INVITED PAPER

Display Holography's Digital Second Act

In an authoritative discussion of digital holography, scientific underpinnings and subprocesses are described, and a connection is established between full-fledged holography and nearer term opportunities.

By V. Michael Bove, Jr., *Member IEEE*

ABSTRACT | Holography, with its stunning 3-D realism and its expressive potential, in the 1970s and 1980s seemed poised to become the next step in the evolution of visual display. Yet apart from certain specialized niches, display holograms are perhaps more rarely encountered in everyday life than they were 20 or 30 years ago. But the recent resurgence of interest in 3-D video for entertainment applications has underlined the limitations of left/right stereoscopic imaging and created a desire for more natural 3-D imagery in which no glasses are required and all perceptual cues to depth are provided in a consistent fashion. Could holography—whose transition from darkroom to digital has taken some years longer than that of photography—capitalize on this opportunity? In this paper, I examine digital developments in holographic printing, holographic projection, and holographic television, and explore connections between holographic imaging and areas such as integral imaging and telepresence.

KEYWORDS | Diffraction; display; holography; telepresence

I. INTRODUCTION

When Dennis Gabor published the short paper "A new microscopic principle" in *Nature* in 1948 [1], the work seemingly did not attract a great deal of immediate notice by either scientific or popular writers, though this research would eventually be the basis for his 1971 Nobel Prize. Remarkably, a mention of the discovery appeared in the *New York Times* [2], likely the first use of the word "hologram" in the popular press, but nearly the only one for the next 15 years.

Gabor's "on-axis" holograms were of foundational importance but the popular imagination in the 1960s was stirred by the "off-axis" (meaning that undiffracted illumination and the oppositely diffracted conjugate image did not show up in line with the desired image) transmission holograms of Leith and Upatnieks [3] and the reflection holograms of Denisyuk [4]. These provided familiar but eerily glowing and context-removed reconstructions of 3-D scenes, with no glasses or other specialized apparatus interposed between the image and the viewer. Further adding to the science-fiction aspect of holograms was their association with another futuristic technology: the laser.

By the 1970s and 1980s holograms had become not only a staple of science-fiction movies (in some, such as *Logan's Run* and *The Man Who Fell to Earth*, the apparent holograms really were holograms, not cinematic special effects) but also a part of everyday life, with embossed holograms appearing as security seals on credit cards and illustrating magazine covers. Schools and museums of holography proliferated, and the medium seemed ready to become the next evolutionary step in visual communication. A number of articles and even a book [5] have been written offering various observations about why that did not happen as predicted. The subject of this paper is the largely unheralded ways in which the current networked digital environment is allowing holography another chance to gain a foothold.

Holography has a range of useful applications in areas including microscopy, metrology, nondestructive testing, and the creation of diffractive optical elements, but here I will concentrate on the display hologram, intended for

Manuscript received May 13, 2011; revised August 31, 2011; accepted October 20, 2011. Date of publication February 13, 2012; date of current version March 21, 2012. This work was supported in part by the Digital Life, Things That Think, and CELab consortia at the MIT Media Lab. This work was also supported in part by the Office of the Director of National Intelligence (ODNI), Intelligence Advanced Research Projects Activity (IARPA), through the AFRL contract FA8650-10-C-7034. All statements of fact, opinion, or conclusions contained herein are those of the authors and should not be construed as representing the official views or policies of IARPA, the ODNI, or the U.S. Government.
The author is with the Media Lab, Massachusetts Institute of Technology, Cambridge, MA 02139 USA (e-mail: vmb@media.mit.edu).

Digital Object Identifier: 10.1109/JPROC.2011.2182071

viewing by humans analogously to a photo or a television image.

It is appealing to construct a narrative in which display holography, such as 2-D image capture, went from a chemical process to an analog electronic process, to a digital electronic process, along the way picking up the ability to deal with moving as well as static imagery. While this is to some degree true, it is also notable that holography came of age contemporaneously with computation, and the digitization of holography started happening relatively early in the technological development of the field (and the association of holography with television very early).

A digital holographic system—just as any electronic imaging system—requires four main elements: content capture, a distribution mechanism, signal processing/computation, and a display technology. With widespread diffusion of inexpensive computation sufficient to handle the processing requirements of digital holography (for at least some applications), high-quality image capture by even small and inexpensive cameras, multiple digital distribution channels and standards for high-resolution imagery, a resurgence of technological development in the area of electronic displays, and another round in the regular cycle of consumer interest in 3-D imaging, conditions seem promising for holography to assume a prominent role among digital media. To succeed this time around, holography will have to escape the limitations on subject matter and capture environments imposed by coherent scene illumination, and will have to be better connected with technologies and standards being developed for other sorts of consumer imaging. Fortunately, recent developments have made this possible.

Holography has been a regular topic of papers in the Proceedings of the IEEE over the past four decades, beginning with a special "mini-issue" on the topic in 1971, which included a mathematical and conceptual overview by Goodman [6] that remains a valuable concise tutorial on the basics, as well as an early overview of digital holography [7]. Since then, display holography papers in this journal have ranged widely, including several looks at electronic capture and transmission of holographic images [8], [9], analysis of spatial light modulators for electronic holography [10], and an introduction to "haptic holography," where a hologram is combined with an electromechanical force interface to provide physical interaction with the reconstructed scene [11].

II. WHAT A HOLOGRAM IS (AND IS NOT)

The term "hologram" is often used to describe any multiview autostereoscopic display such as a lenticular parallax screen, a multiprojector rear-projection display with an angularly selective diffuser, or a volumetric display, as well as what holographers would regard as a "real" hologram. Sometimes the term is even used to describe 2-D displays such as the modern digital take on the old magician's illusion called Pepper's Ghost, most recently promoted by U.K. firm Musion [12].

To a holographer, a display hologram is a diffractive element that when illuminated reconstructs the light wavefronts associated with a desired visual scene. Some purists would add the requirement that the diffraction pattern be generated by interference between a reference beam and the light reflected by a scene—or by computations simulating this interference—but from the perspective of the display itself the origins of the diffraction fringes are not important, just their function.

The main engineering challenges in holographic imaging stem from the inescapable physics of diffraction, dictating an extremely small pixel size, which (unlike other forms of electronic display) remains constant irrespective of display size or viewer distance, making scaleup costly. The "off-axis" form of the equation for diffraction angle of light of wavelength λ meters by a sinusoidal grating of spatial frequency f cycles per meter [13]

$$\sin\theta_{\text{out}} = \lambda f + \sin\theta_{\text{in}} \tag{1}$$

suggests—assuming at least two pixels will be needed per cycle in a discretely-sampled representation of this grating—that in a diffractive display with a reasonable range of view angles, the pixel size must be similar to the wavelength of light being diffracted. It is possible to use optics to trade off view angle against image size but ultimately a given reconstructed light field will require a constant *space-bandwidth product*, which is the product of a linear dimension of the physical hologram (e.g., meters) by its maximum spatial frequency (e.g., cycles per meter).

III. COMPUTING HOLOGRAMS

A. Fresnel and Fourier Holograms

It is common in the literature of computed holograms to divide them into two categories: far-field Fourier holograms, which can be characterized by Fraunhofer diffraction, and near-field Fresnel holograms. The mathematics of Fourier holograms is straightforward—the reconstructed image is effectively the 2-D Fourier transform of the hologram—and provided the basis for much pioneering work in digital holography such as the binary detour-phase holograms of Brown and Lohmann [14] and the Kinoform of Lesem *et al.* [15]. But it is an inherent property of Fourier holograms that they produce essentially 2-D images far from the hologram plane, and they were largely abandoned for computational display holography in favor of the more complex Fresnel hologram. Recently, the Fourier hologram has reemerged in connection with holographic projection, where a far-field 2-D image is precisely what is wanted, and we will revisit these holograms in Section V in conjunction with that application.

Computing a Fresnel hologram requires modeling the optical hologram capture process, where an "object" wavefront emitted by the scene

$$O(x,y) = |O(x,y)| \exp[j\phi_O(x,y)] \tag{2}$$

interferes with a "reference" wavefront

$$R(x,y) = |R(x,y)| \exp[j\phi_R(x,y)] \tag{3}$$

to produce an intensity pattern recorded by the capture material or device

$$I(x,y) = |O(x,y)|^2 + |R(x,y)|^2 + 2|O(x,y)||R(x,y)| \times \cos[\phi_O(x,y) - \phi_R(x,y)]. \tag{4}$$

Specifically for an off-axis hologram the reference wave will be an inclined plane wave

$$R(x,y) = R_o \exp\left[j\frac{2\pi}{\lambda}(\alpha x + \beta y + \gamma z)\right] \tag{5}$$

with direction cosines (α, β, γ) and the object wave can be modeled as a superposition of point-source spherical emitters [at locations (x_i, y_i, z_i)]

$$O_i(x,y) = O_{o_i} \exp\left[j\frac{2\pi}{\lambda}\sqrt{z_i^2 + (x - x_i)^2 + (y - y_i)^2}\right]. \tag{6}$$

Several things are worth noting at this point. First, every point emitter in the scene will potentially contribute to the interference at every point in the hologram, so the computational cost of a scene of even modest complexity will be quite high (and higher still if the scene has occluding surfaces; consider the complications of determining which parts of the hologram plane can "see" which emitters). Second, we have neglected the fact that the emitters also interfere with one another as well as with the reference illumination, but fortunately the "object self-interference" phenomenon actually produces unwanted artifacts in optical holograms, so neglecting the self-interference terms in the computation not only greatly reduces computation but also results in better looking images. Third, computing holograms of this sort will require a 3-D model of the scene, whether from a computer graphics model or a range-finding camera for real scenes. Finally, a hologram computed in this way will in addition to the desired image also reconstruct an unwanted conjugate image and (depending on the diffraction efficiency of the medium) pass some amount of undiffracted illumination toward the viewer. These are mathematically analogous to the opposite sideband and unmodulated carrier in an AM radio system (what is desired is the optical equivalent of single-sideband modulation with a suppressed carrier). If the medium or device on which the hologram is written has small enough pixels to create large diffraction angles, the viewing setup can be arranged such that these will not be visible to the viewer but for lower spatial-resolution holograms it may be necessary to eliminate them mathematically [16].

A variety of techniques have been developed for reducing the computational requirements for the Fresnel hologram, including the use of precomputed lookup tables representing the interference contributions of points throughout image space [17], and approximations that replace multiplication and division with linear differences [18]. A significant speedup is possible if the hologram is simplified to horizontal parallax only (HPO) as it becomes a set of independent 1-D "holo-lines" and the vertical resolution reduces from that required by diffraction to that required by an ordinary 2-D image. This technique is common in optical holography for reduction of blur when a hologram is viewed in white light, and originated in a search for methods that reduce information content in holographic images.

B. Diffraction-Specific Approaches

More commonly than the above-discussed methods, computer-generated holograms—whether HPO or full parallax—are actually generated using a *diffraction-specific technique*, which does not attempt to model optical interference but instead concentrates only on the reconstruction step, assembling a hologram from spatially and spectrally sampled holographic fringes in order to propagate wavefronts in desired directions.

An early such approach is the holographic stereogram, which creates a diffraction pattern that reconstructs a set of 2-D parallax views of a scene in appropriate viewing directions. There are several notable advantageous features of holostereograms over fully computed Fresnel holograms.

- Standard computer-graphics rendering techniques can be used to generate the views. Scene lighting can be complex and the scene can contain atmospheric effects, translucent objects, and other phenomena that can be difficult to model in Fresnel holograms.
- Real scenes can be captured with an array of ordinary 2-D cameras (or a single camera in multiple positions). This technique originated in optical holography as a method for capturing large, naturally illuminated imagery [19].

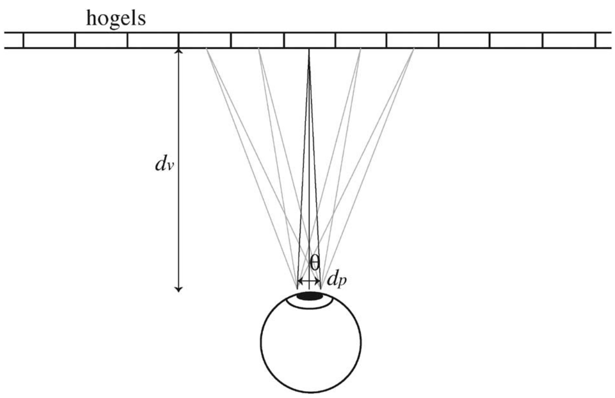

Fig. 1. ***Holographic stereogram. Viewer's eye sees different directional views of different hogels (gray lines), and for smooth motion parallax, more than one view of a given hogel should enter the pupil (black lines). Distances and angles not to scale.***

- A single set of diffractive basis functions can be used for any scene; the generation of the hologram consists of the modulation of these by the intensities of the rendered or captured parallax views.
- The information content of the hologram is essentially that of the set of parallax views, and these are amenable to compression using standard techniques (e.g., the multiview extension to the H.264 codec) [20]. If sufficient computation is available at the display it may be most appropriate to transmit these and to generate the diffraction pattern at the display.

A detailed discussion of holographic stereogram theory is provided in [21] but the basics are straightforward. Fig. 1 shows a typical arrangement, in which the hologram is segmented into regions (commonly called *hogels*, a term coined by Lucente [22]), which function as a set of parallax apertures that project a set of parallax view pixels in different directions. These are computed as a linear combination of a set of basis fringes (each corresponding to a direction) modulated by the view pixel values in each direction. As shown in the figure, the pupil of the eye selects appropriate view directions from each hogel.

The more general class of diffraction-specific algorithms contains many degrees of freedom beyond the stereogram geometry discussed above. The reconfigurable image projection (RIP) approach [23] allows placing holographic emitters at distances other than infinity, and allows basis fringes to overlap on the hologram plane as needed for optimal windowing of the functions. Viewed along a continuum, in the stereogram the basis fringes are independent of scene content and of hogel location on the hologram plane, in the RIP algorithm they may be a function of the location of the emitter in space and of the hogel on the hologram, and in the method to follow they can be a function of the scene content as well (specifically the distance to points in the scene).

As noted above, the parallax view generation for diffraction-specific algorithms uses standard graphics rendering techniques (though often with uncommon camera geometries such as a shearing orthographic camera), and thus can take advantage of both common graphics processor hardware and software rendering pipelines. The signal processing needed to convert the views to diffraction patterns turns out to be well matched to graphics processors as well—in particular programmable shaders—and it has proven to be possible to compute HPO holograms of approximately standard television definition (SDTV) at frame rates fast enough to give smooth motion [24].

In return for the computational advantages (including straightforward parallelization when the hologram plane is segmented into independently computable regions) typical diffraction-specific methods create approximations to arbitrary wavefronts with segments of constant spherical curvature (or planarity) in a discrete set of directions. A direct consequence of this limitation is that a large number of view angles are needed in order to create smooth motion parallax for a viewer. It is possible to compute a bound on the width of a hogel based on human angular acuity and viewer distance (analogously with the pixel pitch in a 2-D display), while for smooth parallax, more than one view of a point must be entering a viewer's pupil at a time along a parallax dimension. These calculations are developed in [21]. For a pupil diameter d_p and a viewing distance d_v, the angular extent of a single view must be

$$\theta = \tan^{-1}\left(\frac{d_p}{2}\bigg/ d_v\right). \tag{7}$$

Assuming a 4-mm pupil, a 1-m viewing distance, and a 30° overall viewing angle, 262 views would be needed for an HPO image and 68 644 for a full-parallax image.

An additional consequence resulting from the way in which holographic stereograms are generated is that they share the limitation of other stereographic displays known as *accommodation–vergence mismatch*. The distance at which the viewer's eyes are focused is decoupled from the distance to which they converge. While accommodation (focusing) is a weak perceptual cue to depth and effective only up to a few meters of distance, typically viewers can tolerate a very limited degree of mismatch, and as a result the comfortably usable range of vergence—and thus the range of apparent depth—may be limited to less than the display itself is capable of creating [25]. Because geometry causes the mismatch phenomenon to be stronger at closer viewing distances, this issue is becoming of increasing commercial importance as 3-D

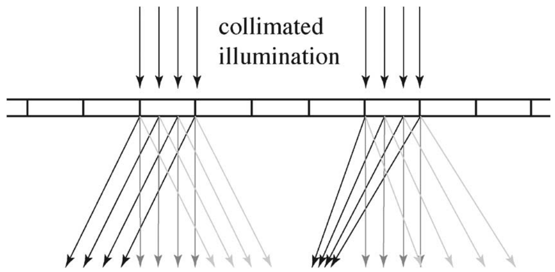

Fig. 2. ***In a typical diffraction-specific hologram (left), a hogel emits light in multiple directions with the same wavefront curvature but different intensities. In a Diffraction Specific Coherent Panoramagram (right), both intensity and curvature can vary with direction, eliminating accommodation–vergence mismatch and giving smooth motion parallax with fewer views.***

moves from theater screens to home televisions and mobile devices [26].

One of the promises of display holography is that by reconstructing light wavefronts it should offer fully consistent perceptual cues, a property not shared with most 3-D display technologies. Research in the Object-Based Media Group at the MIT Media Lab has developed the Diffraction Specific Coherent Panoramagram (DSCP), a new form of stereogram that escapes the above mismatch limitations [27]. The DSCP is an extension of diffraction-specific methods, and like them is computable at video rates by modern graphics processors, but extends them by using a more complete set of holographic basis functions computed on the fly which allow smooth parallax and correct accommodation cues with a small number of views (in our experience typically about a tenth as many along each dimension as a RIP stereogram).

In the DSCP algorithm, when views are rendered, the z-buffers are retained, and the distance values as well as the hogel positions are used to generate vectors of fringe segments that create variable-curvature directional emitters at the scene depths; these are then modulated by the scene intensities at the points (Fig. 2). The calculation used to create these fringe segments is the point-emitter Fresnel interference model discussed above, and thus in the limit of spatial sampling of the hologram plane and angular sampling of the views, the DSCP converges to the Fresnel hologram of the scene. If range-finding cameras are available the depth values associated with the image pixels can be used in the same fashion; this will be discussed in Section VII.

IV. DISPLAYING HOLOGRAMS ELECTRONICALLY

Having computed (or captured) a holographic diffraction pattern, it is necessary to instantiate the signal on a physical material with controllable transmittance and/or phase. An electronically controllable device with this property is called a spatial light modulator (SLM). *Star Wars et al.* notwithstanding, the SLM will be typically employed as a direct-view display device, where the viewer looks toward it (perhaps through some optical elements) just as with any other hologramrather than its creating a holographic image across the room. An exception to this arrangement is where the SLM is diffractively creating a 2-D image projection for a screen, a case that will be treated in Section V.

Knowledge of the physical characteristics of the SLM and the illuminating wavelengths is necessary in order to compute the diffraction pattern, and this provides one motivation for the notion that a hologram should not itself be transmitted but rather computed at the display from some other—ideally more efficient and flexible-representation. Otherwise, a transmitted hologram would work properly on only one size and technology of display.

Potentially any transmissive or reflective light modulation technology might be usable for this application, though the unique requirements of holograms favor those with a particularly high bandwidth. An ideal SLM would be able to control both the intensity and the phase of light, but given that most practical SLMs can affect only one or the other, a phase-only modulator is more desirable as it is theoretically over five times more diffraction-efficient (in terms of intensity of the first-order diffracted light) than an amplitude-only modulator [28]. A detailed analysis of the space-bandwidth requirements for an SLM to display a given hologram to an observer is provided in [10].

A broad range of electroholographic display systems have been built over the past two decades, and overviews of a number of them are given in [29]–[31].

Many researchers have used liquid-crystal SLMs as the basis for holographic displays, most commonly as phase modulators, though a group at Barcelona University combined a phase modulator with an amplitude modulator to enable displaying full complex-amplitude Fresnel holograms [32]. Several teams have reported the display of holograms on digital micromirror devices [33], [34].

The first reported electronic holographic display, "Mark I," developed by Benton *et al.* at the MIT Media Lab in 1989, employed an acousto–optic modulator (AOM), a diffractive device in which electrical signals are converted to acoustic signals in a transparent material (tellurium dioxide in this case) that can diffract light [35], [36]. AOMs have a long history of use in displays, beginning with the (nonholographic) Scophony television displays of the 1930s [37]. More recent Media Lab display designs have been based on lithium niobate guided-wave devices, in which surface acoustic waves diffract light traveling in a subsurface waveguide [38]. These sorts of acoustic modulators are inherently 1-D and so are suited for HPO displays rather than full-parallax ones; while multiple channels can be stacked, the interchannel spacing is too large to provide diffraction in the vertical direction [39]. An additional limitation of these devices is that the diffraction pattern travels with the speed of sound, so creating a stationary image requires having an optical element such as a mirror moving in the opposite direction, short illumination pulses, or some other compensating solution.

In the most basic configuration for a holographic display, collimated monochromatic light (not necessarily coherent, but very narrowband illumination is needed to avoid dispersion since broadband light will be diffracted across a range of angles) is used to illuminate a transmissive SLM, at which the viewer looks directly. From this simple arrangement, one or more of a variety of methods is applied to create a practical display.

- *Reflective SLM*: In order for a display to use a reflective SLM, a beamsplitter must be placed at a 45° angle in front of the modulator so that the illumination source can be perpendicular to the viewer's gaze direction.
- *Color*: Three light sources can be operated sequentially (with the holograms being displayed in frame-sequential color) or three SLMs can be combined with a beamsplitting arrangement.
- *Tiling*: An individual microdisplay may have small enough pixels to give usable diffraction angles, but be too small to be viewed directly (at least by both eyes simultaneously). In this situation, multiple SLMs can be tiled on a plane [40], or to create a larger angular range, on an arc [41].
- *Scanning*: If an SLM is faster than needed, it can be imaged across a larger 2-D area by a mechanical scanning arrangement. Similarly through vertical scanning a 1-D modulator can be used to create an HPO display as in the MIT AOM displays above. Alternatively, an HPO display can be created by using a cylindrical lens to squeeze a 2-D modulator horizontally to allow good diffraction angles, and then scanning its image horizontally [42].
- *Eye tracking*: If the SLM produces a narrow diffraction angle, the viewer's eyes can be tracked and the backlight or the image moved to follow them. An example is a prototype display developed by SeeReal based on a 20-in LCD panel, which employs a steerable light source behind the panel to make two time-multiplexed narrow-view-zone holographic images follow the viewer's pupils [43].
- *Image storage*: In this case, a scanned SLM is not viewed directly but instead used to image onto another rewritable material that holds the hologram until erased or refreshed. In such a system, the secondary hologram is illuminated by a different light source rather than the SLM. An example is the QinetiQ display where a 1024 × 1024 2-D light modulator chip operated at high enough speed that it could be imaged by a lens and shutter mechanism to image it in 25 places to create a 5120 × 5120 hologram on an optically addressed SLM; these modules in turn can be abutted to make a larger image [29]. A different approach was taken by a group at the University of Arizona in collaboration with Nitto Denko Technical, who used an SLM to write parallax views onto an erasable/refreshable photorefractive polymer illuminated by a reference beam [44]. This system is in some ways intermediate between a holographic video display and a holographic printer, though a variation of it has also been applied in live applications, as will be discussed in Section VII.

Unlike the case a few years ago, where the available computation was insufficient for rapid updating of the best SLMs available, now the light modulator is typically the limiting factor on the quality of a displayed holographic image. Development of new display technologies remains an area where significant research awaits.

V. HOLOGRAPHIC PROJECTION

The availability of compact and inexpensive semiconductor lasers in red, green, and blue has created the opportunity for their use in picoprojectors. A common approach to the design of a laser picoprojector is to intensity modulate the lasers electrically while scanning out a 2-D raster; complications of this approach include the need for a high-speed scanning mechanism and the difficulty of rapid modulation of the frequency-doubled lasers used for the green component. But a novel alternative is to illuminate a microdisplay with a collimated beam and drive the microdisplay with a hologram that will reconstruct a desired 2-D image at the screen.

Mathematically the problem of generating such a hologram is a straightforward application of Fraunhofer diffraction. If we consider a hologram $h(u,v)$ illuminated by collimated coherent illumination of wavelength λ and at the back focal plane of a lens of focal length f (Fig. 3), the complex field at a distance $2f$ from the hologram (on the other side of the lens) is

$$I(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h(u,v)\exp\left\{\frac{j2\pi}{\lambda f}(ux+vy)\right\} du\, dv. \quad (8)$$

But actually inverting a discretized version of this Fourier relationship to calculate an appropriate $h(u,v)$ that yields a desired $I(x,y)$ is not so straightforward. A resulting hologram will be complex valued, while light modulators available can modulate the amplitude or phase of the illumination but not both independently; given this choice, a phase-only hologram is desirable both because of the earlier mentioned diffraction efficiency advantage and because it is less prone to damage by the likely high illumination energy as it will not absorb significant amounts.

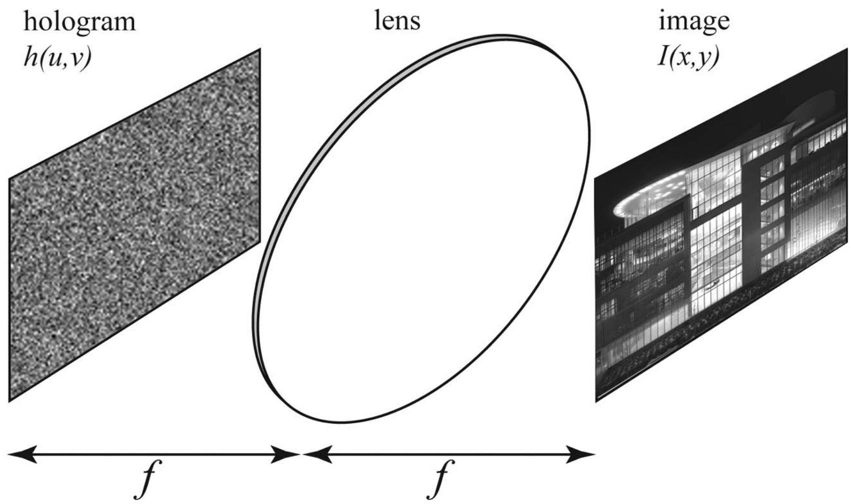

Fig. 3. ***Fourier hologram used as a projector.***

Computing such a phase-only hologram quickly and also minimizing the effect of quantization noise in the hologram on the reconstructed image pose significant challenges. Light Blue Optics, Inc. has developed an optimization method based on a human perceptual model that can be calculated at video rates, and uses the resulting phase hologram to drive a ferroelectric liquid-crystal-on-silicon (LCOS) device functioning as a phase modulator. Their algorithms and projector design are also amenable to several approaches for minimizing the appearance of laser speckle in the projected images [45]. A particular application of this technology adds infrared sensing so that the projected surface can become a touch screen for interactive applications (Fig. 4).

Fig. 4. ***Holographic projector combined with infrared touch sensor, used in an interactive restaurant menu application. Courtesy of Light Blue Optics Inc.***

VI. PRINTING HOLOGRAMS

A useful way to think about a printed digital hologram is to consider it as analogous to an integral photograph. In integral photography, developed by Lippmann in 1908 [46], a photosensitive material is placed at the focal plane of a sheet of tiny convex lenslets, each of which captures a different perspective than its neighbors and images it onto a small area of the film. Then, after a replication step that converts a pseudoscopic image to one with correct parallax, the resulting image is viewed through a lenslet array and recreates the discrete perspectives at appropriate directions, causing the viewer to perceive a 3-D image. In a digitally printed hologram, the refractive lens array of the integral photograph is replaced by an array of diffractive elements performing the same function, modulated by the scene intensities in each direction. While the diffraction patterns could be computed (as discussed above) and imaged directly onto the photosensitive print material with a spatial light modulator, optical design and computation are simplified if instead an array of perspectives is assembled for each local area on the print and then interference with a reference beam is used to create the local diffraction pattern through interference.

The availability of large sheets of photopolymer recording material (requiring no wet processing) with sensitivity in red, green, and blue enabled the building of practical full-color holographic printers. Pioneering examples of holographic printing systems were built in the Spatial Imaging Group at the MIT Media Lab starting in the late 1990s [47], [48]; the availability of standard data formats for 3-D graphics and computer-aided design models, parallax views, and laser-scan data enabled rapid commercialization of an online service-bureau business model, with applications in terrain and data visualization, art, architecture, design, and engineering. Prints can be created from a

Fig. 5. ***White-light illuminated tabletop holographic print provides a broad viewing angle with 600 cm or more of depth. Courtesy of Zebra Imaging.***

variety of data representations, previewed online, and produced for tabletop or wall-hanging geometries with halogen or LED lighting (Fig. 5). U.S. firm Zebra Imaging supplies prints up to 60 cm by 90 cm with the largest prints currently costing \$3500, while Geola in Lithuania offers a variety of services including "mobile phone holograms" in which a parallax image sequence from a phone camera can be converted to a 13 cm by 18 cm portrait for euro50 [49]. Canadian firm RabbitHoles Media has in particular focused its services on providing holographic prints for digital 3-D artists.

VII. HOLOGRAPHIC TELEVISION AND TELEPRESENCE

Not long after Leith and Upatnieks developed the off-axis transmission hologram, they began considering the possibility of holographic television transmission, and in 1965 presented at a conference of the Society of Motion Picture and Television Engineers an analysis of the requirements for capture and transmission of holographic television [50]. Though their analysis was carried out assuming the analog television technology of the time, they made a set of observations that remain the chief design challenges for holographic television today. In particular, they noted the difficulty of creating cameras and displays of sufficient resolution to give good diffraction angles, and that capture of moving imagery requires illuminating the scene with a pulsed laser with an exposure time in nanoseconds in order to avoid movement of the scene of the order of magnitude of the wavelength of light (and thus the elimination of an interference pattern on the camera). But they also noted that holography "appears to hold promise for three-dimensional television . . .The large amount of redundancy in hologram imaging does leave room for hope that considerable bandwidth reduction is possible."

Enloe *et al.* at Bell Laboratories in 1966 managed to transmit an actual hologram using an analog television system; a holographic interference fringe pattern was captured by a vidicon tube camera and sent to a cathode-ray display, which was photographed to create a transparency that reconstructed an image when illuminated with a laser [51]. A team at CBS Laboratories in 1972 was able to take a fringe pattern from a vidicon and directly write it into a thin phase hologram in a reusable thermoplastic material [52]. A great deal of analysis was carried out in the 1960s and 1970s on methods for reducing the information content in holograms, with the goal of real-time transmission [53]. The availability in the 1990s of liquid-crystal light modulators designed for projectors led several groups [54], [55] to build analog holographic television transmission systems using these for reconstruction. Optical scanning holography, proposed by Poon *et al.* [8], adds more sophisticated signal processing to such systems. Here instead of capturing a holographic interference pattern on an imaging device, the scene is scanned with a time-varying Fresnel zone plate (the result of the interference between a plane wave and a spherical wave) and the reflected light picked up by a photodetector. Processing to reduce the information content of the signal is then applied.

These first two waves of hologram transmission were entirely or at least largely analog, and research in the area became fairly quiet after the mid-1990s. In the past several years, a digital third wave of real-time hologram capture and transmission has emerged, and has positioned itself as the next generation not only of holography but of telepresence as well. This recent work has concentrated on capturing imagery with incoherent light typically using inexpensive cameras, and then generating fringe patterns in real time that reconstruct appropriate light fields. The most practical approaches do not transmit the hologram but rather generate it at the display, and thus can take advantage of existing approaches for compressing and transmitting images instead of seeking to develop compression algorithms for diffraction patterns.

One branch of current holographic telepresence research addresses the relationship between the lightfield of an integral imaging setup and that of a Fourier hologram [56]. With the rapid resolution increases that are occurring in image sensors, it is becoming practical to acquire integral images with standard camera sensors. Because electronic image sensors are much smaller than photographic plates (or than a desired display), integral images can be captured on a video camera by placing a large field lens and an aperture between the lenslet array and the camera. Then, each subimage (a region of the overall captured image covered by one lenslet) is processed to create a corresponding hologram. Since these are independent of one another this processing step can be performed in a highly parallel fashion in software or dedicated hardware. The result is then displayed on a spatial light modulator illuminated by a collimated laser source (or three in the case of color imagery) [57]. Conversion in the opposite direction has also been reported, with holographic image capture and integral image reconstruction, though not in real time [58].

Another approach is to capture and transmit stereograms and then convert the parallax images to holograms for display. A group at the University of Arizona has reported transmission and display of images on a 100 cm by 100 cm refreshable photorefractive polymer display at a rate of 0.5 frames/s (limited by the writing of the material with a pulsed laser and SLM, not by the capture or transmission) from an array of 16 small cameras [59]. Zebra Imaging has also claimed real-time telepresence from a camera array to a holographic display but as of this writing has not provided public demonstrations or published details of the display technology. The author's group at the MIT Media Lab has demonstrated image capture using range-finding cameras (including the Microsoft Kinect), network transmission, and conversion on a personal computer with three standard graphics processors to HPO DSC Panoramagrams for display at 15 frames/s [60]. For undistorted scene geometry geometric correction is needed, as range-finding cameras produce perspective views while diffraction-specific algorithms require an orthographic camera in the parallax direction. The process in brief is to capture a set of perspective range images spanning a horizontal baseline corresponding to the intended viewing line, then for each orthographic view to be generated sample from the rays in all perspective images those whose horizontal angle is within some tolerance angle from the orthographic viewing direction, and finally create a point cloud and render the orthographic views from the point cloud. The resulting holograms have been displayed on both our real-time acousto–optic display and Arizona's refreshable polymer display (Fig. 6). It is possible to create a usable hologram with a single range-finding camera but it will have missing occluded regions visible from viewpoints offset from that of the camera; ideally multiple range-finding cameras should be used. ■

Fig. 6. ***Frame from holographic sequence generated from consumer range-finding camera. Courtesy of University of Arizona College of Optical Sciences.***

Acknowledgment

The author would like to thank students and colleagues of the Object-Based Media and Spatial Imaging Groups of the MIT Media Lab for their contributions to this work. He would also like to thank Zebra Imaging, Light Blue Optics, and the College of Optical Sciences of the University of Arizona for graciously providing illustrations.

REFERENCES

[1] D. Gabor, "A new microscopic principle," *Nature*, vol. 161, no. 4098, pp. 777–778, May 15, 1948.

[2] "New microscope limns molecule," *The New York Times*, p. 35, Sep. 15, 1948.

[3] E. N. Leith and J. Upatnieks, "Wavefront reconstruction with diffused illumination and three-dimensional objects," *J. Opt. Soc. Amer.*, vol. 54, no. 11, pp. 1295–1301, 1964.

[4] Y. N. Denisyuk, "Photographic reconstruction of the optical properties of an object in its own scattered radiation field," *Soviet Physics Doklady*, vol. 7, pp. 543–545, 1962.

[5] S. F. Johnston, *Holographic Visions*. Oxford, U.K.: Oxford Univ. Press, 2006.

[6] J. W. Goodman, "An introduction to the principles and applications of holography," *Proc. IEEE*, vol. 59, no. 9, pp. 1292–1304, Sep. 1971.

[7] T. S. Huang, "Digital holography," *Proc. IEEE*, vol. 59, no. 9, pp. 1335–1346, Sep. 1971.

[8] T.-C. Poon, M. H. Wu, K. Shinoda, and Y. Suzuki, "Optical scanning holography," *Proc. IEEE*, vol. 84, no. 5, pp. 753–764, May 1996.

[9] Y. Frauel, T. J. Naughton, O. Matoba, E. Tajahuerce, and B. Javidi, "Three-dimensional imaging and processing using computational holographic imaging," *Proc. IEEE*, vol. 94, no. 3, pp. 636–653, Mar. 2006.

[10] L. Onural, F. Yaras, and H. Kang, "Digital holographic three-dimensional video displays," *Proc. IEEE*, vol. 99, no. 4, pp. 576–589, Apr. 2011.

[11] W. Plesniak, R. S. Pappu, and S. A. Benton, "Haptic holography: A primitive computational plastic," *Proc. IEEE*, vol. 91, no. 9, pp. 1443–1456, Sep. 2003.

[12] R. Yu, "Holograms could soon give virtual meetings new life," *USA Today*, p. 5B, Feb. 24, 2011.

[13] S. A. Benton and V. M. Bove, Jr., *Holographic Imaging*. Hoboken, NJ: Wiley, 2008, p. 54.

[14] B. R. Brown and A. W. Lohmann, "Computer generated binary holograms," *IBM J. Res. Develop.*, vol. 13, no. 2, pp. 160–167, Mar. 1969.

[15] L. B. Lesem, P. M. Hirsch, and J. A. Jordan, "The kinoform: A new wavefront reconstruction device," *IBM J. Res. Develop.*, vol. 13, no. 2, pp. 150–155, Mar. 1969.

[16] W. Wang, W. Yue, and L. Ai, "A new method for eliminating zero-order and conjugate

image in digital holography," in *Proc. SPIE—Holography, Diffractive Optics, and Applications II*, 2005, vol. 5636, pp. 849–855.

[17] M. Lucente, "Optimization of hologram computation for real-time display," in *Proc. SPIE—Practical Holography VI*, 1992, vol. 1667, pp. 32–43.

[18] H. Yoshikawa, S. Iwase, and T. Oneda, "Fast computation of Fresnel holograms employing difference," in *Proc. SPIE—Practical Holography XIV and Holographic Materials VI*, 2000, vol. 3956, pp. 331–335.

[19] J. T. McCrickerd and N. George, "Holographic stereogram from sequential component photographs," *Appl. Phys. Lett.*, vol. 12, no. 1, pp. 10–12, Jan. 1, 1968.

[20] A. Vetro, T. Wiegand, and G. J. Sullivan, "Overview of the stereo and multiview video coding extensions of the H.264/MPEG-4 AVC standard," *Proc. IEEE*, vol. 99, no. 4, pp. 626–642, Apr. 2011.

[21] W. Plesniak, R. Pappu, J. Underkoffler, M. Lucente, P. St.-Hilaire, S. A. Benton, and V. M. Bove, Jr., *Holographic Imaging*. Hoboken, NJ: Wiley, 2008.

[22] M. Lucente and T. Galyean, "Rendering interactive holographic images," in *Proc. ACM SIGGRAPH*, 1995, pp. 387–394.

[23] W. Plesniak, M. Halle, V. M. Bove, Jr., J. Barabas, and R. Pappu, "Reconfigurable image projection holograms," *Opt. Eng.*, vol. 45, no. 11, 115801, Nov. 2006.

[24] Q. Y. J. Smithwick, J. Barabas, D. E. Smalley, and V. M. Bove, Jr., "Real-time shader rendering of holographic stereograms," in *Proc. SPIE—Practical Holography XXIII*, vol. 7233, 723302, 2009.

[25] D. M. Hoffman, A. R. Girshick, K. Akeley, and M. S. Banks, "Vergence-accommodation conflicts hinder visual performance and cause visual fatigue," *J. Vision*, vol. 8, no. 3, pp. 1–30, Mar. 2008.

[26] J. Hecht, "3-D TV and movies: Exploring the hangover effect," *Opt. Photon. News*, vol. 22, no. 2, p. 2027, Feb. 2011.

[27] Q. Y. J. Smithwick, J. Barabas, D. E. Smalley, and V. M. Bove, Jr., "Interactive holographic stereograms with accommodation cues," in *Proc. SPIE—Practical Holography XXIV*, vol. 7619, 761903, 2010.

[28] S. A. Benton and V. M. Bove, Jr., *Holographic Imaging*. Hoboken, NJ: Wiley, 2008, pp. 59–61.

[29] C. Slinger, C. Cameron, and M. Stanley, "Computer-generated holography as a generic display technology," *IEEE Computer*, vol. 38, no. 8, pp. 46–53, Aug. 2005.

[30] S. A. Benton and V. M. Bove, Jr., *Holographic Imaging*. Hoboken, NJ: Wiley, 2008.

[31] F. Yaras, H. Kang, and L. Onural, "State of the art in holographic displays: A survey," *J. Display Technol.*, vol. 6, no. 10, pp. 443–454, 2010.

[32] R. Tudela, E. Martin-Badosa, I. Labastida, S. Vallmitjana, and A. Carnicer, "Wavefront reconstruction by adding modulation capabilities of two liquid crystal devices," *Opt. Eng.*, vol. 43, no. 11, pp. 2650–2657, Nov. 2004.

[33] P. Ambs, L. Bigue, and Y. Fainman, "Dynamic computer generated holograms displayed on a digital micromirror device *Diffractive Optics and Micro-Optics*, vol. 75, R. Magnusson, Ed. Washington, DC: OSA, 2002.

[34] M. Huebschman, B. Munjuluri, and H. Garner, "Dynamic holographic 3-D image projection," *Opt. Exp.*, vol. 11, no. 5, pp. 437–445, 2003.

[35] P. St.-Hilaire, S. A. Benton, M. Lucente, M. L. Jepsen, J. Kollin, and H. Yoshikawa, "Electronic display system for computational holography," in *Proc. SPIE—Practical Holography IV*, 1990, vol. 1212, pp. 174–182.

[36] P. St.-Hilaire, S. A. Benton, M. Lucente, and P. M. Hubel, "Color images with the MIT holographic video display," in *Proc. SPIE—Practical Holography VI*, 1992, vol. 1667, pp. 73–84.

[37] H. W. Lee, "The Scophony television receiver," *Nature*, vol. 142, no. 3584, pp. 59–62, 1938.

[38] D. Smalley, Q. Smithwick, and V. M. Bove, Jr., "Holographic video display based on guided-wave acousto-optic devices," in *Proc. SPIE—Practical Holography XXI*, vol. 6488, 64880L, 2007.

[39] P. St.-Hilaire, "Scalable optical architectures for electronic holography," Ph.D. dissertation, Media Arts and Science Department, Massachusetts Inst. Technol., Cambridge, 1994.

[40] K. Sato, A. Sugita, M. Morimoto, and K. Fujii, "Reconstruction of color images at high quality by a holographic display," in *Proc. SPIE—Practical Holography XX*, vol. 6136, 61360V, 2006.

[41] J. Hahn, H. Kim, Y. Lim, G. Park, and B. Lee, "Wide viewing angle dynamic holographic stereogram with a curved array of spatial light modulators," *Opt. Exp.*, vol. 16, no. 16, pp. 12372–12386, 2008.

[42] N. Okada and Y. Takaki, "Horizontally scanning holography to enlarge both image size and viewing zone angle," in *Proc. SPIE—Practical Holography XXIII*, vol. 7233, 723309, 2009.

[43] R. Haussler, S. Reichelt, N. Leister, E. Zschau, R. Missbach, and S. Schwerdtner, "Large real-time holographic displays: From prototypes to a consumer product," in *Proc. SPIE—Stereoscopic Displays and Applications XX*, vol. 7237, 72370S, 2009.

[44] S. Tay, P. A. Blanche, R. Voorakaranam, A. V. Tunc, W. Lin, S. Rokutanda, T. Gu, D. Flores, P. Wang, G. Li, P. St.-Hilaire, J. Thomas, R. A. Norwood, M. Yamamoto, and N. Peyghambarian, "An updatable holographic three-dimensional display," *Nature*, vol. 451, no. 7179, pp. 694–698, Feb. 7, 2008.

[45] E. Buckley, "Holographic laser projection," *J. Display Technol.*, vol. 7, no. 3, pp. 135–140, Mar. 2011.

[46] M. G. Lippmann, "Épreuves réversibles donnant la sensation du relief," *J. de Phys.*, vol. 4, no. 7, pp. 821–825, Nov. 1908.

[47] R. S. Nesbitt, S. L. Smith, R. A. Molnar, and S. A. Benton, "Holographic recording using a digital micromirror device," in *Proc. SPIE—Practical Holography XIII*, 1999, vol. 3637, pp. 12–20.

[48] M. Klug, M. A. Holzbach, and A. Ferdman, "Method and apparatus for recording one-step, full-color, full-parallax, holographic stereograms," U.S. Patent 6 330 088, 2001.

[49] S. Zacharovas, A. Nikolskij, and J. Kuchin, "Mobile phone digital holography," in *Proc. SPIE—Practical Holography XXIV*, vol. 7619, 76190O, 2010.

[50] E. N. Leith, J. Upatnieks, B. P. Hildebrand, and K. Haines, "Requirements for a wavefront reconstruction facsimile system," *J. Soc. Motion Picture Television Eng.*, vol. 74, no. 10, pp. 893–896, Oct. 1965.

[51] L. H. Enloe, J. A. Murphy, and C. B. Rubinstein, "Hologram transmission via television," *Bell Syst. Tech. J.*, vol. 45, no. 2, pp. 335–339, Feb. 1966.

[52] R. J. Doyle and W. E. Glenn, "Remote real-time reconstruction of holograms using the Lumatron," *Appl. Opt.*, vol. 11, no. 5, pp. 1261–1264, 1972.

[53] T. Okoshi, *Three-Dimensional Imaging Techniques*. New York: Academic, 1976.

[54] K. Sato, K. Higuchi, and H. Katsuma, "Holographic television by liquid-crystal device," in *Proc. SPIE—Practical Holography VI*, 1992, vol. 1667, pp. 19–31.

[55] N. Hashimoto, K. Hoshino, and S. Morokawa, "Improved real-time holography system with LCDs," in *Proc. SPIE—Practical Holography VI*, 1992, vol. 1667, pp. 2–7.

[56] R. Oi, T. Mishina, K. Yamamoto, and M. Okai, "Real-time IP-hologram conversion hardware based on floating point DSPs," in *Proc. SPIE—Practical Holography XXIII*, vol. 7233, 723305, 2009.

[57] K. Yamamoto, T. Mishina, R. Oi, T. Senoh, and T. Kurita, "Real-time color holography system for live scene using 4K2K video system," in *Proc. SPIE—Practical Holography XXIV*, vol. 7619, 761906, 2010.

[58] B. Javidi and S.-H. Hong, "Three-dimensional holographic image sensing and integral imaging display," *J. Display Technol.*, vol. 1, no. 2, pp. 341–346, Dec. 2005.

[59] P.-A. Blanche, A. Bablumian, R. Voorakaranam, C. Christenson, W. Lin, T. Gu, D. Flores, P. Wang, W.-Y. Hsieh, M. Kathaperumal, B. Rachwal, O. Siddiqui, J. Thomas, R. A. Norwood, M. Yamamoto, and N. Peyghambarian, "Holographic three-dimensional telepresence using large-area photorefractive polymer," *Nature*, vol. 468, no. 7320, pp. 80–83, 2010.

[60] J. Barabas, S. Jolly, D. E. Smalley, and V. M. Bove, Jr., "Diffraction specific coherent panoramagrans of real scenes," in *Proc. SPIE—Practical Holography XXV*, vol. 7957, 795702, 2011.

ABOUT THE AUTHOR

V. Michael Bove, Jr. (Member, IEEE) received the S.B. degree in electrical engineering, the S.M. degree in visual studies, and the Ph.D. degree in media technology from the Massachusetts Institute of Technology (MIT), Cambridge, in 1983, 1985, and 1989, respectively.

He heads the Object-Based Media Group at the MIT Media Lab, where he researches consumer electronics, user interface, and display technology. He serves as technical advisor to the One Laptop Per Child Foundation, and is coauthor with the late Stephen A. Benton of the book *Holographic Imaging* (Hoboken, NJ: Wiley, 2008). He holds 14 patents in areas relating to interactive television, printing, and image processing.

Dr. Bove served as general chair of the 2006 IEEE Consumer Communications and Networking Conference (CCNC) and will co-chair the 2012 International Symposium on Display Holography. He is a Fellow of the International Society for Optics and Photonics (SPIE).