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Optical field data compression by opto-digital means

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Abstract

Compression of optical field data is of interest due to the many applications where this kind of information processing is necessary. In particular, holographic recording has significant requirements in a high volume of both phase and amplitude data. We analyze and present a comparison between the performances of two lossy compression methods applied over optical field data: the optical scaling compression technique based on a virtual optical system that performs a scaling of the optical field data, and the JPEG format. In particular, we study the compression of optical fields data extracted from off-axis digital holograms. Our results show that optical scaling is better suited for the compression of the highly random phase information found in the optical field data of 3D diffuse objects. Data loss and volume reduction for each method are measured and compared.

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(Some figures may appear in colour only in the online journal)

1. Introduction

Digital holography is a powerful technique that allows optical processing by computational means. This technique has given rise to the development of sophisticated opto-digital methods that profit from both the properties of optical systems and the flexibility of digital data processing algorithms. Among the applications of digital holography, we find metrology, microscopy, medical imaging, and optical security [1–10], to name a few. Specifically, digital holography allows for recording information from 2D and 3D objects [11, 12], providing additional degrees of freedom for optical processing [13–15], and consequently making possible the reconstruction of scenes with depth [16].

Digital holography requires the record of an intensity pattern containing eitherphase and amplitude information, implying the recording of interference fringes [17] or multiple phase-shifted images [18]. As a result, a large volume of data needs to be processed and stored digitally. Techniques to reduce the challenges imposed by this volume of data have been proposed, dealing mainly with quantization techniques [18–20], filtering [21], and both lossless and lossy data compression algorithms [22, 23].

One of the most used image compression algorithm is the Joint Photography Expert Group (JPEG) lossy compression format [24]. JPEG format works by subdividing the input image into 8×8 pixel blocks. A discrete cosine transform (DCT) is then applied to each block, and a quantization of the components of the resulting transform is performed. This quantization is the lossy part of JPEG format. The data is further compressed by application of the lossless Huffman coding [25]. The loss and degree of compression achievable by JPEG format can be controlled by a user defined quality factor (QF) that can take values between 1 and 100. This

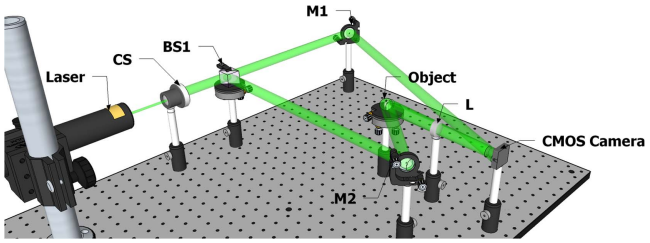

Figure 1. Scheme of the off-axis Fourier holographic setup. (CS: collimation system, BS: beam splitter, M: mirror, L: lens).

factor determines the coarseness of the quantization steps of the DCT.

JPEG compression has been applied to digital holograms [26], but it has been shown to have decreased compression performance with inputs exhibiting random noise [27]. A first approach would be a reductionby filtering the noise from the input. However, in data extracted from a hologram of a diffuse object, the near random oscillations of the phase carry information required for an adequate reconstruction. In this sense, noise cannot be removed, since it contains the information we must compress.

A different compression approach, whose performance is not dependent on the input, might be better suited to deal with the optical field data. In this sense, we have a technique based on using a virtual optical system to perform a scaling of the optical field data [28]. The proposal presented in [28] is based on the processing of the joint power spectrum (JPS) captured by using a CCD camera in a JTC cryptosystem. As usual, the input plane of the encryption system contains the information of the object to be encrypted attached to a random-phase mask and another random-phasemask that acts as the encrypting key. The JPS, which contains the encrypted object information, is captured by a CCD camera. The FT of the captured JPS allows obtaining a filtered region less than the total JPS region. In order to increase the volume reduction, an optical scaling operation is implemented. The scaling technique uses an optical operation, namely, image formation with magnification less than one by means of a positive lens. It should be mentionedthat the main cause of loss of the optical scaling is precisely the finite size of the scaling lens. This size sets a limit to the high frequency of the compressed object. The input placed in the object plane of the lens is the optical field data, obtained after filtering the relevant information from the hologram. Operating directly over the optical field data instead over the hologram, ensures that the scaling does not result in the subsampling of holographic microfringes. After filtering and scaling, a compression of up to 94% over an input hologram is reported.

A way to confirm our assumptions is to evaluate the performance of the mentioned optical scaling procedure in comparison with the well-known JPEG compression format. We will show that the performance of optical scaling and JPEG compression are noticeably different when applied over both the phase and amplitude information of optical field data. In particular, this difference in terms of achievable compression will be noted when considering the reconstruction quality and efficiency of both methods. The quality is assessed by measuring the correlation coefficient (CC) between the reconstructed objects from compressed and uncompressed data [29]. The compression efficiency is the volume difference expressed in kilobytes (KB). We employ these metrics for both JPEG compression and optical scaling when applied to actual optical field data.

2. Hologram registering and optical field data extraction

In order to evaluate our technique, we register the information of a diffuse 3D object by means of the off-axis Fourier digital holographic setup shown in figure 1.

In the CMOS camera plane, we register the interference between a reference plane wave and the Fourier transform (FT) of the light reflected by the input object, given by (see figure 2(a))

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

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

$$P(v, w) = \exp(-\mathrm{i}2\pi f(v \cos\alpha + w \cos\beta)), \tag{2}$$

where the angles α and β determine the tilt of the reference wave, and f is the focal length. We now perform the FT of the registered hologram,

$$h(x, y) = o(x, y) \otimes o^*(x, y) + p(x, y) \otimes p^*(x, y) + o(x, y) \otimes \delta(x - f\cos\alpha, y - f\cos\beta) + o^*(x, y) \otimes \delta(x + f\cos\alpha, y + f\cos\beta). \tag{3}$$

In equation (3), $o(x, y)$ and $p(x, y)$ 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 reference beams corresponding to the central order. 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 equation (2). Taking advantage of this spatial separation, we select the order corresponding to the FT of the third term of equation (3), filtering the remaining terms. After applying the inverse Fourier transform over this filtered term, we finally obtain the optical field data $O(v, w)$ (see figure 2(b)). A FT over this optical field data will reconstruct the object data $o(x, y)$. The object shown in figure 2(c) will be the reference against which we will measure the quality of the reconstructed objects from the compressed optical field data.

3. Quality and compression performance

Although filtering significantly reduces the amount of data to be stored, in the subsequent analysis we use the optical

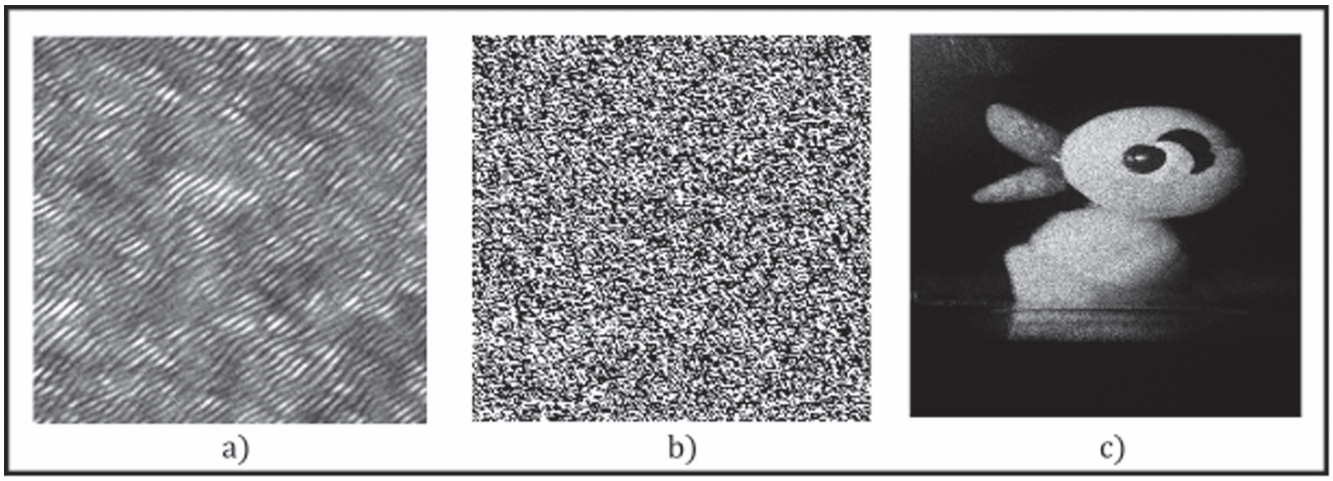

Figure 2. (a) Hologram, (b) intensity of the optical field data and (c) intensity of the object reconstructed from the optical field data.

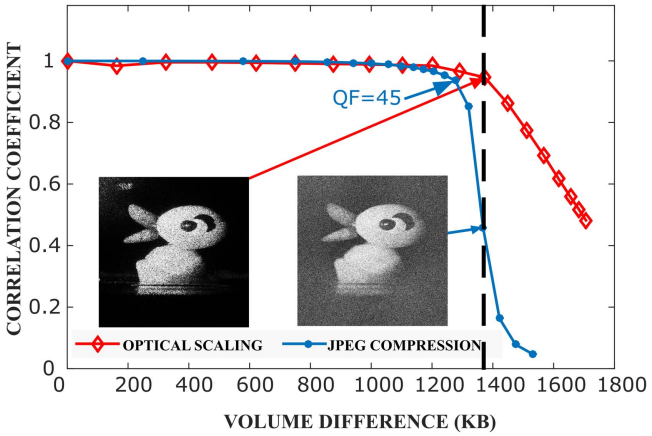

Figure 3. Correlation coefficient between the object reconstructed from the uncompressed and compressed field datafor optical scaling and JPEG compression in terms of the achieved volume difference.

field data as the input to be processed by both compression methods. The experimental data to be compressed are recorded by using CMOS EO-10012M camera, with a pixel size of 1.67 μm $\times$ 1.67 μm and 3480 pixel $\times$ 2748 pixel resolution. The object has maximum dimensions of 18 mm $\times$ 24 mm $\times$ 16 mm. The focal length of the lens was 200 mm. A Laserglow Technologies diode pumped solid state laser operating at a wavelength of 532 nm and an output power of 50 mW is employed. The angle between the object and reference beam was approximately 5°, and the pixel size of the camera used allows for a maximum angle of 9.13°, thus ensuring that we can resolve the highest frequency of the interference pattern. This optical field data will be processed with the scaling compression method for values of magnification between 0 and 1 [28]. On the other hand, for comparison purposes, the same data is compressed using JPEG compression with QF between 1 and 100. Then, we proceed to evaluate the volume difference, defined as

$$\Delta V = V_R - V_C, \tag{4}$$

where V_R is the volume of the uncompressed optical field data and V_C is the volume of the compressed optical field data, both volumes expressed in KB. In our experimental case, the original optical field data area is 940 $\times$ 940 pixels and depth of 8 bits resulting a data volume of $V_R = 1726$ KB The volume of the compressed optical field data is the number of bytes of the file in a computer memory after applied optical scaling and JPEG compression techniques.

Since we are dealing with lossy compression, we must also compare the quality of the reconstructed objects. We achieve this by digitally reconstructing the objects from the compressed and uncompressed optical fields and then evaluating their quality by using the CC defined as

$$\mathrm{CC} = \frac{\sum_m \sum_n (A_{mn} - \bar{A})(B_{mn} - \bar{B})}{\sqrt{\left(\sum_m \sum_n (A_{mn} - \bar{A})^2\right)\left(\sum_m \sum_n (B_{mn} - \bar{B})^2\right)}}, \tag{5}$$

where m, n are the pixel coordinates, A the object intensity reconstructed from the uncompressed optical field, B the object intensity reconstructed from the compressed field data and $\bar{A}$, $\bar{B}$ are the mean values of A and B, respectively.

In figure 3, each marker of the JPEG curve represents a decrease of the QF in steps of 5, starting at 100. This value corresponds to $\Delta V = 0$. Each point of the optical scaling curve corresponds to a decrease of 0.05 of the magnification value stating at 1 when $\Delta V = 0$. The JPEG compression achieves the largest volume decrease within the QF range between 100 and 45, and further reduction of the QF severely degrades the reconstructed object quality for a small increase in the volume difference (see media 1). On the other hand, optical scaling allows for a lesser loss of quality than JPEG compression at high compression ratios, as shown in the figure 3 at $\Delta V \geqslant 1380$ KB (see dotted line and inset figures).

In [27], it was demonstrated that the JPEG compression format shows decreased performance when the distribution of data is random. In diffuse objects, phase information has more random distribution in comparison with the amplitude information. In consequence, the behavior of the compression format should be different in both cases. To verify this, we proceed to evaluate the phase and amplitude information independently for each method. In order to perform the evaluation, we measure the volume difference of the phase and

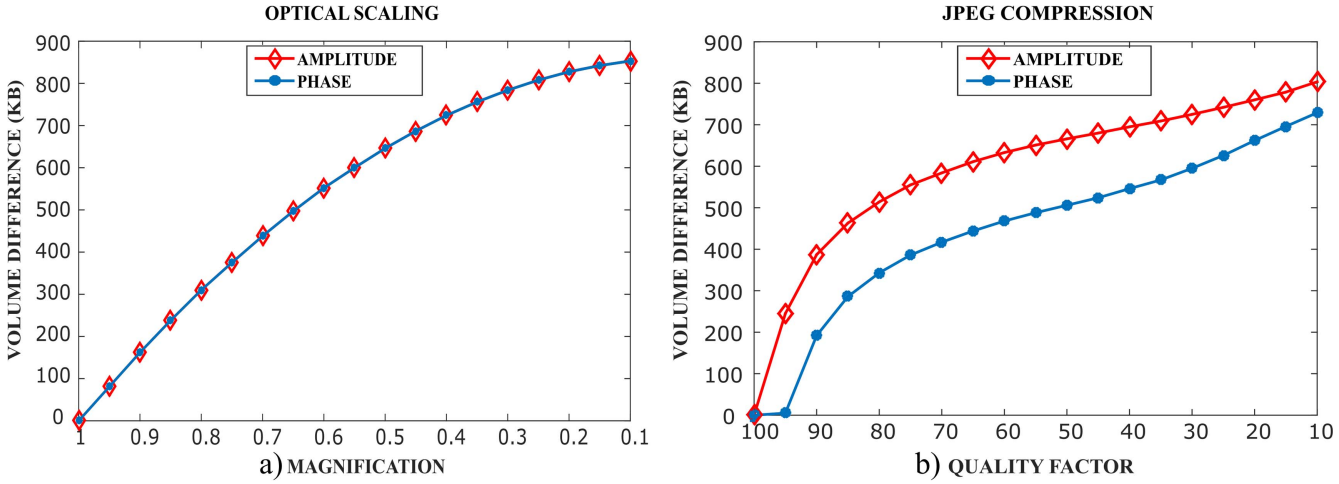

Figure 4. Volume difference of the phase and amplitude of the compressed data in terms of: (a) the magnification and (b) the QF.

the amplitude of the compressed optical field data in terms of the magnification and the QF parameters.

Figure 4 confirms that there is a difference in the performance of both methods. Optical scaling compression (figure 4(a)) shows the same behavior for both phase and amplitude information. On the other hand, JPEG compression (figure 4(b)) shows a significantly lower performance when applied to phase information. While these results seem to show that optical scaling is better suited to the compression of phase information of the optical field data, it is worth noting that the loss caused by both methods is qualitatively different. In the case of optical scaling the reconstructed object shows loss of high frequencies, while in the case of the JPEG compression it shows an increase in noise. In this sense, while optical scaling shows a more predictable behavior for optical field data, there may be cases where the loss of high frequency fringes is not desirable.

4. Conclusions

Since phase carries a significant amount of the holographic information, it is necessary to achieve the maximum possible compression with the minimum loss. Methods used for general image compression like JPEG or other spatial or spectral quantization compression methods were not developed for random distributions. In this work we verified that the optical scaling procedure is an adequate alternative with better performance in comparison with JPEG compression for random data distributions. We believe that efficient compression of optical field data requires taking into account the properties of phase information, therefore other optical methods should be further explored.

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