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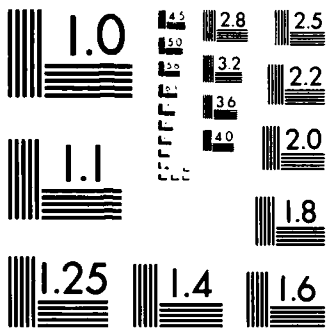

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Computer-generated holograms of geometrical shape and synthetic, discriminant function (SDF) matched filters are modeled and produced. The models include ideal correlations and Allebach-Keegan binary holograms. A distinction between Phase-Only-Information and Phase-Only-Material Filters is demonstrated. Signal-to-noise and efficiency measurements were made on the resultant correlation planes.

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Optical Implementation of the Synthetic Discrimination Function

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Armament Laboratory, Eglin AFB, FL 32542

Abstract

Computer-generated holograms of geometrical shape and synthetic discriminant function (SDF) matched filters are modeled and produced. The models include ideal correlations and Allebach-Keegan binary holograms. A distinction between Phase-Only-Information and Phase-Only-Material Filters is demonstrated. Signal-to-noise and efficiency measurements were made on the resultant correlation planes.

Introduction

Much attention is focused on the use of coherent optical pattern recognition (OPR) using matched spatial filters for robotics and intelligent systems. The OPR problem consists of three aspects -- information input, information processing, and information output. This paper discusses the information processing aspect which consists of choosing a filter to provide robust correlation with high efficiency.

The filter should ideally be invariant to image shift, rotation and scale; provide a reasonable signal-to-noise (S/N) ratio and allow high throughput efficiency. Such generalized matched filter algorithms are reported by Casasent[1], Lee[2], and Caulfield[3].

The physical implementation of a spatial matched filter involves many choices. These include the use of conventional holograms or computer-generated holograms (CGH) and utilizing absorption or phase materials. Conventional holograms inherently modify the reference image by non-uniform emphasis of spatial frequencies. Proper use of film nonlinearity provides improved filter performance by emphasizing frequency ranges crucial to target discrimination. In the case of a CGH, the emphasis of the reference magnitude and phase can be controlled independently of the continuous tone or binary writing processes.

This paper describes computer simulation and optical implementation of a geometrical shape and a Synthetic Discriminant Function (SDF) matched filter. We chose the binary Allebach-Keegan (AK) CGH algorithm[4] to produce actual filters. The performances of these filters were measured to verify the simulation results. This paper provides a brief summary of the matched filter theory, the SDF, CGH algorithms, Phase-Only-Filtering, simulation procedures, and results.

Background

Spatial matched filters are used to detect the presence of specific patterns in an image. Vander Lugt[5] combined matched filter techniques, well documented in books on communication theory, with holographic techniques to provide a real time optical correlator. The Vander Lugt Filter of a function f(x,y), created through conventional holographic techniques, yields the following transmittance function:

$$H(u,v) = A^2 + |F(u,v)|^2 + AF(u,v)e^{j2\pi au} + AF^*(u,v)e^{-j2\pi au} \quad (1)$$

where $F(u,v)$ = Fourier Transform of $f(x,y) = \mathcal{F}\{f(x,v)\}$

$A\,e^{-j2\pi au}$ = the off-axis reference wave used to provide the spatial carrier for the hologram.

$a = \frac{\sin\Theta}{\lambda}$ = the filter's spatial carrier freq (Θ = off-axis angle)

The filter contains the D.C. bias, A^2; the baseband magnitude, $|F(u,v)|^2$; and two terms heterodyned to $\pm a$. These heterodyned terms contain the complex valued information describing the reference input f(x,y). If the spatial carrier frequency is sufficiently high, the heterodyned terms are separable and no aliasing exists. When the filter is illuminated by the Fourier Transform of an input function g(x,y) and the resulting image inverse transformed, three terms result. A baseband product of the reference and input magnitudes is brought to focus on axis. The heterodyned terms form the correlation and convolution images spatially separated from the baseband image when the carrier frequency is sufficiently high. The correlation image is used to detect the presence of the reference pattern in the input image. This ideal correlation is symbolized by:

$$R_{fg}(x,y) = f(x,y) \circledast g(x,y) = \iint f(x-x_o,y-y_o)g(x_o,y_o)dx_o dy_o$$
$$= \mathcal{F}^{-1}[F^*(u,v)G(u,v)] \qquad (2)$$

where $\circledast$ denotes correlation

An optical matched filter only approximates the ideal case. The continuous tone hologram has a limited dynamic range and thus introduces nonlinearity. The CGH algorithms sample the complex transmittance in space and quantize the phase and amplitude. The filter output, then, cannot be modeled by equation (2) but rather by

$$R'_{fg}(x,y) = \mathcal{F}^{-1}\left\{H(F^*(u,v)) \cdot G(u,v)\right\} \qquad (3)$$

where $H(F^*)$ describes the Holographic Function operating on the filter transform. In general, F^* and G are complex but $H(F^*)$ is a real, zero phase function.

Synthetic Discriminant Function

The filter reference function, f(x,y), used in our work was an SDF. The SDF has been widely described in the literature[6-8] and will only be summarized here. In this case the SDF is used to provide rotation invariance. The SDF is designed to provide a constant cross-correlation peak between the filter function F, and all members of a set $\{g_n\}$. In other words,

$$g_n \circledast f = \text{constant}$$

where $\circledast$ denotes a correlation process and the constant is typically chosen to be unity. For our work, the set $\{g_n\}$ consists of two-dimensional images of a tank rotated every 10^o. The filter function f is a linear combination of an image training set which may be a subset of $\{g_n\}$.

$$\text{Thus, } f = \sum_i e_i \cdot g_i \qquad (4)$$

where the e_i are chosen to give cross correlations as close as possible to one for each member of the training set. That is, the quantity $\sum_i |f \cdot g_i - 1|^2$ is minimized.

The SDF is calculated digitally, off line, resulting in a two-dimensional, digital, object space image. To then implement the SDF optically, two techniques can be used: (1) transform the digital image to an optical image via a high resolution CRT or digitally addressed camera and produce a Vander Lugt Filter in the conventional holographic manner, or (2) retain the image in a digital format and produce the filter through computer-generated hologram techniques. Because of increased flexibility and repeatability, the latter technique was chosen.

Computer-Generated Holograms

Computer-generated holograms have found applications in optical information processing, interferometry, synthesis of novel optical elements, laser scanning, and laser machining.[9-12] With computer-generated holograms we can implement computer-optimized optical pattern recognition masks.[13] The hologram transmittance function is expressed in equation (1). If we represent the image f(x,y) using a digital representation, the transmittance function H(u,v) can be computed digitally.

The computer writes the hologram by transferring the transmittance function to an appropriate holographic medium. Typically the computer drives a plotter or scanner and writes the hologram one point at a time. The primary limitation is writing resolution. A conventional optically generated hologram may have a resolution of one quarter of a micron. A computer system using visible light to write holograms (plotters, flying spot scanners, CRTs, etc.) cannot achieve resolutions much better than several microns. Writing systems utilizing electron beams are currently achieving better than 1 micron resolution. The electron beam systems are typically binary and thus the transmittance function must be quantized in some fashion into two levels, "on" or "off". Binary holograms are attractive because binary computer-graphics output devices are widely available and because problems with nonlinearities in the display and recording medium are circumvented.[14] When photographic emulsions are involved, granularity noise is reduced.[15]

Several computer hologram types are modeled and produced at Eglin. These include continuous tone holograms and three classes of binary holograms: Brown-Lohmann (BL)[16], Lee[17], and Allebach-Keegan (AK)[4] binary holograms.

The continuous tone holograms are sampled and quantized versions of the theoretical optically produced hologram. When the sampling frequency is sufficiently high, this CGH most closely resembles the optically produced hologram. Of course, even the largest computers cannot reasonably match the large space-bandwidth-product typical of optically produced holograms.

The Brown-Lohman (BL) binary hologram uses a clear aperture to represent each pixel value. The aperture is made larger or smaller according to the magnitude of that pixel value. The aperture is then shifted to increase or decrease the path length according to the pixel phase value (detour phase).

The Lee binary hologram uses four apertures for each pixel.[17] Each aperture is positioned to cause a quarter-wave phase shift by increased path length. The two non-negative quadrature terms are weighted to vector sum to the appropriate magnitude and phase for each pixel. The two appropriate apertures are opened according to their weight.

The CGH used in our experiments was the Allebach-Keegan. Squires and Allebach[18] performed a thorough analysis of various common binary CGH algorithms with respect to three error categories. In most cases, the total RMS reconstruction error was minimal with the AK algorithm. The AK algorithm encodes the object as quadrature components calculated in the same manner as the Lee method. The binary value of the individual hologram elements is determined through comparison with an ordered dither threshold mask. In the physical construction of an AK hologram, each hologram sample point is left clear when that quadrature component is greater than the threshold. All other areas are opaque. Allebach provides a formal description in reference 4.

Phase-Only-Filters

In the Fourier representation of images, spectral magnitude and phase tend to play different roles and, in some situations, many of the important features of a signal are preserved if only the phase is retained. Oppenheim[19] shows that when the magnitude portion of an image Fourier Transform is set to an arbitrary constant and the phase left intact, the reconstructed image closely resembles the original. The Phase-Only image typically emphasizes the edges by which we recognize shapes by essentially performing a high pass filtering. For example, only the edges tell us the difference between a circle and a square. This is very closely related to high pass filtering. As in the previous example, the low pass version of the circle and square are indistinguishable but the high pass versions are distinctly different. Most images have spectra where the magnitude tends to drop off with frequency. In the Phase-Only case, we set the magnitude of each pixel to unity. This implies multiplying each pixel magnitude by its reciprocal. Thus the Phase-Only process applied to a mound shaped Fourier Transform is high pass filtering.

The advantage of using a Phase-Only image or High-Pass image is the increase in optical efficiency of the resultant matched filter. As shown in equation (1), the transmission of each hologram element depends on the magnitude of the reference image Fourier Transform. As the magnitude drops off for high frequencies, so does the transmission of light through the holographic filter, and hence, filter efficiency is low. If we set the magnitude to unity (Phase-Only-Filter) for all frequencies the overall efficiency increases dramatically. Thus, efficiency is increased while subsequent correlation and reconstruction remains useful. Horner[20] shows that the maximum throughput efficiency of an ideal autocorrelation of a 2-D rect function is only 44% while the autocorrelation using a Phase-Only-Filter achieves 100% efficiency. Phase-Only-Filters have generated great interest in applications involving limited input power.

The Phase-Only process just described implies only the phase portion of the image information was used to produce the holographic filter. Thus, we may call this process a Phase-Only-Information process. A separate but related process is accomplished during the production of the physical hologram. When the holographic filter is exposed by the filter image and reference beam, a latent image is stored on the film (see equation (1)). If developed and fixed, the film absorbs light according to the illuminating intensities which created the latent image.

$$T_a(u,v) \propto H(u,v) \qquad (5)$$

where $T_a(u,v)$ is the amplitude transmission and $H(u,v)$ is the filter transmittance function defined in equation (1).

If we bleach the hologram after development, the metallic silver is removed and $T_a = 1$. The accompanying shrinkage of the emulsion causes a change in the path length through the holographic medium. The resultant wavefront phase is dependent upon the latent image

H(u,v) store on the film. For the bleached hologram we obtain the expression

$$T_a(u,v)=e^{iH(u,v)}. \qquad (6)$$

which essentially defines a phase modulation process. Note that there is no absorption involved. This bleached and other phase holograms merely vary the phase of the light passing through the hologram. The absorption hologram necessarily absorbs light striking it and is thus inefficient with its use of incoming light. This "phase media" hologram transmits all of the light (ignoring the emulsion, substrate, and reflection losses). Phase holograms are very efficient but as is evident in equation (6) they are very nonlinear. This nonlinearity causes an increase in noise due to intermodulation distortion.

The choice of absorption or phase holographic material is dependent upon the application. Use of a phase-only material is entirely independent of Phase-Only-Information. Thus, six separate cases were studied:

(1) Amplitude and Phase Information + Absorption Media,
(2) Phase-Only-Information + Absorption Media,
(3) High-Pass Filtered Information + Absorption Media
(4) Amplitude and Phase Information + Phase (Bleached) Media,
(5) Phase-Only-Information + Phase (Bleached) Media,
(6) High-Pass Filtered Information + Phase (Bleached) Media.

Computer Simulations

Figure 1 outlines the basic steps of implementing the theory. Two filter input image types were used for this experiment. The first was a 10 x 10 pixel square centered in a 128 x 128 pixel field. This input image served to set a baseline and verify the computer encoding by providing a known transform. The second computer image was an SDF of a nonsymmetric, edge-enhanced object -- in this case a tank. The SDF was constructed as a linear combination of 36 tank images. The 36 images represent a set of 36 infrared tank images taken at a constant depression angle and with the tank rotated 10 degrees per image. The SDF is a 128 x 128 image.

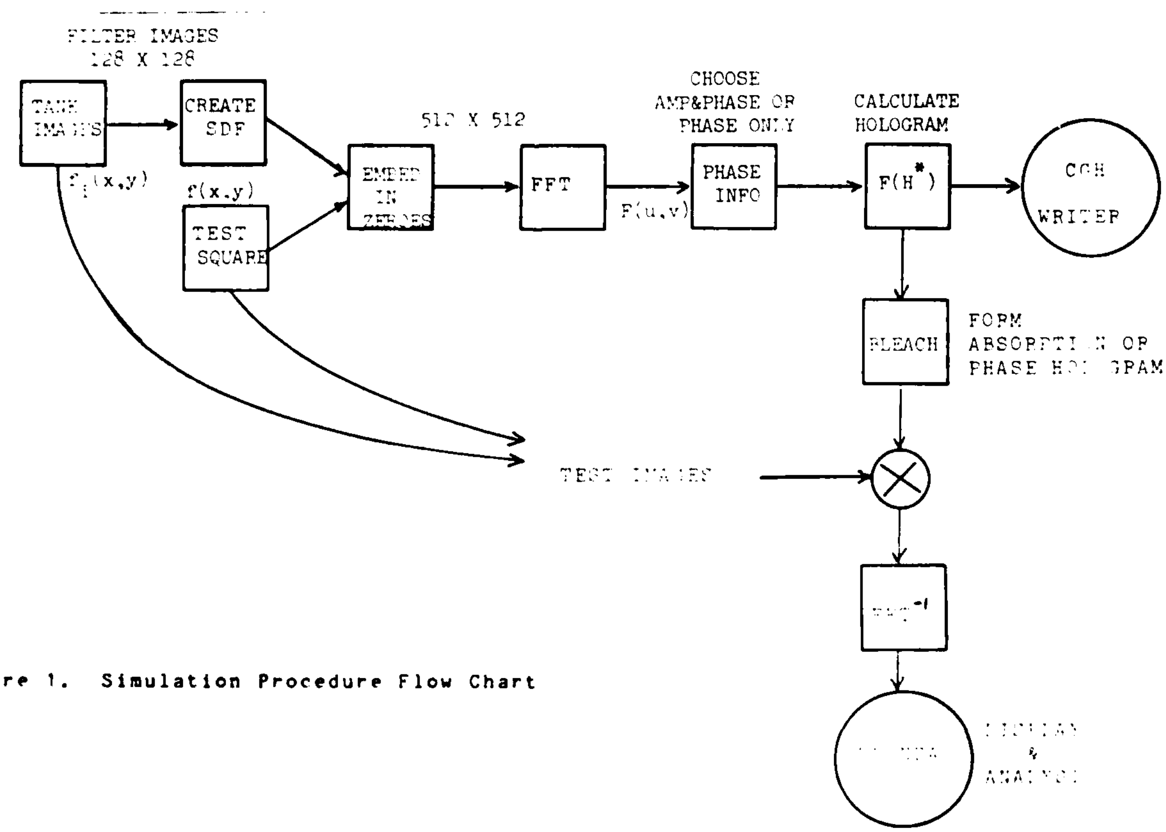

Figure 1. Simulation Procedure Flow Chart

We pad the 128 x 128 images with zeroes to create a 512 x 512 array which when Fast Fourier Transformed (FFT), yields a diffraction image that is smooth over four pixel intervals. The 512 x 512 diffraction image is band limited to 64 cycles/frame by the padding process. When Phase-Only-Information is chosen, the diffraction image is divided by the magnitude at each pixel location to assign unity magnitude. This result is input to the AK hologram algorithm.

The result of the AK hologram step is a binary 512 x 512 matrix. A value of 1 is assigned to those hologram sample points where a clear aperture should exist (based on the AK algorithm), and a zero value is assigned elsewhere. Figure 1 indicates two options exist after calculating the AK hologram (matched filter). The digital hologram is used as the input to CGH writing devices to physically implement the matched filter for use in an optical system. This task has been accomplished using the Honeywell Electron Beam writing device. The Honeywell system can create either absorption or phase holograms. A second option indicated in Figure 1 is to simulate the optical correlation process with the computer (VAX-750). The phase hologram is simulated by converting the binary transmittance values to phase delays. A phase shift of a half wavelength is chosen to simplify the programming and to minimize the D. C. term of the hologram. The complex Fourier Transform of a test image is multiplied by the CGH filter image. The result is inverse Fourier Transformed to create the correlation or output plane as described by equation (3). The final result is then displayed on DeAnza image processing hardware and analyzed for efficiency and signal-to-noise ratio.

Optical Implementation and Testing

In the Honeywell e-beam direct writing system, the hologram fringe pattern is created by a combination of beam deflections and workstage translations. Both are under control of the e-beam computer. The achievable number of pixels (10^{10}) can approach that of interferometrically recorded off-axis holograms because of the submicron resolution. For our experiments, Honeywell fabricated our 512 x 512 holograms with one micron spacing between pixels. These absorption holograms consist of etched chrome on 2-inch-square glass substrates.

The completed filters were placed into the optical correlator shown in Figure 2. The appropriate input image was placed before the Fourier transform lens. We recorded the output plane on film for qualitative analysis. We performed the quantitative analysis by measuring the input plane energy, correlation spike energy, and total correlation plane energy using an E.G.& G. 550-1 radiometer with appropriate masks.

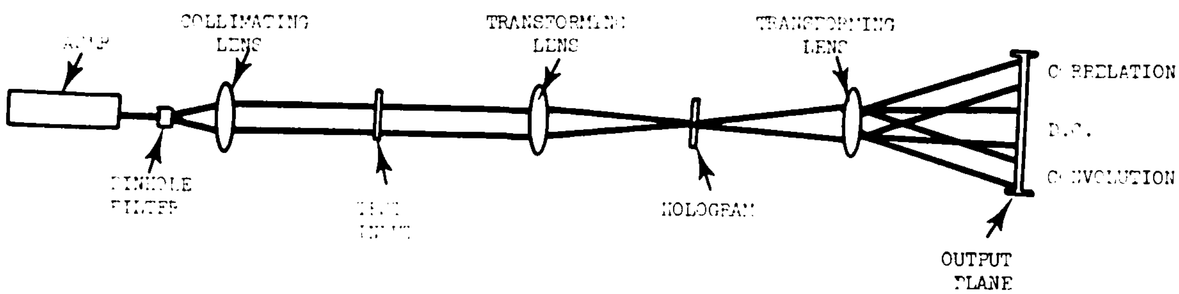

Figure 2. Setup for Optical Testing

Results

The simulation results are given in Table 1. Column 1 specifies the image used to produce the holographic filter. Column 2 specifies the test image to be correlated with the filter image. We determined, for each of these cases, signal-to-noise ratio and efficiency. The signal-to-noise ratio is defined as the peak amplitude of the correlation spike divided by the root mean squared average of the entire correlation plane. The efficiency is defined as the energy in the correlation spike divided by the input energy. The results are given for six combinations of absorption or phase modulation (bleached) holograms and normal, phase-only, and high pass information. The normal columns represent the results when the normal Allebach-Keegan algorithm is applied to the filter image; that is, the threshold is based on the FFT maximum as per reference 4. The phase-only columns apply to those cases where the filter image FFT magnitude was set to unity preserving the information phase at each point. The high pass columns apply to those cases where the AK threshold was lowered to emphasize higher spatial frequencies. That is the threshold is based on the square root of the maximum as per reference 21.

We ran six simulation cases. The autocorrelation of a square using the AK algorithm is presented as a reference. We then caused the AK algorithm to cross-correlate the SDF with various views of a tank chosen at random from the 36 images in the training set. In each, the signal-to-noise ratio and efficiency are tabulated so as to easily compare the absorption and phase modulation hologram materials along with the various pre-emphasis techniques applied to the filter image.

FILTER IMAGE	TEST IMAGE	SIGNAL-TO-NOISE RATIO (PEAK/AVE) ABOSRPTION NORMAL	PHASE ONLY	HIGH FREQ	BLEACH NORMAL	PHASE ONLY	HIGH FREQ	EFFICIENCY(COR.SPIKE ENERGY/INPUT ENERGY) ABSORPTION NORMAL	PHASE ONLY	HIGH FREQ	BLEACH NORMAL	PHASE ONLY	HIGH FREQ
SQUARE	SQR	69	277	203	69	277	203	3%	6%	11%	11%	24%	44%
	TANK												
SDF	10°	11	27	28	11	27	28	0.03%	0.6%	1%	0.1%	3%	4%
SDF	40°	5	7	8	5	7	8	0.1%	0.5%	0.9%	0.4%	2%	4%
SDF	130°	11	30	30	11	30	30	0.03%	0.7%	1%	0.1%	3%	4%
SDF	240°	6	16	17	6	16	17	0.2%	0.8%	1%	0.6%	3%	5%
SDF	270°	7	20	19	7	20	19	0.01%	0.5%	0.7%	0.05%	2%	3%

TABLE 1. Simulation Results of Alleback-Keegan CGH Matched Filter

Discussion

Table 1 shows the signal-to-noise ratio is independent of the choice of absorption or phase modulation (bleach) materials. Because the domain of valu[illegible] the absorption hologram includes only 1 and 0, the $y = e^{ikx}$ mapping yields on[illegible] -1 when k is set to pi. For this binary case, the bleaching process can be repre[illegible]d by y = 2x-1, a linear process. Thus the correlation plane structure and signal-to[illegible]se ratio are independent of bleaching. However, the efficiency increases dramaticall[illegible] with bleaching making phase modulation materials the obvious choice for binary holograms.

The pre-emphasis of the filter image by either high pass or Phase-Only-Filtering improves the signal-to-noise ratio and the efficiency. The signal-to-noise ratio is about the same for the high pass and Phase-Only-Information filters. However, the efficiency is higher for high pass filtering than for Phase-Only-Filtering. Because the high pass filter was chosen in an ad hoc fashion[21], there may be room for further improvement. Figure 3 shows the holograms and resulting correlations for the three cases of filter information pre-emphasis. The correlations shown in Figure 3 are normalized to show the relationship between the spike and the noise and do not show the difference in throughput efficiency.

Conclusion

The holographic matched filter in conjunction with the SDF shows promise in deformation invariant pattern recognition applications. A possible implementation of such theory is through computer-generated holography. This paper has described computer simulations which demonstrate the feasibility of implementing a SDF filter using the Allebach-Keegan CGH algorithm.

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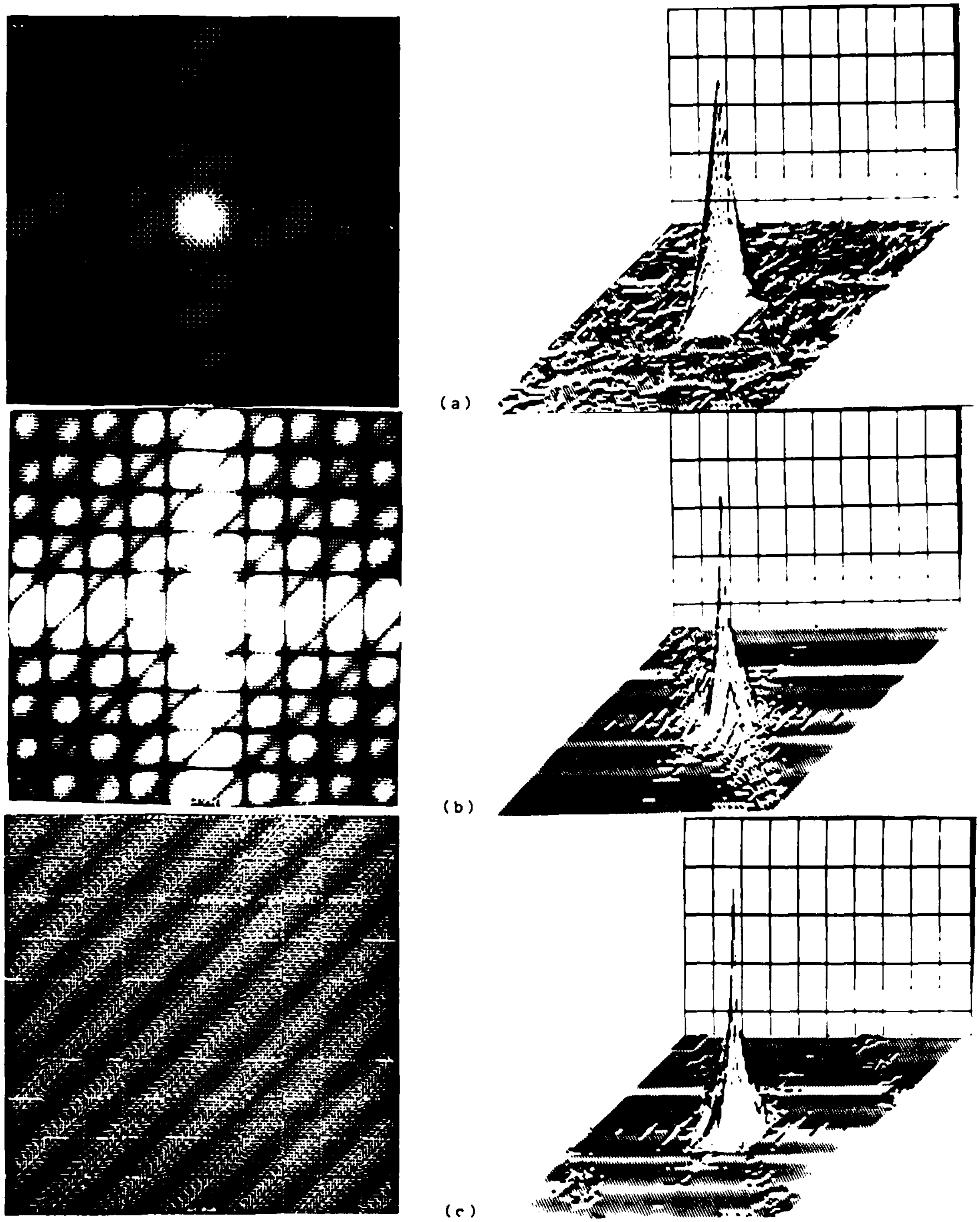

Figure 3. AK Hologram of a Square and the Resulting Autocorrelation using (a) Normal Threshold, (b) High Frequency Emphasis and (c) Phase-Only-Information