Progress in holography

As this method of imaging becomes better understood, it can offer the best solution for problems in fields as diverse as architecture, medicine and mechanical engineering.

Emmett N. Leith and Juris Upatnieks

With the award of the 1971 Nobel prize in physics to Dennis Gabor, holography has reached a new pinnacle of prestige. Gabor won his prize for the invention of holography, a form of wavefront reconstruction in which a coherent reference wave appears to unlock a three-dimensional replica of an object from a two-dimensional standing-wave pattern.

The science of holography has taken some curious turns in its relatively short 25-year history. The time divides itself naturally into three periods: The first could be considered a precursor stage, when the aim was to record wavefronts diffracted from crystals that had been irradiated with x radiation or electron waves. If reconstruction with visible light were successful, a highly magnified image of the crystal lattice would result. Recording the phase of the radiation was, however, a difficult problem that was soluble only for rather special cases. (For a description of this early work, carried out principally by Sir Lawrence Bragg and Hans Boersch, see reference 1.)

In 1948, Gabor developed a way to introduce a coherent background or reference wave, and the second period began. The third stage began in the early 1960's, when high-quality holographic imagery was demonstrated; the beginnings of this stage coincided in time with the development of the first lasers. Our attention here shall center on the latter two stages, particularly on the more recent work, for the history of holography gives us indications of what it can be reasonably expected to do in the future.

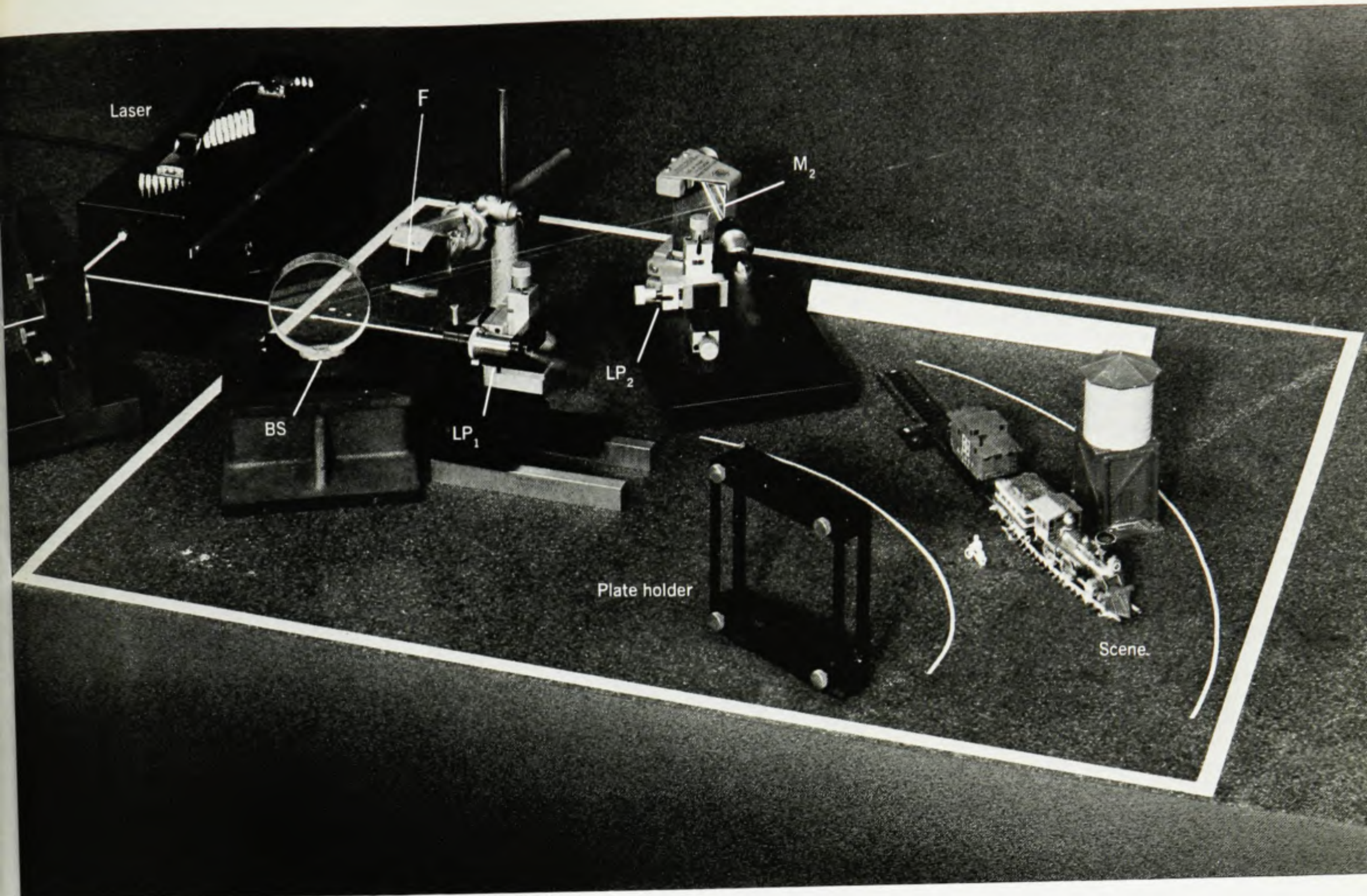
Emmett Leith and Juris Upatnieks are both at the University of Michigan, Ann Arbor; Leith is Professor in the Electrical Engineering Department, and Upatnieks is a Research Engineer at the Institute of Science and Technology.

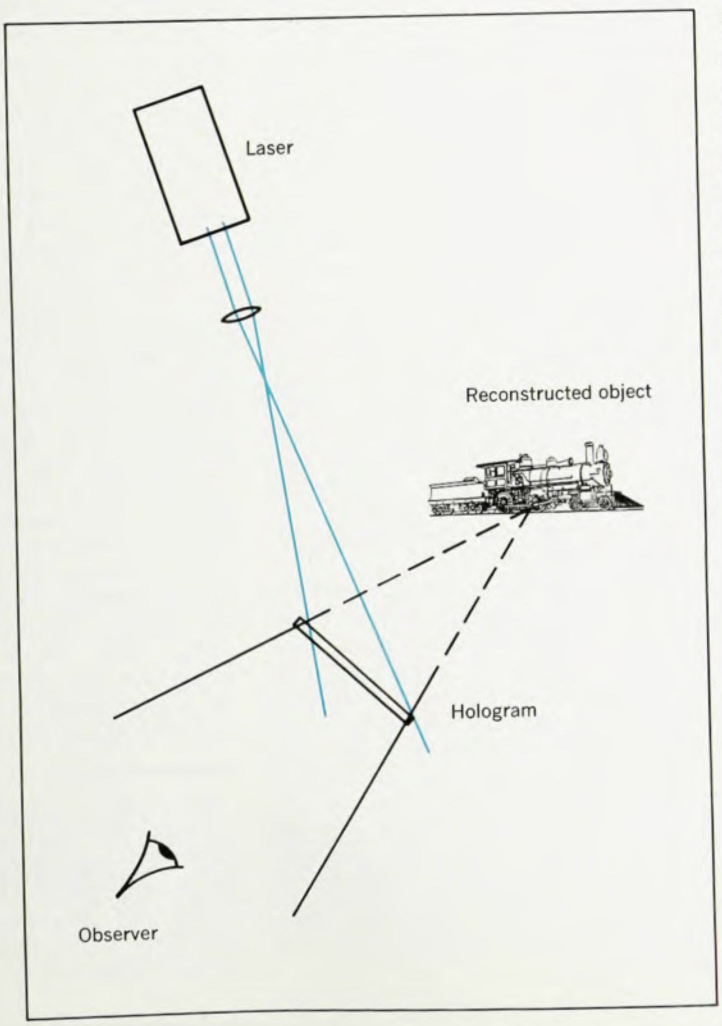
Early holography

Gabor's method, simple and elegant, solved in quite a general way the basic problem of recording the phase, as well as the amplitude, of a wave. In three principal papers between 1948 and 1951,[2] he developed the theory in considerable depth and offered convincing experimental results. Gabor's original purpose, to record electron waves and regenerate them at optical wavelengths, thereby compensating with optical techniques for the uncorrectable aberrations of electron lenses, is an historical point that today receives at best a passing notice. However, the holographic process has been revealed to have far more potential than one could, at that time, have imagined.

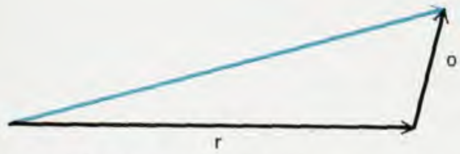
The excitement that must have attended the first accomplishment of the method is known, perhaps, only to Gabor and his associates. Our own excitement in 1960, when we duplicated for our own curiosity the experiments he described, was considerable, even though the expected results were known beforehand. With an eyepiece, we followed the optical paths of the reconstructed wavefronts downstream to their focal position and observed a sharp, well defined image that had the startling property of having no apparent antecedent; nowhere in the optical system was there an object with which to associate the image (see figure 1). The mathematics, simple and easily understood, fully predicted the result; yet, the physical realization seemed altogether mysterious. The first time must have produced a powerful impact indeed!

Interest in holography continued strong for several years afterward, and produced some notable pioneers. Gordon Rogers explored the new technique in many ways, uncovering new ramifications and new insights; one of his best known contributions[3] is his extensive development of holographic image-forming principles in terms of Fresnel zone-plate theory, by which one can grasp in a highly intuitive way the first-order imaging properties of holograms. M. E. Haine, James Dyson and T. Mulvey applied[4] holography to electron microscopy. In the US, Ralph Kirkpatrick and his two students, Albert Baez and Hussein El-Sum, became interested in holography, particularly in its application to x-ray imagery. El-Sum produced the first doctoral thesis in holography.[5] In Germany, Adolf Lohmann first applied communi-

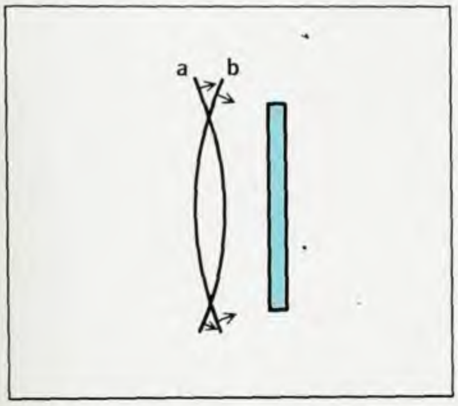




Typical arrangement for holography of a three-dimensional, opaque object (photo, top). The light emerging from the laser is deflected by mirror M_1 to beam splitter BS. The transmitted beam is diverged by lens LP_1, so that it illuminates the scene at right. The reflected beam, after passing through the variable attenuator F, is reflected by mirror M_2 to lens LP_2. The now diverging reflected beam illuminates the plate (held in the plate holder) as the reference beam. When the fringes produced by interference between object and reference beams are recorded on the plate, the result is a hologram. Under illumination by the reference beam alone (diagram, bottom) the developed plate, or hologram, regenerates the object wave, and an observer who looks through the hologram sees what appears to be the original object.
Figure 1



Principle of the coherent background. When the object wave o is attended by a strong coherent background (or reference) wave r, the resultant wave (color) has a phase that varies only slightly from that of the background wave, and the loss of phase of the total field is relatively unimportant. Both the phase and the amplitude of the object wave are preserved to a high degree through its interference with the background wave.
Figure 2



The twin image occurs because the two wavefronts a and b, which have equal but opposite curvature, produce the same fringe pattern when "interfered" with a coherent background wave. On reconstruction, the hologram produces both waves, regardless of which had been present during the recording.
Figure 3

cation-theory techniques to holography and, in consequence, suggested the single-sideband method[6] for removing the "twin image," one of the residual defects of the process. Despite the initial impetus, however, interest in holography waned in the middle 1950's, although activity never completely ceased.

The principal reason for the loss of interest was the relatively poor imagery, due mainly to the previously noted twin image, which occurs because the recording process is sensitive only to the intensity of the incident radiation. As a consequence, the reconstruction process not only recreates the original wave, it also creates a conjugate wave that, under collimated illumination, forms an image in mirror symmetry to the "true" image with respect to the plane of the hologram. Whichever image one elects to use, he must view it against the out-of-focus background of the other, and the result is a noisy image.

The origin of the conjugate image can be described in various ways. Basically, the introduction of the coherent background wave renders the inevitable loss of phase of the total wave (signal plus coherent background) relatively unimportant; the phase of the total wave can vary only slightly from the background wave if the latter is strong (see figure 2), and the phase of the signal is manifested by its interference with the background. Nevertheless, the recording process has a fundamental ambiguity: It cannot distinguish between signals with equal and opposite phase, relative to background (figure 3), because both produce the same intensity. Alternatively, we may say that the surface that records the hologram cannot distinguish an object wave from the left from an object wave in a position of mirror symmetry on the right; the resulting interference pattern is the same. In either view, the reconstruction process resolves the dilemma by generating waves corresponding to both situations.

High-quality imagery

In the early 1960's, several papers appeared that proved to be forerunners of the great explosion of activity that ushered in the next stage of holography. We announced at the October 1961 Optical Society of America meeting a number of new concepts, including the off-axis or spatial-carrier frequency method of holography, which removed the twin-image problem in a simple and practical way.[7] In this method, the reference and object waves are brought together at an angle, to form a rather fine fringe pattern. The resulting hologram, behaving like a diffraction grating, produces several nonoverlapping diffracted orders. The zero-order wave produces the usual inseparable twin images which, in combination with other defects of in-line holography, result in poor imagery; but each first-order diffracted wave produces an image of high quality.

When, however, we extended the process to continuous-tone object transparencies instead of the black and white transparencies used in holography until then, another defect became prominent. The difficulty was the well known "artifact" problem of coherent light—each extraneous scatterer (for example, a dust particle) produces a wake of diffraction patterns that contaminate the resultant image. We surmounted this problem with *diffused* coherent illumination, which properly used, smooths the field produced by these scatterers.

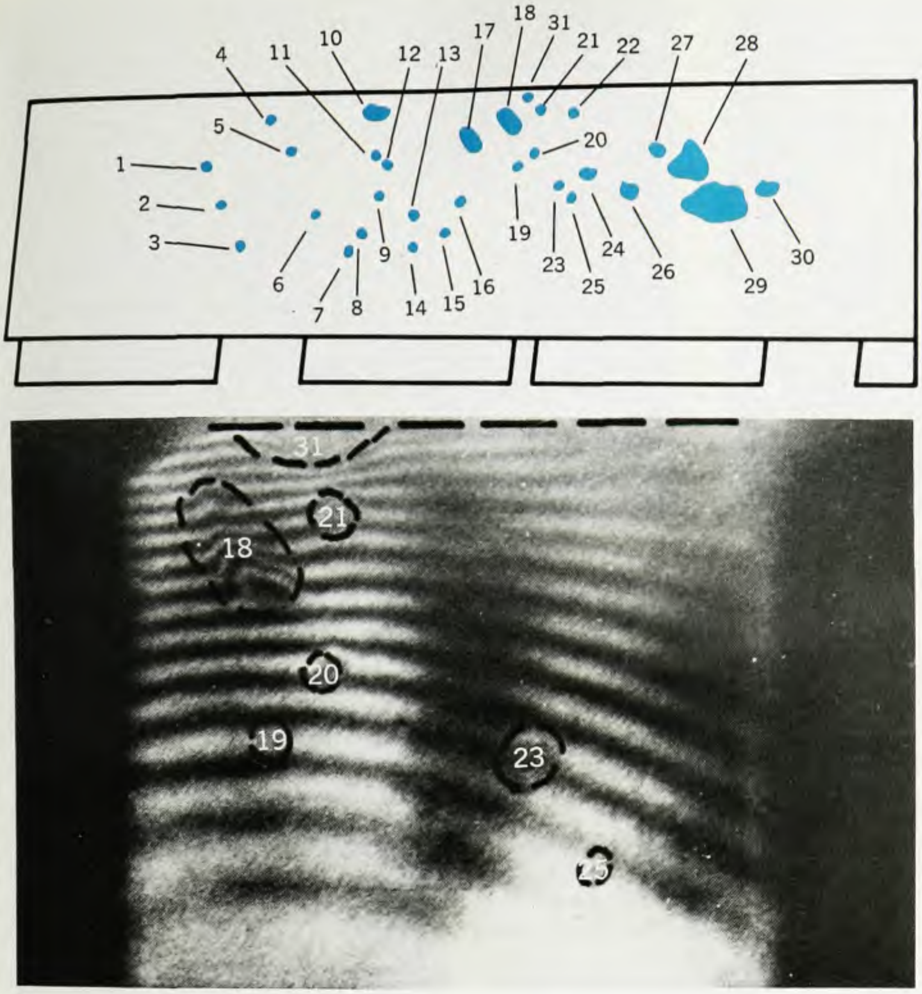
During the course of this work, the laser became available; we used it, as well as the mercury arc source, although it was not at all necessary. Its brightness reduced the exposure time and its great coherence made careful equalization of the object and reference beam paths unnecessary. It offered, however, a thousand times the needed coherence, violating the basic rule that, in a coherent system, one should not be more coherent than necessary. As a consequence, the artifact problem was aggravated. On balance, with transparencies, either the laser or the mercury arc source should do quite well. Indeed, with proper optical system design, the coherence requirements for off-axis holography reduce exactly to those for in-line holography.[8]

Finally, we exploited the great potential of the laser by using three-dimensional, reflecting objects. For such objects, the coherence length should be of the order of the scene depth, a requirement that generally cannot be met with the mercury source. The laser also permits enormous quantitative advances: larger holograms and large objects.

About the same time, Yu. N. Denisyuk of the USSR introduced a new concept into holography, the "volume hologram," which combines holography with the Lippman color process.[9] Object and reference beams are introduced from opposite sides of the recording plate, and the resulting fringes are embedded within the emulsion as surfaces running nearly parallel to the emulsion surface, with half a wavelength spacing between them. Typically, the number of fringes in a cross section is about 50, although for very thick (a few mm) recording materials, there may be thousands. The twin image is eliminated by the thickness effect and, in addition, the holograms, because of their wavelength selectivity, can be viewed in white light derived from a point source. Denisyuk's work is a cornerstone of modern holography. Related work was reported by Pietr J. van Heerden,[10] whose concern was principally with holographic memories. During this same period, Brian Thompson and George Parrent used Gabor's in-line method, in combination with the pulsed laser, for their particle-sizing work, an application ideally suited for this configuration because the objects are extremely simple and a noise-free image was not needed.[11]

The great surge

By late 1964, holography had become probably the most active field of research in optics, engaging hundreds of groups throughout the world. Discovery and invention dominated the next three years; this period produced several techniques of color holography,



Defects in a section of an airplane trim tab are examined with double-exposure hologram interferometry. The trim tab was holographed a section at a time; each segment was recorded in two exposures, with thermal stress applied for the second exposure. In this way, the various defects were mapped (top). In the holographic image of one section of the wing (bottom), the defects are seen as defects in the fringe patterns that overlay the image. The wing was also examined with conventional, ultrasonic testing methods; the two methods gave substantially similar results. Courtesy C. Vest and D. Sweeney.
Figure 4

hologram interferometry in its various forms, techniques for holographic imagery through scattering and aberrating media, and many other basic concepts. The vast potential that had been inherent in holography now emerged with astonishing force.

By 1967, however, the discoveries began to diminish and the inventions took on an increasingly restrictive aspect, becoming more concerned with the design of specific configurations. The holographic world appeared to be consolidating its gains. Serious analysis of the holographic process in its various aspects became more evident, and, undoubtedly due to pressure by management and in response to the prevailing economics (in the US), applications received greater attention. Despite the shift in emphasis, however, the activity in holography remained at a high level.

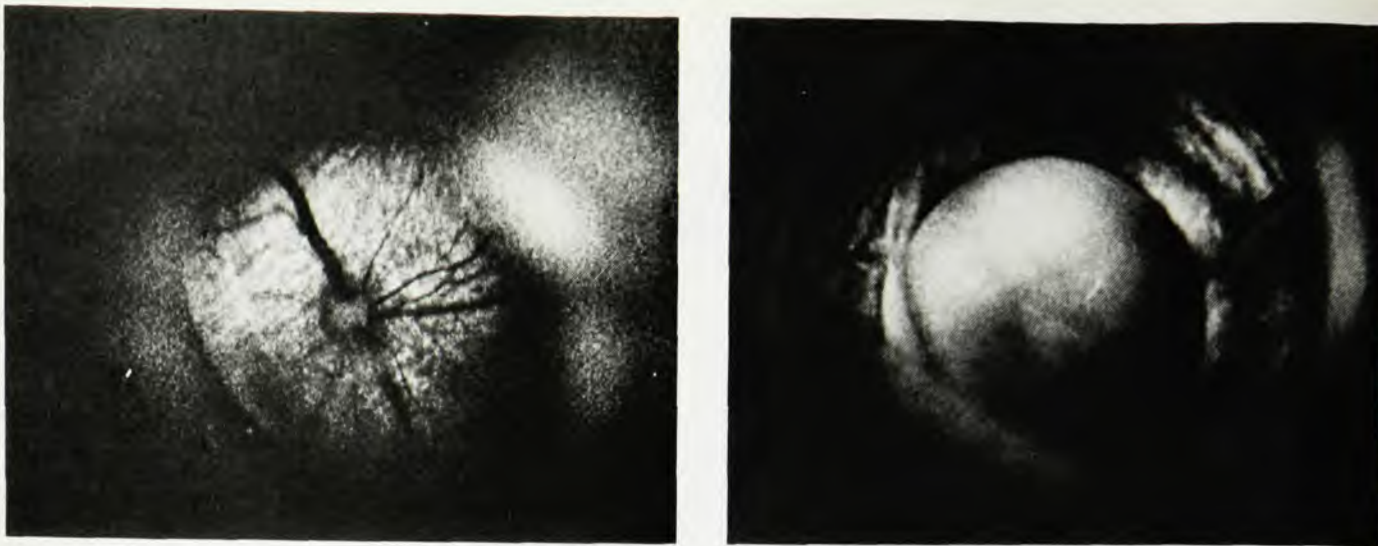
Holography was found capable of an astonishingly wide variety of tasks that were normally done in other ways. Holographic methods could be useful in optical metrology and offered some interesting possibilities for spectroscopy. Optical memories using holographic techniques seemed destined to make significant inroads into the huge computer-memory field. Optical reading and feature-recognition machines that used holography were visualized. Microscopy, at least in the visible wavelength range, seemed promising. With hologram interferometry, a wide variety of nondestructive testing techniques became available, ranging from early detection of fatigue failure, to the detection of "debonds" in multilayered materials such as tires and honeycomb panels (figure 4), to the determination of heat flow in transparent materials, to the study of bending moments and to the dynamic operation of audio speakers and other sound-transducing equipment. A most ingenious and unlikely application of hologram interferometry is the determination of the complex mode structure of a laser.[12] Merely to list the applications of hologram interferometry in reasonable completeness would fill a page. Even in conventional interferometry, it was found that one could apply to the hologram essentially all the techniques—such as schlieren, dark field, and phase contrast—normally done with the actual object.[13]

Holography, we have noted, can be used to detect and examine aerosol particles, such as atmospheric pollutants. Not only was holography unique for visual displays of many kinds, including portraiture, but it could also be used in instrumentation for conventional stereo imagery. Holographically produced optical elements showed promise for improving the performance of optical elements. The versatility of holography seemed limitless. (See figures 5 and 6 for examples.)

Practical uses

Serious efforts to commercialize holography became visible in the late 1960's. Many small companies dedicated to a particular aspect of holography sprang up, and in larger companies, the basic-research programs were reoriented toward product development. Equipment was designed for bringing holographic measuring and testing techniques into the factory, and prototype holographic memories began to develop.

By the end of the 1960's, some defects in the holography bandwagon showed themselves. The hoped-for commercial products either failed to materialize or were not competitive with conventional products. The tremendous versatility of holography proved insufficient to ensure its success; holography would have to be in some way an improvement over the established methods. Often, however, the old ways were better, at least within present state-of-the-art limitations. Thus, holography programs were curtailed or eliminated,



Medical application for holographic three-dimensional imagery. The eye of an anesthetized cat was holographed. From this single hologram it was possible to image any plane throughout the eye: Photo at the left shows the retina, with the blood-vessel structure and optic disk clearly visible, and photo at the right shows the iris. Courtesy J. Caulkins and C. Leonard.
Figure 5

and some small companies disappeared. In many quarters an atmosphere of gloom was observed, but whether or not the level of activity has diminished is problematical: As some groups abandoned holography, others appeared. The number of papers published has decreased slightly but remains high.

In retrospect, this course appears to have been predictable. The attempt to apply holography indiscriminately to all conceivable situations tended to force it into unsuitable molds. In addition, when the game is played for the multi-million dollar markets, the longshot strategy enters the picture, and to date none of the longshot, large dollar volume areas has paid off.

Increasingly, we find evidences of an alternative approach. As holography has become more widely understood, persons with specific problems and goals have examined it and, occasionally, have discovered that holography appears to offer the best available solution. Additionally, holographers have become more sophisticated in their judgments of holography's capabilities and have searched more deeply for applications. The result is an increase in the number of applications that withstand critical evaluation; such applications are typically those that are highly specific or those in which some fairly simple holographic principle is incorporated harmoniously into a basically nonholographic system. These approaches stand in contrast with the bolder, albeit less successful, ones that pit holography in a broad way against a well developed and well established technology.

A recent example is the work of Ralph Wuerker and Lee O. Heflinger, who used[14] pulsed-laser hologram interferometry to examine the thermally produced deformations in an antenna to be carried on a satellite. The antenna, placed in a space-simulation vacuum chamber, was heated with a solar-radiation simulator. A hologram was made by a double-exposure process, so that the resulting image formed by the hologram was a coherent superposition of the image formed during each exposure. The deformation occurring in the interval between exposures was thus manifested as a fringe pattern overlaying the image; the greater the deformation, the finer the fringe pattern. Here the task is one to which holography is highly suited, and to which other techniques are ill suited.

Anthony Vander Lugt used[15] a holographically produced spatial filter in an optical processing system to analyze cloud motion. The input was a succession of pictures of cloud cover taken by a satellite. Certain frames are converted into Fourier-transform holograms and used as spatial matched filters for the next few successive frames. Portions of the cloud pattern that remain completely unaltered produced a bright cross-correlation spot in the output. Portions that are unaltered except for linear displacement produce displaced cross-correlation peaks. Picture segments can be identified with the corresponding output peaks by covering portions of the input data by an adjustable aperture. If such operations are performed on successive frames, the velocities of the various cloud segments can be found. Rotation of cloud masses can be measured by adjustment of the filter orientation. Alteration of the cloud structure can be determined by measurement of the correlation peaks. As the cloud structure changes with time, later frames can be introduced as spatial filters, so that the filters can be continuously updated. The spatial matched filter thus fits centrally into the system, performing in a simple way precisely the tasks required.

Most promising areas

Presently, the areas of holography that appear most promising are probably hologram interferometry, holographic memories and hologram optical elements.

Shortly after it was announced in 1965, hologram interferometry became the major type of application, a position it retains to the present day and will likely retain at least into the near future. Recently other techniques involving coherent light have developed.[16] For example, interferometers using the well known "speckle" phenomenon of coherent light can do many of the jobs to which holography is suited, such as detection of vibration and measurement of deformations. This method is easier to carry out than hologram interferometry but generally lacks its precision and sensitivity. Thus the method is complementary to, rather than competitive with, holography.

Hologram interferometry has proved quite valuable in certain specific situations. In general situations (such as nondestructive testing techniques for detection of cracks and debonds), it has shown itself to be competitive with such standard techniques as x-ray and ultrasonic analysis (figure 4). However, hologram interferometry has as yet made few if any inroads into the standard nondestructive testing methods.

Holographic memories show promise but face an uncertain future. The absence of an erasable, reusable and sufficiently sensitive recording material has generally limited holography to read-only memories, which seem promising when viewed in terms of broad design concepts, such as cost per bit and memory size versus access time. John La Macchia,[17] however, has indicated that serious engineering problems become evident at the prototype stage: variation of diffraction efficiency from one bit to another; inability to achieve satisfactory high diffraction efficiencies and high signal-to-noise ratios simultaneously; detectors that lack uniform sensitivity; expensive and bulky light deflectors; and lasers with inadequate power, insufficient lifetimes and high operating costs.

These are not fundamental problems, but merely problems of engineering design and, quite possibly, they are solvable either by pushing present technology to its limit or by further advances in the appropriate technologies. We can expect that these problems will be surmounted within a time period of five to ten years. Holographic-memory development is apparently being actively pursued by various groups in the US, Germany and Japan.

The outlook for holographic optical elements is presently quite good. There are two basic reasons for this optimism. First, the aberrations of holograms have by now been explored in considerable depth. Second, experimental techniques for producing high-quality, high diffraction-efficiency, low-noise holograms have been developed. John Latta[18] has pioneered in the use of the computer to investigate these aberrations in great detail, and has explored the tandem combination of optical elements in arrangements that greatly reduce the aberrations (figure 7).

Diffraction gratings can be produced by holographic methods.[19] Indeed, because this process involves merely the interference of unmodulated light beams, it should perhaps be viewed as conventional interferometry rather than holography and, in such a context, was explored by James Burch many years ago. The recent advances in holographic recording technology, however, are generally applicable here also.

Major problems to be solved

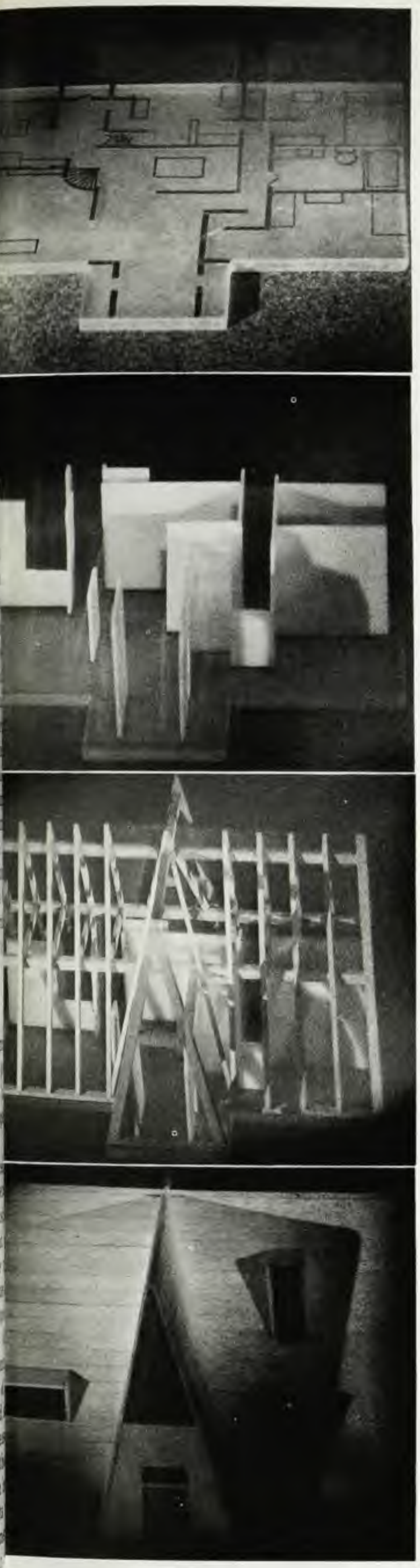
The intensive research of the past seven years has resolved many difficulties, but severe problems remain that block many of the hoped-for attainments in holography.

The lack of recording materials is one of the foremost problems. At present, high-resolution photographic film is the most commonly used material. Its deficiencies are severe and include lack of optical flatness, variation from plate to plate and among batches of emulsion, nonlinearity, a messy chemical-development process that swells the emulsion and generally leaves some permanent distortions, insensitivity to light in comparison with conventional emulsions, and lack of erasability and reusability. These deficiencies have promoted a search for alternative materials, but the results have generally been disappointing; photographic film remains, in general, the best material.

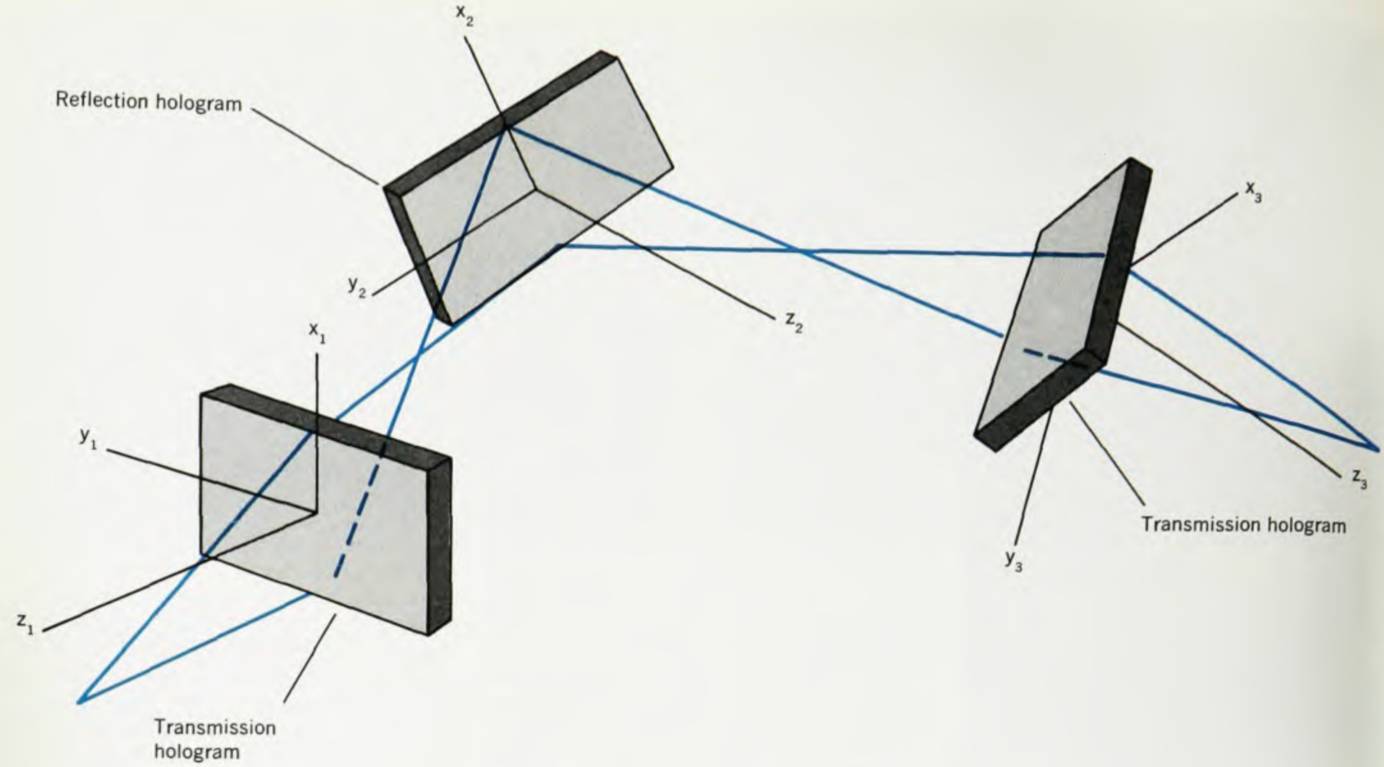
Bleaching techniques, in which the silver deposits in the developed negative are changed into a transparent material with an index of refraction different from the surrounding emulsion, has led to dramatic increases in diffraction efficiency of holograms. A hologram formed from a diffusely scattering object generally has a diffraction efficiency such that only about 0.5 to 1.0% of the incident light is converted into the reconstructed wave. Bleaching under controlled conditions can raise this conversion to 15 to 20% while preserving good image quality. Even higher diffraction efficiencies can be achieved, but at the expense of increased noise.

Alternative materials include photochromic glasses, which, by virtue of their molecular grain size, offer extremely good resolution and low noise but are several orders of magnitude less sensitive than even the very slowest photographic emulsions. They are erasable but generally have extremely low diffraction efficiency. Holograms of excellent quality have been produced on photopolymers, dichromated gelatin and lithium niobate. Magneto-optic materials, such as MnBi, have produced holograms that can be rapidly formed and erased. But none of these alternative materials is likely to displace photographic film as the most commonly used recording medium.

Another severe problem area is laser speckle, a defect that never escapes the notice of those viewing holograms. Yet, the problem lies not with holography, but with the coherent light that holo-



Architectural structures are visualized through holography. A model of a building, in various stages of construction, was formed by multiple storage of images; each image can be read out separately by using the Bragg diffraction effect of thick emulsions. A 5.5-deg rotation of the plate produces the next successive image, and intermediate orientations produce adjacent pairs of images in superposition. As the observer rotates the plate, he can see the structure at any desired stage of completion, and because the images are fully three-dimensional, he can perceive the various structural relations vividly. Courtesy L. Fader and C. Leonard.
Figure 6



Computer analysis of holographic optical elements in tandem. In this model, developed by John Latta, the geometry is extremely general; it allows for any orientation and spacing of the various elements, as well as for both transmissive and reflective elements. Computer programs that optimize the design of such holographic systems are available. Figure 7

graphy requires. The problem is generally solvable only with the introduction of massive redundancy into the viewing system. For the case where the final image is a recording of the holographically formed image, the redundancy takes the form of a multiplicity of superimposed images (ten or more), each the same except for uncorrelated speckle patterns. Alternatively, the redundancy can take the form of an imaging system with the *f*-number far smaller than necessary for the desired resolution. When the hologram is to be viewed directly, these methods do not apply, except in the awkward case of projecting a multiplicity of pictures at a frame rate higher than the retention time of the eye. In general, the proposed solutions to the speckle problem come with a high price tag and are no panacea.

The light source is a problem that has been yielding to advances in technology. We obtain 1000 times more power, at 1/100 the price per milliwatt, than was available when lasers were first applied to holography. Coherence is better than ever; even pulsed lasers now have coherence properties suitable for holography. Holographic portraiture is one quite dramatic result of pulsed-laser holography. There is, however, need for further improvement in producing powerful, highly coherent, inexpensive and compact lasers.

The future prospects for holography evidently depend on the development of further viable applications, without which holography would become only a laboratory curiosity. Much work remains to be done in the aforementioned problem areas; unfortunately, the reduction of government and industrial research funding for nonmission-oriented and long-term research has adversely affected prospects here. In any event, whatever its usefulness may be, holography will remain a subject of fascination to all who have the opportunity to make holograms and, indeed, even to those who must content themselves merely with viewing them.

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