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Letters to the Editor

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Multiemulsion On-Axis Computer Generated Hologram

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A key problem in computer holography is the realization of a transparency that controls both the amplitude and phase of a transmitted wave at each point in accord with a computed complex function. There are many approaches to simultaneous amplitude and phase control, including sandwiching of two independent transmitting structures,[1,2] the use of quadrature holograms,[3] carrier frequency holograms,[4] detour phase holograms,[5] and related methods.[6-8] Sandwich transparencies are generally difficult to align properly, and quadrature holograms must be reconstructed in a precision interferometric arrangement. Carrier frequency holograms and detour phase holograms reconstruct twin images; as a consequence, they are both wasteful of resolution, and in computer-generated form are low in realizable diffraction efficiency. Kinoforms[9] make better use of available resolution and can be highly efficient, but suffer a degree of background noise due to the discarding of amplitude information.

We wish to report on a new type of computer generated hologram that retains the advantages of a kinoform but provides effective control over *both* amplitude and phase transmittance. By means of multiemulsion color film, a sandwich filter is recorded with no need for later alignment. An added benefit of this approach is that the film can be purchased and processed through any drug store; the experimentor need not have personal access to any film processing facility.

The basic principle we have used can be explained as follows. Color reversal films contain several emulsion layers, each ideally sensitive to light in a different region of the visible spectrum. Our particular experiments have used Kodachrome II, which has three layers sensitive individually to blue, green, and red light. These emulsions give rise to dye images that are predominantly blue absorbing (yellow), green absorbing (magenta), and red absorbing (cyan), respectively. If a developed transparency is illuminated by monochromatic light, such light will be attenuated predominantly by just one of the three emulsions. The other two emulsions, while not attenuating the light, do exert an influence on the phase of the transmitted light, presumably through both relief and index changes (preliminary experiments indicate that both effects play a role). Thus with a judicious pair of exposures to the color film, and illumination of the processed film with monochromatic light, both the amplitude and the phase of the transmitted light are controlled.

In our own experiments, we began with a matrix representation of the image we wished to obtain from our computer-generated hologram, in this case an array of binary ones and zeros in the form of the letters *A*, *B*, *C*, and *D*. These characters were imbedded in a field of 32 × 32 elements. Phase coding was applied to these elements to lower the dynamic range of the spectrum; each data value f_{nq} was multiplied by $\exp(i2\pi nq/N')$, where N' is the actual size of the data block embedded in the 32 × 32 array. The phase coded array was then Fourier transformed using a two-dimensional FFT program to produce a 32 × 32 array of complex Fourier coefficients,

$$F_{mp} = A_{mp}\exp(i\theta_{mp}), \quad \begin{Bmatrix} m \\ p \end{Bmatrix} = 0,1,\ldots,31. \tag{1}$$

Separating amplitude and phase information, we have two 32 × 32 matrices, one with elements A_{mp} and the second with elements θ_{mp}, which always lies between 0 and 2π.

These two matrices are displayed sequentially on a CRT and photographed using different color filters. The basic 32 × 32 patterns are replicated 4 × 4 times, and each Fourier coefficient is displayed with a 2 × 2 grid of spots. Hence there are 256 × 256 spots displayed by the CRT for each exposure. The exposure contributed by each CRT spot is controlled by the time duration that the electron beam spends on that spot, generating gray levels that are for all practical purposes continuous. The displayed patterns are photographed using a 35-mm single lens reflex camera with a 55-mm lens, mounted 80 cm from the CRT face and shielded by a cardboard tube.

Exposures are made on regions of the film characteristic where the densities to red and cyan light are approximately linearly related to the logarithms of the red and cyan exposures, respectively. For exposures of the amplitude information, the entire linear dynamic range of the

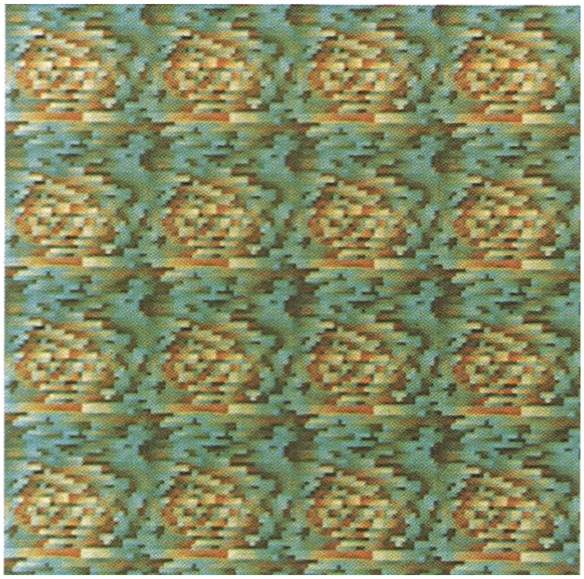

Fig. 1. Magnified photograph of a hologram.

red-absorbing emulsion is used; the red exposures are made such that the final amplitude transmittance to red light is proportional to the desired amplitude.

For exposing the emulsions that control phase, we again operate on the linear portion of the H & D curve, where the density to cyan light is linearly proportional to the log of cyan exposure. Here we adopt the assumption, often used in the past, the phase shift is proportional to density.[10-12] In addition, by separate experiments in which sawtooth patterns are displayed and photographed, it is possible to determine the exposure excursions necessary to achieve phase matching over the 0 to 2π range. In our experiments these excursions were found to lie well within the linear region of the H & D curve.

It should be noted that the red-absorbing emulsion will also suffer relief and index changes, and as a consequence some unwanted phase changes may be introduced. We have compensated for this affect by lessening the log of the cyan exposure by an amount proportional to the log of the red exposure, the proportionality constant being determined experimentally.

In our experiments, the first displayed pattern, representing amplitude information, was photographed through a Kodak Wratten 26 red filter. The second displayed pattern, representing phase information, was photographed through a cyan filter. Care is taken to avoid moving the camera between exposures and thereby destroying registration. The exposed film is sent to a local Kodak processing laboratory. Finally, the processed transparency is illuminated by 6328-Å light from a He–Ne laser. The red light is attenuated by the red absorbing emulsion and phase shifted by the blue- and green-absorbing emulsions. The desired image is obtained in the focal plane of a positive lens, where it appears centered about the optical axis.

Experimental results obtained using the above procedure have been excellent. Figure 1 shows a magnified picture of a hologram. Figure 2 shows an (unretouched) Polaroid photograph of the reconstructed image.

Since a kinoform is simply a special case of the above hologram with all amplitude information set equal to a constant value, it is possible to make kinoforms by the above procedure. In this case, to save computer time, we expose only the phase information under computer control through a cyan filter. The film is later reexposed to a flat white object through a red filter. With the use of black tape to block those regions of the transparency that lie outside the region of phase exposure, an excellent kinoform results, in fact the best kinoform we have been able to make by any method. Figure 3 shows a Polaroid photograph of the image produced by such a kinoform. Comparing Figs. 2 and 3, the nonuniform intensities of the image dots in Fig. 3 are probably due to the fact that the kinoform has discarded amplitude information.

Returning to the general case, there are several sources of error for which we have not yet attempted to compensate. First, there is exposure cross talk between emulsions; i.e., the blue- and green-sensitive layers are also slightly exposed by red light and vice versa. Second, in addition to the red-absorbing emulsion affecting the phase transmission, the green absorbing emulsion is partially absorbing in the red (dye cross talk). Third, the relief image depends on spatial frequency (but this dependence is much less pronounced than that of the relief image in bleached Kodak 649-F). However, even without compensating for these errors, surprisingly good results were obtained.

To summarize, multiemulsion films (e.g., Kodachrome II) can be used to control directly amplitude and phase for holograms and complex spatial filters. These transparencies are similar to sandwich type holograms, but the alignment problem is reduced to the display's ability to reposition its address accurately. The sensitivity of ordinary color films is extremely high relative to that of holographic plates, and direct exposure from a CRT is possible.[13] The most restrictive limitation of such films is their low resolution; for example, the frequency response of Kodachrome II extends out to the range 96–135 lp/mm.[14] Thus color films would be of little use for high-density optical memories. However, due to limitations of expense and display capability, computer-generated holograms seldom contain more than 1024 × 1024 Fourier coefficients, and such holograms can be easily recorded on a 35-mm color transparency, particularly since no high frequency carrier is required. A great advantage of color film is its availability and the high degree of accuracy and repeatability associated with commercial processing. We have affectionately given this new hologram device a name: Referenceless On-Axis Complex Hologram, or ROACH. We believe this will be a very useful device for those interested in computer generated holograms.

Fig. 2. Image reconstructed from the hologram (amplitude and phase controlled).

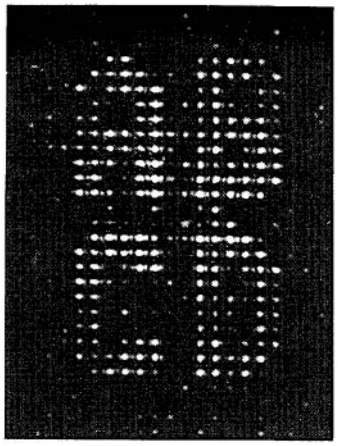

Fig. 3. Image reconstructed from a kinoform (only phase controlled).

We are grateful to A. A. Sawchuk whose courtesy and assistance enabled us to make kinoforms at the University of Southern California facilities at one time when we were experiencing difficulties with our own equipment.

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Digital Stereophotogrammetry of the Ocular Fundus

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Crock and Parel[1] have demonstrated the feasibility of generating contour maps of the ocular fundus using stereophotographs taken with a Zeiss fundus camera. Such maps appear especially attractive for the early detection of chronic simple glaucoma, a leading cause of middle-age blindness. In their procedure the fundus photographs are interpreted like pictures of the earth's surface taken with a fictitious survey aircraft. The stereophotographs are then placed in an aerial stereoplotter and contour lines drawn in the usual way by a trained operator. The contour maps obtained with this procedure look very impressive and suggest the possible medical value of the technique. However, as noted by Crock,[2] the stereoplotter procedure remains much too expensive—in time and money—for mass screening or routine clinical use.

In an effort to reduce the time and cost associated with the aerial stereoplotter technique, a pair of monochrome stereophotographs was digitized using a CRT-type scanner controlled by a LINC-8 minicomputer. (The scanner features a 128 × 128 array of picture elements, each element having 128 possible gray levels. The digitization errors were measured at less than 1% and the scan nonlinearities estimated at less than 2%.) These photographs were considered of average quality and represented a typical ocular fundus, except perhaps for some cupping of the optic disk. To ensure an interesting experiment, only a portion of the original stereo pair was digitized, namely, the optic nervehead and its immediate surroundings. Following digitization, the LINC-8 was connected by a telephone line to a larger CDC 6400 computer and the digitized data transmitted to the CDC 6400 for subsequent processing.

To generate the required contour maps, a computer program, called STEREO, was written and compiled on the CDC 6400. The STEREO algorithm was designed to duplicate digitally the analog operation of the aerial stereoplotter used by Crock and Parel.[1] In particular, the program located and compared respective points on the two stereophotographs using a conventional correlation integral. The purpose of the correlation integral was to measure the apparent parallax associated with each point of the ocular fundus. The parallax measurements were then converted to equivalent heights above or below the nominal level of the fundus surface. A second software algorithm, called CONTOUR, then converted the resulting height map to a contour map, and a third software package, called PLOTTER, displayed the calculated results using a CRT peripheral. The CRT image was then photographed, and glossy prints were produced for medical examination.

Figure 1 contains the height map generated by the program STEREO. The darker areas of the height map represent deeper (posterior) portions of the ocular fundus, and the lighter areas indicate higher (anterior) ones. Each gray-level step represents approximately 100 μ of elevation change. Altogether, five distinct gray levels occur in the height map of Fig. 1, thus indicating a height difference of about 500 μ between the highest and lowest portions of the digitized area of the fundus.

Occasional high or low spots will be noted here and there on the height map. Such irregularities, called contouring noise, result when the program STEREO becomes uncertain about the exact height of a particular point on the ocular fundus. Such uncertainties arise from a number of sources: noise traceable to film granularity, errors generated during digitization, and confusion between the pigment epithelium and inner retinal surfaces. By design, the program STEREO must make some decision on the height of a given point, with the inevitable result that

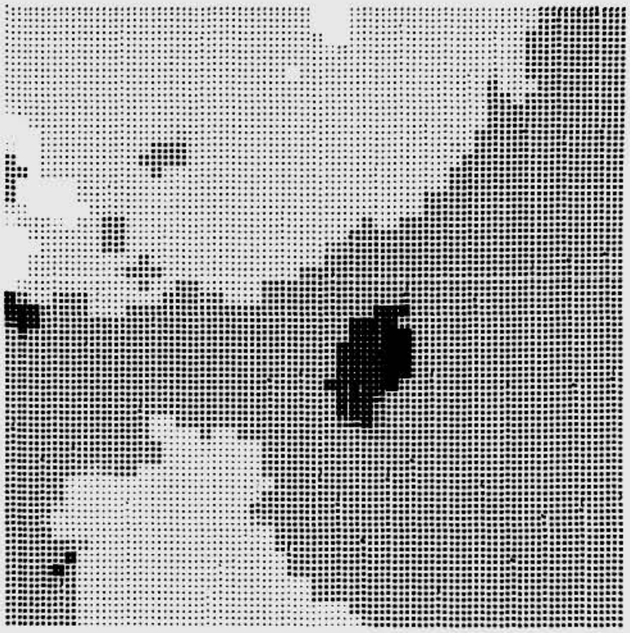

Fig. 1. Height map of the optic nervehead and its immediate surroundings. The darker (lighter) areas represent deeper (shallower) regions.