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Three-Dimensional Television using Optical Scanning Holography

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Abstract

We first review a real-time three-dimensional (3-D) holographic recording technique called optical scanning holography (OSH) and discuss holographic reconstruction using spatial light modulators (SLMs). We then present how the overall system can be used for 3-D holographic television (TV) display with a wide-angle view of a 3-D image, and address some of the issues encountered. Finally, we suggest some techniques to alleviate the issues encountered in such a 3-D holographic TV system.

Keywords : optical scanning holography, holographic TV system, holographic information reduction, twin-image elimination.

1. Introduction

The first television transmission of a hologram was demonstrated in 1966 [1]. The interference between the Fresnel diffraction pattern of an object transparency and an off-axis plane wave formed a spatial carrier-frequency hologram to be recorded by a TV camera. The holographic information was then transmitted over closed-circuit TV, displayed on a 2-D monitor, and photographed to form a hologram, which was displayed subsequently by a coherent optical system. Since a hologram has a tremendous amount of information, information reduction techniques have been investigated in order to alleviate the problems associated with reduced image resolution and restricted field of view upon holographic reconstruction. In addition, if holographic information is to be refreshed at a TV rate, information reduction techniques can lower data transmission rate through the channel linking the holographic acquiring end and the holographic reconstruction/display end. Indeed live 3-D TV using hologram formation and transmission is a formidable problem. Nevertheless, much progress has been made [2-16] and novel devices have been invented [17-19].

In this paper, we discuss the use of optical scanning holography (OSH) to achieve holographic recording upon optical scanning the object [13]. This way of acquiring holographic information does not suffer from the limited spatial resolution of the TV camera used for acquiring holographic information. Also, twin-image noise can be eliminated without the use of an off-axis plane wave, thereby lowering the data transfer rate for transmission and the spatial resolution requirement of spatial light modulators (SLMs) for display. In addition, optical scanning holography can operate in an optically incoherent mode, whereby making speckle-free holographic imaging possible for high-resolution applications. For holographic reconstruction, we will concentrate on coherent spatial light modulator reconstruction and make some remarks.

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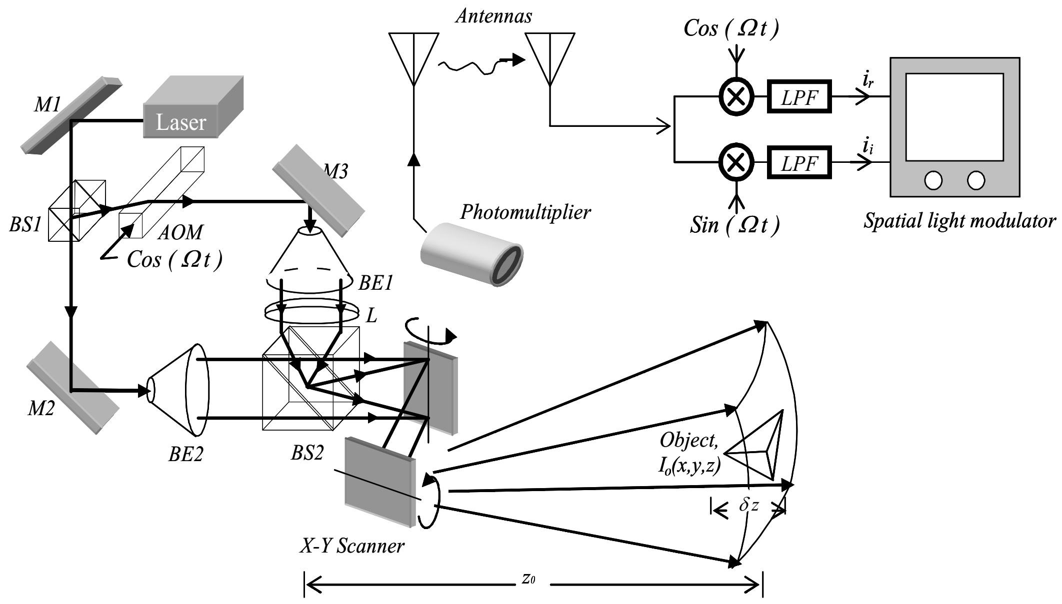

Fig. 1. 3-D Television System Using Optical Scanning Holography (M's, mirrors; AOM, acousto-optic modulator; BSl, 2, beam splitter; Bel, beam expanders; L, focusing lens; electronic multiplexer; LPF, low pass filter).

2. Optical Scanning Holography (OSH) for Holographic Real-time Recording

OSH is a technique in which holographic information of a target can be obtained by 2-D optical heterodyne scanning [13]. The basic setup is shown in Fig. 1. In the figure, the laser beam is split into two paths by beam splitter BS1. The frequency of the upper laser beam is up-shifted by frequency Ω through an acousto-optic frequency shifter (AOFS). The two laser beams are then collimated by $10\times$ beam expanders (BE1 and BE2). Lens L1 provides the spherical wave after beam splitter BS2. Beam splitter BS2 combines the collimated plane wave and the spherical wave. The superposition of the plane wave and the spherical wave gives the so-called time-dependent Fresnel zone pattern (TDFZP) of the form $\sin[\,(\pi/\lambda z)(x^2+y^2)+\Omega t]$, where z is the distance measured from beam splitter BS2 to the target, $I_0(x,y;z)$, and λ is the wavelength of the He-Ne laser. This TDFZP is then projected onto the target and scanned in a 2-D raster covering the area of the target object. The photomultiplier collects all the light and its heterodyne current output is given by

$$i_\Omega(x,y) \propto \int \sin[\,(\pi/\lambda z)(x^2+y^2)+\Omega t] \otimes I_0(x,y;z)dz \tag{1}$$

where $I_0(x,y;z)$ is the intensity distribution of the object located at z away from the x-y scanner, $\otimes$ denotes two-dimensional correlation involving transverse x, y coordinates. Note that x = x(t) and y = y(t) are both function of time, and the integration of z is over the depth of the target object. It is important to note that the heterodyne current $i_\Omega(x,y)$ has a carrier frequency Ω, which can now be radiated through a transmitting antenna. At this point, the holographic acquiring end is complete.

3. Holographic Beconstruction using Spatial Light Modulator

At the receiving stage, an antenna picks up the transmitted signal and the signal is to be electronically processed as shown in the figure and finally we have two processed currents i_r and i_i as outputs. For example, when $i_\Omega(x,y)$ is multiplied by $\cos(\Omega t)$ and then

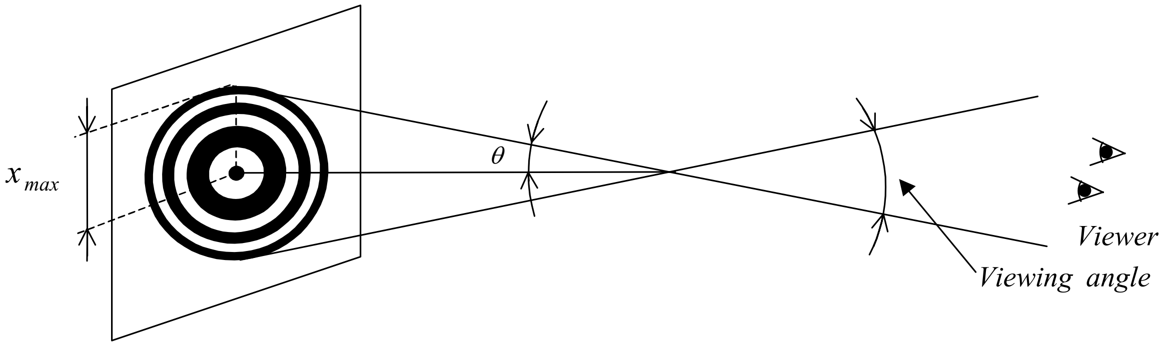

Fig. 2. Viewing angle for on-axis point object hologram.

lowpass-filtered, we can extract the phase of $i_\Omega(x,y)$ to give $i_r = \int \sin[(\pi/\lambda z)(x^2+y^2)] \otimes I_0(x,y;z)dz$. When the current is displayed in synchronization with the signals used to drive the x-y scanner, we have a 2-D record and the record is called the sine-hologram, $H_{sin}(x,y)$ [20]:

$$H_{sin}(x,y) = \int \sin[(\pi/\lambda z)(x^2+y^2)] \otimes I_0(x,y;z)dz . \tag{2a}$$

Similarly, for the processed output current i_i, we have the cosine-hologram:

$$H_{cos}(x,y) = \int \cos[(\pi/\lambda z)(x^2+y^2)] \otimes I_0(x,y;z)dz . \tag{2b}$$

The holograms can be combined to become a complex hologram:

$$\begin{aligned} H_j(x,y) &= H_{cos} - jH_{sin} \\ &= \int \exp[-j(\pi/\lambda z)(x^2+y^2)] \otimes I_0(x,y;z)dz \end{aligned} \tag{3}$$

This hologram can be inputted to a phase spatial light modulator (SLM) for optical holographic reconstruction. Alternatively, we can convolve digitally the hologram with the free-space impulse response [21], $h(x,y;z) = \frac{j}{\lambda z}\exp[-j(\pi/\lambda z)(x^2+y^2)]$, and this corresponds to optical reconstruction without twin image noise at a distance z from the hologram by illuminating the hologram with a plane wave.

4. Holographic TV Considerations and Issues

Let us now consider the overall holographic display system in some detail. For simplicity, we take the object to be an on-axis point object located at z_0, as shown in fig. 1. Hence $I_0(x,y;z) = \delta(x,y;z_0)$ and according to eq. (2b), the point-object hologram is $H_{cos}(x,y) = \cos[(\pi/\lambda z_0)(x^2+y^2)]$ An instantaneous spatial frequency along the x-direction within the hologram is. $f_{inst}(x) = (1/2\pi)(d/dx)(\pi/\lambda z_0)(x^2) = (x/\lambda z_0)$ Now by matching $f_{inst} = f_o$, the spatial resolution of a spatial light modulator, we can find the size of the limiting aperture, $x_{max} = \lambda z_0 f_0$, of the hologram. Defining the numerical aperture of the hologram as $NA = \sin\theta = x_{max}/z_0$, we have $NA = \lambda f_0$, where 2θ is the viewing angle, as defined in fig. 2, for on-axis Fresnel-zone plate reconstruction. According to the Nyquist sampling, the sampling interval $\Delta x \le 1/2f_0$, and hence, in terms of NA, we have $\Delta x \le \lambda/2NA$. Assuming the size of the SLM is 1×1, the number of samples (or resolvable pixels) is $N = (1/\Delta x)^2$, and in terms of NA, we have $N = (1\times 2NA/\lambda)^2$. Therefore, for a full parallax 20 mm-by- 20 mm on-axis hologram that is presented on a SLM, $\lambda = 0.6\ \mu m$, and a viewing angle of 60 degrees, the required number of resolvable pixels is about 1.1 billion in the SLM, well beyond the current capabilities of real-time SLMs. As an example, Hamamatus's electron-beam-addressed spatial light modulator (EBSLM) has a spatial resolution about $f_o = 8$ lp/mm, which gives the viewing angle of about 0.6 degrees. Obviously, it is not suitable for 3-D display. Nevertheless, 2-D displays of holograms are adequate [10]. However, the EBSLM system can be used to update holograms at video rate if 2-D display (or sequential 2-D display along depth) of holograms is desired. In what follows, we will discuss some issues encountered in 3-D holographic TV and provide some solutions for the problems.

4.1 Off-axis holography issue

Returning to the spatial resolution requirement of SLMs, we can see that for off-axis holograms, $f_{inst}(x) = f_c + (x/\lambda z_0)$, where $f_c = \sin\theta_r/\lambda$ is the carrier frequency of the off-axis hologram and θ_r is the angle of the off-axis plane wave reference [21]. Off-axis holography is used to alleviate the well-known twin-image noise in on-axis holography. For θ_r=30 degrees, f_c is about 1300 cycle/mm, which is well beyond the capabilities of modern real-time SLMs. Hence we see that the use spatial carrier demands recording media of high resolution. To alleviate the problem, the use of on-axis holography has become more important and relevant for holographic 3-D display [22]. There are some modern and novel ways of using on-axis holography with complete twin-image elimination [23, 24].

4.2 Holographic information reduction

The calculated 1.1 billion pixels in the SLM is certainly well beyond the current capabilities of real-time SLMs. However, since we are used to looking at the world with our two eyes more or less on a horizontal level, we are usually satisfied with only horizontal parallax. Hence, for a 256 vertical lines, the number of pixels required is $256\times(1/\Delta x)$ ~ 8.5 million if vertical parallax is eliminated, and the possibility with real-time holographic TV becomes tangible. This technique of information reduction indeed is the well-known principle of rainbow holography [25]. Optical scanning holography with horizontal parallax is possible if we scan the objects with a 1-D FZP, which can be done, for example, by masking the 2-D FZP with a slit. The slit will be placed between beamsplitter BS2 and the scanning mirrors. This information reduction is also important for data transmission consideration. As calculated previously, a single frame of 20 mm × 20 mm hologram having a viewing angle of 60 degrees requires about 1.1 billion pixels on the SLM. To update such a frame with 8-bit resolution at 30 frames per second, a serial data rate of 1.1 billion samples/frame × 8 bits/sample × 30 frames/sec = 0.26 Terebit/sec is required for full parallax. However, by sacrifying vertical parallax, the data rate becomes 2 billion bits per second, which is manageable with advanced modern optical communication systems [26].

5. Concluding Remarks

We have considered 3-D TV using optical scanning holography for holographic recording and spatial light modulators for display. Some issues encountered with such technique are explained and suggestions for improvements are discussed. While we have discussed two important issues such as the use of on—axis holography and horizontal parallax to achieve 3-D display, other SLM issues such as phase uniformity and contrast ratio are also critical, but not discussed in the present paper. As far as the transmission of holographic information is concerned, current technologies can handle a small 20 mm by 20 mm hologram (with viewing angle of 60 degrees) transmission at video rate. As for the issue of SLMs, one of the bottlenecks we discussed is its limited spatial resolution. Using some of the best quality SLMs commercially available (100 lp/mm), the achievable viewing angle is about 7 degrees [27]. In the movie Star Wars, Luke Skywalker's adventure begins when a beam of light comes out of the robot R2-D2 which projects a small 3-D holographic image of Princess Leia. This is tangible with current technologies. However, the "Holy Grail" for holographic display research is the realization of live 3-D and life-size interactive displays such as "The Doctor" in the science fiction series Star Trek Voyager, who is a holographically projected computer program devised by "Starfleet" as the Emergency Medical Hologram (EMH). To put things into perspective, it took over half a century, from the first adopted video standard (480 lines and 640 pixel horizontally) to nowadays high-end computer terminals (1024 lines and 1280 pixel horizontally). How long does it take to find the “Holy Grail?”

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