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Cross-talk free selective reconstruction of individual objects from multiplexed optical field data

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ABSTRACT

In this paper we present a data multiplexing method for simultaneous storage in a single package composed by several optical fields of tridimensional (3D) objects, and their individual cross-talk free retrieval. Optical field data are extracted from off axis Fourier holograms, and then sampled by multiplying them with random binary masks. The resulting sampled optical fields can be used to reconstruct the original objects. Sampling causes a loss of quality that can be controlled by the number of white pixels in the binary masks and by applying a padding procedure on the optical field data. This process can be performed using a different binary mask for each optical field, and then added to form a multiplexed package. With the adequate choice of sampling and padding, we can achieve a volume reduction in the multiplexed package over the addition of all individual optical fields. Moreover, the package can be multiplied by a binary mask to select a specific optical field, and after the reconstruction procedure, the corresponding 3D object is recovered without any cross-talk. We demonstrate the effectiveness of our proposal for data compression with a comparison with discrete cosine transform filtering. Experimental results confirm the validity of our proposal.

1. Introduction

Since the seminal work by Gabor et al [1], holography remains a field with vast applications, including metrology [2] and microscopy [3]. In particular, the advances in computing together with low cost and high resolution digital cameras have made digital holography an important tool in optical processing techniques due to its great versatility and applicability. During last years, digital holography has been used in optical security [4–6], reconstruction of amplitude and phase [7], deformation measurement, synthesis and display of dynamic holographic 3D scenes [8], 3D measurements, dynamic digital holographic interferometry [9], phase-shifting color digital holography [10], improvements in spatial resolution [11], among others.

There is a variety of possible configurations for registering digital holograms, like on-line holography with phase shifting, off axis holography, self-interference holography, and coherent optical correlators, among others. The reasons for choosing a specific setup depend on the desired application and the available equipment. For example, off axis holography only requires a single shot to register the entire object information, but limits the bandwidth of the registered object, while on-line holography ensures maximum utilization of the sensor resolution at the cost of requiring several holograms and additional elements in the experimental setup. Correlators, however, produce holograms containing the correlation between the object and any desired function. This capability is of importance in pattern recognition and optical security [6]. Some of the techniques developed for correlators can be applied to off-axis and on-line holographic setups [12].

On the other hand, processing of holographic information presents issues, like the noise in the reconstructed objects [13–15], and the fact that high quality digital hologram recording requires high resolution sensors, leading to large data volumes to be stored, transmitted and processed.

In this sense, compression of holographic data is a problem that needs to be addressed. Several methods have been proposed to achieve data compression of digital holograms, using a variety of approaches depending on the type of holographic data. Amongst these approaches we find the use of quantization [16], digital scaling of the holograms [17], and applications of digital algorithms for lossless and lossy compression [17–21]. Some of the most well know compression methods used for images and holograms perform a spectral filtering and quantization of the input data by means of Fourier, discrete cosine or wavelet transforms [21–24]. Some of these compression techniques show reduced performance when dealing with random or near random signals [25]. This makes them unsuitable for compression of the near random phase found in the optical fields produced by diffuse objects [26]. In this sense, opti-

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cal compression may present higher or similar performance than digital methods for holographic data [27,28], with the added advantage of their potential deployment in actual optical systems.

One of the main techniques for handling multiple holographic data is multiplexing, which combines several holograms into a single package, in such a way that the resulting package could be later processed to extract the information of each individual hologram. To deal with these challenges, different approaches have been developed to achieve holographic data multiplexing using: multiple wavelengths [29], modulation with gratings [30,31] and spatial positioning [32]. These approaches are of interest in many cases, like: the use of multiple reference beams coming from the same source in pulsed digital holography [33], tilted wavefronts for superresolution [34], specially fabricated masks in order to obtain multiple digital image holograms [33], the shifting or rotating the real-world object [8] or any element of the experimental setup [35], several wavelengths in color digital holographic interferometry [9] and phase-shifting color digital holography [10], recorded images of an object under illumination from multiple angles [11], and multiples images registered with a moving detector [36].

However, we find that spatial and angular multiplexing are limited by: (a) the position of the objects in the reconstruction plane to ensure that there is no cross-talk between them, (b) the maximum possible frequency of the modulation gratings for a given hologram resolution, and (c) the fact that there is no way to retrieve the optical field data of a single object before reconstruction.

Davis & Cottrell [37] proposed multiplexing phase only filters using complementary random binary masks. The resulting hybrid filter behaves like a linear combination of both filter functions and the weight of each individual filter function could be controlled by the ratio of white pixels between the binary masks. Although the proposal was effective in demonstrating the method, it was limited to simple phase only filter functions. When dealing with digital holograms of diffuse 3D objects, we must take into account that the optical field data contains both amplitude and phase.

Also, one of the main limitations of the use of binary masks is that they induce a loss of information, however holographic data is inherently redundant [38]. This allows for reconstructing the object from partial or occluded optical fields. Furthermore, we can increase the redundancy of this data by performing a digital padding procedure of the optical field data, ensuring an increased resistance to the loss due to sampling at the cost of larger data volume [39]. Padding has been successfully employed for optical information processing in topics such as multiplexing of optically encrypted data [16,31,40–42] and optical field compression [27,28,43].

Our proposal combines this padding procedure and binary masks to achieve multiplexing without significant quality loss. We show that the binary mask can be conceived as a “selector key” that allows extracting only certain objects from the multiplexed package prior to reconstruction. In this way, the position of the objects to avoid superposition in the reconstruction plane is no longer necessary [44]. Additionally, depending on the padding used, and the number of objects to be multiplexed, the resulting package can have reduced volume, thus achieving multiplexing and compression simultaneously for the optical fields of diffuse objects.

2. Hologram recording, filtering and padding

In order to demonstrate our proposal, we require the phase and amplitude of the optical fields of several objects. There are several possible methods to obtain this data, however in this work we use an off-axis Fourier holography setup (Fig. 1) to record the holograms of three 3D objects [38]. A filtering procedure is then applied to the holograms in order to recover the phase and amplitude of the corresponding optical field [45], as shown next.

One of the arms provides a reference beam given by

$$R(v,w) = Ae^{2\pi i f(v\sin\alpha + w\sin\beta)} \tag{1}$$

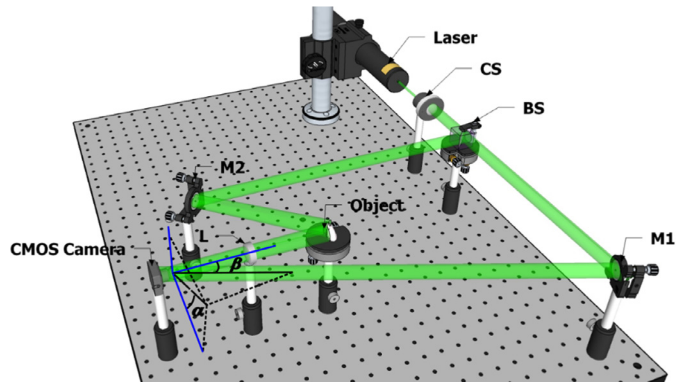

Fig. 1. Off-axis Fourier holographic setup (CS: collimation system, BS: beam splitter, M: mirror, L: lens, α, β: reference beam incidence angles).

where A is a constant beam amplitude, λ the wavelength, f the lens focal length and α and β the incidence angles and $v = x/\lambda f \quad w = y/\lambda f$ the coordinates in the CMOS camera plane.

This reference beam interferes in the CMOS plane with the Fourier transform (FT) of the light reflected by the 3D object, allowing the capture of the hologram, given as

$$\begin{aligned} H(v,w) =& |A|^2 + |O(v,w)|^2 + \\ & O(v,w)e^{-2\pi i f(v\sin\alpha + w\sin\beta)} + O*(v,w)e^{2\pi i f(v\sin\alpha + w\sin\beta)} \end{aligned} \tag{2}$$

where * means complex conjugate and $O(v, w)$ is the optical field data corresponding to the FT of the light reflected by the object $o(x, y)$.

Since the only data necessary to reconstruct the object is the optical field given by the function $O(v, w)$, we can filter this term and discard the remainder terms of Eq. (2). To do this, we first must consider that the hologram represented by Eq. (2) is sampled with a CMOS camera. This results in a digital hologram that is a matrix of discrete elements with dimensions equal to the camera resolution. Once we have the information in this matrix representation, we can perform the discrete Fourier transform (DFT) of the digital hologram. This results in a new matrix representation of the object plane, containing a central order (corresponding to the Fourier transform of the first two terms of Eq. (2), after sampling), the reconstructed $o(x, y)$ object and its twin image [38]. These orders are separated due to the interference fringes arising from the angles of incidence of the reference wave on the camera plane, given by α and β.

Given an object with an extension of $N \times N$ pixels in the object plane, we can digitally take only the matrix elements containing the reconstructed object and place them in a new matrix with size $N' \times N'$, where $N' > N$. After performing the inverse discrete Fourier transform (IDFT) of this new matrix, we obtain a padded optical field data containing only the information needed for reconstruction with increased data redundancy. The padding percentage can be calculated as $(N'/N - 1)$.

3. Resistance to random sampling of the optical field data

Using the optical field data extracted from a hologram with the procedure described above, we proceed to test the resistance to random sampling. To do this, we generated random binary masks of the same size as the optical fields. These masks have set percentage of pixels with value unity (a white pixel) and the remaining pixels have value zero. We multiply the optical field with binary masks with decreasing percentages of white pixels [37]. We measure the quality loss by calculating the normalized mean square error (NMSE) between the reconstruction from the optical field $I(p, q)$, and the reconstruction from the optical field multiplied by a binary mask with decreasing percentages of white pixels