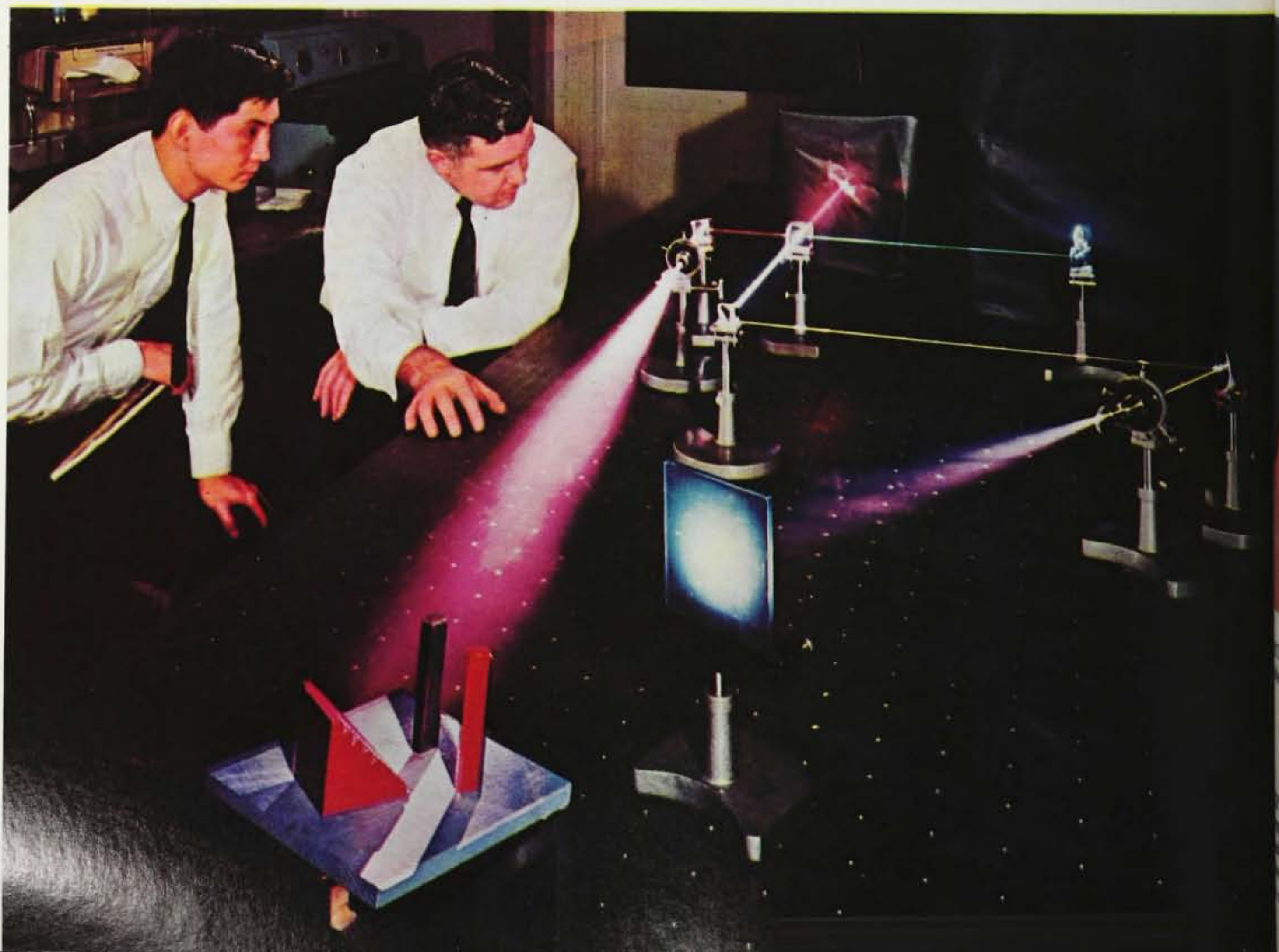
HOLOGRAPHY AND INTEGRAL PHOTOGRAPHY

These two complementary methods of 3D imaging both have their special advantages. Lensless photography, or holography, provides a method for precise distortion measurements, information storage and studies, such as bubble-chamber photography, that require great depth of field. Lenslet, or integral, photography does not need coherent light and is therefore tolerant of subject motion.

ROBERT J. COLLIER



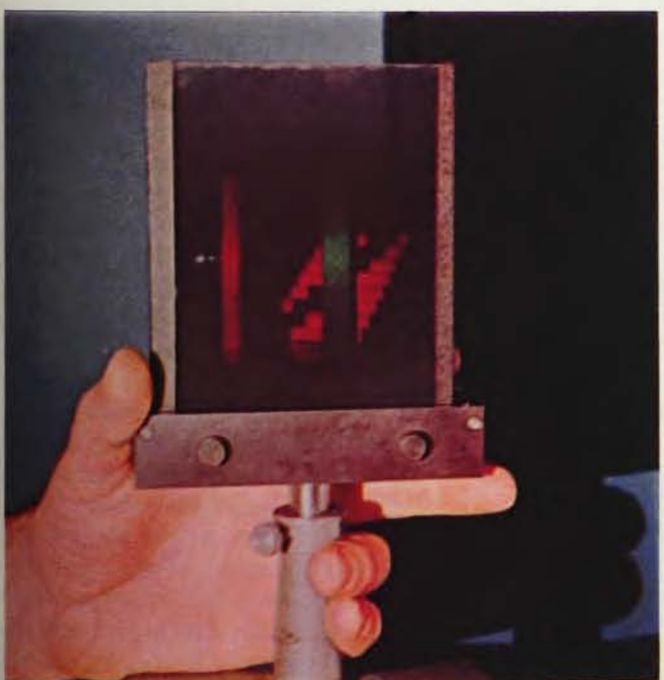
RECENT REVIVAL of interest in things optical, at least for those of us who have had only a desultory brush with formal training in optics, has been stimulated in the main by the emergence of the laser. Armed with helium–neon, argon cw lasers and ruby pulsed lasers, many former microwave or laser physicists and electrical engineers have turned to exploring and exploiting that art of lensless photography called "holography." Applying concepts from other disciplines to their new field, optical neophytes have done much to reveal the manifold potential of holography. Unlettered in optical lore, they have also at times blundered into the often unrewarding task of reinventing processes whose properties and limitations have long been investigated. Nevertheless such unwitting archeology does, on occasion, exhume an old idea that may be significant to current efforts and technology. While working with laser-illumination methods for recording and reconstructing three-dimensional images without lenses, holographers have become aware of older 3D image-recording techniques requiring myriads of lenslets. Whether lensless or lenslet, each of these (autostereoscopic) methods allows observation of a 3D image without special viewing apparatus.

Though there are other conceptual links between lensless and lenslet methods (discussed below), there are historical links as well. To holographers the name Gabriel Lippmann is well known: The high-resolution photographic emulsion used to make holograms is called a "Lippmann emulsion," and holograms that reconstruct multicolor images with white-light illumination are often referred to as "Lippmann type." Lippmann received the Nobel prize in physics in 1908 for creating the first method of color photography. It depends on recording light-interference patterns and thus is strongly related to holography. In the same year Lippmann proposed a conceptually simple lenslet method of recording and displaying 3D images. The process is called "integral photography." William L. Bragg provides another such link. Bragg's law governs response of certain holograms to illumination, and he attempted to provide 3D reconstruction of atomic structures with the aid of a lenslet array.

Holography and integral photography play complementary roles in spatial image recording and reconstruction; in this article I will examine these roles. (The reader who desires to learn more about holography and its flamboyant record will be aided by references 1 and 2.) My concern here is only with the visible region of the electromagnetic spectrum; holography at other wavelengths is not covered.

Method of holography

Holography, in the optical region, normally uses a laser beam that is separated into a coherent subject-illuminating beam and a coherent phase-related reference beam. The laser light reflected or transmitted by the subject intersects and interferes with the reference beam (figure 1). A high-res-

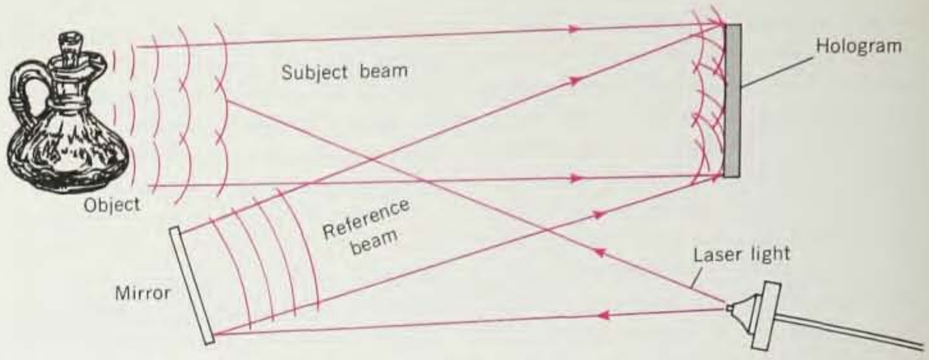


MULTICOLORED 3D IMAGE. Hologram (above) recreates subject scene (opposite) when illuminated with white light.

TEST PATTERN. White-light reconstructed hologram image of this pattern gives an indication of color range and fidelity.

EXPERIMENTAL ARRANGEMENT for producing a multicolor-imaging hologram (opposite). Red light from a helium–neon laser and blue light from an argon laser combine to form reference and subject-illuminating beams. Light from subject scene (two small pillars and a set of stairs) is reflected to hologram plate (blue rectangle in center), while the reference beam impinges on the opposite side of the plate.

olution photographic plate, inserted into the interference region and properly exposed, will record the interference pattern. After development, the plate is called a "hologram." This silver-grain replica of the interference pattern is a very closely spaced, complicated diffraction grating. Dennis Gabor's original discovery (1948) was that such a hologram, when repositioned and illuminated by the original coherent reference beam, will diffract and transform a portion of the reference wave into the shape and direction of the original subject wave, thus reconstructing the relative amplitude and phase properties of the latter wave (figure 2). If the subject were 3D, the viewer of the reconstructed subject wave would see, in full depth and with full parallax properties, a virtual 3D image appearing in the identical volume of space occupied by the subject (figure 3).



FORMATION OF A HOLOGRAM. Laser light is separated into a reference beam and a subject-illuminating beam. Light reflected from the subject interacts with reference beam, and hologram records the resultant interference pattern. —FIG. 1

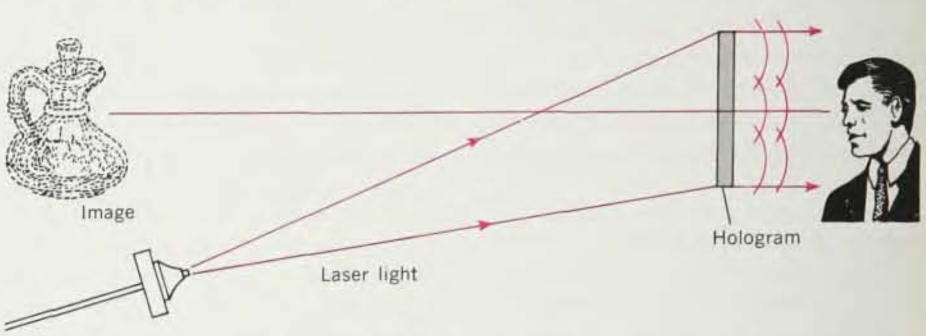


IMAGE RECONSTRUCTION. When hologram is illuminated by reference beam, it transforms the reference wave into the shape and direction of original subject wave, thus reconstructing the relative amplitude and phase of the latter. —FIG. 2

Method of integral photography

There are many multiple-lenslet techniques for 3D image recording bearing somewhat confusing, permuted names such as "parallax stereograms," "parallax panoramagrams" and "panoramic parallax stereograms." Variants of these methods, which utilize lenticular screens containing small cylindrical lenses placed adjacent to the photographic emulsion and which sometimes require a panning movement of the camera, are responsible for commercial 3D greeting cards, postcards and op art. Lippmann's method of integral photography is simpler than these in concept and capable of producing 3D images with fully observable parallax comparable with that which is obtained from the holographic method.[3]

Integral photography allows incoherent light to illuminate the subject. The light reflected by the subject is imaged by each one of an array of tiny spherical lenslets (called a "fly's-eye lens") onto a photographic plate placed behind the lenslets and close to their back focal plane. Each image is a complete picture of the subject seen from a unique aspect.

We can understand the imaging process by considering the recording of one object point (figure 4). Since the focal length of the lenslets may be only a few millimeters, the object point will normally lie many focal lengths distant on one side of the lenslets. Then the image will form approximately at the back focal plane on the other side of the lenslets. Corresponding to position in the array, each lenslet sees the object point from a unique angle and thus forms an image point that is displaced from the lenslet optic axis by a unique distance and direction. After exposure to this array of bright point images, we make an accurate positive image consisting of an array of transparent spots on an opaque background. The developed plate is replaced in the back focal plane in original register with the lenslet array and is illuminated from the rear with diffuse incoherent light (figure 5). Each transparent point image emits a spherical wave that emerges from the lenslet as a narrow beam whose direction corresponds to the off-axis position of the point image. These beams converge to form a bright spot at the original location of the object point. The name "integral photography" derives from integration of all tiny images into a final 3D image by their projection through the complete array of fly's-eye lenses.

More complex images formed by integral photography are real and pseudoscopic (see glossary). This property results from the two-step integral-photograph process behaving essentially as an autocollimating device and sending the original subject light directly back on itself. Such a device inverts the depth positions of subject points and causes points that appear in the foreground, when viewed normally,

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to appear in the background when viewed from the autocollimating screen.

Phase information

With coherent light and a reference wave, the hologram method records light-interference fringes on a photographic plate. Intensity of the light-interference pattern has a component that is a cosinusoidal function of the relative phase between subject and reference wave. This intensity can be recorded linearly on the plate so that the plate's amplitude transmission is a similar function of phase. Thus hologram recording preserves subject-wave phase information, and illumination of the hologram with the original reference wave recreates the coherent subject wavefront with all of its phase and amplitude properties intact. One of the most significant areas of application for holography depends on this ability of the hologram to conserve phase information.

Phase recording by means of holography provides a unique opportunity to perform interferometric experiments on diffusely reflecting irregular surfaces. Suppose that a subject were illuminated with laser light and that a reference beam were employed in combination with the light reflected from the subject to form a hologram. Assume that the subject remains in position illuminated with laser light. After processing we can replace the hologram in its taking position so that the *reconstructed* subject wave, diffracted out of the reference beam by the hologram, is exactly in register with the *actual* subject wave. Looking through the hologram we can obtain a zero beat between the coherent wave actually coming from the subject and the coherent wave appearing to come from the coincident image. If a stress is applied to the subject so that a deformation strain is set up, we can observe real-time interference fringes or beats between the strained-subject wave and unstrained-image wave. This method can be used to investigate new materials, new stress configurations, thermal expansion and creep. It can also be used as an aid to precision manufacture, such as the grinding of lenses, and as a routine, nondestructive stress test on manufactured parts. It is significant that the technique is now passing from the holographer's laboratory into the hands of

DEFINITIONS

Autocollimating screen reflects a light ray back on itself.

Bragg effect is observed when crystal planes are illuminated with x rays. Significant directional diffraction occurs when the incident light is directed against the planes at the Bragg angle θ, related to crystal-plane spacing d and wavelength λ by Bragg's law: $2d \sin \theta = \lambda$ (1st order). θ is also the angle at which the light must be reflected from the planes for observation. The same effect is observed at optical wavelengths in thick holograms and allows multicolor imaging.

Lippmann–Bragg holograms (reflection holograms) are recordings of the standing wave between coherent subject and reference waves traveling in nearly opposite directions. The interference surfaces are recorded (in photographic emulsion) as partially reflecting periodic silver surfaces extending throughout the depth of the emulsion, nearly parallel to the emulsion surface. When such holograms are illuminated by white light at the reference-beam angle (which turns out to be the Bragg angle for the periodic surfaces), multicolor images can be obtained. This record is similar to that giving rise to Lippmann color photographs. The images are reflected out of the illumination by the hologram.

Orthoscopic image is a three-dimensional image having depth and parallax properties similar to those observed with actual three-dimensional objects. That part of the image known to be the front appears closer to the observer, and when the observer moves to one side he sees more of that side of the image.

Pseudoscopic image is a three-dimensional image having depth and parallax properties opposite those normally experienced. That part of the image known to be the front appears to the eye of the observer to be farther away than parts of the image known to be in the rear. Parallax observation is also reversed; in moving to one side, the observer sees more of the subject's opposite side.

Parallax panoramagram is a lenticular screen pictorial display with observable depth and limited parallax properties. Both in taking and in viewing, a screen composed of an array of thin plastic cylindrical lenslets is placed close to the photographic emulsion which is exposed to the subject light through the lenslets. Either a panning movement of the taking camera, a rotation of the subject, or a very large objective lens is needed to obtain the desired results. Current 3D greeting and postcards are produced by this technique.

Planar (thin) holograms are formed so that the spacing between the recorded interference fringes is large compared to the thickness of the recording medium. Such holograms behave as complicated planar diffraction gratings. Small angles between reference and subject waves produce the result.

Volume (thick) holograms (Bragg-effect holograms) are formed so that the spacing between the recorded interference fringes is small compared with the thickness of the recording medium. Such holograms behave as three-dimensional or Bragg-diffraction gratings. Large angles between reference and subject waves produce this result, provided that the recording medium is at least several wavelengths thick.

Spatial frequency (cycles per millimeter)—A monochromatic plane-wave field of light is an amplitude distribution in space that is sinusoidally periodic with plane wavefronts. The spatial period in the direction of the wave normal is λ, the wavelength. The number of periods per unit distance (or the spatial frequency) in the direction of the normal is $1/\lambda$. The number of periods per unit distance along some arbitrary coördinate axis is the general definition of spatial frequency and is the product of the normal-direction spatial frequency $1/\lambda$ times the direction cosine of the wave normal to the arbitrary axis.

Varifocal mirror consists of a Mylar sheet, aluminized and stretched taut over a loudspeaker. The loudspeaker driven at about 30 Hz causes the Mylar mirror to assume successively convex, planar and concave shapes. A point of light will be imaged at different points in space for the different mirror shapes. A successive display of planar contours (for example, from a cathode-ray tube or projector) synchronized with the mirror deflection can produce 3D images when the display is imaged by the varifocal mirror.

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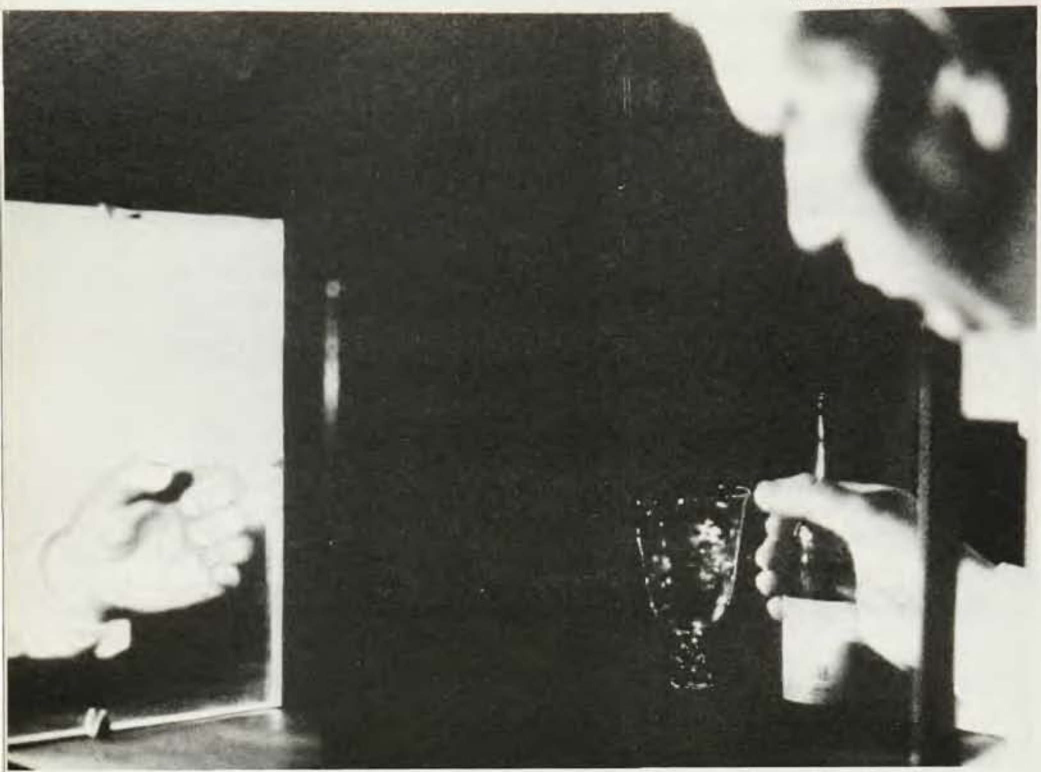


HOLOGRAM IMAGE is formed in space. The man shown in the photograph has reached behind a laser-illuminated hologram to grasp the 3D image of a wine bottle. The mirror to the left shows that no actual object exists there. —FIG. 3

people whose main business is the analysis of strain and deformation.

Double-exposure interferometry

An attractive property of holography is that the hologram can be multiply exposed so that image waves, recorded at different times, can be simultaneously reconstructed and their beats observed. In this case interference fringes or beats have high contrast (figure 6). A double-exposure technique has been useful in pulsed-laser interferometry. For example, shock waves produced by projectiles passing through air, or gas-density changes owing to thermal sources can be recorded more easily with pulsed-laser, double-exposure holography methods than with previous methods; moreover they can be recorded in depth. Here the photographic plate is first exposed to undisturbed air space and then to the perturbation; subsequent coherent illumination of the processed hologram gives an interferogram because of the optical-path differences in the superimposed individual reconstructions.

Engineers use holographic interferometry to study periodically vibrating surfaces—for instance, membranes. If we illuminate a membrane with laser light and combine the reflections with a reference beam to expose a photographic plate, we essentially form a double-exposure hologram. That is, the useful result is a hologram recording of the membrane image at each end of its swing. Upon reconstruction, interference between the two superimposed coherent images provides fringes, hence deformation information. According to engineers working with this method, information is often better than that gained from Chladni patterns, is more applicable to strongly curved surfaces and supplements conventional vibration-analysis tools.

We can apply the double-exposure method to contour mapping of solid objects. One recent method surrounds the subject by a medium of given refractive index and takes the first hologram exposure; then the subject is immersed in a medium of different index and the second exposure taken. When a finished hologram is illuminated, we have two coherent-light images differing only in longitudinal magnification. Interference between the superimposed images results in contour-line interference fringes that can be viewed without difficulty.

No focusing

No imaging lenses are required to form a hologram. Diffraction of coherent light from a subject is recorded on a photographic plate that is linearly exposed to the intensity of an interference pattern formed by the diffracted light and a reference beam. The subject image is reconstructed without imaging lenses. As Gabor discovered, illumination of a hologram with the original reference beam is the only requirement. Consequently we can apply holography to a variety of imaging situations in which depth of field is normally a problem and to situations in which a volume must be recorded and examined later for evidence of some event.

The advantages of not having to focus can be applied to microscopy. Normal microscopic examination of a slide containing tiny moving organisms requiries sharp and dexterous focusing over a field that is small in lateral extent as well as in depth. Events of interest may easily elude the observer. The hologram, capable of imaging a large volume, affords the opportunity of "freezing the action" in a 3D image of the slide so that events can be examined at leisure. Efforts in a number of laboratories are concerned with development of microholography. Although the hologram with its large effective aperture, is, in principle, capable of imaging a wide field with high resolution, as yet the resolution is limited by a number of noise sources.

Hologram cameras are commercially available for application to a related task, that of measuring aerosol particles in a given volume. With a pulsed laser one can "freeze" moving particles in a 3D image of desired volume. Then imaged particles can be conveniently examined with microscopes and TV cameras.

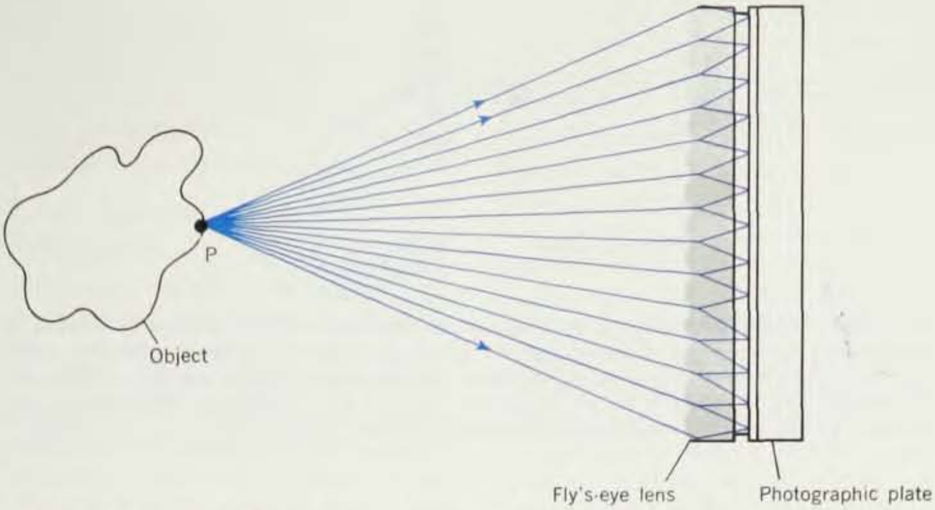
The US and Japan are currently evaluating the application of holography to bubble chambers. Evidence of interesting events may occur anywhere within the chamber volume. It is expected that a high-resolution 3D image of the volume, with no depth-of-field restrictions, will facilitate a search for anticipated particle tracks.

A rather different result of the lensless, nonfocusing aspect of holography can be applied to the realization of an optical memory. Since the subject wave is not imaged onto the hologram plane, information is not localized as in ordinary photographs but instead can be more or less uniformly distributed over the hologram. One high-capacity, semipermanent optical memory, currently being explored at Bell Laboratories, employs a so-called "page-organized" memory plane. A page of information in the form of a mask containing an array of up to 10^4 transparent spots on an opaque background is illuminated with laser light and recorded in a tiny hologram about 1 mm in diameter. In the same manner, 10^4 pages are stored as 10^4 holograms side by side on the same photographic plate. The total number of bits to be stored in this form will thus be 10^8 bits on a photographic plate 12 cm × 12 cm. When illuminated by a narrow laser beam, any of the tiny holograms will project the original-size image of the 10^4- bit page it has stored onto an array of 10^4 photodetectors. Each photodetector is located behind the site of an original input-page spot (figure 7). Readout time is in the microsecond range.

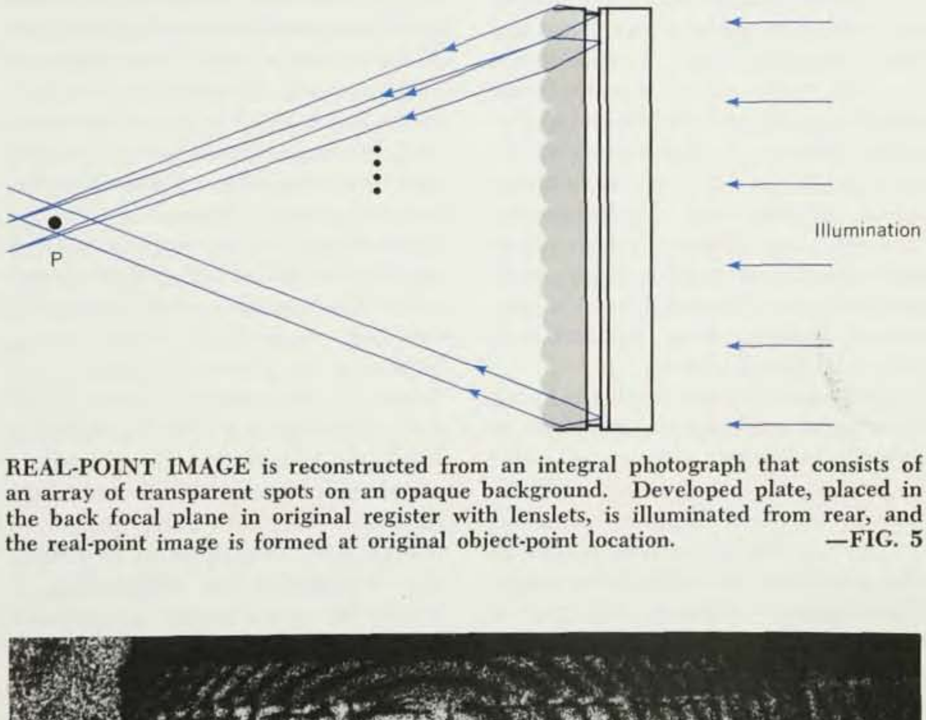
There are several properties of a hologram that are attractive for this application. First, the hologram does not require lenses to image; that is, the imaging optics are part of the photographic record. This is an economic benefit. Second, the resolution obtainable in a unit-magnification imaging situation such as this is nearly diffraction limited. Therefore each imaged spot is as small and as intense as possible, thus improving signal-to-noise ratio at the photodetector. Third, the unfocused, uniform distribution of information in a hologram is a feature that contributes significantly towards the likelihood for success in hologram optical memories. Information about the entire array of transparent spots on the input-page mask will be present to a useful degree all over the hologram. A small dust particle or blemish on the hologram will not obscure a bit as in a focused-image memory plane but will, in effect, only reduce the imaging aperture of the holograms, thus causing resolution to suffer a small but tolerable amount.

Pictorial display

In the sinusoidal density and spacing of silver-grain interference fringes, ho-

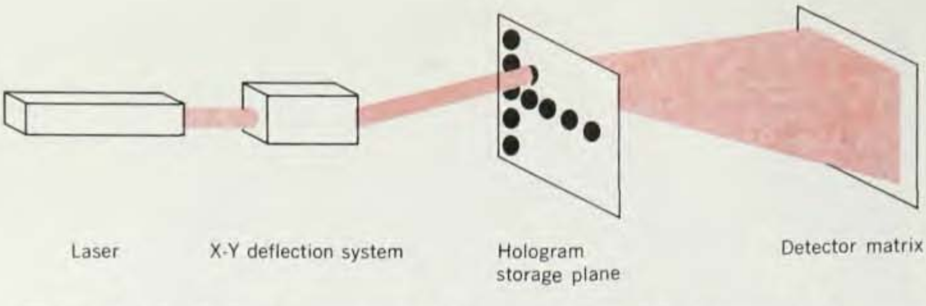


INTEGRAL PHOTOGRAPH. Light reflected by the subject is imaged through an array of fly's-eye lenses onto a photographic plate that is placed behind the lenslets close to their back focal plane. Each lenslet sees the object point from a unique aspect, thus forming a unique image point on the plate. —FIG. 4



REAL-POINT IMAGE is reconstructed from an integral photograph that consists of an array of transparent spots on an opaque background. Developed plate, placed in the back focal plane in original register with lenslets, is illuminated from rear, and the real-point image is formed at original object-point location. —FIG. 5

HOLOGRAPHIC INTERFEROGRAM (made by double exposure) shows the concave distortions of the cooled surface of a thermoelectric module. —FIG. 6



OPTICAL MEMORY. A page of information consisting of 10^4 transparent images is illuminated with a laser and recorded on a hologram about 1 mm in diameter. 10^4 pages can be stored this way on a hologram storage plane (shown above). When illuminated with a narrow laser beam, any one of the holograms will project the original image into a detector matrix reproducing the entire page. —FIG. 7

lograms record both amplitude and phase of a subject wavefront as it strikes the photographic plate. When a hologram is properly illuminated, this information is retrieved in an exact recreation of the subject wave. Had the subject been a solid object, the viewer of such a recreated wave would see a 3D image of the subject located behind the hologram and indistinguishable from the laser-illuminated subject itself. To accomplish this one must illuminate the subject with coherent laser light. As we shall see, as far as pictorial display is concerned, coherent laser illumination is not an unalloyed blessing.

Conventional photographic methods have produced pictorial displays in virtually every two-dimensional information medium we have, and the viewer of such displays takes for granted a sophisticated combination of high resolution and wide color range. 3D imaging, without requiring a viewer to wear special glasses, would doubtless be a welcome feature if it were added to the present quality of two-dimensional pictures. On the other hand, a sacrifice of color, resolution or size of display to obtain three-dimensionality in the image requires a careful consideration of the benefits. The present limitations of holography warn that immunity from sacrifice is not likely to be the case when holography is applied to popular pictorial display. Taking due note of the admonition offered recently[4] to those who would detract from the infinite potential of laser applications, let us attempt to assess laser holography for pictorial display on the basis of currently known properties.

Holograms can produce an imaged scene in which we can observe parallax and depth, but, since the scene must be laser illuminated, its size is limited by the laser power and coherence length. With cw lasers currently used for holography, the scene generally reduces to one of small toys, chessmen and bookends. Subjects must be inanimate and stock still; for a movement of a fraction of a wavelength washes out the all-important, fine-lined interference pattern. Normal motions are allowed only if the exposure times can be limited to about 10 nanoseconds. Development of the pulsed, Q-switched, single-mode, ruby laser is beginning to allow holograms to be formed of live, moving, reflecting objects. Development of faster recording emulsions tuned to the ruby-laser wavelength has also contributed to the formation of such holograms. Although these developments in pulsed-laser holography are encouraging, it would be unwarranted to conclude that the method will soon produce poster-size, panchromatic, 3D pinups. Obtaining the necessary increased energy in three primary colors may be destructively hard on the lasing materials and laser optical components, to say nothing of the materials and optical components of the subject. Some improved hologram-formation technique will be required before large hologram images of large live subjects in multicolor will be commonplace.

Speckle patterns

A great advantage that holography provides over other 3D imaging methods is that the observer can focus with equal clarity on any portion of the imaged scene as if it were the original. Depth of field in the observed reconstructed image is limited mainly by the observer's eye. However, the clarity with which one views the subject is somewhat a matter of how one defines "subject." Reflected light from laser-illuminated subjects displays a speckle pattern. Coherent light reflected from microscopic variations on the subject surface forms a random interference pattern that is not localized but pervades the entire viewing space. The size of the speckles in the pattern varies inversely with the aperture of the viewing instrument (related to the smallest resolved object spot), and in normal viewing situations the limiting aperture is the eye. With remarkable fidelity, the hologram plate records and reconstructs the subject laser light that impinges on it. This reconstruction, of course, includes the speckle pattern. The viewer can thereby see with great clarity the speckle pattern superimposed on the subject detail. If he steadily gazes at the reconstruction, his ability to see small detail is substantially reduced by the random dot pattern. Oscillating the head averages out the random pattern and restores the ability to resolve detail, but this becomes a strain after the novelty has worn off. To avoid speckle-pattern observation, we can illuminate the hologram with light of lesser monochromaticity than laser light, but then the image becomes slightly blurred because of the angular dependence of hologram diffraction on input wavelength. The problem is less significant as one goes to larger holograms and grosser subjects, but this avenue is restricted by available laser power and coherence length. When the viewing instrument is not a human eye but, for example, a TV camera, the aperture of the device can be opened enough to make the speckle pattern insignificant.

Color reproduction

Holograms illuminated with white light can produce multicolor, 3D images from the same photographic emulsion that yields only two-dimensional, black-and-white negatives with ordinary photographic methods. Holography certainly uses more of the storage capabilities of photographic emulsion. One multicolor-imaging method illuminates a subject with red green and blue laser light and records the standing-wave pattern between reference and subject waves traveling in nearly opposite directions. This method is closely related to Lippmann's color-photography method,[5] whereby point-by-point interference of a subject with itself is obtained by imaging the subject onto a photographic emulsion backed with a mercury mirror surface. The reflection sets up a standing-wave pattern in the emulsion; each color in the subject forms its own standing-wave pattern. To record the pattern, the resolving power of the emulsion must be very high since the standing-wave maxima are separated by about half the wavelength of the light components. When this condition is met, the speed of the emulsion is extremely low. The situation is the same for multicolor, white-light-reconstructing holograms.

Illumination of partially reflecting silver-grain surfaces that record the standing-wave patterns in either the Lippmann photographs or the multicolor-imaging holograms is very much akin to x-ray illumination of atomic planes in crystals. Angle of illumination and angle of observation are critical for satisfying Bragg's law. Although it is unfortunate for pictorial display, the illumination must be directional, and true colors can be seen only from the proper direction. The more desirable diffuse illumination is not allowed. The connection with Lippmann's color method reminds one that although the Lippmann process was simpler in principle than the subtractive color processes developed later, it was never commercially of value.

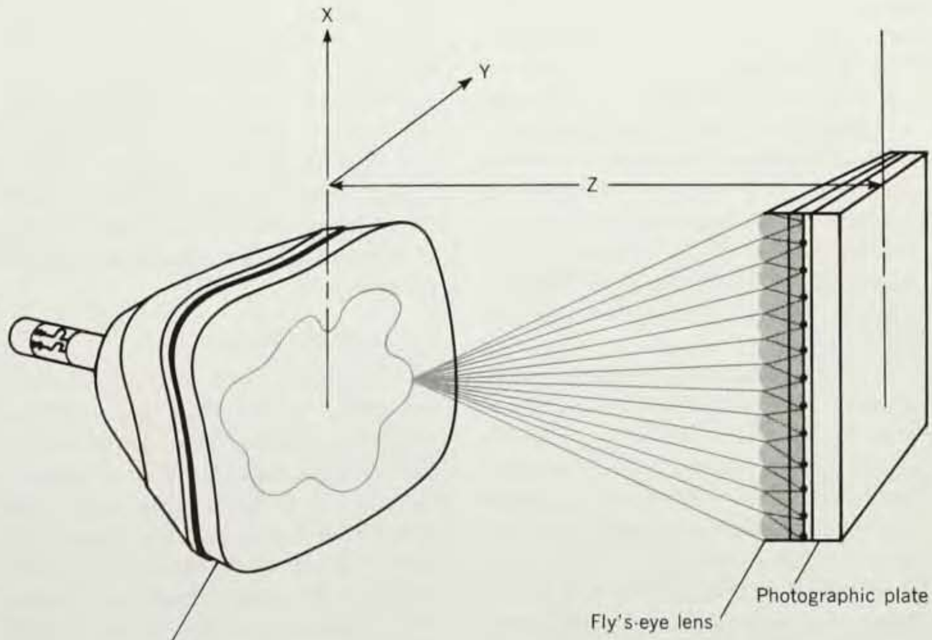
The central problem of multicolor holography is color crosstalk; that is, planar holograms formed with one color will give off displaced images when illuminated with another. One solution, different from the Lippmann concept, is to color-mask the hologram surface during formation and reconstruction illumination. The surface can be color multiplexed with red, green and blue filter masks used in a manner similar to the division of color television screens into red, green and blue emitting areas. With proper masking, one can form a multitude of tiny, nonoverlapping holograms. Each individual hologram is made with light of only one color. When illuminated behind the same mask, the nonoverlapping assembly of holograms will reconstruct a good multicolor image. A simple color-multiplexing method either for the top of the emulsion or as part of the emulsion itself has yet to be developed, but this method allows faster photosensitive media for multicolor-hologram imaging than required for Lippmann-type holograms.

Lenslet recording

While holography records phase information, integral photography records spatial frequencies of the subject light or, in other words, records directions of subject light rays. Each lenslet's small aperture can receive only a narrow bundle of light rays from any one object point. Since the object point is, in general, many focal lengths away, the accepted bundle of rays may be thought of as a parallel beam of light. The lenslet focuses this beam to a point at the back focal plane and thus plots its intensity at a given position relative to the lenslet optic axis. An adjacent lenslet receives, from the same object point, a similar bundle of light rays with a slightly different mean direction. This bundle can again be considered as a parallel beam whose intensity is plotted by the lenslet on its back focal plane, but at a slightly different position relative to its optic axis than for the previously considered lenslet. Thus, in effect, the array of tiny lenslets sample the directions of light coming from any given object point and plot the intensity of each sample of direction or spatial frequency in unique positions relative to the lenslet optic axes. The power spectrum of the object point is recorded in this manner; the same will be true for each object point.

This recording of intensity and direction of subject light rays is sufficient to reconstruct a 3D image of a solid object by projecting images back through the lenslets. Quality of reconstruction is limited by the granularity of sampling introduced by discrete lenslets, by limited depth of field (associated with diffraction effects from a small lenslet aperture and with unsharpness owing to the finite relative aperture of the lenslet[6]) and by aberrations, predominantly spherical aberrations. Despite these limitations, we can achieve 3D image reconstructions of adequate quality for popular pictorial display.

Thus integral photography, by recording spatial frequency or spatial gradient of the phase, and holography, by recording phase information, are both capable of 3D image reconstruction. Further, since each lenslet plots behind it information about all of



COMPUTER-CALCULATED CONTOURS representing the intersection of a generated surface with discrete depth planes, $z = 0,1,2...$, are sequentially displayed on a cathode-ray-tube screen. The fly's-eye lens and photographic-plate combination undergoes multiple exposures: Each one is at a distance from the CRT screen corresponding to a particular z value, thus recording a 3D image. —FIG. 8

3D IMAGE depicted in this integral photograph is of a computer-generated surface showing contours. The actual image had a depth of 15 cm. —FIG. 9

the object points, integral photography achieves more-or-less uniform distribution of subject information over the record in a manner similar to that achieved by holography of diffuse subjects.

Incoherent light

Because integral photography requires only incoherent light, it is applicable to the recording of 3D images in situations where the subject illumination is the ambient incoherent light and where the subject is self-luminous. Because the very fine-lined interference patterns so necessary to coherent-light holography are not formed or recorded with integral photographic methods, the tolerance of the latter method to subject motion and to lower-resolution photographic emulsion is greater. Subjects not suitable for holography such as the interior of furnaces, jets and plasmas can thus be imaged in three dimensions by integral photography.

A suitable subject of the integral-photography method is the fluorescent trace on a cathode-ray tube. The integral photograph can form a permanent record of the output of a computer that is generating some unknown surface in three-dimensional space.[7] Instead of gathering information in the form of nomographs or a two-dimensional contour map, one can obtain a 3D image of the surface as a direct readout of the computer's CRT output terminal. One method requires the computer to calculate contours resulting from intersection of the generated surface with discrete depth planes $z = 0,1,2$, etc. The calculated contours are sequentially displayed on the output cathode-ray-tube screen. The photographic plate and fly's-eye lens combination is exposed to the first contour display, corresponding to $z = 0$. After exposure the plate-and-lenslet-array combination is stepped back from the CRT screen at a distance corresponding to that between the $z = 0$ and $z = 1$ planes. The $z = 1$ contour is displayed on the cathode-ray screen, and the same photographic plate is given a second exposure through the lenslet array. This process is repeated through the total sequence of contours with the plate–lenslet combination stepped in distance from the screen and multiply exposed in the manner described in figure 8. Projection of diffuse light through the positive record and lenslets produces a 3D image of the computed surface viewable from many aspects (figure 9).

A second method involves a varifocal mirror[8] that can provide a real-time, 3D multiaspect image of the computer-generated surface. The varifocal mirror is an aluminized Mylar sheet stretched taut over a large loudspeaker driven at a frequency of 30 Hz so that the reflecting sheet assumes convex, planar and concave shapes. Light cast on the mirror is imaged at various distances corresponding to the mirror shape. If the contour presentation of the CRT screen is synchronized with the mirror-surface deflection, it is possible to form, in real time, a 3D image of the generated surface that has considerable parallax property. Then integral photography can form, with a single exposure, a permanent record of this image that preserves parallax properties.

Pseudoscopic images

Although images reconstructed from a hologram can be virtual or real, orthoscopic or pseudoscopic (depending on the reference and illuminating beams), the normal integral photograph produces a real pseudoscopic image. Illumination of the finished integral photograph, properly registered behind the lenslets, in effect makes subject rays travel back into the subject space along paths opposite to their original directions. This process implies that the light converges at the original subject position giving rise to the real image. Since a viewer cannot insert his head between the illuminated integral photograph and the image without blocking the light, he must view it from a position corresponding to the back of the subject. Light seen emerging from the real image is now diverging, but depth is inverted insofar as points in the "front" of the subject image are further from the eye of the viewer.

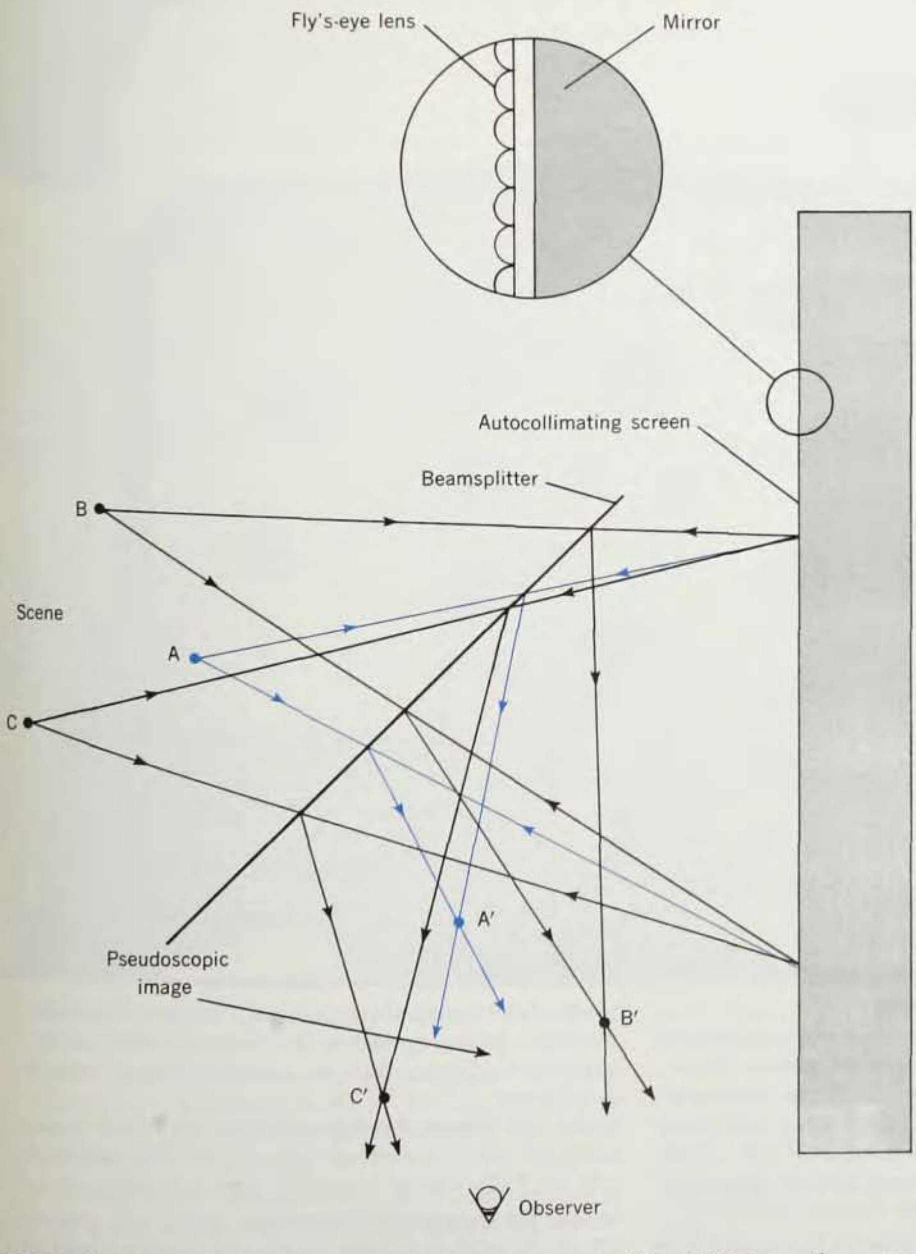
Some sort of second process must invert the pseudoscopic image and obtain the desirable orthoscopic image in which depth and parallax properties appear normal. There are a number of techniques for doing this. A hologram[9] can be formed with the real pseudoscopic image, emerging from a laser-illuminated integral photograph, as subject. Then if one illuminates the hologram with the conjugate to the original reference beam—a process that normally produces a pseudoscopic image of an actual physical subject—the pseudoscopic image of the pseudoscopic subject will result in an orthoscopic image. That is, two depth inversions return the image to its normal appearance. But the hologram image requiring laser-light illumination has some drawbacks as previously discussed. The earliest technique for inversion of the integral-photograph pseudoscopic image[10] was simply to make a second integral photograph with the image from the first as subject. Again double pseudoscopy produces a final orthoscopic image. More recently we have explored some methods that either allow the original subject to be converted into a pseudoscopic image before any photography takes place, or convert the pseudoscopic image of a single integral photography into an orthoscopic image without any further photography. The methods involve casting the light projected through an integral photograph onto an autocollimating screen. Image depth is inverted upon reflection from such screens (figure 10). The latter can be easily formed by placing a plane mirror at the back focal plane of a fly's-eye lens, by floating small glass balls, with refractive index equal to 2, on a pool of mercury or by merely using one form of a commercial product called Scotchlite (a reflective sheeting, manufactured by 3M Co, that consists of a layer of tiny glass balls on a substrate, and which is familiar on car bumpers as a warning device).

Advantages and disadvantages

In interferometry, where coherent light has unique application, holography stands alone in its ability to provide interferometric information in depth and to allow experiments on diffusely reflecting subjects. When a volume contains an interesting object whose location is not known a priori and therefore cannot be brought into focus, holography should prove very useful. In the field of optical read-out memories, holography provides an opportunity to develop cheap, reliable memory planes tolerant to the normal deficiencies of real recording media. In some cases the same memory functions can also be supplied by arrays of lenslets, but any advantage over holography has yet to be shown.

In pictorial imaging the advantage swings more towards integral photography. Still, holography will find a use in the display of small objects and perhaps will augment museum collections. The hologram is such a simple method of packaging a 3D image that it appears certain to find a place in textbooks—particularly chemical and mathematical texts—in which unfamiliar molecule arrangements and topographies require viewing from many aspects. Techniques are currently being developed whereby we can obtain full 360-deg views of a subject from flat sheets of photographic film. These appear to satisfy many requirements of textbook format. However, for large advertising displays, 3D portraits on walls, posters, road signs and perhaps TV closeup displays, integral photography has the advantage. The ease of working with live subjects and providing multicolor images, the convenience of forming the record with incoherent white light and of viewing the image with normal, diffuse, white-light illumination are powerful persuaders. It is probable that, as development proceeds, fabrication of quality lenslets will be less costly, and amateur integral-photography cameras will be available. Neither holography nor integral photography appear destined to do away with conventional photography. Two-dimensional photography will probably remain unrivaled, in pictorial imaging, for clarity and beauty of image. 3D imaging does hold out hope as a mode of abstract art as well as pictorial realism.

Holography and integral photography are, with respect to some of their properties, closely related and, if intelligently combined, can complement one another in 3D imaging. Methods of cutting, interlacing and multiplexing to increase information storage and to avoid redundancy can be applied with success both to holograms and integral photographs. As a given experiment can often be done with either method, we expect mutual growth of lensless and lenslet photography.



INVERSION OF DEPTH by an autocollimating screen. The light from the scene ABC retroreflects from the screen to form an inverted-depth (pseudoscopic) real image A′B′C′, which is observed with the aid of a beam splitter. —FIG. 10

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