Adaptive deformation of digital holograms for full control of depth-of-focus in 3D imaging

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***Abstract* –Through adaptive deformation of digital holograms it is possible to manage and control the depth of focus in 3D imaging. Objects lying at different distances can be set simultaneously in-focus.**

I. Introduction

One attractive feature of DH over other interference microscopy techniques is its intrinsic 3D imaging capability, allowing to explore, by means of numerical diffraction propagation, the volume in front the hologram plane (i.e. the detector plane). For imaging objects at different depths holograms are numerically reconstructed in planes that are parallel to the hologram but at different distances. However, for objects having 3D extension or 3D shape, only some portions of the object can be in good focus in each of those planes. The limited depth of focus is affecting all optical and imaging systems, even if this paradigm is much more evident in microscopy, where the need for large magnification has as direct consequence the harshly squeezing of the depth of field. In classical optical microscopy the problem is resolved by scanning mechanically the 3D volume with the aim to extract "in-focus" information. By such a procedure it is possible to build-up a single image, named Extended Focus Image (EFI), in which all points of the object are in-focus. In microscopy, however, it remains unresolved the problem for objects changing their shape during the measuring time (i.e. for dynamic events). However various solutions have been proposed by adopting DH. Since all the methods in DH are based on a single image acquisition it is clear that those methods are useful for dynamic objects (i.e. objects that change their shape during the observation under the microscope).

Here we show a new method completely different from the aforementioned methods. It has the advantage to be very simple and without additional computational efforts in respect to a standard reconstructions. It can be used for any type of objects either microscopic as well as macroscopic. The idea behind is very simple and is related to that fact that the diffraction pattern taken in a given plane along the optical axis, it is essentially a magnified copy of that in others planes in proximity of the first given plane. An adaptive deformation applied to digital holograms causes a magnification that allow to manage and control the depth of focus in numerical reconstructions. We demonstrate here the method in both lens-less as well as in microscopy configuration.

II. Working Priciple

Considering a digital hologram of an object recorded at distance d from it, the numerical reconstruction of the object in focus is obtained numerically at distance d from hologram plane by adopting the well known numerical modelling and computing of the diffraction Fresnel propagation integral.

If an affine geometric transformation, a deformation, is applied to the original recorded hologram h, consisting in a simple stretching described by $[\xi' \eta'] = [\xi \quad \eta \quad 1]T$ through the operator

$$T = \begin{bmatrix} \alpha & 0 \\ 0 & \alpha \\ 0 & 0 \end{bmatrix} \qquad (1)$$

given by $h(\xi',\eta') = h(\alpha\xi,\alpha\eta)$ we obtain the propagation integral changes in,

$$B(x,y,d) = \frac{1}{i\lambda d} e^{ikd} \iint h(\alpha\xi,\alpha\eta) e^{\frac{ik\alpha^2(x-\xi)^2}{2d\alpha^2}} e^{\frac{ik\alpha^2(y-\eta)^2}{2d\alpha^2}} d\xi d\eta =$$

$$= \frac{1}{i\alpha^2\lambda d} e^{ikd} \iint h(\xi',\eta') e^{\frac{ik(x'-\xi')^2}{2D}} e^{\frac{ik(y'-\eta')^2}{2D}} d\xi' d\eta' = \frac{1}{\alpha^2} b(x',y',D) \qquad (2)$$

Such simple stretching applied to the hologram has very interesting consequences on the numerical reconstructions.

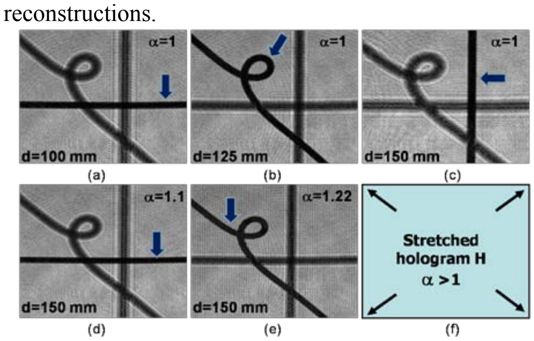

Fig. 1 Reconstructions of original and stretched holograms. Stretching the hologram it is possible to put in focus wires at various depth.

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In fact from Eq.(2) it is clear that the new hologram reconstructs the object in focus at changed distance $D = \alpha^2 d$ while $x' = \alpha x$ and $y' = \alpha y$. The hologram has been simple stretched with an the elongation factor α.

III. Results

The impact that the stretching has on numerical reconstructions, is shown in Fig.1. The object was made of three different wires positioned at different distances from the CCD array. The horizontal wire, the twisted wire with the eyelet and the vertical wire were set at distances of 100mm, 125mm and 150mm, respectively. The numerical reconstructions at the above distances give an image in which each wire at a time is in good focus, as shown in Fig.1a, 1b and 1c, at the corresponding recording distances. The arrows indicate the wire in focus in each reconstructed image.

The results shown in Fig.1 demonstrates that the depth of focus can be controlled by means of the uniform stretching of the holograms according to Eq.(2). In case of $\alpha<1$ the objects results to be at shorter distance in respect to the real distance.

This interesting results implies that by opportune and adaptive deformation of digital holograms different parts of the 3D scene that are a different depths can be obtained in good focus in a single reconstructions as will be demonstrated below. In fact the next logical step was to understand how to deform an hologram for having in focus in the same reconstruction plane different objects lying at different distance from the hologram plane (i.e. CCD sensor). In this case the deformation has to be adapted to the various situations being no longer uniform. If we consider, in general, a polynomial deformation of the form $[\xi' \; \eta'] = [1 \quad \xi \quad \eta \quad \xi*\eta \quad \xi^2 \quad \eta^2]T$ it can be adapted to the various situations.

This time the deformation has been applied only to a portion of the entire holograms.

We used values for and γ such that the equivalent average shrinkage in the central part was $\alpha = 0.85$ that allows to put in focus the wire with the eyelet at distance of d=100mm.

In Fig. 1c it is clear that the hologram is unchanged (black area) everywhere except that in the region where it was applied the adaptive deformation. The shrinkage of the hologram in that area has as effect to moving forward the eyelet that is now in focus. In fact in Fig.2 is shown the reconstruction at d=100 mm where are clearly visible the horizontal wire in good focus together with the eyelet of the wire.

Apart, from the obvious distortions in the neighbours, the result shown in Fig.2d demonstrates that two portions of the objects, falling inside of the field of view of the same hologram, but a different distances, can be obtained in-focus at sane time.

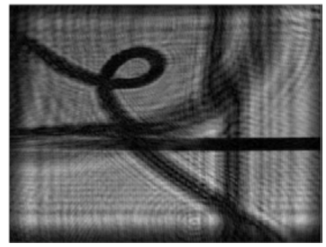
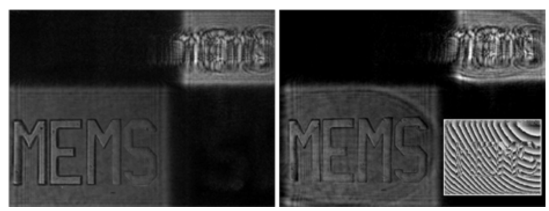


Fig. 2 Horizontal wire and eyelet both in focus even if at two different depth.

As final demonstration we show here one more case in which we were able to recover the EFI image for a tilted object in microscope configuration. The object is a silicon wafer with letters "MEMS" written on it. The object was tilted with an angle of 45°. The details about the recording of the hologram are detailed reported in ref.[17]. In this case we applied a quadratic deformation on the entire hologram. The deformation was applied only along the x-axis. The quadratic deformation allowed to get an EFI image of the tilted object as shown in Fig.3. In Fig3a is shown the reconstruction of the undistorted hologram at distance of d= 265 mm. It is important to note that while the portion of the object with letter "S" in good focus, the rest is gradually out-of-focus, due to inclination angle of the object.



(a) (b)

Fig. 3 Reconstructions of original and stretched holograms. Showing in (a) only "letter "S" in focus while in (b) all the target is in focus.

In Fig.3b is shown the reconstruction obtained on the quadratic deformed hologram and it shows that now all the letters "MEMS" are in good focus. In the inset in Fig.3a is shown also the phase-map difference calculated by subtracting the two hologram the deformed and the original one. The phase map indicates that the defocus tilt between the two hologram has been mainly removed by the deformation.

In conclusion we have shown that by means of the holograms adaptive deformation it is possible to control the focus depth in many situations. This novel method will open more potentialities in the 3D imaging and microscopy in coherent light by DH.

References

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