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The Creation of Holograms Utilizing Fiber Optics

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THE CREATION OF HOLOGRAMS UTILIZING FIBER OPTICS

by

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Holography involves the interference of two light beams, namely a reference beam and an object beam. Instead of the conventional method using beam splitters and mirrors to direct the light path, fiber optic bundles are used and high quality holograms have been produced. When fiber optic bundles are used, a spatial filter is not needed to produce a "clean" beam of light for the reference beam. Fiber optic bundles also provide greater flexibility of illumination for the object beam and/or for the reference beam. Also, it is easier to illuminate the object from many directions. Finally, the distance from the entrance to exit in the fiber optic bundle is unchanged. Therefore, the optical path of the bundle remains unchanged, preserving the coherency inherent in the laser beam.

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CHAPTER I

INTRODUCTION

The use of a lens to image an object is one of the oldest principles in optics and photography. In the late 1940's, a new method of forming optical images without a lens was developed and this new technique was called holography.

Holography was invented with a specific application in mind - to improve the resolving power of electron lenses. The potential of holography, however, far exceeds this original use. With holography, we can record a realistic three-dimensional image on film and then study its details later.

It is the intention of this research to introduce a new method for making a hologram. Presently, to make a hologram, a highly stable system free of vibration is needed. In addition, coherency and path lengths play an important role in the production of a high quality hologram. One of the major goals of this research is to reduce the noise produced by the laser in the reference beam, which eventually will result in a higher quality image being produced upon reconstruction of the hologram. Furthermore, the possibility will be investigated of using fiber optic bundles as a replacement for the beam-splitter, mirrors and spatial filter which are customarily used to guide both the object beam and the reference beam to the film. These flexible fiber optic bundles have many advantages over the traditional optical components which are commonly used in the production of holograms.

CHAPTER II

HISTORICAL DEVELOPMENT OF HOLOGRAPHY

Photography basically provides a method of recording a two-dimensional irradiance distribution of an image. Each "scene" consists of a large number of radiating and reflecting points of light. The waves of each of these points all contribute to a complete wave which is transformed by an optical lens in such a way that it collapses into an image of the radiating object. This image is then recorded onto a photographic emulsion. Basically, the lens causes each point in the scene to contribute light to only one point in the film.

In holography, however, no lens is used and each point in the scene contributes light to every point in the film. The object waves are recorded in such a way that a subsequent illumination of this record serves to reconstruct the original waves, even in the absence of the original object. The photographic record, called a hologram, bears no resemblance to the original object but contains in the form of an optical code all the information of the object and looks like a hodgepodge of specks, blobs, and whorls upon the developed film.

The progress of holography can be divided into three periods. In the first stage, the aim was to record wavefronts diffracted from crystals that had been irradiated with x-radiation or electron waves and, upon reconstruction with visible light, produce a highly magnified image of the crystal lattice. However, the difficulty in recording the phase of the radiation hindered further progress. The second stage began in the late 1940's when Dennis Gabor (1948) solved the basic problem of recording the phase of the wave as well as its amplitude. During that period, the resolving power of the electron microscope fell short of resolving atomic lattices, simply due to the spherical aberration of the electron lenses. However, Gabor realized that an aberrated image formed with coherent radiation still contained all of the information about the structure of the objects, provided both the amplitude and phase distribution in the image could be recorded. Unfortunately, in a "regular photograph," the film records only intensity and the phase is lost. Gabor argued that the phase was left out because there was nothing to compare it with. Thus, he introduced a known wave as a phase standard. It was this consideration that eventually led him to invent the technique of holography. His idea was to record the aberrated image superimposed on a strong coherent background of electron waves. He then attempted to enlarge the image by a reconstruction process with longer wavelength visible light instead of the shorter wavelength electron waves. Gabor did not succeed in improving the resolving power of the electron microscope but his holographic process has revealed far more potential than one would have imagined at that time. Gabor's concept of a reference beam stimulated renewed interest in holography. Gordon Rogers (1950) developed the image-forming principle in terms of Fresnel zone-plate theory. Haine, Dyson and Mulvey (1952) introduced the "transmission method," whereby lenses were used between the object and the hologram to magnify the diffraction. This increased the effective resolution of the photographic plate and also improved on the arrangements to increase its stability. Paralleling these early attempts, El-Sum (1952) produced an artifical x-ray hologram of a thin wire and managed to obtain a reasonable reconstruction, proving at least the feasibility of x-ray holography. In 1956, in Germany, Lohmann was the first to apply communication theory techniques to holography and suggested a single-sideband method for removing the "twin-image," one of the residual defects of the process.

Interest in holography waned in the middle 1950's, although activities never completely ceased. Some of the limitations to early holography were the lack of an intense, coherent source, long exposure times of the order of hours, and relatively poor imagery due mainly to the presence of a "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 illumination forms an image in mirror symmetry to the "true" image with respect to the plane of the hologram. Either image must be viewed against the out-of-focus background of the other, and the result is a noisy image.

The third stage of holography development began in the early 1960's when high quality holographic imagery was demonstrated by Leith and Upatnieks (1962, 1963, 1964). The beginnings of this stage coincided in time with the development of the first lasers. Leith and Upatnieks, with their new set-up which used an off-axis reference beam, were able to completely eliminate the "twin image" problem. In the reference beam method a beam-splitter is used to divide the original laser beam into two parts called the reference beam and the object beam. These two beams are then brought together at an angle to form an interference pattern on the hologram. The resulting hologram behaves like a diffraction grating, producing several non-overlapping diffracted orders. The zero-order wave produces the usual inseparable "twin-image" which, in combination with other defects of in-line holography, results in poor imagery. But each first-order diffracted wave produces an image of high-quality. Leith and Upatnieks first dealt with objects which were dark letters against a transparent background. They then extended the effectiveness of their process to two types of objects which are not suitable for the conventional wavefront reconstruction technique. These are objects which do not transmit a strong background wave (e.g., transparent lettering against a dark background) and continuous-tone objects. The slightest speck of dust on the lenses or mirrors gave rise to its own hologram, reducing the effective aperture of the hologram and reconstructing itself as noise. The invention of the laser with its great intensity permitted enormous quantitative advances in holography, namely larger holograms and larger objects. The most striking contribution of the laser is the formation of a truly three-dimensional image. Leith and Upatnieks also introduced the concept of diffuse illumination holography. Diffusing the light that illuminates the object effectively causes each point of the object to radiate a spherical wavefront, hence the information concerning each point of the object is spread out over the whole hologram. The striking feature of a hologram made of objects so illuminated is that the reconstruction can be viewed without optical aid and is viewed through the hologram as if it were a window. The object appears behind the window just as in the original scene and one may view the complete scene from a wide range of perspectives. With this new diffuse -

illumination hologram technique, the superposition of more than one hologram on a single photographic plate is possible. This concept led to developing a method of multicolor holography using coherent light in each of the three primary colors, each with its own reference beam.

About the same time, Denisyuk (1963) introduced a new concept into holography, the "volume hologram," which combines holography with the Lippman color process. Object beam and reference beam are introduced from opposite sides of the recording plate, which contains a thick layer of high-resolution emulsion. The hologram, because of its wavelength selectivity, can be viewed in white light. There are some major drawbacks. Firstly, the depth of any scene is limited since a "thick" emulsion is only about 15 micrometers thick and can form only a limited number of interference points. Secondly, it can be viewed only with a bright-point source of light, such as a small high-intensity lamp. Related work was done by van Heerden (1963) concerning three-dimensional optical storage. Large amounts of information can be stored in "bulk" as if every little cube with sides equal to the wavelength of light acts as an independent information storage cell; it is particularly suitable for associative memories, in which a fast search for a specific piece of information is possible. Then Parrent and Thompson (1964) used Gabor's method in combination with a pulsed laser for particle-sizing work. Gabor's technique is ideally suited for this configuration because the objects are extremely simple and a noise-free image is not needed.

By late 1964, holography became the most active field of research in optics. Several techniques of color holography, interferometric holography, holographic imagery and many other basic concepts were developed. By 1967, however, the discoveries began to diminish and inventions took an increasingly restrictive aspect mainly due to pressure from management; thus applications received greater attention. In the late 1960's, serious efforts were made to commercialize holography. The basic research programs were reoriented towards product development. Various types of equipment were designed for bringing holographic measuring and testing techniques into the factory, but some defects were present and the hoped-for commercial products either failed to materialize or were not competitive with conventional products.

Steve Benton (1969) pioneered a new kind of holography, "a rainbow hologram," a kind that led to the holographic moving scenes. White light was used in the reconstruction, and the image was extraordinarily bright. However, the process of constructing a true color hologram is a very cumbersome process and time consuming. First, three master holograms have to be constructed with laser lights of different colors. Then the projected real images of these three master holograms are multiplexed onto a fourth hologram sequentially, again with three different colors of laser light. These three master holograms must be aligned very carefully to assure that their reconstructions are exactly superimposed.

Other techniques involving coherent light have been developed which can do many jobs for which holography is suited, such as detection of vibration and measurement of deformation with high precision and sensitivity.

Holography was found useful for an astonishingly wide variety of tasks that were done normally in other ways. Optical memories using holographic techniques are making their way into the huge computer-memory field. With hologram interferometry, non-destructive testing techniques became available. Holography is now used to detect and examine atmospheric pollutants.

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, have led to a dramatic increase in diffraction efficiency. A hologram formed from a diffusely scattered object generally has a diffraction efficiency of about 0.5% to 1.0%. Bleaching under controlled conditions can increase the fraction of the incident light which is transmitted into a first order (holographic) image while preserving good image quality. This "diffraction efficiency" for a bleached hologram is about 15% to 20%. Higher diffraction efficiencies could be achieved but at an expense of increased noise.

CHAPTER III

HOLOGRAPHIC APPARATUS AND TECHNIQUES

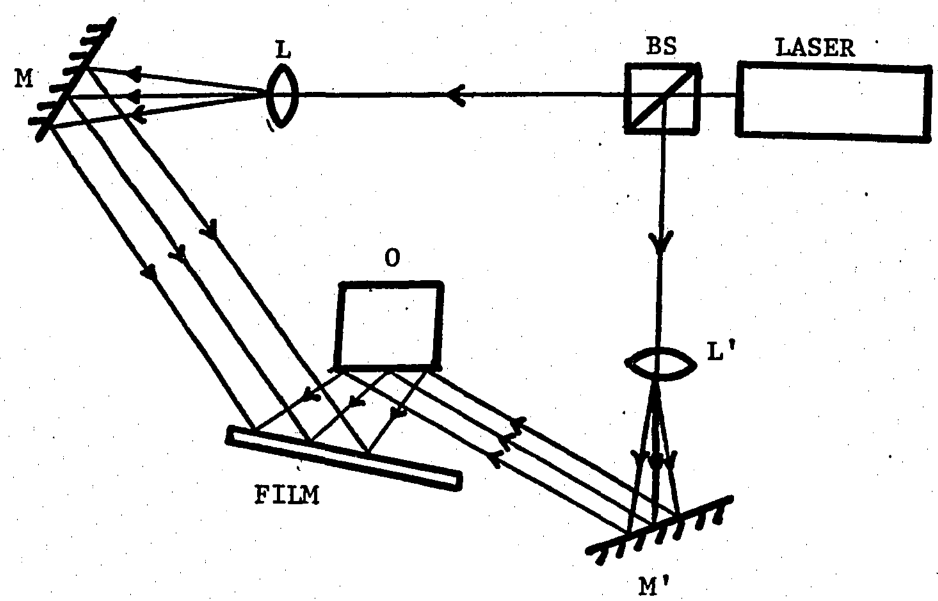

Figure 1. Arrangement of holographic apparatus.

A typical experimental arrangement for making a hologram is shown in Figure 1. Light from the laser is split into two parts by the beam splitter (BS). The object beam usually passes through a microscope lens (L'), strikes a mirror (M'), strikes the object (O) and then falls upon the film. The reference beam from the beam splitter, passes through a microscope lens (L), strikes a mirror (M) and then falls upon the film where it interferes with the object beam. Separation of the reference beam and the object beam permits the adjustment of their respective intensities to provide the proper ratios at the film plane.

To maintain proper balance, highly reflective objects were used when making a hologram.

The platform used for this research is made of heavy steel and supported with piers inside a box filled with sifted silica sand. This unit is then placed on two not fully inflated innertubes which act as a vibration damper. The tubes, in turn, rest on a table which is isolated from the floor with rubber feet.

The laser employed was a Spectra Physics Model 134 Helium - Neon gas laser of three milliwatts power. The output is a monochromatic, coherent beam of red light with a wavelength of 642.8 nanometers. In order to maximize the stability of operation of the laser output, the laser is not turned on and off for each exposure. Instead, the laser is turned on to warm up for five minutes before the hologram exposure is made.

The holographic film used for this work is AGFA GEVAERT 10E75 which is a fine grain, very slow film with a high resolution in excess of 3000 lines per mm. The relative spectral response of this film is indicated as in Figure 2.

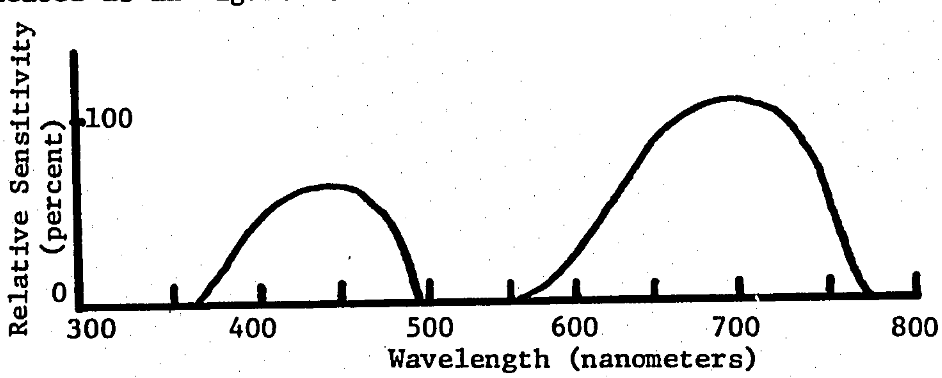

Figure 2. Relative spectral response of Agfa-Gevaert 10E75 film.

The response of this film is good at the 642.8 nanometer (nm) wavelength of the laser light. The fact that this film is not sensitive in the 500 nm to 530 nm region, permits the use of a dark room "safe light," which radiates in the 500 nm - 550 nm (green) region. The "safe light" which was used was a Kodak Type 3 (Green) filter, suggested by Rogers (1978).

To make a hologram, the system is allowed to rest for one minute to damp out vibrations and air currents. A black cardboard, placed in front of the laser beam, is carefully raised to allow the beam to enter the system. After the proper exposure time, the black cardboard is then lowered to block the laser beam. The hologram is then processed immediately.

The chemicals which are commonly used in the processing of holographic film are Kodak D-19 developer, Kodak Stop-Bath, and Kodak Rapid-Fixer. The film is processed in the developer for five minutes, stop-bath for thirty seconds, and fixed for three minutes. Finally, the film is rinsed under running water for another five minutes.

The intensity and clarity of the holographic image observed is dependent upon the relative intensity of the reference beam compared to the object beam. Successful holograms are most likely when the intensity of the reference is equal to or greater than the intensity of the object beam. Successful reference beam to object beam intensity ratios range from 1:1 to 10:1 with 1:1 to 3:1 being more common. For this investigation, a Pasco Scientific Model 8020 light photometer was used to measure the relative intensities of the reference beam and the object beam. The best holographic image resolution was produced when the intensity of the reference beam was equal to that of the object beam. Adjustment of the reference beam/object beam ratio with some decrease in energy can be accomplished with neutral-density glass filters, available in plastic squares or glass plates. These filters have different amounts of aluminum deposited along the surface, and are graded for attenuation in tenths of decibels.

Good holographic images require that the interference of the reference beam and the object beam occur in a very small distance along the photographic film. A vibration of any of the optical components may cause a change in the position of either the reference beam or the object beam. This change in relative position results in an interference pattern which is blurred or non-existent. Even very small vibrations may prevent the high resolution interference needed for creating holograms.

None of the early attempts to construct holograms in this research were successful because of vibrations and air currents. Having a more rigid support for the components brought some improvements but the hologram quality was still low. The vibration problem was significantly reduced by moving the holographic table to a part of the building where the floor vibrations were less pronounced. In addition, more massive supports for the mirrors, the beam-splitter, the object support and the film holder were designed and built. These supports significantly reduced the movements of the various components. The mass of each support is approximately two kilograms. Finally, the problem of air currents was overcome by blocking off all the air vents in the room.

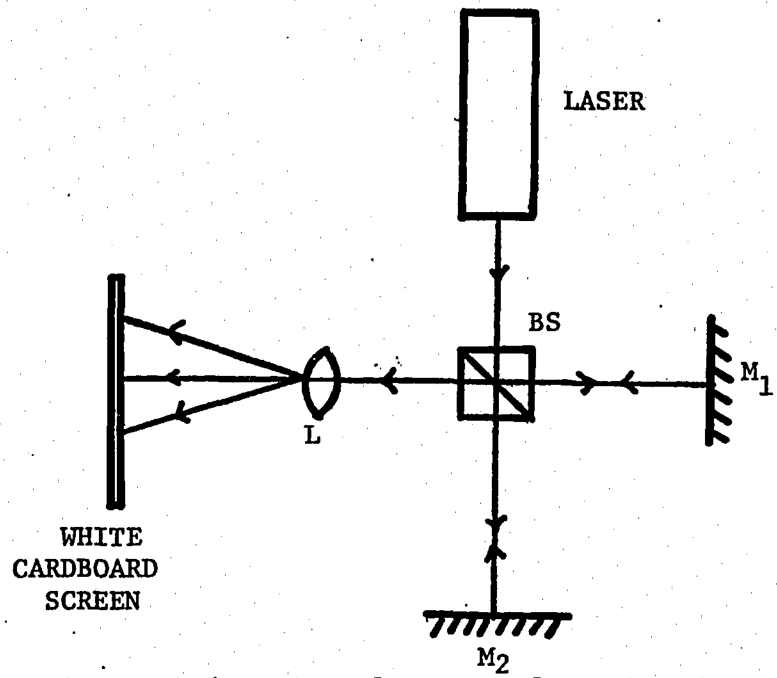

Figure 3. Michelson interferometer for vibration testing.

A simple Michelson Interferometer is commonly used to test the degree of vibration in a holographic system and to evaluate whether the vibration has been reduced to a level which may lead to successful holograms. In Figure 3 is shown a typical Michelson Interferometer for testing vibration level. In this device, the laser beam is divided by the beam splitter (BS) into two parts. The part of the original beam which is reflected by the beam splitter toward front surface mirror M_1 is then reflected back by M_1 through the beam splitter and on to the white viewing screen. The part of the original beam which passes straight through the beam splitter to strike front surface mirror M_2 is then reflected back by M_2 towards the beam splitter where it is then reflected towards the white viewing screen. Usually, a converging lens, L, is used between the beam splitter and the white viewing screen to enlarge the zone of interference for better viewing. The pattern one observes in similar to Figure 4. The constructive interference provides the bright fringes and destructive interference provides the dark bands. The quality of the hologram construction possible can be judged from the lateral movement of the fringes which are observed. If the bright fringes move back and forth less than one-tenth of the fringe-to-fringe distance, good holograms are possible. If vibrations or air currents cause the fringe movement to exceed half of the fringe-to-fringe distance, hologram images are very poor or non-existent. Any success at reducing the fringe movement will lead to higher quality holograms.

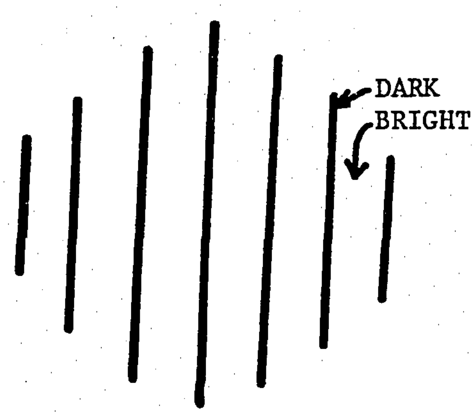

Figure 4. Destructive and constructive interference pattern.

In the research, a comparison of the output light with and without the aid of a spatial filter was made. A spatial filter is an instrument which transforms a "noisy" laser beam into an expanding beam, to produce a "clean" diverging spherical wavefront.

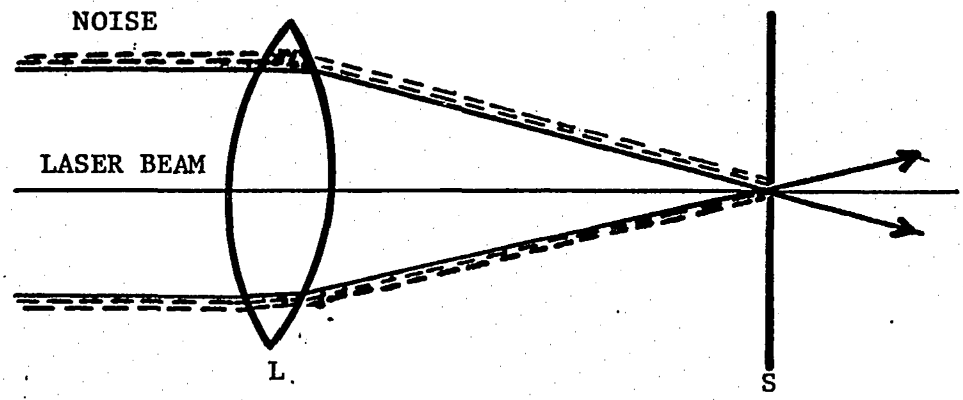

Figure 5. Spatial filter.

The spatial filter instrument consists of a pinhole S, and a short focal length converging lens L, as in Figure 5. The pinhole and the lens are coaxial so that the laser beam passes first through the lens and then through the pinhole. The power of the lens controls the convergence of the beam and the diameter of the pinhole determines the degree of filtering. The lens focuses the laser beam at the pinhole and only the undisturbed portion of the laser beam passes through the pinhole. The metal surrounding the hole, filters off the scattered beam which results from the various imperfections created by the laser and the beam splitter. The smaller the pinhole, the cleaner the beam will be with regard to uniformity of the radiation. An alignment procedure is given in Appendix I.

A minor investigation was undertaken to study the physical appearance of the developed holographic film when three different types of reference beams were used. (The object beam remained the same for all three cases.) The optical components in the reference beam path in these three cases were:

a) a simple lens to diverge the beam

b) a spatial filter

c) a fiber optic bundle

First, a lens was placed in the reference beam and the hologram exposure was made. The resulting hologram contains blobs and whorls upon the developed photographic film as in Figure 6. On this film, relatively wide zones of blackness are separated by relatively wide zones of clear film. This condition is not suitable for the production of high quality holograms.

Next, the lens was removed and a spatial filter was placed in the path of the reference beam. Again, an exposure was made. The resulting hologram (illustrated in Figure 7) has black areas more evenly distributed without the blobs and whorls, which occurred with the lens. Essentially, the spatial filter expands the center portion of the laser beam so that only the central region falls upon the photographic film producing a more uniform illumination. Thus, more of the information from the object beam may be recorded as an interference pattern on the photographic film. The proper reference beam/object beam illumination ratio may occur over a wider area of the film if the reference beam intensity is more uniformly distributed on the film.

Finally, a fiber optic bundle was used instead of the spatial filter. The hologram obtained with the fiber optic bundle had specks distributed uniformly all over the developed photographic film with an absence of the blobs and the whorls as in Figure 8. The uniformity of the film blackening using the fiber optics bundle is as good as that made with a spatial filter. Furthermore, the holographic image

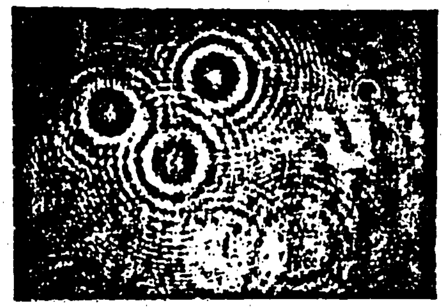

Figure 6. Hologram when the reference beam passes through a lens.

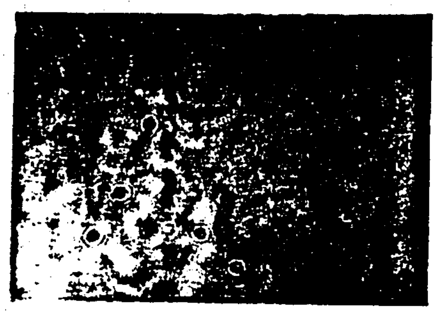

Figure 7. Hologram when the reference beam passes through a spatial filter.

Figure 8. Hologram when the reference beam passes through a fiber optic bundle.

quality was as good for the fiber optic bundle as for the spatial filter film.

The output end of an optical fiber can be thought of as a radiating aperture. Each fiber acts as a separate source producing a cone of light illuminating the film. By having a bundle of fiber optics acting as a reference source, an evenly distributed hologram is produced, providing more interference points for the object beam.

From the diffraction patterns produced, it may be concluded that in state-of-the-art of fiber optics, coherent light propagates down each fiber in the system and emerges retaining proper phase and amplitude relationship. Such results suggest the possibility of using larger fiber arrays in wavefront reconstruction.

CHAPTER IV

FIBER OPTICS THEORY

Optical devices such as periscopes, telescopes and mirrors convey light from place to place to form "pictures." Extensive research in this field of light transmission has resulted in the development of a practical and inexpensive system of light guidance called fiber optics. Fiber optics consist of finely drawn strands of flexible glass fibers which convey light by total internal reflection. Light enters one end of each fiber and bounces back and forth until it exits at the other end of the fiber. A parallel array of these fibers will carry an image from one end of the fiber bundle to the other. They can transmit pictures whose resolution depends upon the number of fibers. More fibers give a clearer image. Recent developments in plastic have permitted the construction of fiber optics from plastic instead of glass. This construction is described in Appendix II. The plastic fiber optic bundles tend to be more flexible and more economical while possessing excellent light transmission characteristics. In general, the amount of transmitted light in a fiber bundle is dependent upon the following factors:

a) light intensity at the input,

b) light loss at the input air-fiber interface,

c) cross-sectional area of light-transmitting fibers,

d) light loss along the length of the light guide, and

e) light loss at the output air-fiber interface.

Within the light guide, light energy is lost by absorption. Since the absorption loss is an exponential function of length, its length should be as short as possible. The multiple reflection of a light ray from wall to wall along the length of the fiber optic depends on the total internal reflection of the light ray at each wall. The condition required for total internal reflection is illustrated in Figure 9.

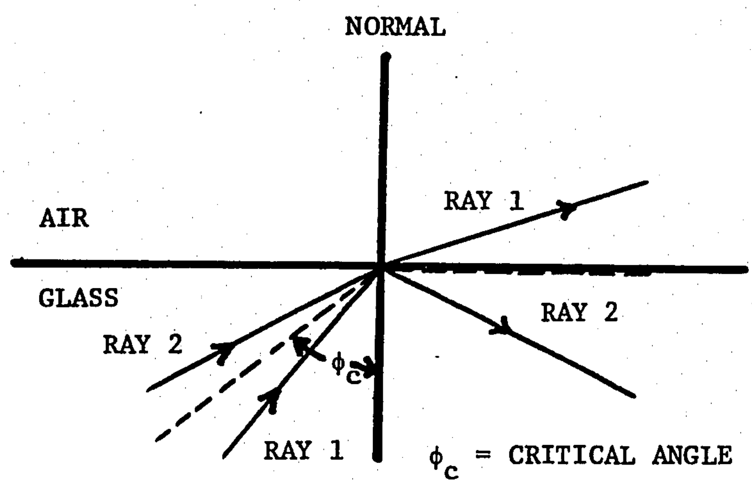

Figure 9. Relationship between total internal reflection and the critical angle

Ray 1 represents a light ray which strikes the air-glass interface inside the critical angle and "escapes" from the glass region. Ray 2 represents a light ray which strikes the air-glass interface outside the critical angle and is therefore totally reflected. The angle which forms the dividing line between these two conditions is called the critical angle (ϕ_c) and may be calculated from the equation $\sin \phi_c = \frac{\mu_a}{\mu_g}$ where μ_g is the index of refraction of glass. μ_a, the index of refraction of air, has an accepted value of $\mu_a = 1.000276$ for red light but $\mu_a = 1$ is satisfactory for most calculations. The critical angle for a given glass material is typically calculated then from $\sin\phi_c = \frac{1}{\mu_g}$. Since a nominal index of refraction is about 1.55, a typical critical angle would be approximately 40^o.

One of the specifications of a fiber optic is a quantity called the numerical aperture (N.A.) The numerical aperture is a measure of the light-collecting ability of the fiber optic and is related to the maximum entrance angle a light ray may have and still experience total internal reflection. This entrance angle θ is illustrated in Figure 10.

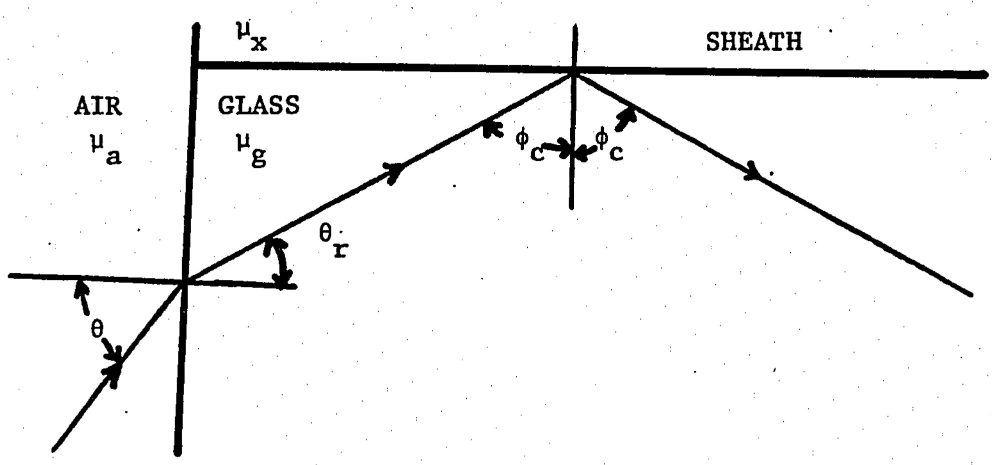

Figure 10. The relationship of the maximum entrance angle θ to the critical angle ϕ_c.

According to Snell's Law,

$$\mu_a \sin\theta = \mu_g \sin\theta_r.$$

but $\sin\theta_r = \cos\phi_c$,

so $\sin\theta = \frac{\mu_g}{\mu_a}\cos\phi_c$. (1)

also $\sin^2\phi_c + \cos^2\phi_c = 1$,

therefore $\cos\phi_c = (1 - \sin^2\phi_c)^{1/2}$.

Rewriting the cosine in terms of the sine function for Equation (1),

$$\sin\theta = \frac{\mu_g}{\mu_a}(1 - \sin^2\phi_c)^{1/2}. \qquad (2).$$

If the glass fiber is surrounded by a thin glass sheath with index of refraction μ_x, we can use the critical angle definition to give

$$\sin\phi_c = \frac{\mu_x}{\mu_g}.$$

Substitution into Equation (2) yields

$$\sin\theta = \frac{\mu_g}{\mu_a}(1 - \frac{\mu_x 2}{\mu_g 2})^{1/2}.$$

Finally,

$$\sin\theta = \frac{(\mu_g 2 - \mu_x 2)^{1/2}}{\mu_a}$$

Thus an interesting result is obtained in that the maximum acceptance angle of the fiber optic system depends only on the indices of refraction of the system. The acceptance angle of a conventional optical system depends on the physical dimensions of the system.

Since we are normally dealing with an optical fiber in air where $\mu_a \approx 1$,

$$\sin\theta \approx (\mu_g 2 - \mu_x 2)^{1/2},$$

and the quantity $(\mu_g 2 - \mu_x 2)^{1/2}$ is defined as the "numerical aperture" and abbreviated as N.A. Thus N.A. = $(\mu_g 2 - \mu_x 2)^{1/2}$ where it is necessary, of course, that the sheath μ_x be less than the glass μ_g. Typical values might be $\mu_g = 1.61$ and $\mu_x = 1.53$ giving a numerical aperture of 0.55. For this numerical aperture of 0.55, the maximum entrance angle θ would be 33°. That is, all light within a cone with an apex angle of approximately 66° would be transmitted by this fiber optic system.

CHAPTER V

FIBER OPTIC EXPERIMENTS

The following experiments have resulted in the first known holograms ever constructed using fiber optics for illumination in this manner.

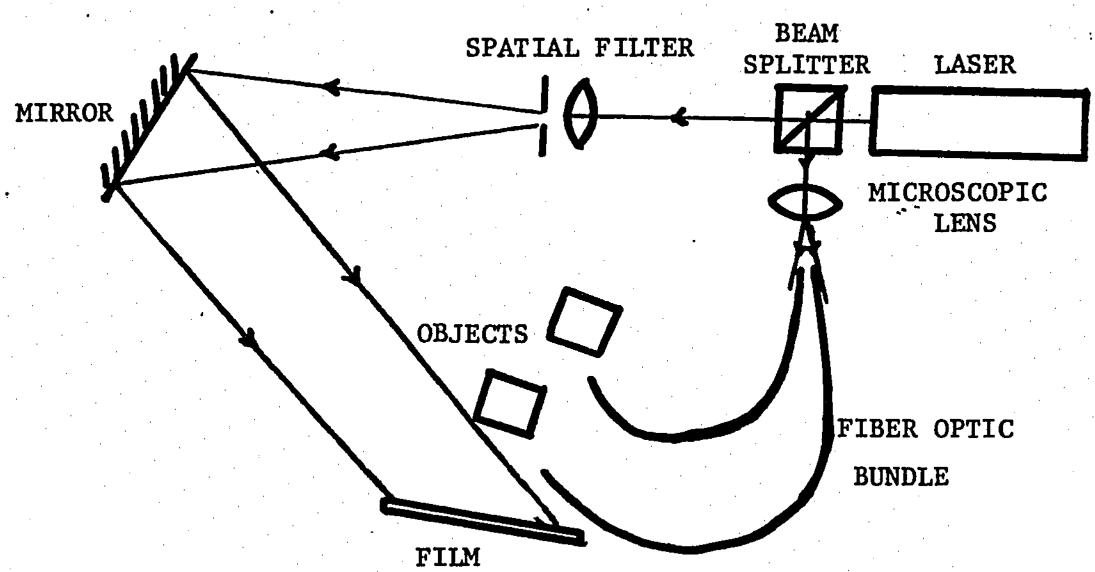

Figure 11. Depth of field set-up where objects (dice) are illuminated using fiber optics.

The first fiber optic experiment concerned the possibility of using fiber optics to carry the object beam. One advantage of using fiber optics is that a fiber optic bundle has more flexibility than a mirror to direct the beam in any direction towards the object. The fiber optic bundles used in this experiment are 1/8 inch in diameter and contain 1470 fibers.

Before taking a hologram, the intensities of the reference beam and object beam were measured with a photometer (PASCO Model 8020). It was found that they were in the ratio of 1:1, which was the correct ratio needed in this experiment, without the aid of any filters. An exposure time of thirty seconds was used to make the hologram. The resultant hologram yielded a high-quality image of the object upon reconstruction. Both objects were clearly visible and the parallax property of the hologram was easily observed. The front die was five centimeters closer to the film than the die in the back, demonstrating the depth-of-field phenomenon.

In the next investigation, the arrangement of Figure 11 was used. In this set-up, the fiber optic bundle replaces the spatial filter and mirror in providing the reference beam illumination. The object was illuminated by four fiber optic bundles. A hologram was made, making sure the intensity ratio was again in the right proportion (1:1). The physical appearance of holograms is a good indication of the potential quality of the holographic images. Widely spaced very dark regions on the film, separated by very light density regions, are not likely to yield good holograms. The following is a list of reference beam elements and the character of the resultant hologram film.

1. Mirrors, no spatial filter - wide bands, rings, whorls - low quality hologram.
2. Mirrors with spatial filter - small bands, closely spaced speckle pattern - good quality hologram.
3. Fiber optics - small bands, closely spaced speckle pattern - good quality hologram.

The images of the hologram made with a fiber optic reference beam were of quality equal to those made with a spatial filter. No distinction in image quality could be observed. One interesting observation could be made, however, in the fiber optic hologram. This was the observation of the end of the fiber optic bundle appearing as a small "honeycomb" image in the hologram. The overlapping of the light rays from the bundle provided both as object beam and reference beam on the film for the bundle and the image could be observed from any position.

G. L. Rogers and Margaret Benyon (1973) were the first to produce a holographic recording of a complete closed surface. An ordinary hologram provides a complete three-dimensional record of the front surface of the body only. For some purposes, it would be useful to record the back surface as well; thus a complex mechanical part can be more readily visualized. A three-dimensional copy of the rear surface of the body in the form of a plastic cast was produced. The first part of the exposure was to record the front surface of the body. The second part of the exposure was then to record the back. The two exposures taken were not of equal duration. To compensate for the phenomenon of photographic inertia, the second exposure is shorter in this technique.

Figure 12 represents the experimental arrangement for constructing a rather complex hologram of the front and back sides of a die using fiber optics for both the object beam and the reference beam. This holographic arrangement illustrates the versatility of fiber optic illumination.

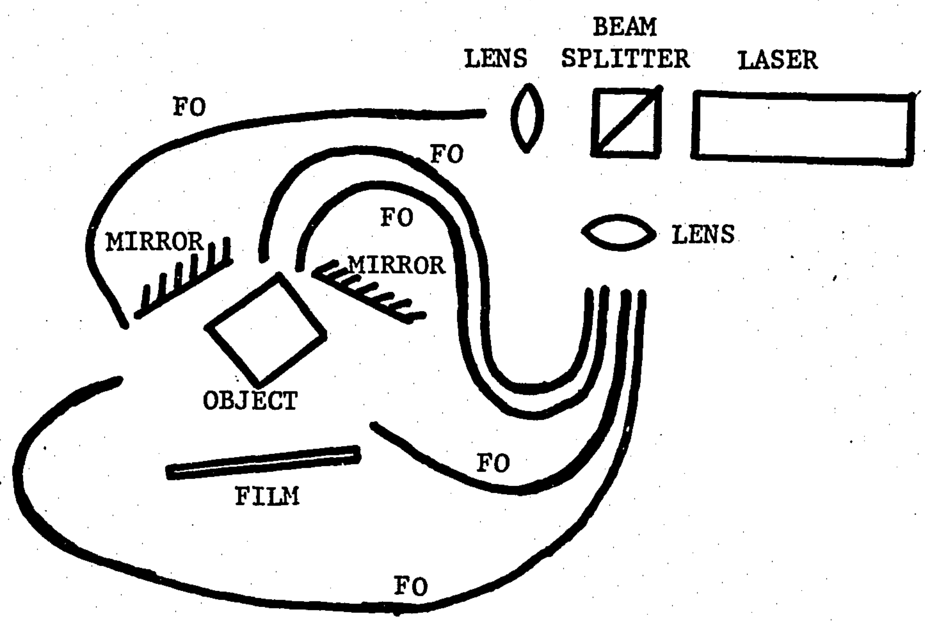

Figure 12. Holographic illumination using fiber optic bundles.

The Figure 12 set-up uses five fiber optics bundles (FO). Four of the fiber optic bundles were used to illuminate the object. Two fiber optic bundles were used to illuminate the front surface of the die and the other two bundles were used to illuminate the back surface of the die. Two mirrors were used to reflect the image of the back surface onto the holographic film. The fifth fiber optic bundle was used as a reference beam illumination. Again the reference object intensity ratio was adjusted to be 1:1 by moving the reference beam illumination closer or further from the film. An exposure time of thirty seconds was used for this hologram.

The resulting hologram, upon reconstruction with a laser, gave a very high quality image formation. Six images (three virtual and three real) were clearly visible. It is not necessary that fiber optic bundles be used in the laser beam which reconstructs this holographic image. Parallax was very evident with changes in viewer position along the film. The reflected images were as clear as the direct images and the real images were distinct enough to project on to a viewing screen. The very high quality of this detailed hologram is strong evidence of the promise of this new technique of using fiber optic bundles to convey illumination for both the object beam and the reference beam.

CHAPTER VI

CONCLUSION

This thesis has reported on several techniques for making holograms and on the behavior of various components of the holographic apparatus. Unique to this thesis is the use of fiber optic bundles to convey illumination from the source for the object beam and for the reference beams. Three major advantages accrue when using fiber optic bundles. These are:

1. By using a fiber optic bundle for the reference beam, there is no need for a spatial filter. Besides being expensive, spatial filters are difficult to adjust and require much patience to achieve optimum illumination. The beam splitter may also be omitted if one choses.

2. There is a very distinct advantage (over mirrors) in the flexibility provided for placing the fiber optic bundle illumination where it is wanted, either as the object beam or the reference beam. Furthermore, it is not only possible, but easy, to illuminate the object from many directions by using fiber optic bundles.

3. One prerequisite to making good quality holograms is for the optical distance traveled by the reference beam to be equal to the optical distance traveled by the object beam. This condition tends to preserve the coherence inherent in the original laser beam. Making adjustments of alignment with traditional mirror systems usually involve changes in the optical path length and so a compensating change must be made in the reference beam path. In contrast to this,

the distance from entrance to exit in a fiber optic bundle is unchanged by reorientation of the bundle direction, so the optical path remains essentially unchanged.

In summary, the use of fiber optics for making holograms provide great versatility to the object illumination, while at the same time removing the need for a spatial filter to provide high quality holographic images. This technique is certain to be adopted by others in the field.

APPENDIX I

Alignment Procedure for the Spatial Filter

1) Set up the laser and its carrier on the optical bench.

2) The pinhole position must be carefully adjusted so that the pinhole is located exactly at the focal point of the lens.

3) By repeated vertical and lateral adjustment, the pinhole can be located over the focal point so as to allow the maximum amount of the laser beam to go through the pinhole and diverge on to the other side.

Visual Alignment

1) Place a sheet of white paper behind the spatial filter for a viewing screen to observe light coming from the pinhole.

2) Simultaneously, adjust the two pinhole adjusting screws until a spot appears on the viewing screen. When the spot appears, adjust each pinhole screw alternately until the spot is of maximum brightness and roundness.

APPENDIX II

Fiber Optics Made From Plastic

Du Pont's chemical research with plastic has made possible the production of plastic fiber optics that are economical, more flexible and possess excellent light transmission characteristics. This new plastic light-transmitting medium, called Crofon, is based on the same principle as glass fiber optics.

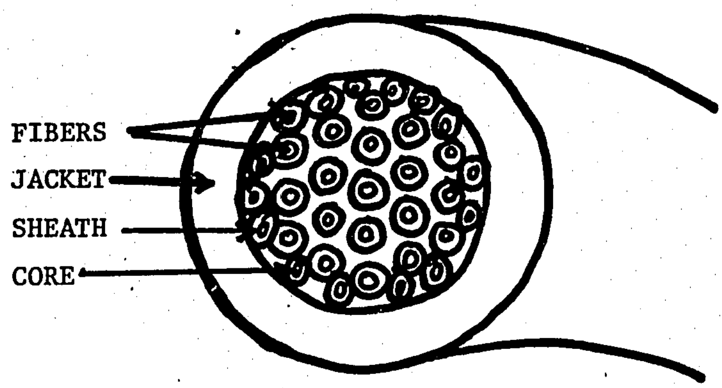

Figure 13. Cross section of a plastic fiber optic light guide.

Crofon light guides consist of a number of 10-mil diameter plastic fibers that are randomly bundled in a common jacket. Each fiber has a Lucite polymethyl methacrylate core with a transparent polymer sheath of lower refractive index. The jacket is made from Du Pont Alathon polyethylene resin. Crofon light guides typically contain 16, 32, 48, or 64 fibers. The path of a light ray in a single Crofon fiber is shown in Figure 14. The role of the low index of refraction sheath is to maintain total internal reflecion within the fiber (Figure 14). Note that a light ray entering the Crofon fiber at an incident angle of 35^{o} is refracted at an angle of 23^{o}. This ray approaches the fiber wall with an incident angle of 67^o. Since the Crofon core has an index of refraction of 1.489 and the sheath has an index of refraction of 1.370, the critical angle is 67^o and total internal reflection will take place.

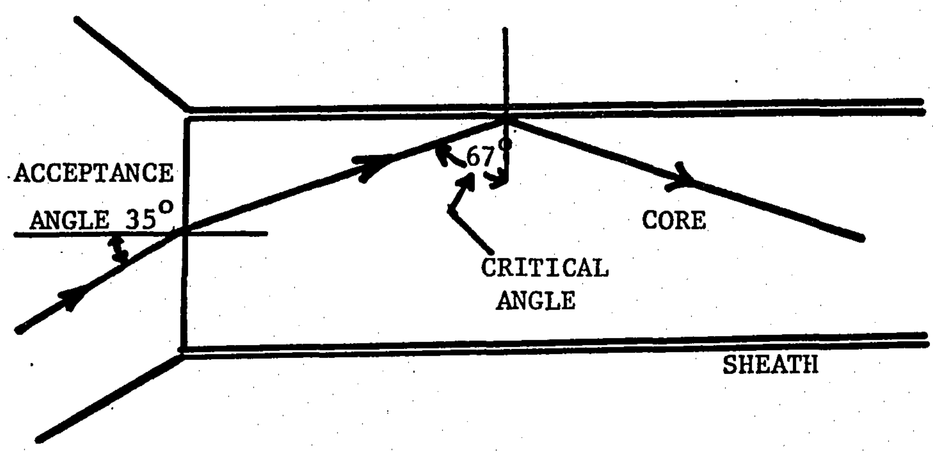

Figure 14. Path of light ray entering Crofon fiber optic.

Thus, light rays which strike the core sheath medium at angles greater than the critical angle, are reflected back into the core and travel to the other end of the fiber by a zigzag path of successive reflections. Crofon light guides therefore accept light from a cone with an apex angle of 70^o and emit a similar cone at the output end.

Shown in Figure 15 is a light ray in a fiber which is striking the low index of refraction sheath at an angle which is inside the Crofon critical angle. This light which escapes the core into the sheath is reflected from the sheath wall back into the fiber.

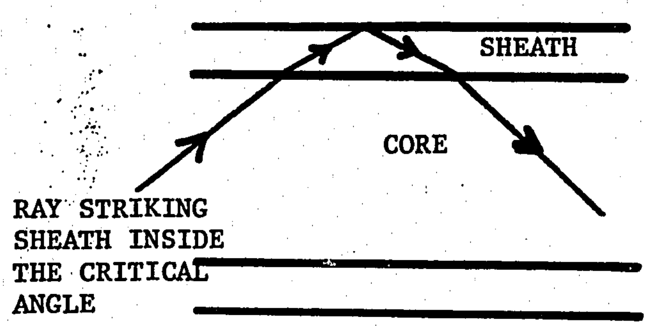

Figure 15. Reflection of light ray from the sheath.

APPENDIX III

Photographing Holograms

When a holographic film is viewed with ordinary room light, all that can be seen is the speckle and whorl patterns of Figures 6, 7, and 8. When the hologram is viewed with proper monochromatic radiation, it is possible to observe both the real images and the virtual images. The real images of course can be projected onto a viewing screen while the virtual images cannot. It is possible, however, by means of a camera pointed at the hologram, to record the virtual images on film. Shown in Figure 16 is a reproduction of a camera view of a hologram made with fiber optic illumination. The objects for the holographic scene were two chess pieces. In the center is the direct view of the castle and knight. At the right and left are mirror reflected views of the back sides of the objects. The exposure time for this picture was 10 minutes at f/11 on 35 millimeter plus-x film.

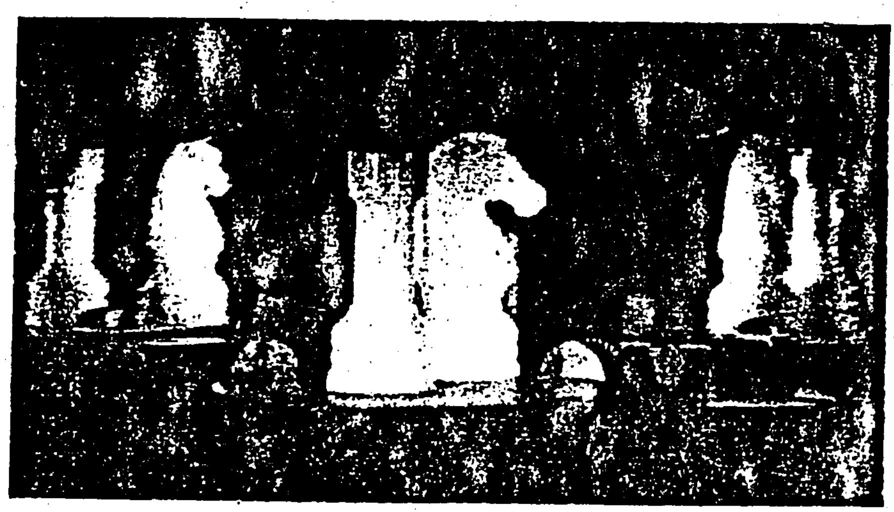

Figure 16. Camera view of a holographic scene.

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