CLOSE-UP

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Holography: The Second Decade

Dr. Stephen Benton

Holography is a lensless three dimensional imaging medium that produces fascinating images that stand alone in space. Holograms appear to move as the viewer changes position and, in the case of rainbow holograms, they change color as well. Holograms are based on the physical principles of recording the interference pattern made from light waves reflected by an object (which will form the final image) and waves coming from a bright point light source. This interference pattern depends critically on the wave properties of light, rather than the particle properties that are used in silver halide photography. Successful holographic recording requires sufficiently pure wave forms that only lasers can provide. Previously, lasers were necessary not just to expose holograms, but to view them as well. However, recent research described below has resulted in new types of holograms that can be viewed with ordinary white light sources.

The first decade of holography began with the exhibition in 1964 by Emmett Leith and Juris Upatnieks of the fruits of their application of the continuous-wave helium-neon laser to the principles of wavefront reconstruction advanced by Dennis Gabor in 1948. These remarkable three-dimensional laser photographs triggered a major scientific and popular boom for holography.

The art and technology rapidly advanced, reaching its peak in the large-scale pulsed ruby laser work at Conductron Corporation, later taken over by the McDonnell-Douglas Electronics Corporation. The room-sized portrait of Professor Gabor, taken shortly before he received the Nobel Prize in Physics in 1971, and several other ambitious commercial displays remain as totems from this first golden age of holography.

But as many technical problems proved surprisingly intractable, and as holography remained expensive, industrial and government support for further work dwindled, the rate of scientific publication ebbed, and the first decade ended with the dismantling of the McDonnell-Douglas Electronics Corporation facility in early 1974. The medium was then left in the hands of a few individual investigators, artists, and hopeful entrepreneurs whose work, largely unpublished, has stimulated the present second surge of interest in holographic displays. Although second-decade holograms are firmly based on physics and insights established before1974, they do look different from first-decade holograms. They tend to be brighter and larger, many require only common white-light sources for illumination, and some incorporate motion in natural scenes. In addition, they are less expensive than before, so that more holograms are being presented directly to the public.

Holographic Image Luminance

In its second decade, holographic display development has been putting a stronger emphasis on practical systems, reliable and affordable, producing an image quality that can compete for a media-inundated audience.

Demands for high image luminance as well as high contrast, extreme depth, large area, and wide angles for viewing tax the ingenuity of holographic designers. As passive devices, holograms can make available for viewing only a modest fraction of the illumination flux, much less than for a simple diffraction grating on the same material. The sensitometry of the photosensitive material and its processing, as well as the laws of physics, determine the maximum attainable diffraction efficiency, but the emergence of light diffracted in unwanted directions, either as granularity noise or intermodulation noise, limits the useful diffraction efficiency even further because of contrast degradation. Twenty percent is representative of many bleached silver-halide materials, although the deep shadows increasingly seen in illumination beams belie some progress along these lines.

Laser illumination of full-parallax holograms still produces the most visually impressive results, but is proving impractical in many cases because of the limited light available, as well as constraints on laser use and their cost. The largest available helium-neon laser is just sufficient to illuminate a typical 11 inch x 14 inch (30 cm x 36 cm) hologram to produce an image luminance of 74 cd/m^2 (22 fL), which is indeed competitive with modern color television levels.

The luminance of super-pressure mercury arcs with line-isolating filters is sufficient to replace lasers with source areas small enough to avoid noticeable blur of a deep image. However, the 4-nm wide emission waveband causes an unacceptable dispersive blur. Although this can be approximately compensated by an intermediate diffraction grating, this is rarely done in practice. Instead, it was quickly realized that reduction of the depth of the image to some fraction of the viewing distance would permit the use of larger sources and wider wavebands without perceptible blur. Large-lens and two-hologram techniques permitted the image actually to straddle the hologram plane, so that relatively low luminance sources, such as incandescent lamps with interference filters, could produce quite bright and clear, if shallow, images. Thus, many holograms became things to look *at* rather than *through*.

Common white-light sources such as the sun had, of course, already been used for viewing Denisyuk-type volume reflection holograms, where multiple reflections restrict the reconstruction to a narrow band, perhaps 623 to 642 nm for a 6-μm-thick emulsion, for example. A thicker emulsion permits the use of a narrower waveband, and so produces a deeper unblurred image, but also decreases the total reflected flux, and so the image luminance. Reflection holograms were an early hope for full-color imaging, but new finer-grained materials are needed for blue and green results as impressive as those now obtained in red light. Molecular recorders, such as dichromated gelatin of very high quality, have been developed for similar purposes, but color processes are still in the laboratory.

White-Light Transmission Holography

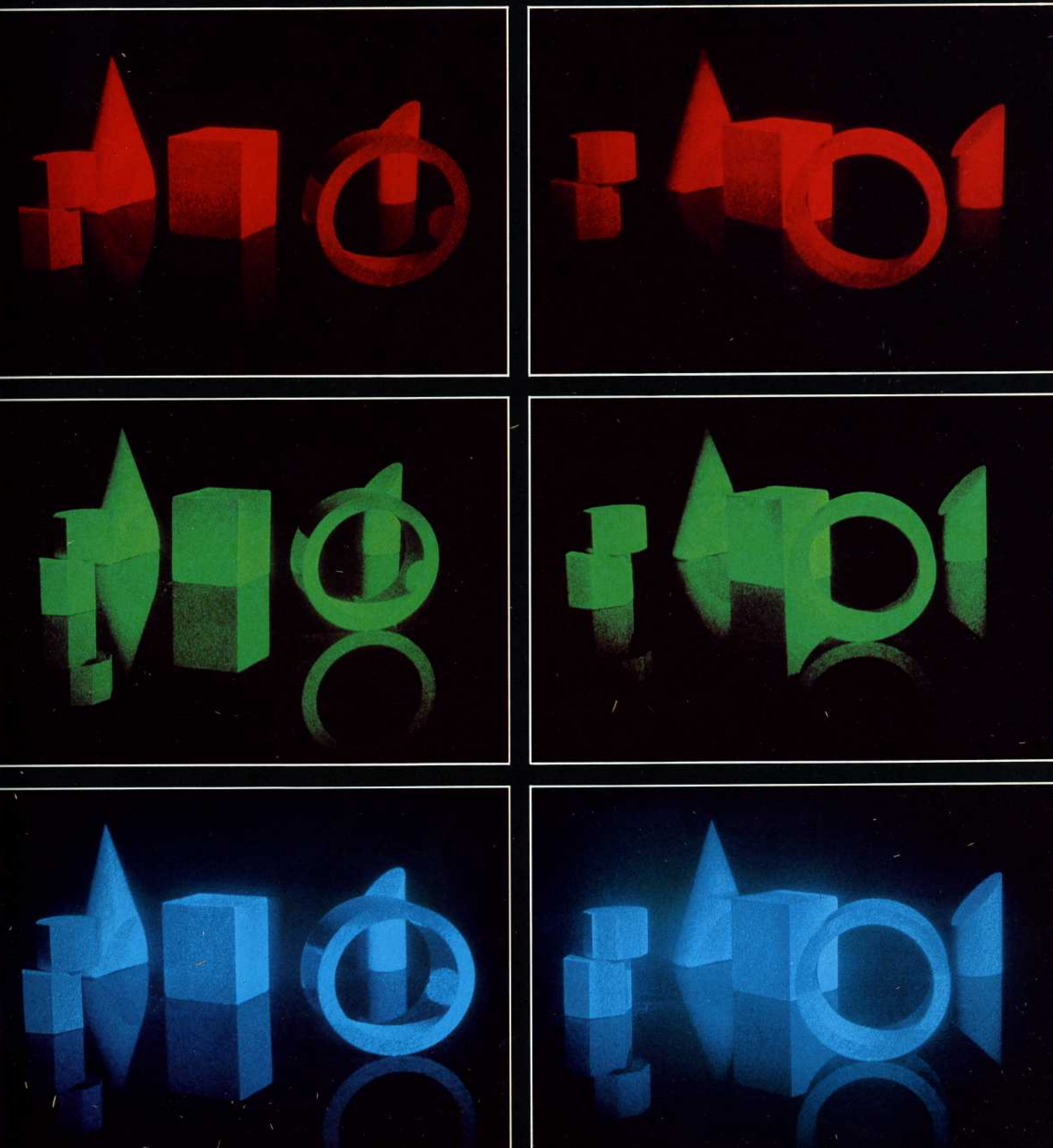
Since 1972, the use of white-light sources for hologram illumination has taken a different direction. Researchers at Polaroid showed in 1969 how the sacrifice of vertical parallax information in holograms could permit the use of point and line sources of white light while retaining the three-dimensionality of the image. The vertical information axis is used instead as a focused diffraction grating to disperse the light chromatically into a vertical spectrum in the viewer's space. As the viewer moves from side to side, he enjoys normal horizontal parallax, hence stereopsis, but as he moves up and down, the same three dimensional image appears in a succession of spectral hues. These were quickly dubbed "rainbow" holograms, perhaps prematurely, as our recent work produces virtually black-and-white images.

The practical advantages of these white-light transmission holograms were not widely understood until 1972, when fine art holograms made by Harriet Casdin-Silver and Stephen Benton were exhibited in and around New York. Not only were non-technical personnel able to set up and maintain the spotlight illuminators, but the resulting images were bright enough to be seen in ordinary gallery and museum conditions. The high luminance is due to the lack of illumination losses to wavelength-selective filtering and to the relative shallowness of the fan over which the diffracted light is distributed, and routinely exceeds 100 cd/m^2 (30 fL). The image depth of such holograms is somewhat limited by the astigmatism common to all horizontal-only schemes, so that fairly large sources can often be used, and brighter images obtained. A typical hologram in sunlight, for example, produces an image luminance at 550 nm of 2×10^5 cd/m^2 (57,000 fL). Because very high diffraction efficiencies are not required in such cases, surface-relief phase-modulating structures can be very useful for white-light transmission holograms. Such structures are readily replicated on plastic surfaces by casting, embossing, and so forth, to produce inexpensive holograms. If the surface is metallized, the image is presented in reflection, making it suitable for decorative surface application.

Holographic Stereograms

The question of synthesizing a "quasi-holographic" image from a multiplicity of photographs taken in ordinary light had an early appeal to holographers. Here, too, the economies of sacrificing vertical parallax soon became apparent, and several schemes were adapted to the white-light transmission mode. The appeal of cylindrical laser holograms, affording a 360° look-around view, was demonstrated in 1967 by T. H. Jeong. Kasahara et al. had proposed a cylindrical stereogram technique for x-ray images, using laser or arc illumination, which was independently being developed by Lloyd Cross and David Schmidt for display and artistic applications.

After seeing some early white-light transmission holograms from Polaroid, Cross and his colleagues were quickly able to merge the two lines of research to produce cylindrical holographic stereograms illuminated with incandescent lamps, and they soon formed the Multiplex Company to manufacture them. Their process photographs the subject in ordinary light as it slowly rotates on a turntable, producing about a thousand perspective still frames. The frames are compressed optically and recorded as abutting thin vertical holograms on a 9½ inch high strip of film in a laser optical rainbow hologram made by Dr. Stephen Benton and photographed by Fritz oro. Although the hologram is viewed with a white light source, the color of the nage changes as the viewer or the camera moves vertically up or down (in this ase three different camera positions are used). With movement horizontally, the amera and the eye experience parallax which results in the apparent displace-ent of the image in three dimensional space.



printer. The processed strip is then rolled into a cylinder and lit from below with a common 79-cent lamp to produce a very persuasive three-dimensional image within. A modest amount of motion can be incorporated as the subject turns, as in Cross and Brazier's "Kiss II," in which an attractive woman winks and blows a kiss at the spectator. Imaginary or impossibly fragile structures can be synthesized from computer-generated perspectives, which are proving valuable for educational purposes.

It is characteristic of second-decade holographic technology that a key component of the process is a low-f-number cylindrical lens, made with bent plastic faces and filled with mineral oil, which is routinely "tuned" to the best aspheric shape with paper clips and tape. More than any other type, these widely displayed images have helped stimulate the new optimism for holography.

Large Holograms

The appeal of large, deep images is undeniable, and records for sheer size continue to be broken. The latest are some 1.0x1.5 m laser-transmission holograms of the Louvre's Venus de Milo, produced at the University of Basançon by J.C. Vienot, J. M. Fournier and G. Tribillon. These have been exhibited in Europe and may soon come to the United States.

Projection-Type Holographic Displays

In situations where many images may be required, as in holographic movies, it becomes important that the holographic storage medium be much smaller than the images it produces, which suggests a projection scheme for image magnification. Many different optical functions may now be incorporated, leading to a variety of such proposals, and the extension to full color is straightforward in many cases. The schemes can be crudely distinguished by the nature of the projection screen, which must itself become a large optical element designed to maintain the integrity of the perspective information, permitting each eye to see only the image intended for it. In all cases, image luminance remains a problem, as it can be no greater for the same image depth, resolution, contrast, etc., in a projected image than for a full-size hologram visible to the same audience and lit with the same light source. But their capacity for full color, motion, and design flexibility makes projection systems a promising holographic topic for the second decade.

Are Holograms Here to Stay?

After several quiet years, holography has found a fresh optimism and a new conviction that, in the near future, some type of holographic image will be a daily experience for many people. Just what niches holography will carve out in the structure of modern visual communications is not much clearer now than it was ten years ago, and public interest seems to be building toward a frenzy of enthusiasm reminiscent of those heady days. Is there a danger that holography will yet again be caught up in a wave of rising hope, only to founder if technical progress fails to match the pace, as happened earlier?

In many ways, the atmosphere is similar to that of the late 60's. Public recognition of the term "hologram" is awesomely high, but still not very accurate. The early "James Bond" impression of room-sized full-color moving illusions is still being perpetrated, as in a recent *Hardy Boys Mysteries* prime-time TV broadcast, and holographic video projections à la *Star Wars* are becoming routine science-fiction fixtures. The confrontation with reality is often disheartening, as when a chagrined TV talk-show host discovers that holographic images come out flat on home receiver screens!

In many other ways, though, the atmosphere is different. The availability of reasonably priced holograms has made them frequent components of science and art curricula, helping to de-mystify the medium. As the scope of holography evolves and is interpreted by artists, increasingly frequent exhibitions are being mounted in cities around the world. Holographic displays in stores and shopping malls are also providing the direct experience that is necessary to appreciate the realities and the impact of the medium.

Holography is being taken seriously as a business as well. Cylindrical stereograms have already established themselves as prestige display features, and only await true mass production for a wider impact. Holographic jewelry is widely sold. The recent acquisition of Holotron Corporation, which holds exclusive rights to more than 150 patents and patent applications in holography, including those of Leith and Upatnieks, by Holosonics, Inc., signifies a recent change in the holographic atmosphere. Although the patents touch on diverse applications of holography, a central one claiming "an off-axis hologram of a three-dimensional diffusely reflecting object" looms as a dark cloud over many fledgling enterprises. Although research and educational efforts are unlikely to be affected, the impact on the commercial developments that have done so much to stimulate holography's second decade will take some time to be realized.

Is holography being taken seriously as art? This is an important issue because holography is a field that, like photography, is emerging from the intersection of science and art. The technical development of the medium continues to depend very much on the stimulation of simply seeing things that were not expected. Although holographic hardware is becoming increasingly available to artists, in the form of sand-box optical tables with PVC pipe carriers for optics, for example, it is still considered exotic, and the esthetic/technical compromises are more frustrating than those of familiar media. But every year a few more image makers try their hand, and others become more ambitious. A visit to New York's Museum of Holography would satisfy almost anyone that holography's artistic potential is being carefully and successfully tapped. As these artists continue to discover spaces of unexpected beauty and meaning, so will holography continue to crystallize from an amorphous mass of possibilities into a definable, though varied medium of great visual power.

Of course holography is here to stay. Three dimensional imaging may well evolve into new forms that depend on holographic insights only for their conception, but holography has already reshaped our expectations for the future of image communication.

Dr. Stephen Benton is a Senior Scientist in the Special Photographic Research Group at Polaroid where he conducts research in the physics of imaging systems and the application of lasers to imaging. He is the author of several papers and patents in optical physics, photography and holography.

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