Synthetic aperture single-exposure on-axis digital holography

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Abstract: We present a system for reconstructing single-exposure on-line (SEOL) digital holograms with improved resolution using a synthetic aperture. Several recordings are made in order to compose the synthetic aperture, shifting the camera within the hologram plane. After processing the synthetic hologram, an inverse Fresnel transformation provides an enhanced resolution reconstruction. We show that recognition capacity for high frequency details is increased. Experimental results with a test target and with a microscopic biological sample are presented. Both visualization and correlation results are reported.

OCIS codes: (070.6020) Signal processing; (090.0090) Holography; (090.1760) Computer holography; (100.6640) Superresolution; (110.0180) Microscopy.

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1. Introduction

In recent years, extensive research has been devoted to the development of different applications of digital holography [1-9]. The combination of its singular optical features and computational possibilities makes digital holography specially convenient for digital image processing purposes, for instance, for performing three-dimensional (3D) object recognition [10].

Microscopy applications of digital holography require imaging a sample with high definition. Diverse techniques have been proposed to improve image resolution [11-13]. A drawback for many of these proposals is their intricate set-up and cumbersome procedure. Alternatively, an active synthetic aperture, achieved with a relative movement of the sample and the CCD camera, can also enhance resolution [14-18].

Among the several methods to record digital holograms of microscopic samples, single-exposure on-line (SEOL) digital holography systems benefit from real-time operation and its inherent robustness against external perturbations [19].

Synthetic aperture techniques represent a suitable way to enhance resolution in SEOL digital holography. We have studied the performance of synthetic aperture SEOL digital holography, with the aim of ameliorating imaging and recognition applications. In this paper, we report a system for reconstructing SEOL digital holograms with improved resolution by enlarging the system aperture. No imaging lenses are placed between the sample and the detector. We present images of a USAF test chart showing experimentally that an aperture synthesis procedure offers an enhanced resolution in SEOL digital holography. The method is expanded to microorganisms, an area of increasing interest for optical processing applications.

The rest of the paper is organized as follows. In Section 2 we review the principles of SEOL digital holography and in Section 3 those of synthetic aperture techniques. Our set-up and the synthesis process are explained in Section 4. Experimental results are shown in Section 5. Finally, section 6 summarizes the conclusions of our work.

2. Single-exposure on-line digital holography

In SEOL digital holography [19], the information about the object is captured in only one shot, unlike phase-shifting digital holography [20]. Furthermore, compared to off-axis digital holography [21], SEOL effectively uses all pixels of the CCD sensor. In off-axis holography, a small tilt between reference and object wave separates the zero order, the real and the virtual image in the reconstruction [2]. This angular separation between reference and object wave generates carrier fringes in the hologram plane and limits the space-bandwidth product. Only a part of the sensor area is utilized for reconstruction.

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SEOL reconstructions suffer from a certain blurring owing to the unfocused virtual image, which is superimposed on the focused real image and may degrade the quality of the reconstruction. Nevertheless, this method has allowed clear object visualization [22] and is an appropriate technique for recognition purposes, since both twin images contain information used in the detection process [23]. The dc term, formed by the superposition of object and reference beam intensities, can be removed by recording separately and subtracting those contributions to the hologram or reduced numerically. Since just only one exposure is needed, SEOL digital holography is a robust procedure, not sensitive to environmental noise, such as vibrations. It has been applied to three-dimensional visualization and identification of microorganisms [22].

A hologram consists of the coherent superposition of a reference beam, R, and the light diffracted from the sample, O. When the terms corresponding to reference and object beam intensities are removed, the final digital hologram considered in the SEOL technique can be expressed as

$$\begin{aligned} H(x',y') &= \left|O(x',y')+R(x',y')\right|^2 - \left|O(x',y')\right|^2 - \left|R(x',y')\right|^2 \\ &= R(x',y')O^*(x',y') + R^*(x',y')O(x',y'), \end{aligned} \quad (1)$$

where * denotes the complex conjugate wave, and x' and y' are the spatial coordinates in the CCD plane. Provided that the object is placed in the Fresnel diffraction region, an inverse Fresnel transformation can be applied for reconstruction at a distance d. Since the hologram is recorded by a discretized sensor, the reconstruction integral must be expressed as in Eq. (2), where λ is the wavelength, m' and n' are the discrete spatial coordinates in the CCD plane, and m and n correspond to the reconstruction plane coordinates. Δx, Δy, and $\Delta x'$, $\Delta y'$, represent the resolution in the object and CCD planes, respectively, while M and N stand for the total number of pixels in each dimension.

$$\begin{aligned} O(m,n) = \exp\left[-\frac{i\pi}{\lambda d}\left(m^2\Delta x^2 + n^2\Delta y^2\right)\right] \sum_{m'=1}^{M}\sum_{n'=1}^{N} R(m',n')\,H(m',n') \\ \times \exp\left[-\frac{i\pi}{\lambda d}\left(m'^2\Delta x'^2 + n'^2\Delta y'^2\right)\right] \exp\left[\frac{i2\pi}{\lambda d}\left(m\Delta x\, m'\Delta x' + n\Delta y\, n'\Delta y'\right)\right]. \end{aligned} \quad (2)$$

According to the Fresnel transform applied, the resolution in the reconstruction plane is inversely proportional to the sensor size:

$$\Delta x = \frac{\lambda d}{M\Delta x'},\ \Delta y = \frac{\lambda d}{N\Delta y'}. \quad (3)$$

3. Synthetic Aperture

Optimization of resolution is a matter of paramount importance in microscopy. Microscope objectives or high numerical aperture lenses are able to collect high frequency components of the imaged object, but their use involve some limitations, as the constraints in the working distance and the aberrations induced in the optical signal.

A synthetic aperture, implying a relative movement between the object and the image sensor, was originally implemented in RADAR measurements with a moving sensor. Several recordings of the same scene with different positions of the sensor compose a larger hologram, expanding the range of spatial frequencies captured. The effective aperture is thus increased and, consequently, the resolution is enhanced, as shown by Eq. (3). This expression indicates the limit for the finest resolution that can be attained, provided that no errors are present in the synthesis process. An ameliorated resolution has been shown in a scheme involving heterodyne holography [14] and in a phase-shifting configuration [15-16]. A synthetic aperture has been reported as well in off-axis digital holography [17-18]. In this

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paper, we show a synthetic aperture method which effectively improves the resolution in SEOL digital holography. Concurrently, the speckle size is reduced, and the recognition capacity is enhanced.

4. Set-up and synthesis process

We have arranged a set-up based on a Mach-Zehnder interferometer for recording improved resolution SEOL digital holograms, as shown in Fig. 1. The light source was an argon-ion plasma laser, working at 514.5 nm and supplying about 10 mW. In one of the interferometer arms, we placed a sample illuminated in transmission. The object could be located in a horizontal position, between a couple of mirrors not shown in Fig. 1 for the sake of clarity.

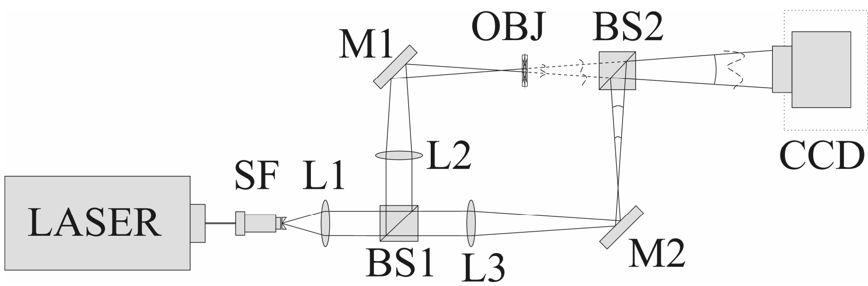

Fig. 1. Experimental set-up. SF, spatial filter; L1, collimating lens; BS1, BS2, beam splitters; L2, L3, lenses in object and reference beams; M1, M2, mirrors; OBJ, sample object.

Lens L3 provided a spherical reference beam whereas L2 formed another spherical beam, with the same curvature, illuminating the object. The focal length of both lenses was f = 125 mm. No lenses were set between the object and the camera, allowing the set-up to be suitable for a more compact form. Magnification could be adjusted by varying the position of the lenses, the sample or the CCD camera. The typical arrangement of our set-up gave a 3.5× magnification in the plane of the CCD. The camera was placed 300 mm away from the object. The whole set-up was mounted on an optical table which was not vibration-isolated.

Two kinds of samples have been used: a USAF-1951 resolution test target and a microscopic biological specimen, sphacelaria alga. Sphacelaria samples are aquatic filament algae, with a width of a few tens of micron. Some of the images of the resolution chart were taken using a diffuser next to it, in order to check speckle size reduction. Generally, a diffuser worsens the resolution, but the superimposed unfocused term of the twin image becomes a diffuse background spread over the image [2]. Diffuse illumination has been widely used in holography since its early times due to its particular properties [24].

A monochrome CCD camera was mounted on a manual 3D linear stage. A central hologram and other eight holograms, contiguous with it, were recorded in different positions of the camera, without changing the distance between the sample and the CCD plane. The nine holograms were reconstructed to check a possible deviation in the reconstruction distance. A correlation algorithm yielded the distances between central and adjacent holograms with accuracy, by measuring the shift of the correlation peak. Peripheral holograms overlapped with the reference one an area big enough to perform these calculations properly. It was very important to calculate the distance between original holograms correctly, since the exact stitching of the partial holograms and the resulting reconstruction strongly depended on the accuracy of these data. The possible tilt between different camera positions was determined through correlation of the overlapping zones and compensated in the synthetic hologram [15]. If tilt factors were not corrected properly, the reconstruction showed misplaced elements. Finally, the composed hologram was reconstructed, applying an inverse Fresnel transformation.

The original holograms consisted of the 1368 × 1024 central pixels of each capture. Considering that primary holograms must overlap, the size of the synthetic aperture was

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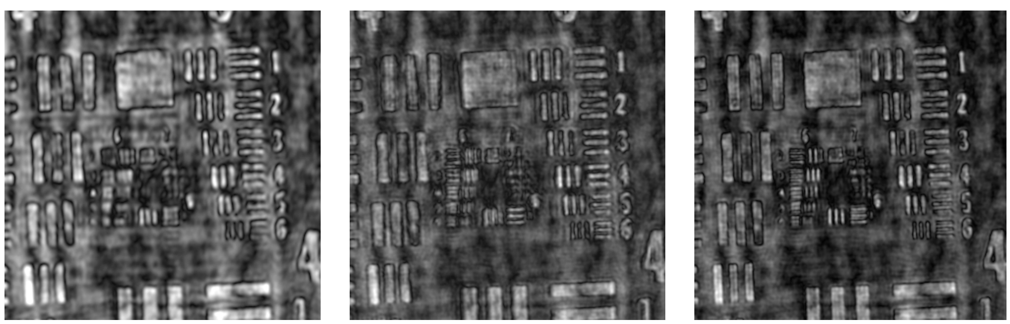
typically about 2700 × 2400 pixels, depending on the exact displacements of the camera for each set of captures. The reason to use no more than the 1368 × 1024 central pixels in each original hologram concerned the need to compare the reconstruction from the synthetic aperture hologram with that from a conventional hologram of a similar size. The latter reconstruction would not be affected by any sort of error which could appear in the processing stage [14-17]. Thus, this comparison allows a method to assess the performance of the synthesis process. Our goal was to show that synthetic aperture techniques in combination with SEOL digital holography lead to a resolution improvement, but also evaluate the resolution improvement and the efficiency of the synthesis process. In addition, the size of the digital holograms considered was convenient for a fast computation. Thus, for each set of measurements, we have compared three reconstructions, using (a) the synthetic aperture hologram, (b) a single original hologram with 1368 × 1024 pixels, yielding a low resolution image, and (c) a high resolution hologram, with the entire 3072 × 2048 pixels of the CCD camera. The high resolution hologram had an overall number of pixels similar to the synthetic aperture. From the experimental results which follow, we have concluded that the resolution for the synthetic aperture reconstruction was superior to the low resolution, and comparable to the high resolution reconstruction. The synthetic aperture reported in this paper is significantly larger than in the related experiments involving overlapping holograms [14-17]. Once that the efficiency of synthetic aperture SEOL digital holography has been shown, nothing prevents using larger original holograms if the application requires it, with adequate computing resources.

5. Results

In this section, we present the results of the synthetic aperture experiments. Figure 2 shows the reconstruction of the resolution chart, for a low resolution, a synthetic aperture and a high resolution hologram. An improvement of resolution is evident when contrasting higher groups of the low resolution and the synthetic aperture images.



(a) (b) (c)

Fig. 2. Reconstruction of a USAF resolution test target using a low resolution (a), a synthetic aperture (b), and a high resolution digital hologram (c).

To quantify the observed resolution enhancement, we have determined the smallest element in the test chart that can be resolved. If we consider horizontal lines, for vertical resolution, the smallest resolved element in the low resolution hologram reconstruction is element 4 in group 5 (45.25 line-pairs/mm). It is element number 4 in group 6 (90.51 line-pairs/mm) for the high resolution and the synthetic aperture holograms. Similar resolution improvement is observed for vertical lines. This comparison shows that the synthetic aperture resolution exceeds that of the low resolution reconstruction, as expected by the size of the apertures. Depending on the exact resolution for each aperture and the possible processing errors, there are some quality differences between some parts of the synthetic aperture and the high resolution reconstructions. The latter is not always the most favorable one. Even if some position or phase errors could be present in the synthesis process, they do not affect

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significantly the resolution achieved with the synthetic aperture, since resolution is roughly the same for the synthetic aperture and the high resolution reconstructions. It is worth to say that correlation of overlapping regions of separately recorded original holograms is high, as expected for accomplishing the synthetic aperture process described in Section 4.

Inasmuch as SEOL digital holography is a convenient method for object recognition, we have also calculated the correlation between the images of higher groups in the resolution test chart, taking the high resolution hologram as a reference. We have compared the regions of the images containing groups 6 and 7 in the chart. Thus, we quantify the correlation between high frequency areas. It is another method to check the improvement of resolution, together with direct image comparison and inspection of the smallest resolved lines in the USAF chart. In Fig. 3, we show the results of the correlations for the low resolution (a) and the synthetic aperture hologram (b), and the autocorrelation for the high resolution hologram (c). The correlations have been rescaled in order to have a value of one for the height of the autocorrelation peak. The correlation peak for the synthetic aperture hologram approaches the value of the autocorrelation for the high resolution hologram, whereas it is noticeably shorter for the low resolution hologram. The images of the high frequency details used for this comparison are shown in Fig. 3(d-f).

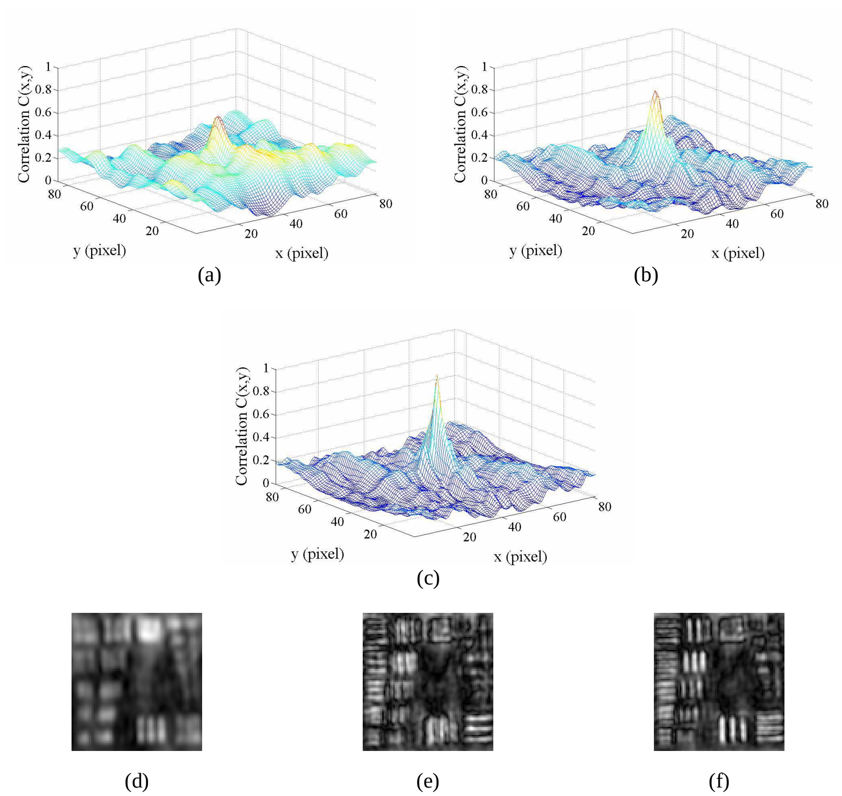


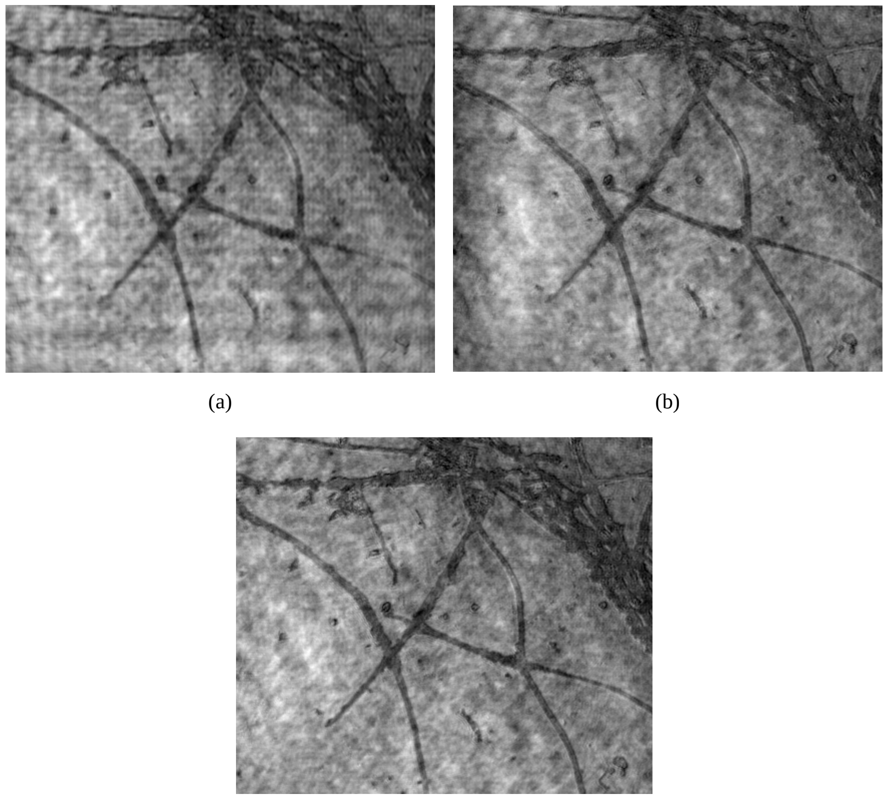
Fig. 3. Correlation between high frequency groups in the resolution test target reconstructions. Correlation peaks, comparing with the high resolution hologram, for the low resolution (a) and the synthetic aperture hologram (b), and autocorrelation for the high resolution hologram (c). Images of the high frequency regions used for these calculations, with groups 6 and 7 in the resolution chart, are also shown: low resolution (d), synthetic aperture (e), and high resolution digital holograms (f).

The differences in the correlation peaks are not so significant when comparing larger areas of the reconstruction, since similarity is assured by low frequency features. The

#88893 - $15.00 USD Received 26 Oct 2007; revised 30 Nov 2007; accepted 7 Dec 2007; published 2 Jan 2008

comparison of correlation peaks in Fig. 3 confirms that the synthetic aperture technique can be applied to enhance recognition processes of high frequency components.

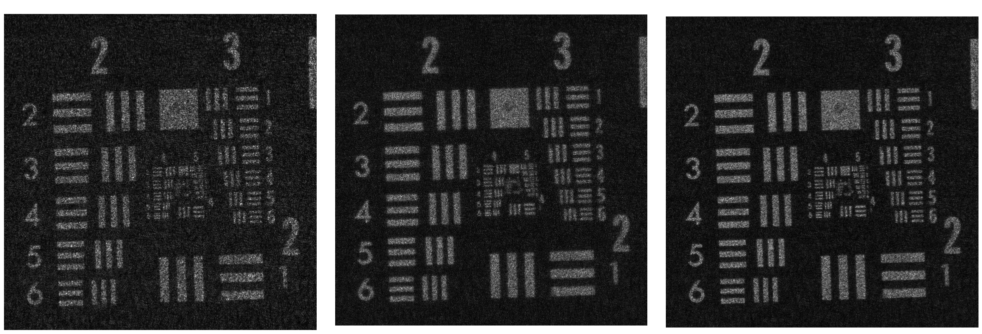
We present, in Fig. 4, the results of recording the holograms of a biological sample, sphacelaria alga. Definition is improved for the synthetic aperture reconstruction, and it is again comparable to the high resolution hologram, which can be verified by correlation process.



(a) (b)

(c)

Fig. 4. Reconstruction of a sphacelaria alga sample using a low resolution (a), a synthetic aperture (b), and a high resolution digital hologram (c).



(a) (b) (c)

Fig. 5. Reconstruction of a USAF resolution test target, with a diffuser next to it, using a low resolution (a), a synthetic aperture (b), and a high resolution digital hologram (c).

#88893 - $15.00 USD Received 26 Oct 2007; revised 30 Nov 2007; accepted 7 Dec 2007; published 2 Jan 2008

In Fig. 5, we have imaged the resolution test chart, when placing a diffuser next to it. We employ a diffuser to test the reduction of the speckle size related to the enlargement of the hologram aperture.

The synthetic aperture reconstruction casts a sharper image than the low resolution one, though the elements in the smallest groups cannot be differentiated in any of the three reconstructions.

In Fig. 6, we see a detail from the images in Fig. 5. The size of the speckle pattern is reduced by effect of the synthetic aperture, and it is similar to the high resolution case.

(a)

(b)

(c)

Fig. 6. Reconstruction detail of the resolution test target, with a diffuser, showing the speckle size for a low resolution (a), a synthetic aperture (b), and a high resolution digital hologram (c).

The results presented in this paper experimentally confirm the feasibility of synthetic aperture SEOL digital holography. These results verify that the synthetic aperture technique improves resolution proportionally to the size of the SEOL hologram aperture, regardless of the unfocused virtual image. Synthetic aperture SEOL digital holography enhances resolution and reduces speckle size. We have reported the application of the method to the visualization of microorganisms and to the better recognition of high frequency features. The resolution improvement presented proves of interest for the recognition and visualization applications of SEOL digital holography.

The technique permits the fast processing of a sample, and could be optimized by using the movement of a CCD camera over a larger area and employing specialized computing resources. The results presented here are valid for imaging and recognition applications involving slowly varying phenomena, since the sensor must be shifted to record partial holograms. However, synthetic aperture SEOL digital holography provides an improved resolution while maintaining its simplicity and immediacy when compared to multiple-step

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recording methods. For instance, in synthetic aperture phase-shifting digital holography, three shots and a computing stage must be performed to generate each original hologram composing the synthetic aperture. On the other hand, the quality of reconstructions is not dependent on the accuracy of the phase-shifting stage. The experiments presented here have been carried out in a optical bench which was not vibration isolated, owing to the robustness of SEOL digital holography.

Once synthetic aperture SEOL digital holography has demonstrated to be an efficient way to improve reconstruction resolution, the scheme could be applied to a larger hologram size and to a greater number of them. The automatization of the method, with an ultra-fast capture, would approach real-time operation.

6. Conclusions

In this paper, we have applied synthetic aperture techniques to SEOL digital holography. Results showing that the use of a synthetic aperture improves image resolution in SEOL digital holography are presented. Evidence of resolution enhancement is observed in the reconstructions from both a test resolution target and microorganisms. Resolution improvement is shown to be helpful to discriminate high frequency details in object recognition.

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