Hybrid computer-optical processing with inexpensive liquid crystal television

Matt Young and Matt Weppner

U.S. National Bureau of Standards, Electromagnetic Technology Division,
325 Broadway, Boulder, Colorado 80303, USA

Abstract

We describe a computer-optical processing system that uses an inexpensive liquid crystal (LCD) television monitor and a selective holographic filter for coherent pattern recognition. Specifically, we use a digital computer to generate an edge enhanced image of an object, expose a Fourier transform hologram of this image, and use the hologram as a sort of matched filter for recognizing the original object in real time.

Introduction

It may not be true that great minds think alike, but it is demonstrably true that a handful of researchers have roughly simultaneously discovered a new liquid crystal, or LCD, television set for use in optical processing.[1-5] The value of such a device, of course, is that it is not self luminous (like a CRT) but, rather, can be used as a spatial light modulator for generating coherent images at video rates.

Typical LCD TVs cost less than US$200 and may be addressed by a TV camera or by a microcomputer with a video frame digitizer. They therefore promise to allow coherent video images and computer generated patterns for holography and optical processing into almost any optics laboratory. We anticipate that they will find their greatest application in the input plane of the optical processor, where they are well suited, for example, to matched filtering and incoherent correlation experiments. Devices with higher resolution than the currently available values of about 120 x 140 pixels (vertical times horizontal) should additionally be useful for change or defect detection[6] and, to a limited degree, to computer generated holograms.[5] In applications where the transform plane can be magnified significantly, the monitor may be located there and used as a computer generated spatial filter or, possibly, a holographic filter.

The devices on the market today are designed for recreation and consist of a twisted nematic LCD screen glued between crossed polarizers. They are viewed in transmission and through a diffuser inclined at an angle of about 45° to the horizon. Removing the diffuser, modifying the hinge on the device, and building a rigid frame takes several hours.

The LCD panel we use is about 55 x 42 mm^2 and uses a raster formed by a grid of fine wires; the pixels are about 0.35 x 0.39 mm^2.[7] The polarizers are not flat and cause a serious aberration in the transform plane[1] as well as a lack of space invariance in spatially coherent systems.[4] The aberration may be corrected by contacting optical glass plates with index matching fluid to both sides of the display or by removing the polarizers entirely and using external polarizers.

The fine wire raster causes many diffraction orders in the transform plane of a coherent processor; these orders contain the information about the raster itself. Therefore, for many applications, it will be necessary to use low pass filtering to eliminate all but the lowest diffraction order of the grid. For this purpose we use a two-stage system with two transform planes.[1] The low pass filtering is performed in the first stage; this leaves the transform plane of the second stage completely unobstructed so that filters or holographic plates may be easily located there.

The LCD display is also well suited to incoherent correlations, where the object is illuminated coherently but diffusely, a hologram is recorded, and correlations are performed with spatially incoherent illumination.[8,9] (In this case, the quality of the polarizers is irrelevant.) Such applications have been hindered in the past by the lack of a suitable incoherent display with the same wavelength as the argon laser; the LCD monitor allows the argon laser to be used throughout the experiment.

Hybrid optical processor

The optical system we use is an extension of that described in reference 1 and is shown here as Fig. 1. An unpolarized 3-mW He-Ne laser beam is split by an uncoated, wedged beam splitter; one of the reflected beams is used as the reference beam in a matched filtering experiment. The transmitted beam is spatially filtered with a 10x microscope objective and a

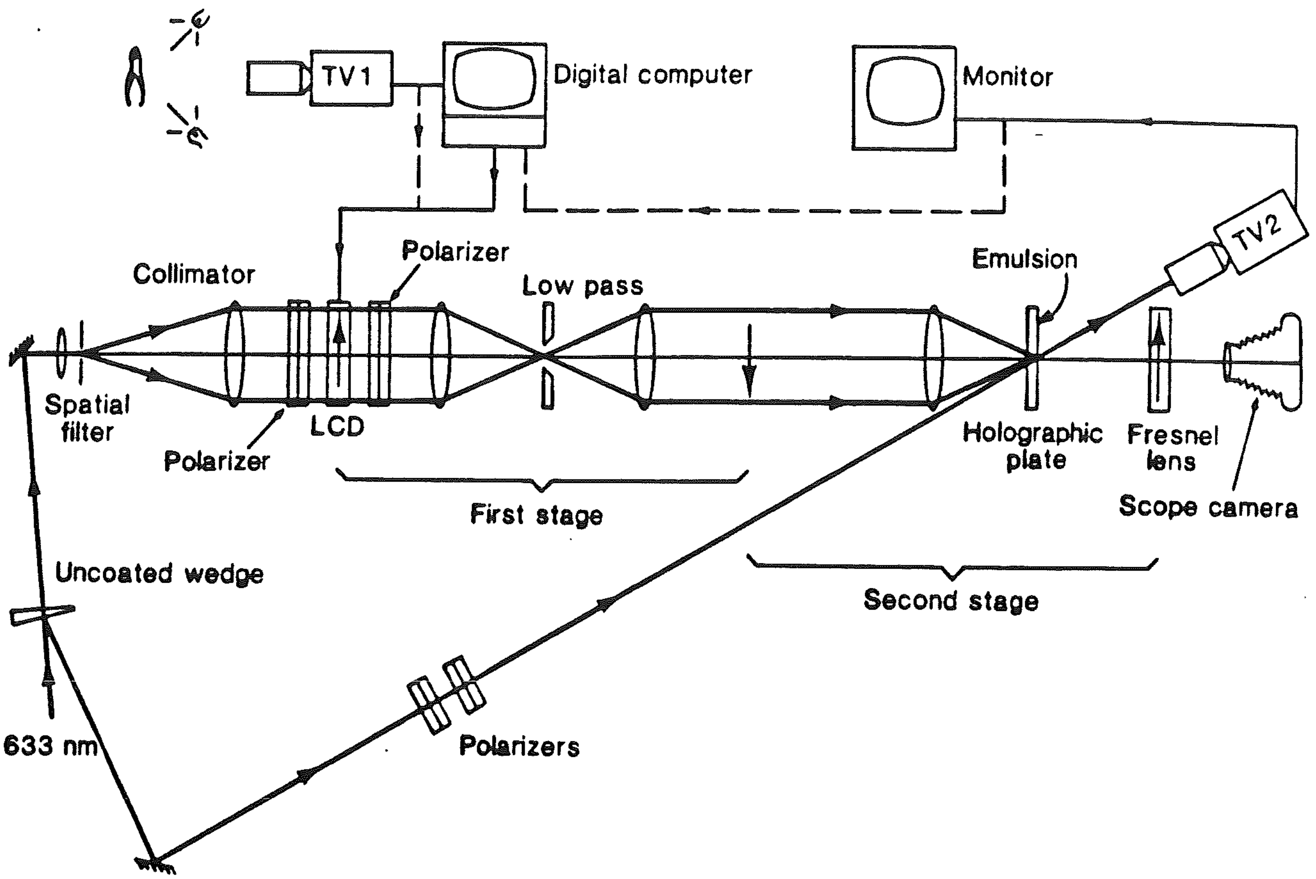


Figure 1. Hybrid processor consisting of a two-stage Fourier optical system that includes a liquid crystal, or LCD, TV monitor as input. A digital computer with a frame digitizer addresses the LCD monitor and a matched filter is recorded on the photographic plate. Camera TV2 displays the cross-correlation functions on a monitor or, alternatively, connects to the frame digitizer, as shown by the dashed line. The three Fourier transform lenses have 250-mm focal length, f/5.6.

40-μm pinhole, collimated with a 360-mm lens, and directed into the two-stage processor. This system consists of a conventional 4-f processor followed by a single-lens processor in which the image is magnified slightly for ease of photographing. The lenses in the processor are all 210-mm copy or enlarging lenses. A Fresnel lens is inserted into the final image plane to serve as a field lens.

We located the LCD monitor in the object plane of the first stage. To optimize the system's performance, we peeled the polarizers from the screen and used external polarizers. We enclosed both the polarizers and the screen in liquid gates by contacting them on both sides to optical glass flats with an index matching oil. The oil has had no effect on the electrical performance of the monitor.

The monitor is addressed by a microcomputer with a video frame digitizing board. To evaluate the performance of the monitor, we generated some patterns, such as that shown in Fig. 2. This pattern is radially symmetric and runs linearly from black in the center to white at the edge, or, in terms of the frame digitizer, from 0 at the center to 255 at the edge. (We used this pattern because the monitor gave unpredictable results with uniform gray or with a gray scale whose gradient was either vertical or horizontal. We attribute this to a defect in the video analog-to-digital (A-to-D) converter, but we do not know whether or not it is just an idiosyncrasy of our sample. A newer model seems to give somewhat better results in this regard.) After optimizing the polarizers and the monitor's brightness control and A-to-D converters, we used a silicon detector to scan along a diameter of the radial transmittance pattern. The result is shown as Fig. 3A. The monitor has an overall contrast ratio of only 10 to 1 and cannot respond to the full dynamic range of the TV camera or frame digitizer. We attribute the low contrast in part to the presence of the wires; these mainly add unwanted light to the nominally black areas, probably because of diffraction or some perturbation of the liquid crystals.

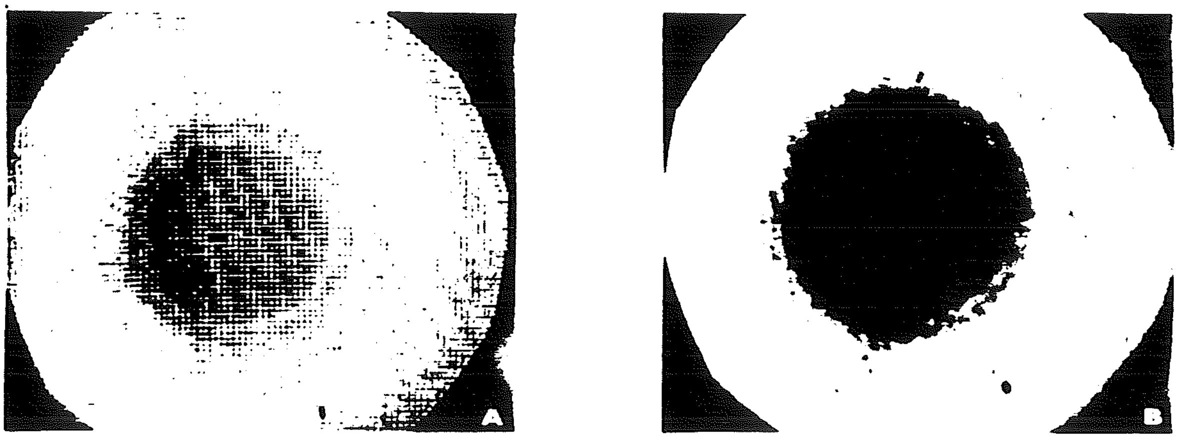


Figure 2. Radial transmittance function displayed on the LCD monitor, A, before low pass filtering, B, after low pass filtering. Contrast ratio of B is 5 times that of A.

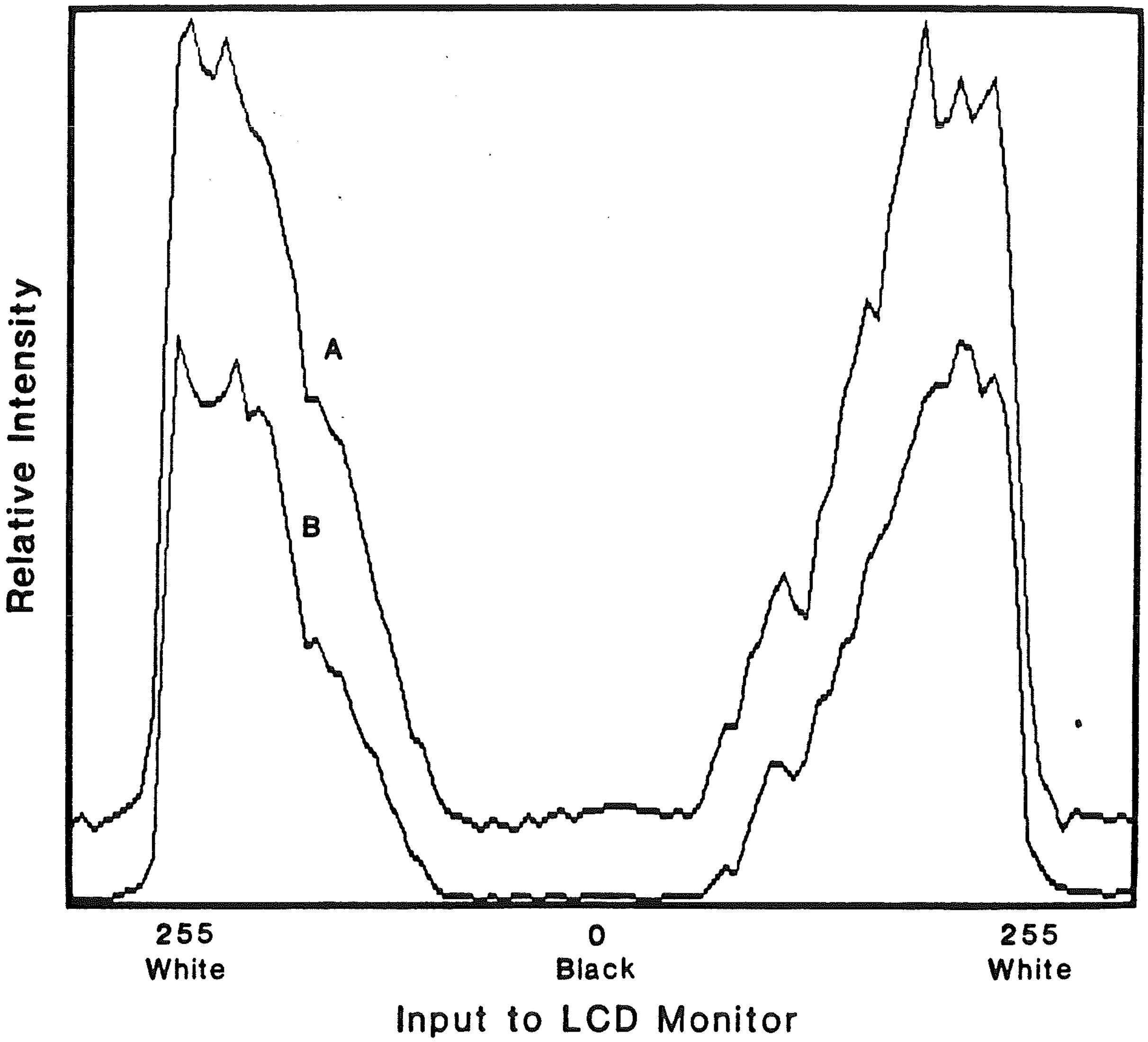


Figure 3. Transmittance as a function of position along a diameter of each of the screens shown in Fig. 2. Horizontal scale is the output of the frame digitizer on a range from 0 (black) to 255 (white).

When we located a 0.4-mm low pass filter in the transform plane of the first stage, we thereby eliminated the wire grid from the image (Fig. 2B) and measured a contrast ratio (Fig. 3B) of about 50 to 1. The monitor, however, still does not respond to the full dynamic range of the incoming TV signal, as is shown by the flat portions of the curve near the center and the edges of the display. These signify a relative lack of both shadow and highlight detail; adjusting the brightness or the video A-to-D converter level simply shifts the sloped portions of the curve horizontally toward or away from the center of the graph.

To complete the system, we located a holographic plate in the transform plane of the second stage and introduced the reference beam through a pair of polarizers for intensity control. (The reference beam angle of about 15° was determined by the size of the transform lens.) For these experiments, we did not collimate the reference beam, so it had a waist at the location of the laser, about 2 m from the hologram. This may reduce the position invariance of the system, but we did not check for position invariance.

Experiment

For our experiment, we illuminated a pair of pliers diffusely with two incandescent lamps and white, matte paper diffusers. Using a TV camera fitted with a zoom lens, we captured and stored an image of the pliers with the computer and the frame digitizer. The image displayed on the LCD monitor is shown in Fig. 4A prior to low pass filtering with the optical system. Figure 4B shows the same image after spatially filtering with the 0.4-mm aperture to eliminate the wire grid. When the low pass filter is chosen properly, only the grid is eliminated from the picture; there is no loss of resolution of the image itself.

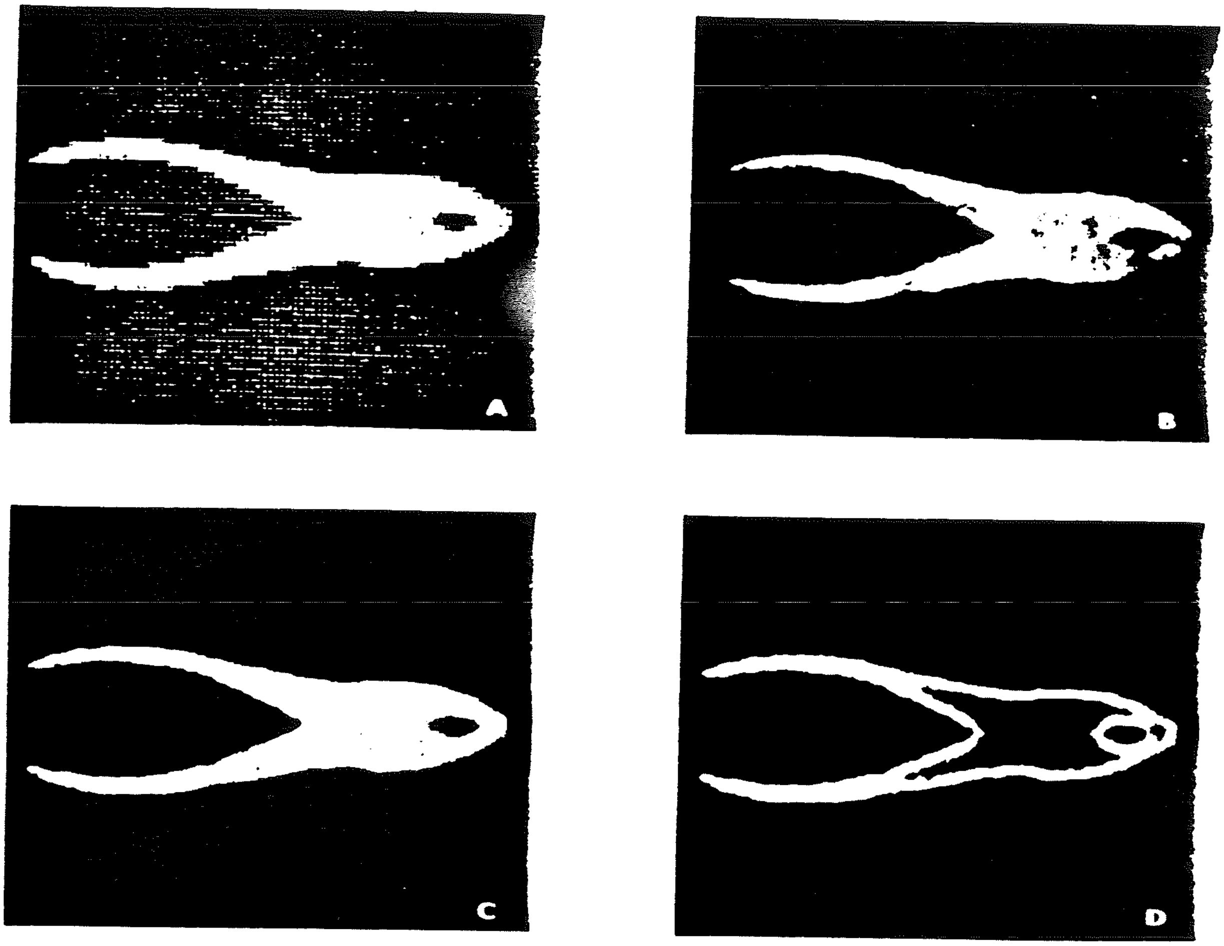
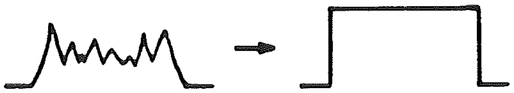


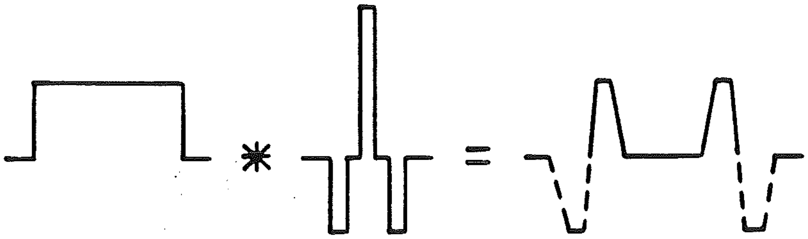
Figure 4. Pair of pliers used as a subject for pattern recognition experiment and displayed on the LCD monitor. A, image of the pliers themselves. B, low pass filtered to remove the pixels on the LCD screen. C, binary image of the pliers, wherein values below a threshold are set equal to 0 and values above that threshold are set equal to 255. D, edge enhanced model of the pliers.

Next we used the computer to prepare a clipped, or binary, image of the pliers, Fig. 4C, where intensities above a certain level are set equal to 255 (white) and those below that level are set equal to 0 (black). In the one dimensional analogy,



(1)

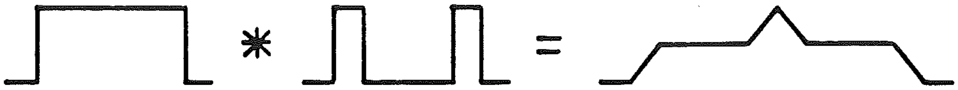
Next, we performed a two dimensional edge enhancement in which we retained only the inside edge of the binary image; that is, the image is black except for a white region that runs along the inside edge of the binary image. Symbolically,



(2)

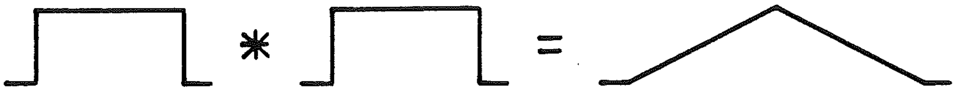
where the asterisk (*) denotes cross correlation and values less than zero are interpreted as zero. We refer to the resulting image as the model; it is shown in Fig. 4D. The width of the enhanced edge is determined by the number of zeros between the peaks of the kernel of the cross correlation integral. We chose this width to be two pixels on the LCD monitor; this corresponds to about six pixels on a conventional monitor with the full resolution of about 380 pixels.

We used the model, somewhat in the manner of references 8 and 9, as the object in a pattern recognition experiment. We inserted a holographic plate in the second transform plane and recorded a Fourier transform hologram of the model. The value of using the model, rather than the object itself, is that the cross correlation function of the model and the object,



(3)

is, with an irregular two dimensional object, sharper than the autocorrelation function of the object itself,



(4)

and permits greater discrimination against similar objects. In addition, the model is located on a black background, and its Fourier transform has a relatively weak dc or zero-order component. As a result, the exposure of the photographic plate is comparatively uniform and allows a hologram to be recorded with roughly constant diffraction efficiency for all relevant spatial frequencies.

Results

Placing the emulsion side away from the transform lens, we exposed some Fourier transform holograms to serve as matched filters for the model. We processed some of them in a potassium ferricyanide bleach (15 mg/mL for 4 min). These may be expected to have a diffraction efficiency perhaps 10 times that of amplitude transmission holograms and are much more tolerant of variations of exposure.[10] Our best filter was just such a phase hologram.

Using a second TV camera denoted TV2 and shown in Fig. 1, we viewed the autocorrelation function of the model on a monitor. Because the image is mostly black, we switched the camera's automatic gain control off to avoid overexposing the autocorrelation spot. The AGC was left off during all the observations that follow. We did not need to synchronize the camera TV2 to the computer, evidently because the decay time of the LCD panel was longer than the frame rate of 1/60 s.

Figure 5A shows a photograph of the central portion of the monitor. The spot is sharp and has a width of about six TV lines; this agrees well with the expected value of two pixels on the lower resolution LCD monitor. The spot can also be seen clearly with the eye and is surrounded by a diffraction ring that does not appear in the photograph.

Next, we displayed the clipped image of the object on the LCD monitor, without moving the apparatus or adjusting either TV2 or the brightness of the monitor. The resulting cross correlation function is shown in Fig. 5B. We then switched to real time and displayed the real object on the LCD monitor. The relative brightness of the object was substantially less than the 255, or white, of the computer processed images. The cross correlation with

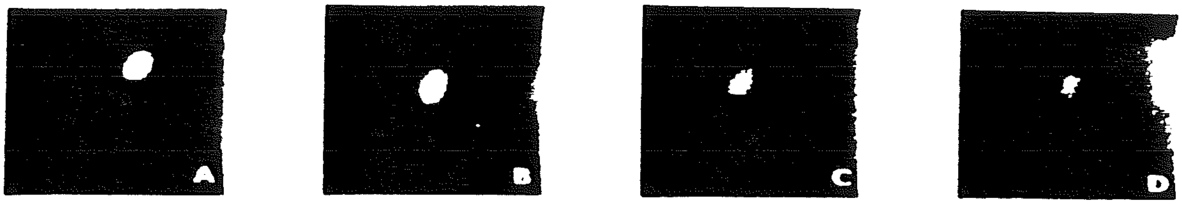


Figure 5. Correlation functions as seen by TV2 displayed on a monitor. A, autocorrelation function of the model. B-D, cross correlation function of the model with (B) clipped tool, (C) tool in real time, and (D) tool rotated 2°. All photographs were taken with the same exposure.

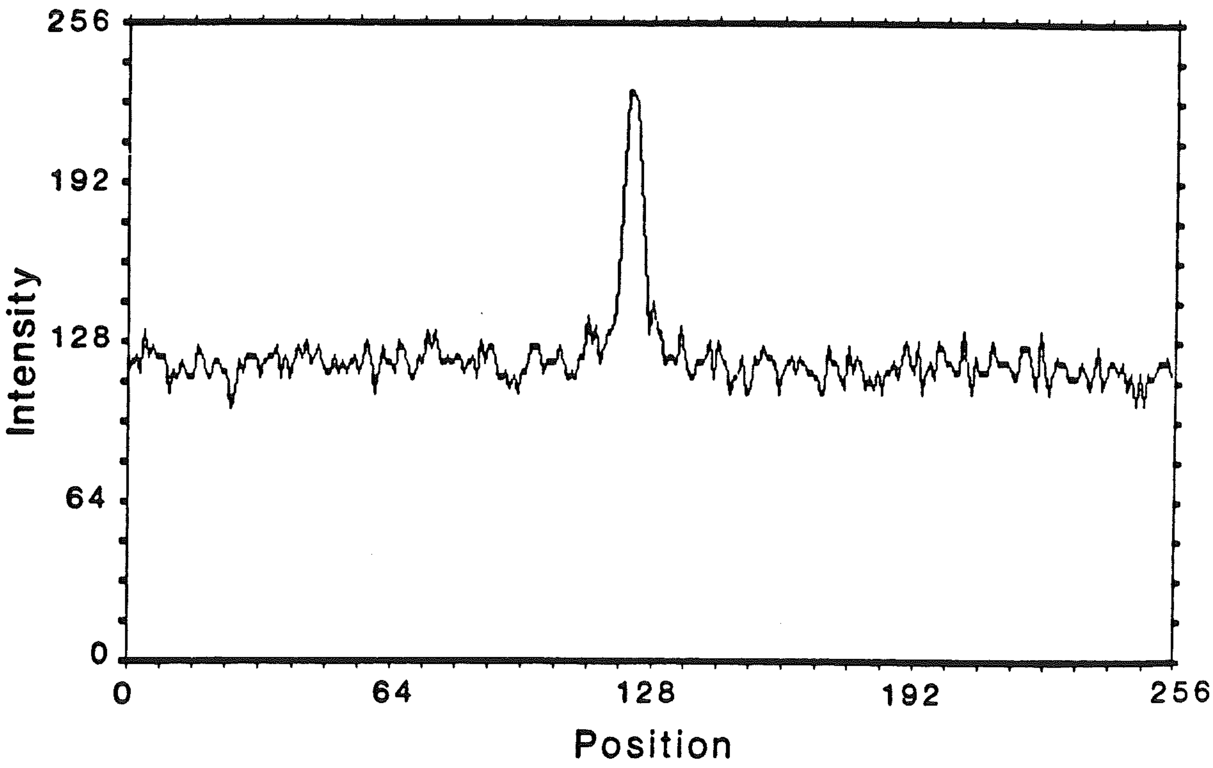


Figure 6. Intensity as a function of position along a horizontal TV line through the center of the cross correlation peak of Fig. 5C. Average of four frames.

the model was weaker but plainly visible on the monitor (Fig. 5C). Finally, we rotated the object 2°. The cross correlation function in this case was still visible and is shown in Fig. 5D.

We then switched the camera, TV2, to the computer and digitized its output. We could not record the autocorrelation function of the model, because that would have required two frame digitizers; indeed, this is one of the reasons that we designed our experiment to examine the cross correlation of the unprocessed object, rather than a processed image, with the model.

We have made no attempt to optimize the diffraction efficiency of the hologram. What was plainly visible on the monitor was not so plain to the computer; the eye does a marvelous job of smoothing and averaging. We therefore digitized four frames and averaged them. Figure 6 is a graph of the relative intensity across one horizontal line in the averaged picture, multiplied by 3 for clarity of display. The constant value of about 115 is simply dark current from the TV camera.

Figure 7 shows a histogram of the entire screen (of which Fig. 6 is a single line). (All values greater than zero are shown as small ticks, whether or not they properly round to zero.) The highest value, 228, represents the cross correlation peak. The average value of the dark current is about 118, and the dark noise fluctuations range from roughly 104 to 132. If we take this to be ±3 sigma, we estimate the signal-to-noise ratio (SNR) to be approximately 24.

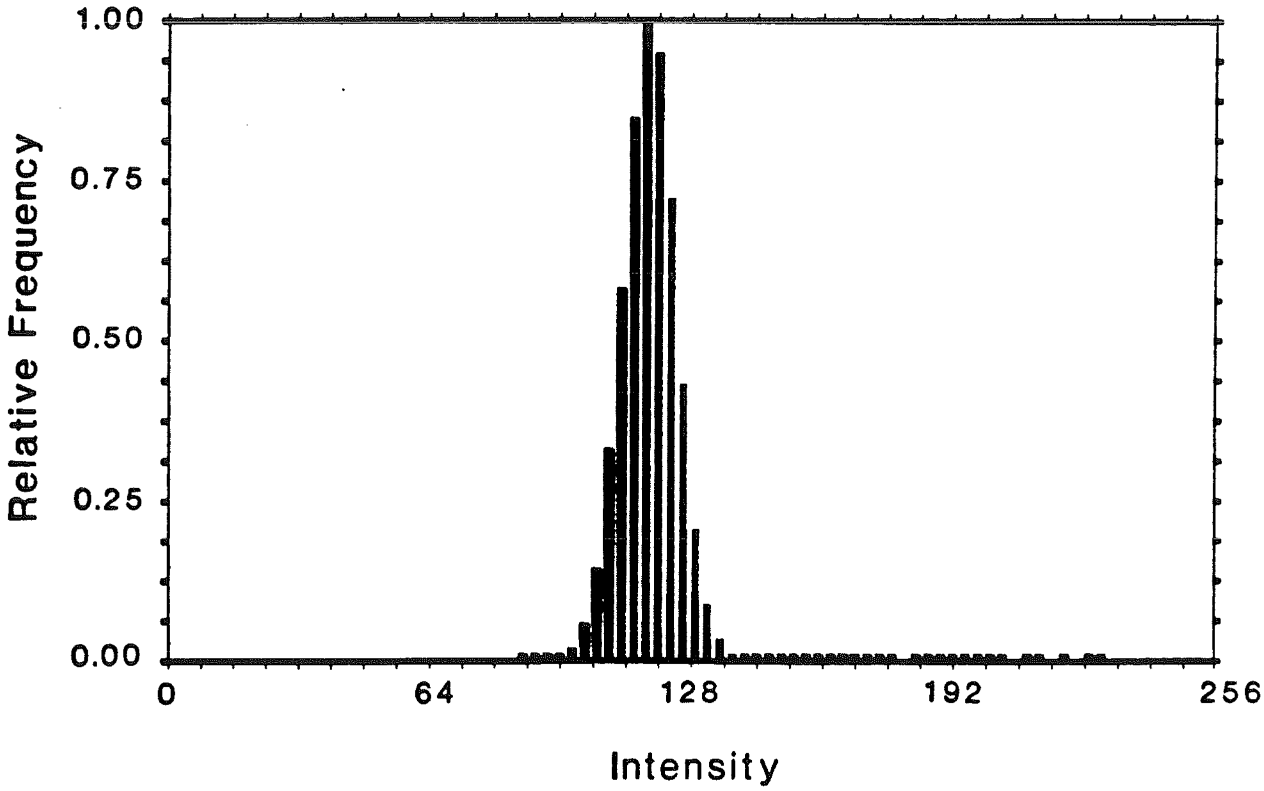


Figure 7. Histogram of the entire screen from which Fig. 6 is derived. The signal peak is 228, the noise average 118, and ±3 sigma about 28. The signal-to-noise ratio is about 24.

Discussion

We have used a digital computer to generate an edge enhanced (but non-negative) model of a tool, prepared a Fourier transform hologram of the model, and cross correlated the model in real time with an image of the original tool.

We might have achieved better discrimination if we had either edge enhanced the tool in real time (as in reference 8) or edge enhanced with positive and negative values (as in reference 9). For practical reasons, we did neither. The latter, in particular, would have required an encoding scheme that required a space-bandwidth product greater than the LCD monitor offered and would not have achieved significantly different results unless we had used the equivalent of heterodyne detection. We could have achieved a similar result by edge enhancing optically (with a bandpass filter in the first transform plane); this achieves a phase shift in the electric field at the location of an edge (as is shown by the presence of a zero of intensity at the edge[11]). We chose, however, to edge enhance by computer since we thought that this would be more readily controllable and result in a simpler, singly peaked intensity distribution at the edge.

Finally, we have performed our experiment using coherent processing. This is far more efficient than incoherent processing, which requires diffused illumination, and has allowed us to use a small He-Ne laser rather than the much higher power argon laser used in references 8 and 9. Except for the limited space-bandwidth product offered by the LCD monitor, most other considerations are about equal, and the use of the small and inexpensive He-Ne laser may therefore militate in favor of coherent processing for this sort of pattern recognition.

Acknowledgments

Matt Weppner is also with the Electrical Engineering Department, University of Colorado, Boulder, Colorado. We are indebted to Edie DeWeese for her excellent manuscript preparation and to Chuck Petersen of EPIX, Inc. for his help with image processing algorithms. Contribution of the National Bureau of Standards, not subject to copyright.

References

1. Young, M., "Low-Cost LCD Video Display for Optical Processing," Appl. Opt., Vol. 25, pp. 1024-1026. 1986.
2. Gregory, D. A., "Real-time Pattern Recognition Using a Modified Liquid Crystal Television in a Coherent Optical Correlator," Appl. Opt., Vol. 25, pp. 467-469. 1986.
3. McEwan, J. A., Fisher, A. D., Rolsma, P. B., and Lee, J. N., "Optical-Processing Characteristics of a Low-Cost Liquid-Crystal Display Device," J. Opt. Soc. Am. A, Vol. 2, No. 13, p. P8. 1985. Abstract only.
4. Liu, H.-K., Davis, J. A., and Lilly, R. A., "Optical-Data-Processing Properties of a Liquid-Crystal Television Spatial Light Modulator," Opt. Lett., Vol. 10, pp. 635-637. 1985.
5. Tai, A. M., "Low-Cost LCD Spatial Light Modulator with High Optical Quality," Appl. Opt., Vol. 25, pp. 1380-1382. 1986.
6. Watkins, L. S., "Inspection of Integrated Circuit Photomasks with Intensity Spatial Filters," Proc. IEEE, Vol. 57, pp. 1634-1639. 1969.
7. Radio Shack Catalog Number 16-151. The use of trade names is intended to specify experimental procedure precisely and does not imply endorsement by the National Bureau of Standards. Other manufacturers' products may work as well or better.
8. Sherman, R. C., Grieser, D., Gamble, F. T., Verber, C. M., and Dolash, T., "Hybrid Incoherent Pattern Recognition System," Appl. Opt., Vol. 22, pp. 3579-3582. 1983.
9. Katzir, Y., Young, M., and Glaser, I., "Pattern Recognition Using Incoherent OTF Synthesis and Edge Enhancement," Appl. Opt. Vol. 24, pp. 863-867. 1985.
10. Young, M. and Kittredge, F. H., "Amplitude and Phase Holograms Exposed on Agfa-Gevaert 10E75 Plates," Appl. Opt., Vol. 8, pp. 2353-2354. 1969.
11. Young, M., "Linewidth Measurement by High-Pass Filtering: A New Look," Appl. Opt., Vol. 22, pp. 2022-2025. 1983.