Holographic Three-dimensional Computer-Aided Imaging

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Abstract

Recent developments in a new method of holographic computer-aided imaging will be reviewed. Our hologram is computed from angular viewpoints of the observed 3D scene. The recorded data are processed to yield a 2D computer-generated hologram. When this hologram is illuminated properly, a 3D image of the scene is reconstructed.

1. Introduction

Conventional holographic recording demands special stability of the optical system and relatively intense light with a high degree of coherence between the involved beams. These requirements have prevented hologram recorders from becoming as widely used for outdoor photography as conventional cameras. In this article we will review recent developments in a new method of holographic computer-aided imaging. In this method, a hologram is computed from a set of angular projections of the observed 3D object, recorded by a conventional digital camera [1]. The recorded data are numerically processed to yield a two-dimensional complex function, which is then encoded as a computer-generated hologram (CGH). When this hologram is illuminated by a plane wave, a 3D real image of the object is reconstructed. The main feature of this hologram is that its transparency values are identical to a Fourier hologram recorded by an interference between two laser beams. It is important to note that this hologram is not related to the well-known multiplex or stereoscopic holograms. The main advantage of this technique is that, although objects in the scene are recorded by a conventional digital camera without wave interference, the process yields a hologram of the observed scene with 3D features.

Several different configurations of this technique are applied for various applications. For instance, integrating spatial filtering into the process of the hologram's computation yields a new pattern recognition system, which is capable of recognizing [2] and tracking targets in the 3D space. The technique of scanning the scene is another issue to be considered. There are different methods of observing the scene and consequently different holograms are obtained by these methods. The two main examples are, on one hand, a hologram computed from a set of different viewpoints along a horizontal arc around the observed object [1]. On the other hand, using a micro-lens array enables us to capture the scene from horizontal as well as vertical points of view, and thus such a technique yields a different type of hologram.

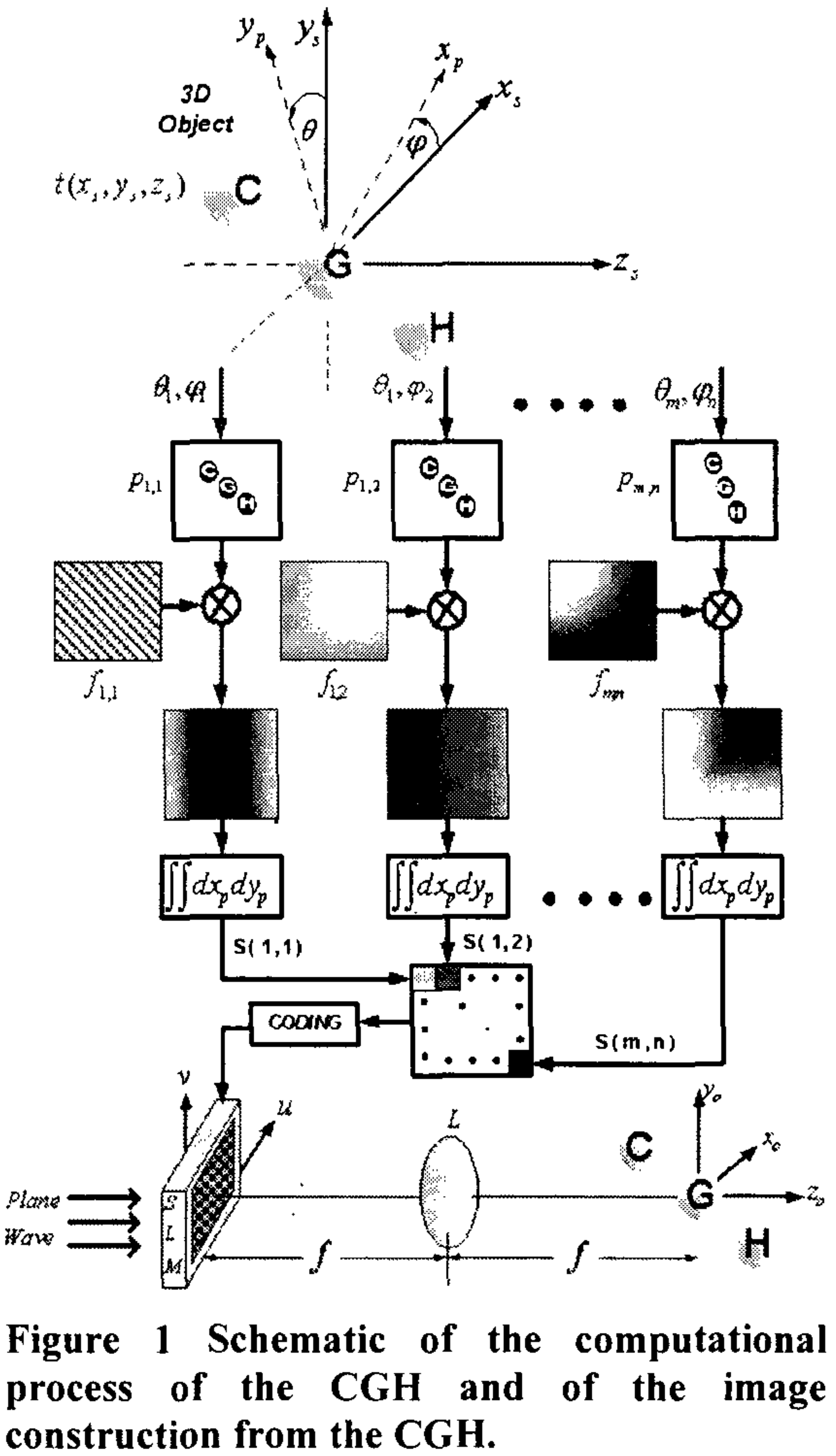

Figure 1 Schematic of the computational process of the CGH and of the image construction from the CGH.

2. Projections Based Algorithm for Synthesizing CGH

The first step in our algorithm of synthesizing the CGH is to create in the computer memory a 3D object that later will be reconstructed by this CGH. Next the set of the object's angular projections are computed. Then a series of mathematical operations are done on the set of projections, the end product of which is a single 2D complex matrix. Finally, the complex matrix is coded to a real and positive-valued matrix to be used as a holographic transparency. The complete computational process is illustrated schematically in the center of Fig. 1; the reconstruction stage is shown in the lower part of the figure.

Let us describe this series of steps more rigorously. The object denoted by $t(x_s,y_s,z_s)$ is defined in a Cartesian coordinate system (x_s,y_s,z_s) as shown in the upper part of Fig. 1, where z_s is the longitudinal axis (the virtual optical axis). For each pair of angles ϕ_m, θ_n in the horizontal and vertical directions, respectively, the m,nth perspective of the object is computed. For each ϕ_m, θ_n, the projected image $P_{mn}(x_p,y_p)$ is recorded in the computer memory as a 2D matrix, where (x_p,y_p) is the coordinate system of each projection.

In the next step of the algorithm, each projected image from the view angle (ϕ_m,θ_n) is multiplied by the exponential function $f_{mn}=\exp[-2j\pi b(x_p\sin\phi_m+y_p\sin\theta_n)]$. This product is then summed to get a single complex value in the following way:

$$s(m,n)=\iint p_{mn}\left(x_p,y_p\right)\exp\left[-j2\pi b\left(x_p\sin\varphi_m + y_p\sin\theta_n\right)\right]dx_p dy_p, \tag{1}$$

where b is a real-valued constant. The next projected image, viewed from an adjacent point having a small incrementally changed angle, is calculated, and a new value, say $s(m+1,n)$, is obtained. The values obtained from Eq. (1) are assembled into a complex matrix. Every value of this matrix corresponds to a different point of view and the matrix is arranged in the same order as the projected images are observed. However, the connections between the hologram points and the various perspectives exist only in the synthesis stage. In the image reconstruction stage, the resulting hologram is global in the sense that each point of the hologram is radiated onto the entire volumetric image. Since the matrix values are complex, the hologram must be coded into real and nonnegative values of a holographic transmittance. When this coded matrix is coherently illuminated, it yields a holographic reconstruction of the object, as is shown in the lower part of Fig. 1.

The same algorithm can be employed on a set of angular perspectives of realistic objects captured by a digital camera from some realistic scene [1], as actually demonstrated by Fig. 2. However, this algorithm is different from that of Fig. 1, because now the scene is observed only from horizontal viewpoints.

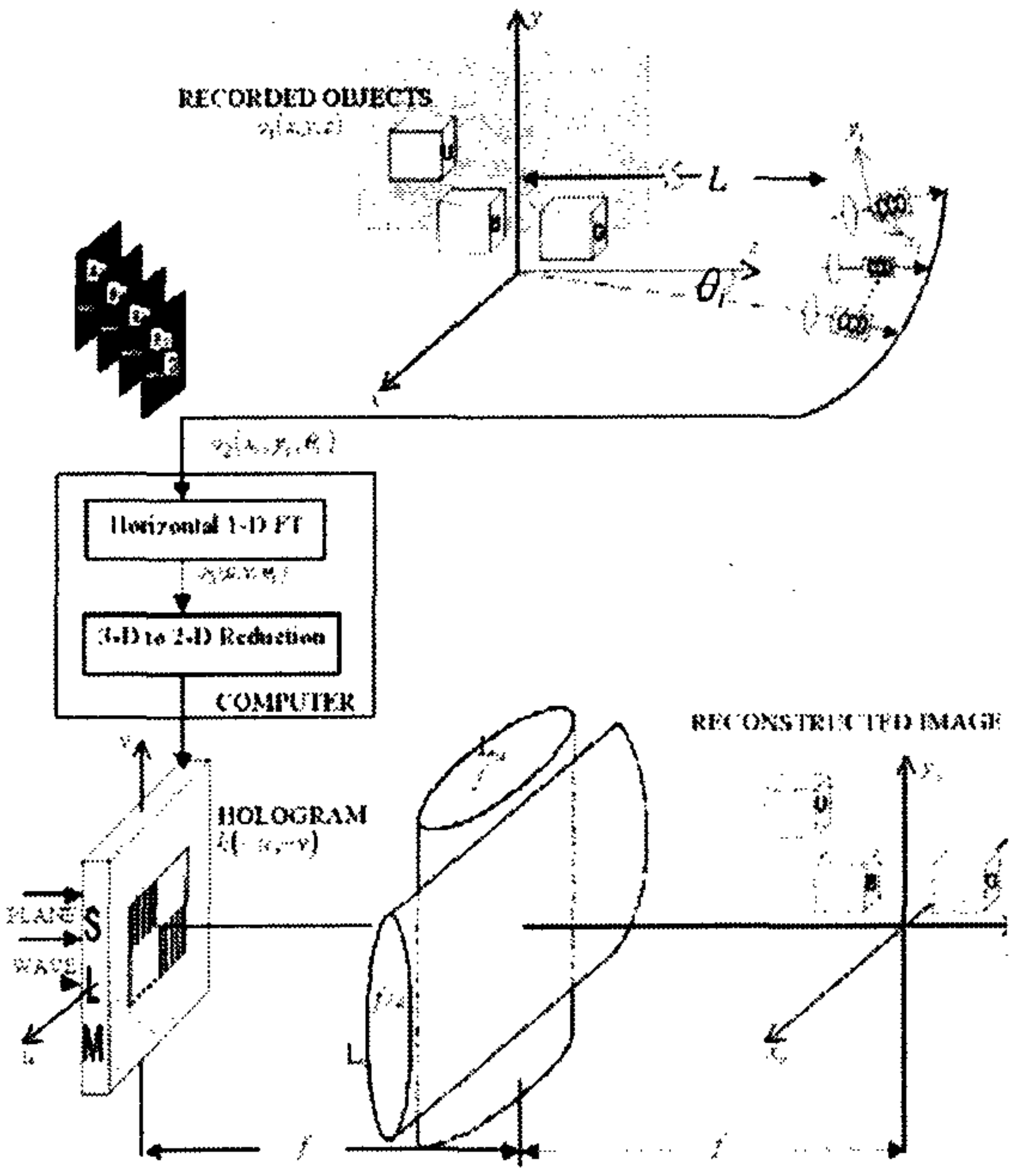

Figure 2 Schematic of the second holographic recording and reconstructing systems.

The recording setup is shown in the upper part of Fig. 2. A 3-D object function $o_1(x, y, z)$ is located at the coordinate system (x, y, z). $o_1(x, y, z)$ represents the intensity reflected from all the observed bodies in the scene. From each point of view, the camera observes the scene through an imaging lens located at a distance L from the origin of (x, y, z). The camera is actually shifted in constant angular steps along a horizontal arc centered about the origin, and it is always directed to the origin. The angle between the camera's optical axis and the z axis is denoted θ_i. For each θ_i, the projected image $o_2(x_i,y_i,\theta_i)$ is recorded into the computer, where (x_i,y_i) are the coordinates of the image plane of each camera. Inside the computer, each projected function is processed in a similar way given by Eq. (1). The hologram values are now stored in computer memory in the form of the complex function. To reconstruct the image from the hologram, the computer should modulate some transparency medium with the hologram values. If the transparency cannot be modulated directly with complex values, one of many well-known coding methods for CGHs might be used. The spatial light modulator (SLM) that we use in this study can modulate the intensity of light with continuous gray tones. Therefore, the complex function obtained by Eq. (1) is coded into a positive real transparency. This holographic transparency is displayed on the SLM and reconstructed by the setup shown in the lower parts of Figs. 1 or 2.

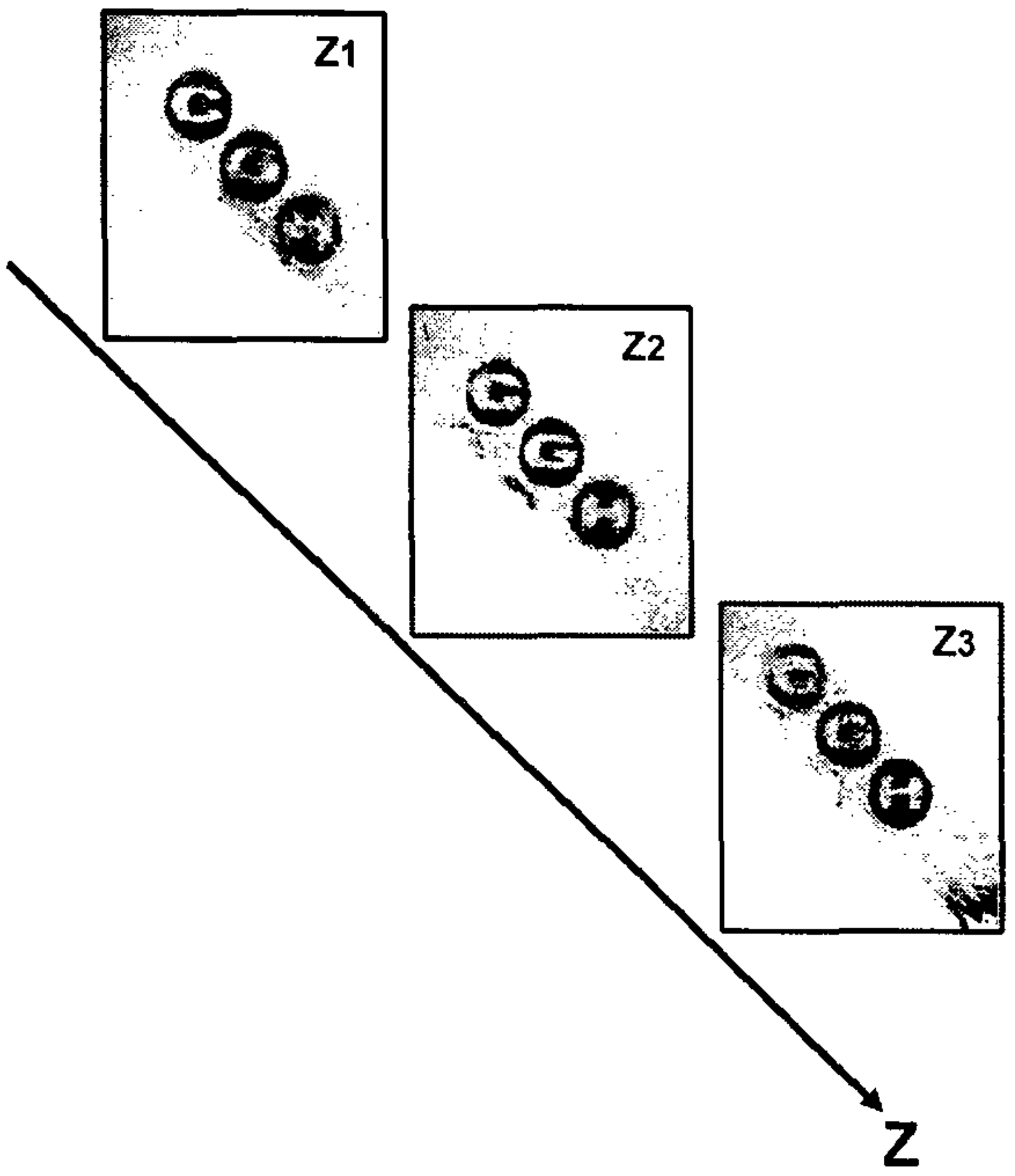

Figure 3 Experimental results of the first diffraction order obtained from the CGH at the vicinity of the back focal plane of L for three transverse planes at z_1=715 mm, z_2=750 mm, and z_3=781 mm.

3. Optical Construction of 3D Objects

The first proposed algorithm was applied on an example of computer-designed 3D objects. The construction stage was demonstrated by an optical experiment on the system shown in Fig. 1. The object used for 3D imaging was composed of three spheres carrying the letters C, G, and H, each of which was located at different depth from the viewer. The coded CGH was displayed on an SLM. A collimated beam from a He–Ne laser illuminates the SLM and propagates through the spherical lens towards the observer. The real image of the computer-designed, 3D object is constructed in the vicinity of the back focal plane of the lens with a focal length of 750 mm. The parameter b in this example was chosen to be equal to 0.9. Figure 3 shows the reconstruction results observed by the CCD for three different transverse planes along the optical axis at distances of 715, 750, and 781mm (±5 mm) from the lens (the distance between the lens and the SLM was 75 mm). The contrast in these figures has been inverted for better visualization. Obviously, the effect, in which every letter is in focus at a different transverse plane, appears in Fig. 3. In comparison with computer simulation, the construction of the object is noisier; this is due to the use of the SLM and the speckle nature of the laser.. SLMs, although they have not reached the technological level of a good holographic transparency, widen the opportunity of implementing dynamic CGHs. This is the main reason that SLM is preferred here over otherwise more suitable holographic transparencies.

In another experiment, the recording was carried out by the system shown in the upper part of Fig. 2 and the reconstruction was demonstrated by an optical experiment shown in the lower part of Fig. 2. The scene observed contains three cubes of size 5 cm × 5 cm × 5 cm located at different distances from the camera.

The reconstruction results from the hologram obtained from optical experiment are depicted in Fig. 4. Figure 4 shows the reconstructed intensity at three transverse planes along the optical axis. At each transverse plane, in the left-hand diffraction order a different letter of a different cube is in focus; thus reconstruction of the 3-D objects is demonstrated.

4. Conclusion

A new process of computing holograms of computer designed 3D objects has been proposed and demonstrated. By fusion of multiple projections of the object, a 2D function has been obtained that contains 3D information of the object. The resulting CGH is equivalent to an optical Fourier hologram of a realistic 3D scene. The experimental construction was successfully demonstrated, thus indicating the potential of the technique for 3D displays.

Possible applications of the suggested CGH are in areas where the 3D representation is required. Areas such as computer-aided design, computer graphics, virtual reality, 3D work stations, tomography, and holographic cameras might benefit from the proposed method. Since our hologram is classified as a Fourier hologram, it can also be applied to the areas of object recognition and target tracking in 3D space.

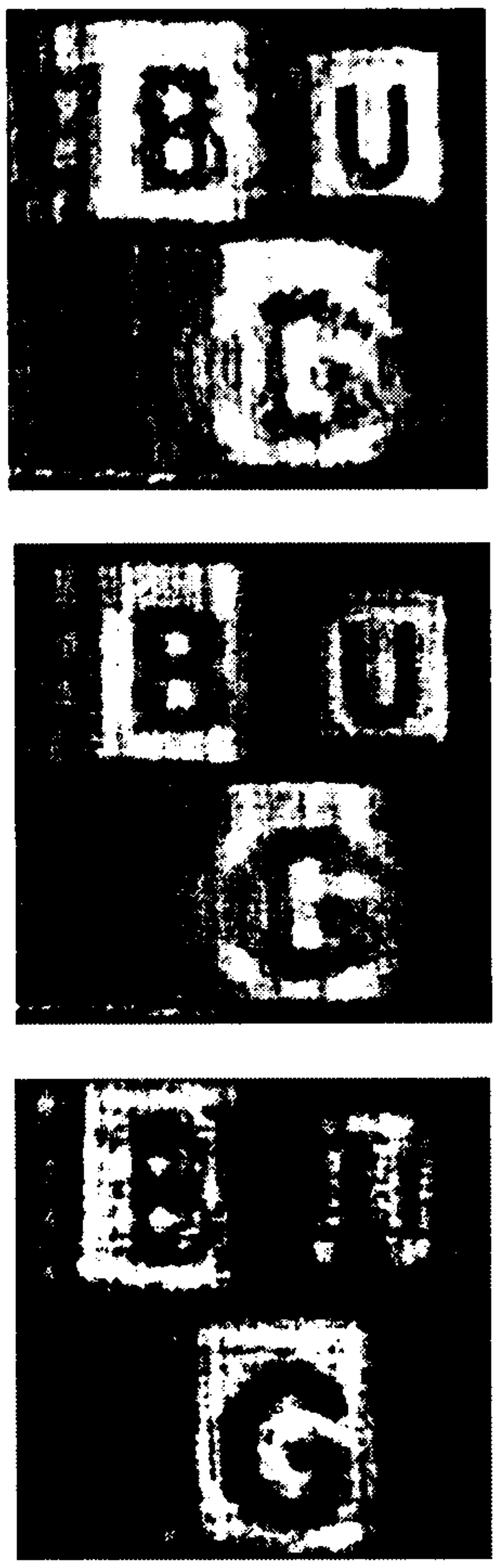

Figure 4 Experimental results from the second hologram at the vicinity of the back focal point of Fourier lens for three transverse planes at (a) z_o=20.5 cm, (b) z_o= 2.5 cm, (c) z_o=6 cm.

5. References

[1] Y. Li, D. Abookasis, and J. Rosen, Appl. Opt. 40, 2864 (2001).

[2] Y. Li and J. Rosen, J. Opt. Soc. Am. A 19, 1755 (2002).