scenes, compressed, and selectively reconstructed through the binary masks without cross-talk. In our example of three scenes, altogether we obtain a global compression of around the 97.81% with respect of the unprocessed holograms.

2. Color hologram recording and processing

Fig. 1 shows an off-axis Fourier holographic system for recording the color digital holograms of a 3D scene. Three laser sources were used, each collimated beam passed through the beam splitter BS2, which generates the color scene illumination and the reference beams.

The beams reflected by mirrors M2 and M3 are the object and reference beams respectively. The reference beam interferes in the CMOS camera plane with the Fourier transform (FT) of the light reflected by the 3D scene, resulting in an off-axis Fourier hologram for each of the three laser sources separately, containing the information of the red, green and blue channels of the color scene.

Off-axis holograms not only contain all the information to reconstruct the scene, but also unwanted information that results in a DC term and a twin image of the scene after reconstruction. We can discard this information and retain the optical field of each color channel with a filtering procedure. This procedure consists on performing the FT of the hologram, and selecting the reconstructed scene, discarding the DC term and the twin image. An inverse Fourier transform (IFT) is then performed on the reconstructed scene, obtaining the complex optical field [22,23]. This procedure is applied to the hologram of each channel of the scene, resulting in three complex optical fields of an area of 640 × 1080 pixels each one.

We now process the resulting optical fields for direct display on a phase-only liquid crystal on silicon (LCOS) spatial light modulator (SLM). As their name indicates, these devices are only capable of phase modulation, however, some works have shown that the phase information contained in a hologram is sufficient for the reconstruction of a diffuse reflecting scene [25]. Furthermore, the device limits the size and resolution of the optical fields that can be displayed with it. Taking these features into account, we must process the information of the 3D color scene to maximize the reconstruction quality. For a single optical field data this procedure consists in the following steps (see Fig. 2).

(1) We discard the amplitude of the optical fields, retaining only the phase information.
(2) These phases are placed side-by-side to form a RGB phase arrangement with the same size as the SLM (1920 × 1080). We call this a phase-only RGB hologram (POH).
(3) This POH is multiplied by a phase grating, such that avoiding in the reconstruction the superposition with the central order produced by the SLM non-diffracted light [12]. We named this result as a POH_G.

After this procedure, we obtain a POH_G that can be directly displayed in the SLM.

We present the results of recording three single different 3D color scenes and its corresponding reconstructions according to the proposed technique.

The registering and recovering setups employ an EO-10012C CMOS camera with a resolution of 3840 × 2748 pixels and 1.67 µm × 1.67 µm pixel size (Figs. 1 and 3). The lasers used were a He-Ne laser with 632 nm wavelength with a power output of 30 mW for red, a DPSS laser with 532 nm wavelength with a power output of 150 mW for green and a DPSS laser with 472 nm wavelength with a power output of 50 mW for blue. The average dimension of the 3D scenes is 28 mm × 15 mm × 14 mm. The registering lens focal length was 500 mm.

3. Reconstruction procedure

In the experimental reconstruction setup (see Fig. 3), we employ a phase-only LCOS-SLM HOLOEYE PLUTO-VIS-006-HR, with full HD resolution of 1920 × 1080 pixel and 8 µm pixel pitch leading to an active area diagonal of 0.7″. The reconstruction lens has focal length 100 mm. In Fig. 4 we show the reconstruction of the POH_G from three different scenes.

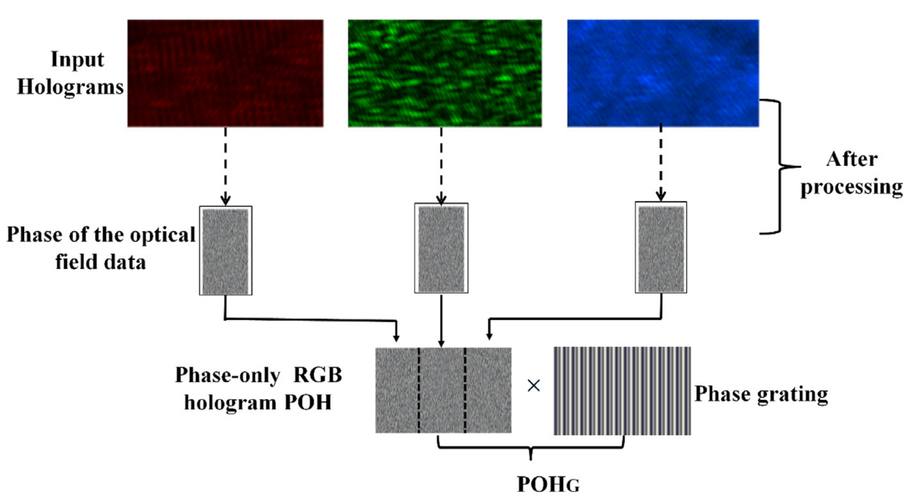

Fig. 2. Flow chart: Input holograms corresponding to the color channel RGB are filtered to retain the phase-only information to build the POH for each scene. This POH is multiplied by a phase grating to obtain the final POH_G.

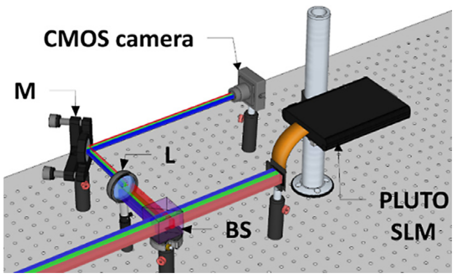

Fig. 3. Scheme of experimental recovery setup. (BS: beam splitter, L: lens, and M: mirror).

Fig. 4. Three individually reconstructed scenes from POH_G's.

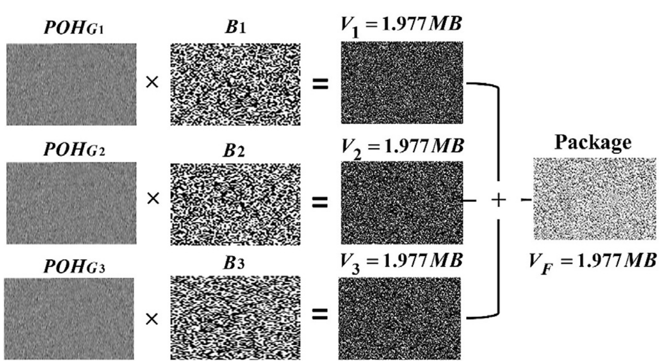

Fig. 5. Sampling with binary masks and multiplexing procedure for the phase-only RGB holograms of three scenes. POH_G: phase-only RGB hologram multiplied by a grating, B: binary mask, V: volume.

4. Compression using random binary mask sampling and multiplexing

We move one step forward regarding compression by multiplexing three color 3D scenes, in a procedure which is described below (see Fig. 5). We first multiply the resulting POH_G of each scene with orthogonal random binary masks. These masks are generated by taking a black image of the same resolution as the POH_Gs to be multiplexed. Then we set a percentage of the pixels of the image whose position is randomly selected as white pixels. To generate the other masks, we take new black images and select the desired percentage of white pixels from the positions that were not selected in the previous masks. In the example of Fig. 5, we multiplex three scenes using masks with 33% of white pixels.

5. Experimental results

We now proceed to multiplex into a single package the POH_G's, sampled with the binary masks. This package contains the information of all multiplexed scenes. If we project this package on the SLM and attempt the reconstruction procedure, we obtain the result show in the upper inset of Fig. 6, with all the scenes reconstructed simultaneously and suffering from cross-talk. A single scene can be extracted from the package by performing a demultiplexing procedure. Since the binary masks do not sample the same pixel, we can select the sampled POH_G corresponding to the scene we wish to reconstruct from the package by multiplying with the corresponding mask. The reconstructed 3D scenes of Fig. 6 are the convolution between the scene information and the FT of the random binary mask. The convolution with the FT of the random binary mask produces a random noise as background, degrading the reconstruction quality. The use of random binary masks is advantageous over non-random binary masks due to the sharp peak of its FT [4]. The FT of a binary mask with non-random distributions might have extended central orders, resulting in blurry reconstruction and loss of specific frequencies.

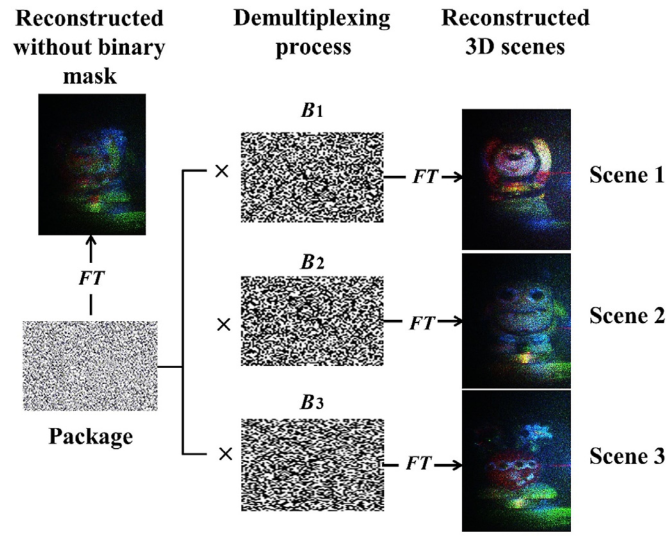

Fig. 6. Reconstruction and demultiplexing procedure for a package containing the POH_G's of three scenes.

We now evaluate the compression achieved with all the discussed procedures. First, we registered holograms corresponding to the RGB channels of each scene, with a resolution of 3840×2748 and 8-bit depth. This means that the total volume of data for each scene is 30.18 MB. We then proceed to filter the complex optical field data from these holograms, obtaining an area of size 640×1080 for each optical field. The phase and amplitude of the optical fields are stored with 8-bit depth. The volume at this stage has been reduced to 3.954 MB for each scene. It is worth noting that, as the procedure is lossless, we have retained all the original data necessary for reconstruction. The compression achieved by filtering can be interpreted as the elimination of data redundancy found in the holographic register.

We then remove the amplitude data to obtain the POH_G that will be projected with our SLM. This hologram has a volume of 1.977 MB. Unlike filtering, there is a loss of information due to the discarding of amplitude data, however as mentioned before, for highly diffuse scenes this loss is not enough to compromise the scene reconstruction.

Finally, we use random binary masks to multiplex several scenes into a single POH_G whose volume is equivalent to that of a single scene. This means that we can compress N scenes into the volume of a single one (See Table 1 for the example with three scenes). The sampling procedure prior to multiplexing is also a lossy procedure, and will induce a degradation of the reconstructed scene inversely proportional to the number of white pixels in the binary mask.

If we want to compress N images, we would need to sample the POH_G's with masks with (100/N) % of white pixels. This means that the more scenes are multiplexed, the more information is lost in each scene, yet a higher compression is achieved. In this sense, the maximum number of images that can be multiplexed with this technique will depend on what we consider “acceptable” noise for a given application.

Table 1
Data volume values for the proposed compression.

	Scene 1 Volume (MB)	Scene 2 Volume (MB)	Scene 3 Volume (MB)	Total Volume (MB)
Unprocessed holograms	30.180	30.180	30.180	90.540
Optical field	3.954	3.954	3.954	11.862
Phase-only RGB hologram	1.977	1.977	1.977	5.931
Multiplexed package	1.977			1.977

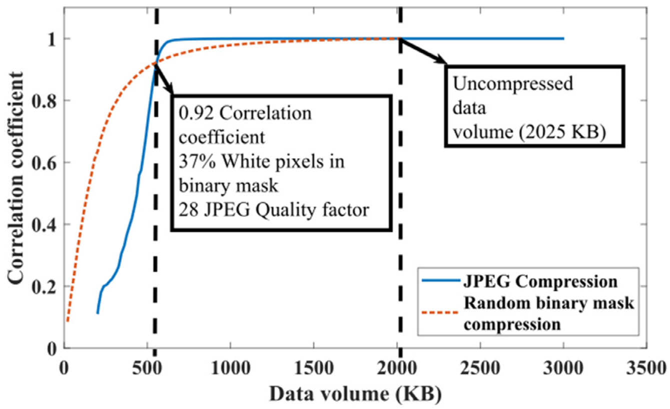

Fig. 7. Correlation coefficient of reconstructed objects from POH_G with different compression ratios obtained by applying JPEG compression (solid line) and binary mask multiplexing (dotted line), both compared with the uncompressed POH_G.

For example, a QR code can be subject to a higher compression while remaining readable, thanks to its inherent tolerance to noise and error correction. This means that a large amount of QR codes can be multiplexed. On the other hand, detailed images with will appear significantly worse with a high amount of compression, and therefore fewer images should be multiplexed to maintain acceptable quality.

To better contextualize the performance of our proposal, we compare the correlation coefficient of numerically reconstructed objects from POH_G with different compression ratios obtained by applying the JPEG compression [26] and the binary mask multiplexing with the uncompressed POH_G. The results are shown in Fig. 7.

Fig. 7 shows that JPEG compression has better performance compared to our proposal for low compression ratios, offering increased reconstruction quality. However, it is worth noting that JPEG compression presents a larger data volume than the original POH_G when very high quality factors are used. This is because the entropy coding used by the JPEG algorithm is ill-suited for near random information, like the one found in the phase holograms of diffuse objects [27]. Furthermore, JPEG alone does not offer a way to selectively multiplex data like our proposed method and cannot be implemented optically. On the other hand, our proposal shows similar correlation coefficient values than JPEG when large amounts of compression are required.

In our experimental demonstration we compressed three scenes, obtaining a final volume of 1.977 MB. The volume reduction achieved in this case is 97.81%. These results are shown in Table 1. It is worth mention that the recovery is performed in a single step with all the illuminating laser sources delivered at the same time by using the setup of Fig. 3.

6. Conclusions

Summarizing, by combining color digital holography with the use of orthogonal binary masks, a compression and cross-talk free multiplexing method for 3D color scenes is achieved in this study. For three individual scenes, a compressed package with a 97.81% volume reduction with respect to the original holograms total volume is obtained, ready for transmission and postproduction for cross-talk free demultiplexing. We also have to stress that the color reconstruction procedure is implemented in a single step bringing and additionally bonus to the method. The experiments also show acceptable reconstructed images, with minor quality losses in return of lower volume. As a common drawback in this approach, the color of the reconstructed images depends on the reflectance at the three wavelengths used in the recording of holograms. Therefore, the color-composite result of the reconstructed image is not fully accurate in color reproduction. Although requiring further research, in view of the remarkable proof-of-concept results we believe this general technique represents a breakthrough in the field.

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References

[1] Wu X, Yu Y, Zhou W, Asundi A. 4f amplified in-line compressive holography. Opt Express 2014;22:19860–72.
[2] Koller R, Schmid L, Matsuda N, Niederberger T, Spinoulas L, Cossairt O, Schuster G, Katsaggelos AK. High spatio-temporal resolution video with compressed sensing. Opt Express 2015;23:15992–6007.
[3] Wang Z, Spinoulas L, He K, Tian L, Cossairt O, Katsaggelos AK, Chen H. Compressive holographic video. Opt Express 2017;25:250–62.
[4] Goodman JW. Introduction to Fourier optics. 3rd ed. Colorado: Roberts & Company Publishers; 2005.
[5] Gabor D. A new microscopic principle. Nature 1948;161:777.
[6] Liu YZ, Dong JW, Pu YY, Chen BC, He HX, Wang HZ. High-speed full analytical holographic computations for true-life scenes. Opt Express 2010;18:3345–51.
[7] Liu J, Hsieh W, Poon T, Tsang P. Complex Fresnel hologram display using a single SLM. Appl Opt 2011;50:H128–35.
[8] Li X, Liu J, Jia J, Pan Y, Wang Y. 3D dynamic holographic display by modulating complex amplitude experimentally. Opt Express 2013;21:20577–87.
[9] Velez A, Barrera JF, Torroba R. Optimized random phase only holograms. Opt Lett 2015;75:146–50.
[10] Makowski PL, Kozacki T, Zaperty W. Orthoscopic real-image display of digital holograms. Opt Lett 2017;42:3932–5.
[11] Yamaguchi I, Matsumura T, Kato J. Phase-shifting color digital holography. Opt Lett 2002;27:1108–10.
[12] Kato J, Yamaguchi I, Matsumura T. Multicolor digital holography with an achromatic phase shifter. Opt Lett 2002;27:1403–5.
[13] Demoli N, Vukicevic D, Torzynski M. Dynamic digital holographic interferometry with three wavelengths. Opt Express 2003;11:767–74.
[14] Makowski M, Ducin I, Sypek M, Siemion A, Siemion A, Suszek J, Kolodziejczyk A. Color image projection based on Fourier holograms. Opt Lett 2010;35:1227–9.
[15] Cuche E, Marquet P, Depeursinge C. Spatial filtering for zero-order and twin-image elimination in digital off-axis holography. Appl Opt 2000;39:4070–5.
[16] Velez A, Barrera JF, Torroba R. One-step reconstruction of assembled 3D holographic scenes. Opt Laser Technol 2015;75:146–50.
[17] Velez A, Barrera JF, Torroba R. Three-dimensional joint transform correlator cryptosystem. Opt Lett 2016;41:599.
[18] Alfalou A, Brosseau C. Implementing compression and encryption of phase- shifting digital holograms for three-dimensional object reconstruction. Opt Commun 2013;307:67–72.
[19] Ferraro P, De Nicola S, Coppola G, Finizio A, Alfieri D, Pierattini G. Controlling image size as a function of distance and wavelength in Fresnel-transform reconstruction of digital holograms. Opt Lett 2004;29:854–6.
[20] Dardikman G, Turko NA, Nativ N, Mirsky SK, Shaked NT. Optimal spatial bandwidth capacity in multiplexed off-axis holography for rapid quantitative phase reconstruction and visualization. Opt Express 2017;25:33400–15.
[21] Velez A, Barrera JF, Trejos S, Tebaldi M, Torroba R. Optical field data compression by opto-digital means. J Opt 2016;18:125701.

[22] Naughton TJ, Frauel Y, Javidi B, Tajahuerce E. Compression of digital holograms for three-dimensional object reconstruction and recognition. Appl Opt 2002;41:4124–32.
[23] Trejos S, Barrera JF, Velez A, Tebaldi M, Torroba R. Optical approach for the efficient data volume handling in experimentally encrypted data. J Opt 2016;18:065702.
[24] Velez A, Barrera JF, Torroba R. Cross-talk free selective reconstruction of individual objects from multiplexed optical field data. Opt Lasers Eng 2018;100:90–7.
[25] Yamaguchi I, Yamamoto K, Mills GA, Yokota M. Image reconstruction only by phase data in phase-shifting digital holography. Appl Opt 2006;45:975–83.
[26] Wallace GK. The JPEG still picture compression standard. IEEE Trans Consum Electron 1992;38 xviii–xxxiv.
[27] Shahnaz R, Walkup JF, Krile TF. Image compression in signal-dependent noise. Appl Opt 1999;38:5560–7.

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