Invited Paper

Synthetic Aperture Digital Holography

Joseph Rosen* and Barak Katz
Department of Electrical and Computer Engineering
Ben Gurion University of the Negev, P.O Box 653, Beer-Sheva 84105, Israel
*Corresponding author: rosen@ee.bgu.ac.il

1 Introduction

Synthetic aperture is a well-known super-resolution technique which extends the resolution capabilities of an imaging system beyond the theoretical Rayleigh limit dictated by the system's actual aperture. Using this technique, several patterns acquired by an aperture-limited system, from various locations, are tiled together to one large pattern which could be captured only by a virtual system equipped with a much wider synthetic aperture.

The use of optical holography for synthetic aperture is usually restricted to coherent imaging [1-3]. Therefore, the use of this technique is limited only to those applications in which the observed targets can be illuminated by a laser. Synthetic aperture carried out by a combination of several off-axis incoherent holograms in scanning holographic microscopy has been demonstrated by Indebetouw *et al* [4]. However, this method is limited to microscopy only, and although it is a technique of recording incoherent holograms, a specimen should also be illuminated by an interference pattern between two laser beams.

We present a new lensless incoherent holographic system operating in a synthetic aperture mode. Spatial resolution exceeding the Rayleigh limit of the system is obtained by digital tiling several Fresnel holographic elements into a complete Fresnel hologram of the observed object. Each element is acquired by the limited-aperture system from different point of view. This method is demonstrated experimentally by combining three holographic elements recorded from white light illumination which is emitted from a binary grating.

The proposed holographic method in this study is based on the recently invented system of a single-channel incoherent interferometer for generating digital Fresnel holograms [5]. In this non-scanning holographic technique, white light is reflected or emitted from a three dimensional (3-

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D) object, then propagates through a spatial light modulator (SLM), and is finally recorded by a digital camera. The SLM is used as a diffractive beam splitter of the incoherent interferometer, so that each spherical beam, originated from each object point, is split into two spherical beams with two different curve radii. Accumulation of the entire interferences within all of the couples of spherical beams creates the Fresnel hologram of the observed object. Three holograms are recorded sequentially, each for a different phase factor of the SLM. The three holograms are superposed in the computer, so that the result is a complex-valued Fresnel hologram that does not contain the twin image and the bias term.

2 Synthetic aperture with Fresnel elements

In this paper we demonstrate a different scheme, dubbed a synthetic aperture with Fresnel elements (SAFE), for holographic imaging of incoherently illuminated objects. The proposed lensless system contains only an SLM and a digital camera. This holographic system has an extended synthetic aperture in order to improve the transverse and axial resolutions beyond the classic limitations. The term synthetic aperture, in the present context, means time (or space) multiplexing of several Fresnel holographic elements captured from various viewpoints by a system with a limited real aperture. The synthetic aperture is implemented by shifting the SLM-camera set, located across the field of view, between several viewpoints. At each viewpoint a different mask is displayed on the SLM, and a single element of the Fresnel hologram is recorded (See Fig. 1). The various elements, each of which is recorded by the real aperture system during the capturing time, are tiled together so that the final mosaic hologram is effectively considered as captured from a single synthetic aperture which is much wider than the actual aperture.

An example of such system with the synthetic aperture, which is three times wider than the actual aperture, can be seen in Fig. 1. For simplicity of the demonstration, the synthetic aperture was implemented only along the horizontal axis. In principle this concept can be generalized for both axes and for any ratio of synthetic to actual apertures. Imaging with the synthetic aperture is necessary for cases where the angular spectrum of the light emitted from the observed object is wider than the numerical aperture of a given imaging system. In SAFE shown in Fig. 1, the SLM and the digital camera, move in front of the object. The complete Fresnel hologram of the object, located at some distance from the SLM, is a mosaic of 3 holographic elements, each of which is recorded from a different position by the system with the real aperture of the size $A \times A$. The complete hologram tiled from the 3 holographic Fresnel elements has the synthetic aperture of the size $3 \cdot A \times A$ which is 3 times larger than the real aperture at the horizontal axis.

The method to eliminate the twin image and the bias term is the same as has been used before [5]; three elemental holograms of the same object and for each point of view are recorded, each of holograms has a different phase constant of the SLM's phase mask. The final holographic element is a specific superposition of the three recorded elements. The digital reconstruction of the final complex-valued mosaic hologram is conventionally computed by Fresnel back propagation.

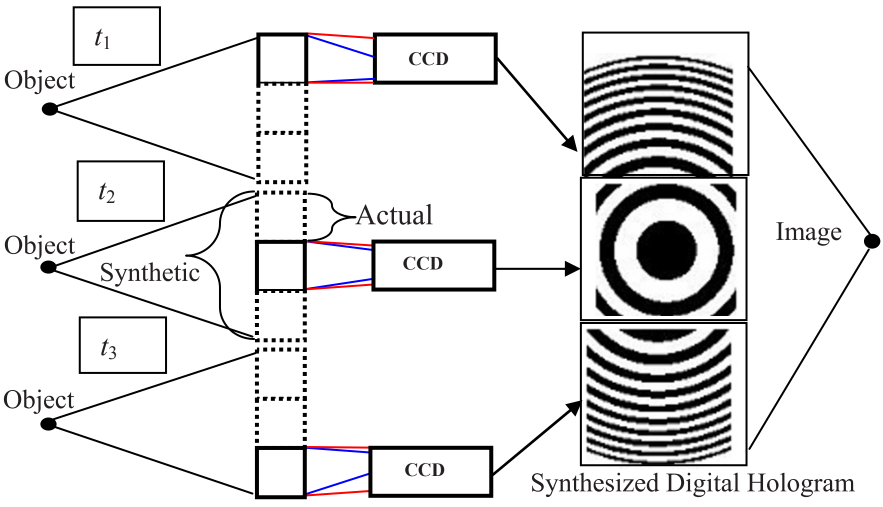

Fig. 1. Scheme of SAFE operating as synthetic aperture radar to achieve super-resolution

3 Experimental results

SAFE has been tested in the lab by the system shown in Fig. 1. The object in this experiment is a binary grating with cycle length of 11 lines per one cm. The distance from the binary grating to the SLM has been 17 cm, and between the SLM and the CCD camera (PCO, Scientific 230XS) 8 cm. The results of the experiments are summarized in Fig. 2. In the first experiment we have recorded a hologram only by the actual aperture without shifting the system, in the setup shown in Fig. 1 at the time t2. Fig. 2(a) shows one of the three masks displayed on the SLM (Holoeye, PLUTO) in this experiment. Each of the three masks has had one of the three different phase factors: 0o, 120o or 240o. As mentioned above, these three phase masks with different phase constants are required in order to eliminate the bias term and the twin image from the holographic reconstruction. The SLM is a phase-only modulator, and therefore the sum of two pure phase functions is no longer a pure phase. Our solution [5] of this problem is to distribute randomly the phase values of the two quadratic functions among the SLM pixels. The three recorded holograms are superposed according to the same superposition equation given in Ref. [5]. Figs. 2(b) and 2(c) are the magnitude and the phase of the superposed hologram, respectively. The resolution along the horizontal direction of the reconstructed image shown in Fig. 2(d) is damaged in the sense that the image is lacking the original horizontal gratings because of the limited aperture used in this case.

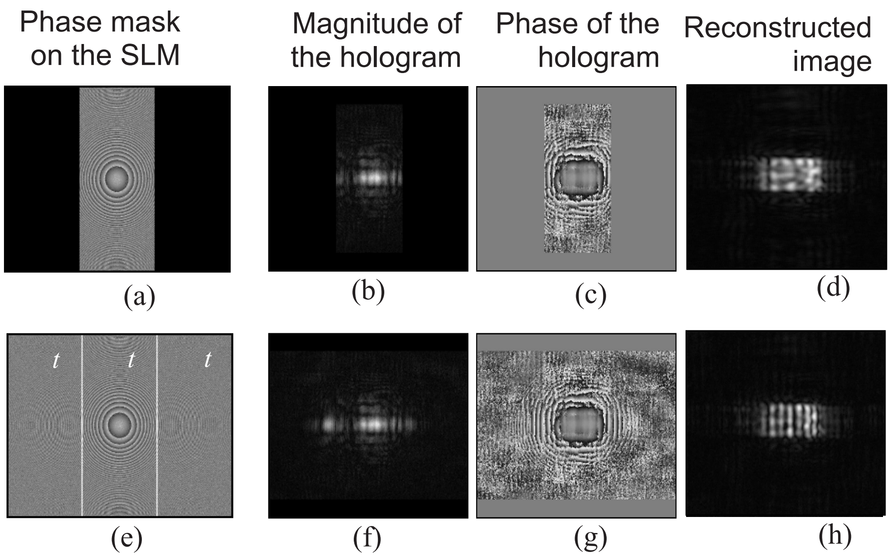

Fig. 2. Results of SAFE with the narrow aperture (Top) and with the synthetic aperture (Bottom).

In the second experiment nine different phase masks were displayed on the SLM, three for each location of the SLM-camera set; left, central and right. Each of the masks has had an actual aperture of 640×1080 pixels. Each of the three masks at every location has had one of the three different phase factors: 0^o, 120^o or 240^o. For each location of the system, the three recorded holograms have been superposed as mentioned before. Fig. 2(e) represents three masks, out of nine, each of which has been displayed at different time (indicated on each mask by t_n, n=1,2,3) and at a different location of the setup along the horizontal axis. The superposed complex-valued holographic element from each system's viewpoint is stored in the computer. Upon completing the system movement along the entire synthetic aperture, all three holographic elements are tiled to a single mosaic hologram. Figs. 2(f) and 2(g) represent the magnitude and the phase of the complete mosaic hologram, respectively. The reconstruction result of the mosaic hologram is depicted in Fig. 2(h). All of the gratings of the observed object are seen well in the reconstructed image, indicating that the synthetic aperture is wide enough to acquire most of the spectral information of the object.

4 Conclusions

In conclusion, we have proposed and demonstrated a process of recording incoherent holograms in the synthetic aperture mode. The synthetic aperture of SAFE considerably increases both the transverse and the axial resolving power. This experiment is a demonstration of a synthetic aperture radar in the visible light where the observed scene is illuminated by white light. The concept of the present system can be applied to all regimes of imaging from microscopy to telescopes, and either for 2-D or 3-D imaging.

5 References

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