Integral holography: white-light single-shot hologram acquisition

Natan T. Shaked[1*], Joseph Rosen[1] and Adrian Stern[2]

[1]*Department of Electrical and Computer Engineering,* [2]*Electrooptics Unit*
Ben-Gurion University of the Negev, P.O. Box 653, Beer-Sheva 84105, Israel
*natis@ee.bgu.ac.il

Abstract: A new method for obtaining digital Fourier holograms, under spatially incoherent white-light illumination and in a single camera shot, is presented. Multiple projections of the 3-D scene are created in the image plane of a microlens array, and a digital camera acquires the entire projections in a single shot. Then, each projection is computer processed to yield a single point in a Fourier hologram. The new method, designated as integral holography, is proved for the general case and demonstrated experimentally for a simple case.

OCIS codes: (090.0090) Holography; (110.6880) Three-dimensional image acquisition; (090.1760) Computer holography; (100.3010) Image reconstruction techniques.

References and links

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1. Introduction

Conventional holography involves the acquisition of an interference pattern created by interfering beams coming from a 3-D scene and a reference beam. The creation of this interference pattern requires a meticulous stability of the optical system, high intensity and narrow bandwidth of the light source used. These strict requirements inhibit the usage of conventional holography for many practical applications.

A partial solution to these problems is suggested by the scanning holography method [1]. According to this method, a digital Fresnel hologram can be obtained, under spatially incoherent illumination conditions, by scanning the 3-D scene with a pattern of a Fresnel zone plate, so that the light intensity at each scanning position is integrated by a point detector. However, the scanning process in this method is performed by mechanical movements, and thus the hologram acquisition is relatively slow.

In order to avoid these mechanical movements, another method for obtaining digital Fresnel holograms, named FINCH (Fresnel incoherent correlation holography), is proposed in Ref. [2]. According to this method, the spatially incoherent light coming from the 3-D scene propagates through a diffractive optical element (DOE) and is recorded by a camera. Then,

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three different holograms, each with a different phase factor of the DOE, are recorded sequentially and superposed in the computer into a digital Fresnel hologram.

A fundamentally different solution is suggested in Refs. [3,4]. According to the methods presented there, the 3-D scene is illuminated by spatially incoherent white light and viewed from multiple angles. For each view angle, the projection of the 3-D scene is acquired by a camera and processed in the computer. The result is a 2-D complex function which represents a digital hologram of the 3-D scene. This function can be encoded into a computer generated hologram (CGH) with real and positive transparency values. Then, the recorded 3-D scene can be reconstructed by illuminating the CGH transparency with a plane wave. Alternatively, digital holography techniques can be employed in order to digitally reconstruct the 3-D scene.

In spite of the great advantages presented by the above described methods and their potential of making holography attractive for many practical applications, the 3-D scene recording process in these methods is still considered long and quite complicated. This occurs because the camera has to be repositioned many times in order to obtain enough 3-D scene projections, required for the synthesis of a hologram with an acceptable resolution.

In the current paper, we present a new method for obtaining digital holograms. This method employs a microlens array (MLA), a device that is usually used in the integral imaging field [5,6], in order to capture multiple projections of the 3-D scene by using a single camera shot, but still under spatially incoherent white-light illumination. We designate the proposed method as integral holography (IH) and demonstrate it experimentally for a simple case.

2. Description of the method

The overall process of obtaining the hologram can be divided into two main stages: the recording stage and the processing stage. In the recording stage, multiple projections of the 3-D scene are captured in a single camera shot, whereas in the processing stage, mathematical operations are performed on these projections in order to yield a digital 2-D Fourier hologram.

Figure 1 shows the IH optical system used for capturing the multiple projections of the 3-D scene. As shown in this figure, an MLA is employed in order to create these multiple projections, whereas a plano-convex lens L_1, positioned at a distance of its focal length f_1 from the 3-D scene and attached to the MLA, is used in order to collimate the beams coming from the 3-D scene and thus to increase the number of microlenses participating in the process. In fact, the plano-convex lens L_1 and the MLA together can be considered as a new equivalent MLA which sees the 3-D scene at a larger distance from the MLA than the distance to the scene without the plano-convex lens L_1. A spherical lens L_2, with a focal length of f_2, projects the MLA image plane onto the camera with the magnification of $-z_2/z_1$. Then, the camera captures the entire MLA image plane in a single shot and sends it to the computer for the processing stage.

Assuming the MLA contains $(2K+1)\times(2K+1)$ microlenses, we number its microlenses by the indices m and n, so that the middle microlens is denoted by $(m,n) = (0,0)$, the upper right microlens by $(m,n) = (-K,-K)$ and the lower left microlens by $(m,n) = (K,K)$. Let $P_{m,n}(X_p,Y_p)$ be the projection created by the (m,n)-th microlens, where X_p and Y_p are the

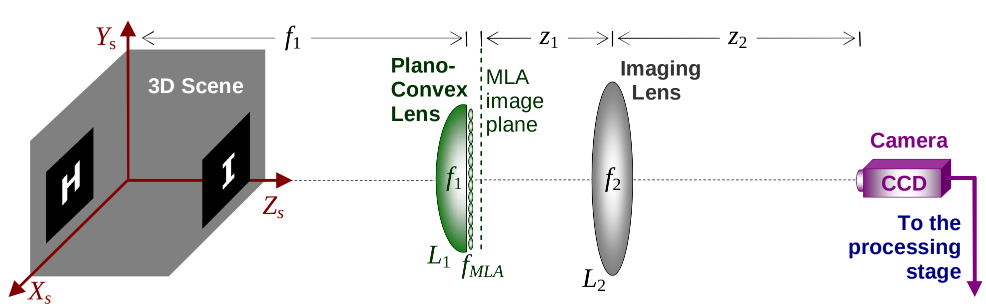

Fig. 1. The optical system used in the IH recording stage.

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axes of this projection. The MLA image plane, captured by a single camera shot in the recording stage, consists of an array of small elemental images, each obtained by a different microlens in the MLA and thus represents another projection $P_{m,n}(X_p,Y_p)$ of the 3-D scene from a different point of view. Figure 2 illustrates the processing stage of the method. In this stage, each of the previously mentioned elemental images taken from the MLA image plane is centered on the same reference point, which yields a set of new projections $P^c_{m,n}(X^c_p,Y^c_p)$. As a result of this centering the radial distance from the reference point is the same for all of the projections. Afterward, each of the centered projections is multiplied by a linear phase function, which is dependent on the relative position of the projection in the entire projection set. Finally, we sum up the result of each multiplication into a single complex value. Mathematically, this process can be described as follows:

$$H_{m,n} = \iint P^c_{m,n}(X^c_p,Y^c_p)E_{m,n}(X^c_p,Y^c_p)dX^c_p dY^c_p, \tag{1}$$

where:

$$E_{m,n}(X^c_p,Y^c_p) = \exp[-j(2\pi b/D)(mX^c_p + nY^c_p)], \tag{2}$$

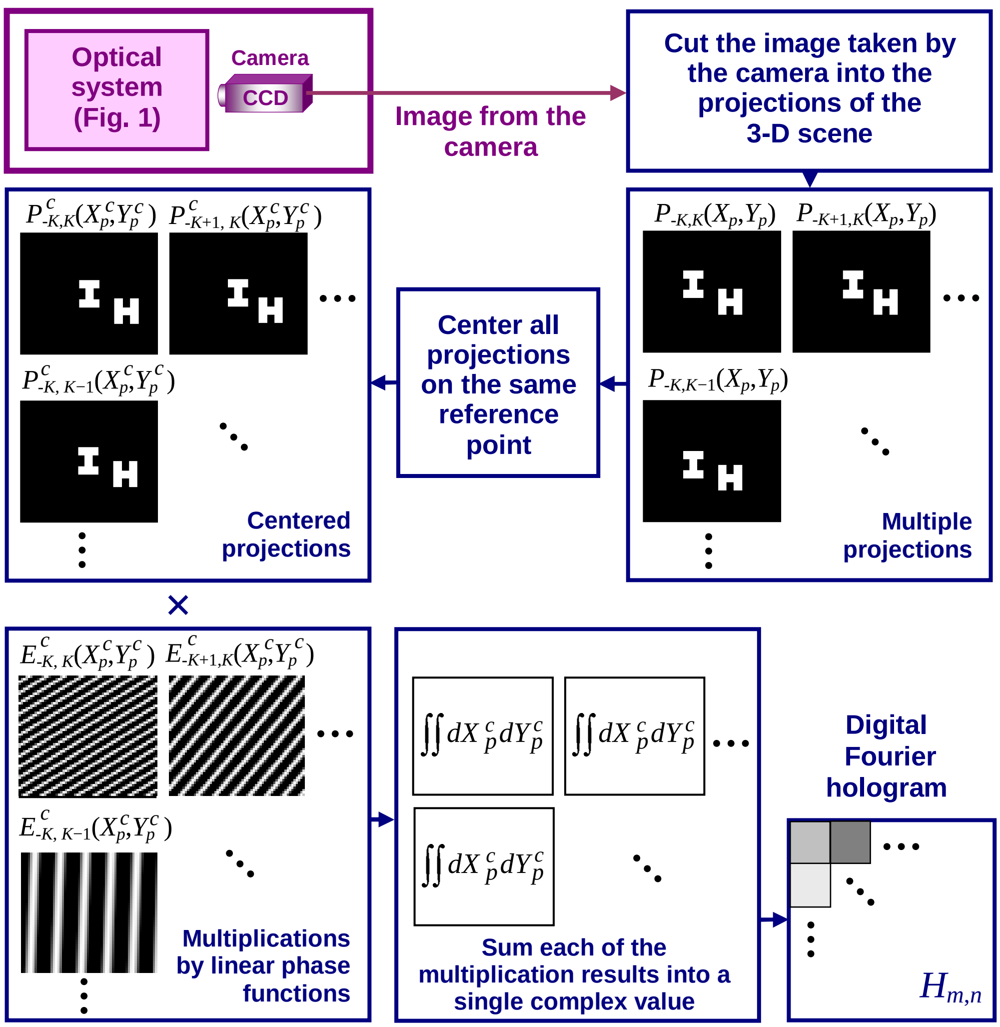

Fig. 2. Schematic of the IH processing stage.

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where D is the distance between the centers of two adjacent microlenses in the array and b is an adjustable parameter. The process is performed for each of the centered projections, which yields a 2-D complex matrix H representing the digital 2-D Fourier hologram of the 3-D scene. This hologram is equivalent to the complex amplitude in the rear focal plane of a spherical lens due to a coherent light diffracting from the same 3-D scene and propagating through this lens.

Recently, Mishina et al. [7] have demonstrated a method of calculating a CGH from elemental images captured by integral photography. Their CGH is a composite of many elemental Fresnel holograms, each created by a different microlens. On the contrary, in the IH method proposed in the current paper, each (m,n)-th pixel in the hologram is contributed only from the (m,n)-th microlens. Therefore, the entire information of the elemental images is compressed into a matrix with the number of elements which is equal to the microlens number. Another difference from the composite CGH method is that the IH hologram is of a Fourier type, and this might open many possibilities of spatial filtering and correlation on the captured images.

3. Equivalence between the proposed method and a digital Fourier hologram

In order to show that the complex matrix H indeed represents the digital Fourier hologram of the 3-D scene, let us first define the mathematical relations between point (x_s, y_s, z_s) in the 3-D scene and its projected point (x_p, y_p) located on the (m,n)-th projection plane (X_p, Y_p) obtained by the MLA. Figure 3 defines certain geometric quantities of the optical system shown in Fig. 1. Simple geometric relationships in this figure yield the following:

$$x_p = \frac{M(mD + x_s)}{1 - z_s / L}; \quad y_p = \frac{M(nD + y_s)}{1 - z_s / L}, \tag{3}$$

where M is the magnification of each of the microlenses in the array, L is the distance between the origin of the 3-D scene and the equivalent MLA (taking into account the effect of the plano-convex lens L_1). By assuming that the maximal value of z_s is much smaller than L, we can apply the approximation $(1-\alpha/\beta)^{-1} \cong 1+\alpha/\beta$, where $\alpha << \beta$, to Eq. (3) and get:

$$x_p \cong M(mD + x_s + z_s mD / L + z_s x_s / L); \quad y_p \cong M(nD + y_s + z_s nD / L + z_s y_s / L). \tag{4}$$

As explained above, each projection $P_{m,n}(X_p, Y_p)$ is centered on the same reference point, which yields the centered projection $P^c_{m,n}(X^c_p, Y^c_p)$. Due to this centering, we subtract MmD and MnD from x_p and y_p, respectively, in order to get x^c_p and y^c_p located on the centered projection $P^c_{m,n}(X^c_p, Y^c_p)$. This means that point (x_s, y_s, z_s) in the 3-D scene is projected to the point (x^c_p, y^c_p) in the centered projection according to the following formula:

$$x^c_p \cong M(x_s + z_s mD / L + z_s x_s / L); \quad y^c_p \cong M(y_s + z_s nD / L + z_s y_s / L). \tag{5}$$

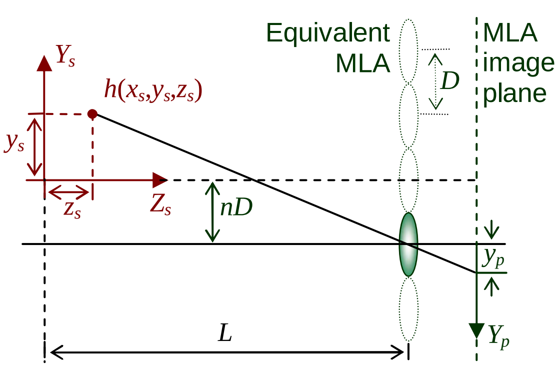

Fig. 3. Cross section of part of the optical system shown in Fig. 1.

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Let us take an infinitesimal element with the size of $(\Delta x_s, \Delta y_s, \Delta z_s)$, located on the 3-D object surface at coordinates (x_s, y_s, z_s) and having the value of $h(x_s, y_s, z_s)$. This infinitesimal element should appear on all of the centered projections planes, but at a different location on each plane. Therefore, based on Eq. (1), the amplitude distribution on the (m,n)-th centered projection plane, caused by a single source point (SSP) in the 3-D scene, is given by:

$$\begin{aligned} H_{m,n}^{SSP}(x_s, y_s, z_s) &= \iint [h(x_s, y_s, z_s)\Delta x_s \Delta y_s \Delta z_s \delta(X_p^c - x_p^c, Y_p^c - y_p^c)] E_{m,n}(X_p^c, Y_p^c) dX_p^c dY_p^c \\ &= h(x_s, y_s, z_s) E_{m,n}(x_p^c, y_p^c)\, \Delta x_s \Delta y_s \Delta z_s, \end{aligned} \tag{6}$$

where δ is the Dirac delta impulse. Substituting Eqs. (2) and (5) into Eq. (6) yields:

$$\begin{aligned} H_{m,n}^{SSP}(x_s, y_s, z_s) = h(x_s, y_s, z_s) \exp\{-j(2\pi bM/D)[m(x_s + z_s mD/L + z_s x_s/L) \\ + n(y_s + z_s nD/L + z_s y_s/L)]\}\, \Delta x_s \Delta y_s \Delta z_s. \end{aligned} \tag{7}$$

Taking into account the fact that the overall distribution of the hologram is a volume integral of all points on the 3-D object, we get the following:

$$\begin{aligned} H_{m,n} = \iiint H_{m,n}^{SSP}(X_s, Y_s, Z_s)\, dX_s dY_s dZ_s = \iiint h(X_s, Y_s, Z_s) \exp\{-j(2\pi bM/D) \\ \times [mX_s + nY_s + (Z_s D/L)(m^2 + n^2) + (Z_s/L)(mX_s + nY_s)]\} dX_s dY_s dZ_s. \end{aligned} \tag{8}$$

Let us use the continuous variables $(u/D, v/D)$ instead of the discrete variables (m,n) and assume that $L >> 2\pi M u_{\max} \delta Z_s \delta X_s$ and $L >> 2\pi M v_{\max} \delta Z_s \delta Y_s$, where $(\delta X_s, \delta Y_s, \delta Z_s)$ is the size of the 3-D scene, and $u_{\max}$ and $v_{\max}$ are the maximal horizontal and vertical coordinate values on the Fourier plane, respectively. Under this assumption, we can neglect the last term inside the integral of Eq. (8) and get the following equation:

$$H(u,v) \cong \iiint h(X_s, Y_s, Z_s) \exp\left\{-\frac{j2\pi bM}{D^2}[uX_s + vY_s + (Z_s/L)(u^2 + v^2)]\right\} dX_s dY_s dZ_s. \tag{9}$$

Eq. (9) has the same functional behavior of the complex amplitude obtained for a Fourier hologram [3] and therefore the proposed IH system indeed creates a digital Fourier hologram.

The transversal minimal distance Δx_s and the axial minimal distance Δz_s that can be resolved through the optical system are given as follows:

$$\Delta x_s = \max\{1.22\lambda L/D,\ p_c z_1/(Mz_2)\}; \qquad \Delta z_s = \Delta x_s L/(KD), \tag{10}$$

where λ is the average wavelength used ($\lambda \approx 0.5\mu m$) and p_c is the pixel size of the recording camera. The axial optical resolution given in Eq. (10) is determined by projecting the axial minimal resolved distance Δz_s on the transverse object plane of the most extreme microlens in the MLA. The parameter b is determined so that the computed Fourier hologram given by Eq. (9) maintains the maximum possible resolution of the system given by Eq. (10). Therefore, the parameter b is given as follows:

$$b = D/(MK\Delta x_s). \tag{11}$$

4. Experimental results

We have experimentally implemented the optical system shown in Fig. 1. Two bright letters, ‘I’ and ‘H’, have been positioned in a dark environment and illuminated by a spatially incoherent white-light source. The size of the letters is 2 cm × 2 cm each, and the distances between them on the optical axis Z, the vertical axis Y and the horizontal axis X are 10 cm, 1 cm and 3 cm, respectively. The plano-convex lens L_1, attached to the MLA on the side of the 3-D scene, has a diameter of 10 cm and a focal length of f_1 = 40 cm. Therefore, the distance between the 3-D scene and the MLA is about 40 cm as well. A hexagonal-format MLA, 5 cm in diameter, with a pitch of 500 μm and with 115×110 microlenses is used. However, only the

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65×65 middle microlenses are employed in the experiment. The focal length of each of the microlenses in the MLA is f_{MA} = 3.3 mm. In order to project the MLA image plane onto the camera with the magnification factor of −2, we have used a spherical imaging lens L_2 with a focal length of f_2 = 10 cm. A CCD camera (PCO, Scientific 230XS), containing 1280×1024 pixels and an 8.6×6.9 mm^2 active area, has been used. We have concatenated several camera planes due to the relatively low number of pixels in our CCD camera (compared to other cameras on the market today). Note that the use of the available hexagonal-format MLA, rather than a square-format MLA, decreases the quality of the reconstruction because of the mismatch between the MLA and the square-format grid of the computer. Therefore, the results in this section should be considered as a simple proof-of-principle demonstration.

Figure 4 shows several chosen projections cut from different parts of the overall MLA image plane which is captured by the camera. As seen in this figure, the relative positions of the two letters change as a function of the location of the projection on the entire MLA image plane. This is the effect that leads to the 3-D properties of the hologram obtained in the end of the process. After capturing the MLA image plane by the CCD camera, we start the processing stage by cutting each of the projections from the MLA image plane and centering the projections on a chosen reference point. The cutting process is performed semi-automatically by detecting the first and the last elemental images in each row of the MLA image plane. Then, the distance between these two extreme elemental images is divided by the number of microlenses utilized in each row of the MLA and the elemental images are

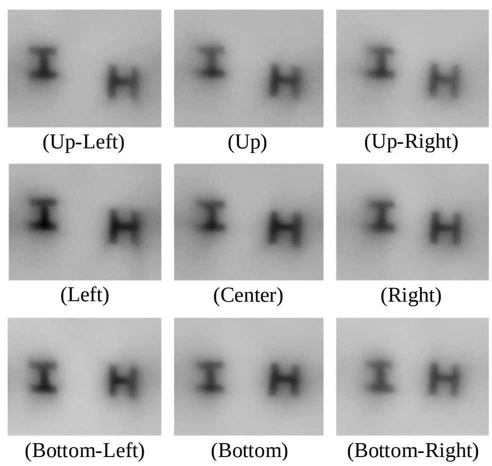

Fig. 4. Several projections taken from different parts of the MLA image plane captured by the camera (contrast-inverted picture).

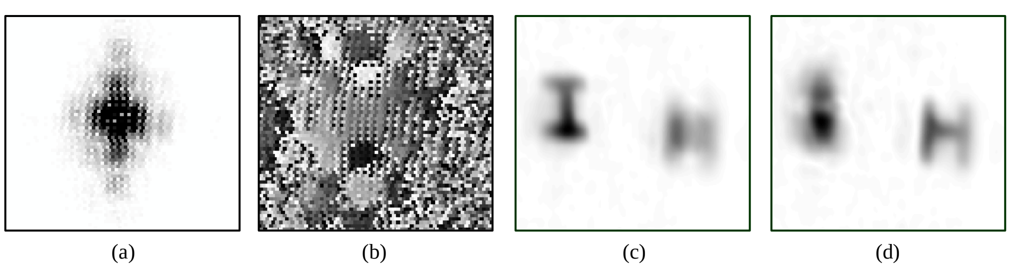

Fig. 5. (Contrast-inverted pictures) (a) Magnitude and (b) phase of the Fourier hologram obtained after performing the processing stage on the captured projections; (c) Reconstruction of the hologram at the best focus distance of the letter ‘I’; (d) Reconstruction of the hologram at the best focus distance of the letter ‘H’. The continuous propagation from the plane shown in (c) to the plane shown in (d) is presented in the linked movie.

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cut from the MLA image plane accordingly. Afterward, digital correlation with a known pattern taken from any of the elemental images is employed in order to fix a common reference point for all the elemental images. Completely automatic cutting and centering methods may be possible and will be considered in our future research.

In the experiment, we have chosen the common reference point to be the center of the letter ‘I’. The meaning of this process is setting the origin of the 3-D scene on the plane of the letter ‘I’. Each of the projections is normalized (divided by its maximal value), multiplied, according to Eqs. (1) and (2), by a linear phase function dependent on the position of this projection in the entire set of projections and then summed up into a single complex value in the Fourier hologram H. The magnitude and the phase of the Fourier hologram obtained in the experiment are shown in Figs. 5(a) and 5(b), respectively. In order to digitally reconstruct the 3-D scene recorded into this hologram, a 2-D inverse Fourier transform is applied to the 2-D complex matrix representing the hologram.

Figure 5(c) shows the results of this inverse Fourier transform. In the reconstruction plane obtained by this operation, the letter ‘I’ is in focus, whereas the letter ‘H’ is out of focus. A Fresnel propagation is applied to this reconstruction plane by convolving it with a quadratic phase [8]. The purpose of this propagation is to reveal other planes along the optical axis of the 3-D scene reconstruction. Figure 5(d) shows the reconstruction in the best focus plane of the letter ‘H’. In this figure, the letter ‘I’ is out of focus. This validates that a volumetric information is indeed encoded inside the hologram synthesized by the proposed method.

5. Conclusions

We have presented and experimentally demonstrated a new method for obtaining digital Fourier holograms under conventional spatially incoherent illumination and in a single camera shot. The new method, designated as integral holography, uses an MLA in order to capture multiple projections of the 3-D scene simultaneously. By integrating the MLA into a digital camera, it may be possible in the future to design a simple and portable holographic camera which can be useful for a variety of practical applications.

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