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ACOUSTO-OPTIC/CCD IMAGE PROCESSOR

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ABSTRACT

Optical image correlators are presented that use acousto-optic and charge-coupled devices as the input and output transducers respectively. Experimental results are presented and the applicability to pattern recognition of a non-linear pseudo-correlation that can also be conveniently computed with these processors, is discussed.

INTRODUCTION

Image processing is perhaps the most natural application of optical information processing because the two dimensions of the optical system and its parallel processing capability are very effectively utilized in this application. The potential of optical image processors however, can only be realized in practice if suitable transducers are available to bring the images into the optical processor with sufficient speed and accuracy and also transducers (detectors) to read-out the processed images. In recent years the development of Acousto-Optic Devices (AOD) and semiconductor detector arrays and light sources, has led to the development of high performance optical processors [1,2]. In this paper we discuss how acousto-optic devices and CCD detectors can be used for optical image correlation. The acousto-optic device is used as the input transducer in the optical processor and it receives the image to be processed in the form of a video electronic signal. The CCD is used as the optical detector in the system and simultaneously as an array of electro-optic correlators. The advantages that can be derived from the use of these relatively mature technologies in the implementation of an optical 2-D correlator are high speed, flexibility, accuracy, small physical size and power efficiency.

In the following section we discuss the general method for performing image correlation with an acousto-optic processor. In section III we review the holographic implementation of such a processor and the experimental results of this implementations are included in section IV.

GENERAL CONCEPT

The correlation $g(\xi,\eta)$ of an input image $f(x,y)$ and a reference image $h(x,y)$ is given by:

$$g(\xi,\eta) = \iint f(x,y)\, h(x+\xi,\, y+\eta)\,dx\,dy. \qquad (1)$$

We are concerned here with the implementation of this operation with an optical system in which the input image $f(x,y)$ is introduced through an AOD. AOD's are 1-D spatial light modulators with a linear space bandwidth product typically equal to 10^3 pixels. The size of the images that we like to be able to process optically is at least $10^3 \times 10^3$ pixels. Therefore, it is clear that an AOD cannot be used to simultaneously modulate a light beam with an entire image. Typically, a single line of the image can be accommodated by the AOD at one time. This fact dictates our processing strategy: the input image is entered into the optical processor and processed one line at a time. The processed image lines are detected and accumulated on a 2-D CCD camera [2]. The image $f(x,y)$ must be sampled in one of its dimensions (in our notation the y-dimension) so that its lines can be applied sequentially to the AOD. In practice this is accomplished by detecting $f(x,y)$ with a raster scanning TV camera. Since the correlation $g(\xi,\eta)$ will be computed from the samples of $f(x,y)$ we replace the integration over the continuous variable y in Eq. (1) by a summation:

$$g(\xi,\eta) = \sum_{n}^{N} \int f(x,n\Delta y)\, h\,(x+\xi, n\Delta y+\eta)\, dx \quad . \qquad (2)$$

Δy is the sampling interval in the y direction and if it is chosen to be at the Nyquist rate (assuming f is bandlimited) the correlation g computed via Eq. (2) does not differ from the continuous correlation. N is the number of lines in $f(x,y)$. We can write the shift in the η direction by $n\Delta y$ in the above equation as a

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convolution with a delta function $\delta(\eta+n\Delta y)$ and derive the following form for the correlation $g(\xi,\eta)$:

$$g(\xi,\eta) = \sum_{n}^{N} \int \left[\int f(x,n\Delta y)\ h\ (x+\xi,\eta')dx \right] \delta(\eta'-\eta-n\Delta y)d\eta' . \qquad (3)$$

This form of the correlation function determines directly the implementation algorithm of the acousto-optic image correlator. The term in the brackets in Eq. (3) is the 1-D correlation in the x direction of the nth line of the input image with all the lines of the reference. Several optical implementations of such a multi-channel 1-D correlator are possible. The term in the brackets in Eq. (3) is a function of two variables ξ and η', and it must be shifted in the η' direction by the distance $n\Delta y$. In other words the 1-D correlations of the first line of the input are shifted by 1 pixel in the η' direction, while the correlations of the Nth line are shifted by N pixels. This can be accomplished in an optical system in one of two ways. An optical scanner can be used after the multi-channel correlator to deflect the light by the appropriate distance for each input line. Alternatively (and in most cases preferably) a CCD camera can be used to detect the 1-D correlations and then shift the detected signal by transferring the charge on the CCD. The full 2-D correlation $g(\xi,\eta)$ is formed by accumulating (summing over n) the shifted 1-D correlation on the time integrating detector array. The operations that must be performed to implement this algorithm optically are summarized in the block diagram of Figure 1.

HOLOGRAPHIC IMPLEMENTATION

We will describe this implementation [3] with the aid of Figure 2. The input pattern is detected by the TV camera. The horizontal sync of the camera is locked to a stable oscillator which acts as the master clock for the entire processor. Each pulse from this oscillator triggers the TV camera to produce an electronic signal corresponding to one of the lines in the input pattern. The video signal is heterodyned to the center frequency of the AOD and after amplification it is applied to the piezoelectric transducer of the AOD. At the end of each horizontal scan by the TV camera, the acoustic wave in the AOD is spatially modulated by the corresponding line of the input pattern. The clock from the master oscillator is delayed by the duration of one raster line and it triggers the pulsed laser that is used as the source in this processor. The duration of the light pulses is made shorter than the inverse of the bandwidth of the video signal. As a result the light diffracted by the AOD each time the laser is pulsed is spatially modulated by one of the lines of the input pattern. The diffracted light enters an astigmatic lens system which expands and collimates the light in the vertical direction. In the horizontal direction the light is Fourier transformed. A 1-D Fourier transform hologram of the reference image $h(x,y)$ in our notation is placed in the Fourier plane of this astigmatic lens system. The hologram contains the reference image transformed in the x direction only. Since the light illuminating the hologram is collimated vertically, the light diffracted by the hologram is modulated by the product of the transform of the current line from the input pattern and all the lines of the reference image. A second

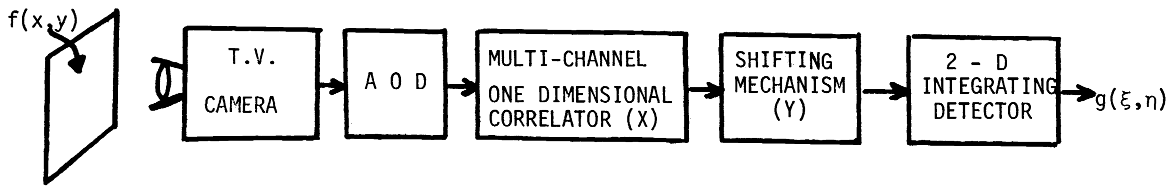


Figure 1. Block diagram of the acousto-optic implementation of the image correlator

A variety of specific optical implementations are possible using this algorithm and the trade-offs involved do not make one of the implementations clearly superior to the rest for all applications. In this paper we discuss a holographic implementation that shares all the characteristics of the algorithm

depicted in Figure 1: the input image is entered in the optical system via the TV camera and the acousto-optic device; a multi-channel 1-D correlator processes each line of the input image and a 2-D time integrating detector is used to accumulate the 1-D correlations and form the full 2-D correlation.

astigmatic lens system is placed after the hologram. The light is now imaged in the vertical direction and transformed again in the horizontal direction. The transform of the product of the transforms produces the correlation (or convolution if desired) between one of the input lines and all the lines of the reference image. The imaging that is performed in the vertical direction causes these 1-D correlations to appear stacked in the vertical direction at the output plane of the optical system. Returning momentarily to Eq. (3), the operation that has been performed up to this point in the processor is the 1-D integral of Eq. (3). A 2-D CCD detector is placed at the output plane of the processor. The photogenerated

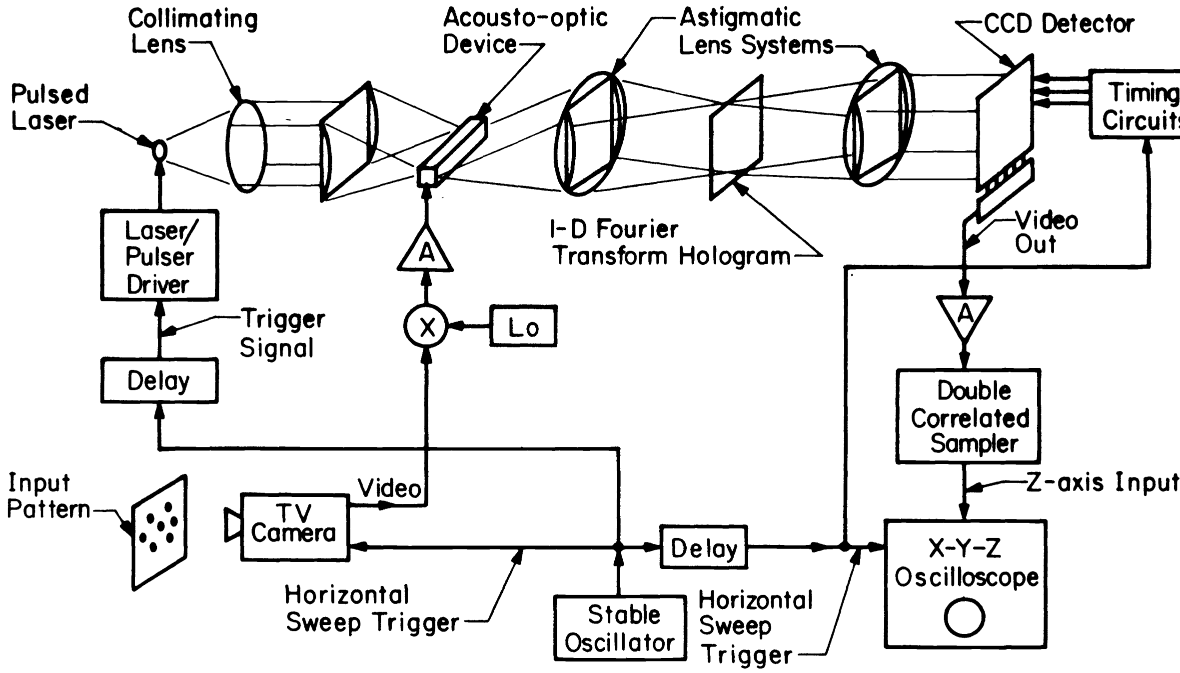


Figure 2. Acousto-optic/CCD image correlator.

2-D charge pattern that is stored in the CCD after it is exposed to the light from each laser pulse, is shifted vertically by one pixel. If we trace the location on the CCD of the charge generated during the nth light pulse we find that after the Nth pulse occurs, it has travelled N-n pixels in the vertical direction. To obtain the 2-D correlation we must (according to Eq. (3)) shift the nth line by n pixels. Since N is fixed (it is the total number of lines in the input pattern) the CCD does perform the appropriate shifting and the entire 2-D correlation forms (shifted by N pixels) after integration on the CCD (the summation over n in Eq. 3) of the light incident on it from N light pulses. The correlation output is read-out continuously by the CCD in the form of a video signal which can be displayed or processed further electronically.

In this processor the 1-D correlations that are formed at the output of the optical system modulate the amplitude of the light. This optical wave must be interferometrically detected in order to obtain a detected signal proportional to the field amplitude rather than its intensity. The interferometric detection method [4] and experimental demonstration of it [5] have been discussed elsewhere. In this paper we wish to concentrate on the 2-D operation that is being performed by the processor of Figure 2, when interferometric detection is not used. In this instance the pattern $g'(\xi,\eta)$ formed on the CCD is given by the following expression [4]:

$$g'(\xi,\eta) = \sum_{n=1}^{N} \left| \int f(x,n\Delta y)\, h\,(x+\xi,\ n\Delta y+\eta)dx \right|^2 \quad (4)$$

The function $g'(\xi,\eta)$ is similar to the correlation in form, with the important exception that the 1-D correlations in the x-direction are squared before the summation in the second dimension is performed. This operation is clearly non-linear but it is shift invariant. Since $g'(\xi,\eta)$ can be very conveniently calculated with the acousto-optic image processor, we investigated its properties to determine its possible utility for pattern recognition. Using the Schwarz inequality it can be shown that

$$g'\,(\xi,\eta) \leq \sum_{n} \left| \int |\, f(x,n\Delta y)\,|^2\, dx\, \right|^2 = G' \quad (5)$$

and the equality holds only for $g'(\xi,\eta) = G'$. This result is significant because it indicates that $g'(\xi,\eta)$ is maximized when the input and the reference images are matched and aligned spatially. Therefore it could be used to recognized patterns. We must however consider the performance of a pattern recognition system based on this operation, when noise is present. A full analysis of this case is beyond the scope of this paper, but we will point out several important facts. First, the signal-to-noise ratio analysis that is typically performed to determine the performance of pattern recognition algorithms that are based on correlation is not appropriate in the nonlinear case. The non-linearity in g' results in noise components at the output that are not normally distributed and therefore the underlying distribution becomes important in the determination of the probabilities of detection and misclassification. Furthermore, patterns that belong to different classes but correlate well (and therefore are likely to be misclassified by a linear correlation algorithm) can be well separated by the non-linear correlation, and vice-versa. For instance, if

$$G = \sum_n \int | f(x,n\Delta y) |^2 \, dx \quad , \qquad (6)$$

is the value of the autocorrelation peak of the image f, we denote by αG the peak value of the crosscorrelation between f and a second image h(x,y) not belonging to the same class as f. α is a constant satisfying $-1<\alpha<1$. The non-linear crosscorrelation of the same two functions is denoted by $\beta G'$, where G' is defined in Eq. (5) and β is a constant satisfying $0<\beta<1$. It can be shown [6] that given α, β is in the range $\alpha^2<\beta<1$ or $\alpha^2<\beta<\alpha$ if the images involved are real and positive. Clearly β can be smaller than α, which intuitively indicates that if this is the case two patterns can be separated more effectively with the non-linear correlation g'. More formally, we calculate the probability of false alarm (the probability of classifying h(x,y) as belonging to the class represented by f(x,y)) as a function of the parameter β for the non-linear correlation case. This function is plotted in Figure 3 for an input SNR=1, assuming a linear processing gain of 10^4, a value of α = .7 and for a fixed probability of detection P_D = .96. On the same diagram the probability of false alarm that we obtain under the same conditions using linear correlator is indicated. We note that in

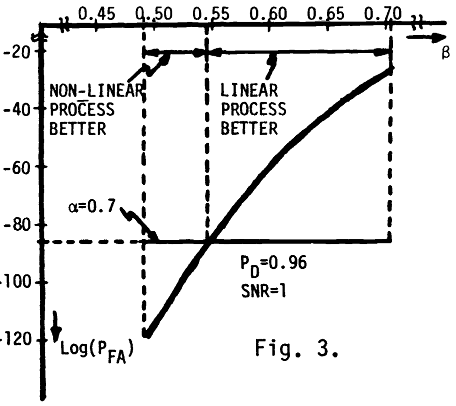


Fig. 3.

Figure 3 there is a very low probability of false alarms for both cases (this is a somewhat superfluous case since α is relatively low and the SNR is high) but we can also see that the probability of false alarm can be smaller for the non-linear correlator. Of course it can also be higher depending on the value of β. β is determined by the images f and h and therefore we conclude from this exercise that a recognition algorithm based on non-linear correlation can out-perform the linear correlator for a certain class of images. In general, the non-linear correlation can provide adequate performance for a large class of pattern recognition applications. A complete statistical characterization of the non-linear correlation will be presented in a future publication.

EXPERIMENTAL PROCESSOR

A photograph of the experimental acousto-optic/CCD image correlator is shown in Figure 4. The apparatus is a hardware implementation of the system shown in Figure 3. The light source used in this experiment is a pulsed laser diode with 50 nsec pulse width. The inverse of the pulse width (1/50 nsec = 20 MHz) must be at least twice the video bandwidth, therefore video signals with up to 10 MHz bandwidth can be processed with the system. The peak power of this laser can be as high as 9w, resulting in an average light power of approximately 10 mW which is adequate for detection by the CCD. A custom fabricated acousto-optic device was the input electronic-to-optical transducer. This device is a shear acoustic wave TeO_2 Bragg cell, with 30 MHz 1dB bandwidth at 820 nm (the laser wavelength), in excess of 400%/watt diffraction efficiency and most significantly, the acoustic delay of the device is 70 µsec. The long acoustic delay is required in this processor so that we can accommodate an entire standard video line (63 µsec). The light diffracted by the AOD is demagnified by a factor of approximately 4 with two spherical lenses, in order to match the size of the video lines from the AOD (4 cm) with the size of the transparencies used to fabricate the hologram (1 cm). The demagnified Schlieren image of the AOD is reflected towards the hologram and Fourier transformed. The hologram was formed from a transparency recorded on a high speed holographic plate (to avoid the phase distortion introduced by the plastic substrate of film) with a HeNe laser. The components that are used for recording the hologram are visible in the far end of the optical bench in Figure 4. The holograms are recorded on dichromated gelatin to obtain high diffraction efficiency. We obtain in excess of 20% efficiency with the dichromated gelatin holograms at 820 nm. The light diffracted by the hologram is reflected towards the CCD, imaged vertically and transformed horizontially. The CCD used in the experiment is a commercially available (Fairchild) 1-D device oriented vertically. Special timing and driving electronic circuits were built to operate the device in the time-delay-and-integrate (TDI) mode necessary for this processor. The 1-D array produces slices of the 2-D correlation surface in the η direction, for a fixed ξ value. The slices

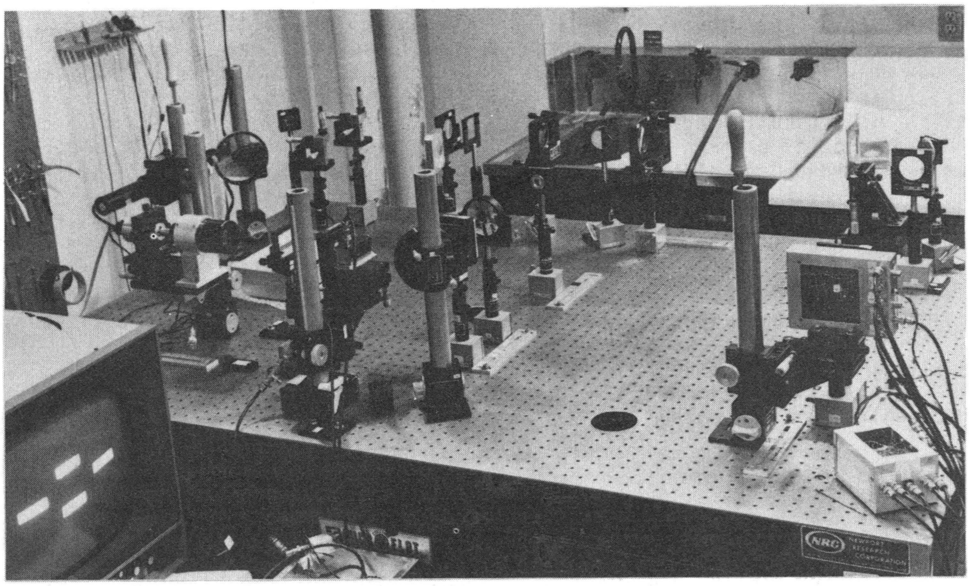
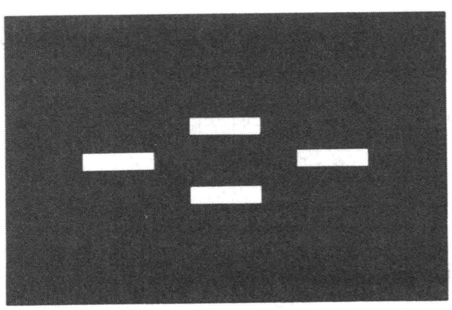
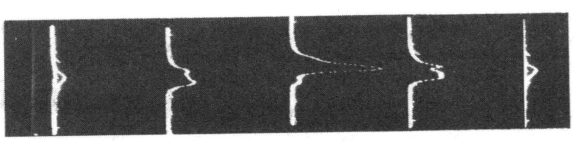


Figure 4. Experimental Acousto-optic/CCD image correlator.

for different ξ values can be observed by translating the CCD horizontally. A 1-D CCD was chosen for this initial experiment, rather than a 2-D CCD which can produce the entire 2-D correlation simultaneously, because its output can be easily monitored on an oscilloscope which has allowed us to easily align and calibrate the system. The input pattern (shown in Figure 5a) was detected by a high resolution TV camera (not shown in Figure 4). The output signal from the CCD for 5 horizontal positions is shown in Figure 5b. This composite photograph is the 2-D autocorrelation of the pattern in Figure 5a computed by the system in Figure 4. Interferometric detection was not used in these experiments, therefore the non-linear correlation described by Eq. 4 is obtained. The pattern in Figure 5a is in good agreement with the autocorrelation expected from the simple pattern in Figure 5a. We attribute the asymmetries noticeable in Figure 5b to non-linearities and phase distortion in the hologram.



(a)



(b)

Fig. 5(a). Input Pattern (b) Optically Computed Auto-Correlation

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