AIR FORCE RESEARCH IN OPTICAL PROCESSING

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SUMMARY

The Air Force is actively supporting scientific research in optical processing through the awarding of contracts and grants to university and industrial research laboratories. The emphasis is on optical and optical-electronic hybrid processing especially in the application area of image processing. A special interest exists in real-time pattern recognition processors for such airborne missions as target recognition, tracking, and terminal guidance. This paper will describe the areas of interest and the ongoing efforts in the Air Force research program.

INTRODUCTION

The history of computer technology indicates quite clearly that with the development of every new computer of larger capacity and faster speed the number of problem solving areas which would be benefitted increases and multiplies. During the past twenty years, the progress in solid state electronic computers has been extremely rapid, to the point that computers influence almost every aspect of our lives. Even though continuing progress in electronic computer technology can be anticipated, we would be remiss to overlook other techniques which show promise of complementing or even replacing the presently prevalent silicon LSI wafer. One promising alternative is provided by optics, including electro-optics and acousto-optics. And certainly not to be overlooked is the area of hybrid optical-analog/electronic-digital processing. Optical systems offer parallel computations with speeds unattainable with present digital computer technology, and the hybrid systems combine this speed and data handling capability with the computational flexibility and accuracy of digital processing. The development of efficient hybrid processors along with continued advancements in pattern recognition and computer-aided decision making will provide us with critical technology needed to maintain our world leadership in computing and signal processing capability.

One of the most promising application areas for this emerging technology is image processing. Imaging sensors are becoming an increasingly important part of such military systems as reconnaisance, missile guidance, target identification and tracking, and space surveillance. Sensors of the future are expected to provide high resolution images at frame rates which will produce data in excess of

10^{11} bits per second--a rate that digital technology will be hard pressed to handle even under the most optimistic projections. A major goal of the Air Force research in optical processing is to increase the flexibility of these processors to the extent that they can perform the functions of most of the image processing algorithms which have pushed digital technology to its limit.

I will discuss the Air Force research interests in terms of the following five categories: pattern recognition, image encoding, incoherent image processing, integrated optics and acousto-optics, and hybrid opto-electronic processing. The first three categories will receive the majority of attention since they deal with image processing.

PATTERN RECOGNITION

The basic type of optical pattern recognition system is the frequency plane correlator or matched filter shown in figure 1. The reference or target information is stored in the processor as the complex conjugate of the Fourier transform. If the target information is present in the input, a peak of light will appear in the output plane, and the location of the peak in this plane will correspond to the relative location of the target in the input scene. Figure 2 illustrates the optical correlator in a more operational scenario in which a real-time input device is employed in the input plane and a large array of potential target filters are stored in the frequency plane. The input device, known as a real-time spatial light modulator, functions as an incoherent-to-coherent image transducer. One such modulator concept currently being investigated (ref 1) is shown in figure 3, and consists of a photocathode, a micro-channel array plate, and an electro-optic plate. The electro-optic plate carries a high resistivity dielectric mirror on one side and a transparent conducting electrode on the other. The input signal illuminates the photocathode which produces an electron image of the optical intensity. The image is then amplified by the microchannel plate and deposited on the dielectric mirror. This charge distribution establishes a corresponding spatially varying refractive index in the electro-optic crystal which is capable of modulating a readout laser beam. Successful operation of this device has been achieved, and current research efforts are aimed at improving its operation so as to meet the original performance goals of 20 line pairs/millimeter spatial resolution, 1 KHz framing rate, an optical quality of less than one tenth wavelength distortion of the wavefront over a 25 millimeter diameter, a sensitivity of one nanojoule per square centimeter, and a long-term optical information storage capability on the order of weeks. Using a new internal processing mode, based on secondary electron emission, the research is proceeding to show that the device is capable of performing level thresholding, contrast reversal, contrast enchancement, image addition, and image subtraction.

A high-accuracy terminal guidance sensor system will consist of an acquisition subsystem that scans the scene in the target area, a reference subsystem containing a photographic or equivalent image of the target and its surround, and a processing subsystem that correlates the real-time scene with the reference image and generates error signals to vector the warhead onto the target. The fundamental difficulty in achieving a practical terminal guidance system lies in correlation of the reference image with a real-time image that differs in scale, aspect, contrast, and even content when sensed in a different spectral band or at a different time than the reference image. In addition to reliability and accuracy of correlation, the processor must be rapid to permit a reasonable guidance error signal bandwidth for fast target approaches. The resulting requirement is for a processing subsystem with throughput rates in excess of 10^7 operations per second, and optical correlation with its vast parallelness at low power and cost is a most promising technology.

Various optical processing approaches to missile guidance are being compared on the basis of input resolution, grey scale requirements, quantity of stored reference imagery needed, cycle times required, accuracy expected, processing needed, etc. The major emphasis has been on finding a processor or correlator architecture that is capable of maintaining correlation in the presence of various image degradations that invariably occur between the input and reference function during terminal guidance. Among the differences that have been considered are: scale, rotation, resolution, contrast, relief, data dropout, aspect, seasonal, years apart, and headings. Techniques are being studied for optimizing matched spatial filter synthesis parameters to improve the signal-to-noise ratio; however, these techniques often accentuate the high frequency detail of the image, thus rendering the correlation more susceptible to image differenes between input and reference. Therefore, space variant processing techniques are also being investigated to realize optimum correlation systems invariant to the dominant degradations. For example, the realization of a rotation-invariant correlation system can be obtained by performing a polar transform on the input and reference imagery. The magnitude of the correlation peak remains unchanged while the location of the peak translates proportional to the rotational difference between the two images. It has been shown that a multiple-invariant, space-variant optical processor is possible in which two functions described by any number of separate distortion parameters can be correlated with no loss in the signal-to-noise ratio of the correlation (ref 2). Other correlation procedures are also being investigated such as optical homomorphic filtering, optical statistical pattern recognition, an optical analog of the invariant moment method, and a hyperspace expansion and clustering technique.

Besides research into improved light modulation and novel filtering schemes for pattern recognition systems, the Air Force has an interest in holographic optical element (HOE) research. HOEs offer advantages of a reduction in the mechanical stability problems of conventional optical systems, a reduction in the number of optical elements, and a reduction in weight, size, and cost, all of which render these elements very applicable to optical systems for aircraft and missiles. The current state of the art in HOEs is limited to transfer function representation of linear, space-invariant optical systems. Unfortunately, such systems represent just a small fraction of the optical systems of interest. For example, only imaging systems with unit magnification are strictly space-invariant. For a space-variant system the impulse response is a function of the position of the impulse or point source of light in the input plane of the system. This means that in order to completely specify the impulse response, the response must be known for impulses located at all possible points in the input plane. Investigations are curently pursuing a sampling theorem-based technique for characterizing 2-D space-variant optical systems. The holograms representing the various impulse responses are multiplexed using a technique which encodes the phase of each reference beam with various diffusers. Another approach being studied involves computer multiplexing of the individual holograms. The research goals include not only a clear understanding of the basic theoretical and practical limitations of these approaches but also the discovery of additional multiplexing techniques (ref 3).

The final area of research interest under pattern recognition deals with the nonlinear processing of imagery. This opens up a whole new realm of possibilities to optical processing. For example, a basic tool in pattern recognition is the histogram which may be synthesized from a succession of intensity level slices such as shown in figure 4. Ideally, a level slice operation converts a continuous tone image into a pattern which represents only those points or areas of the input image which have a given intensity level. Figure 4 shows two non-ideal slices but ones which are sufficient to construct a histogram. The histogram would be constructed from the level slices for all possible input intensity intervals. Note, however, that the transfer function (I_{out} versus I_{in}) is a nonlinear operation. Three different approaches to nonlinear optical processing are currently being pursued: pulse-width modulation employing halftone hard-clipping and coherent filtering, direct use of light modulator nonlinear characteristics, and conversion of input intensities to spatial frequencies by employing the variable grating mode of liquid crystals. In the first approach, an input signal or image with continuous levels is converted into a halftone image that is binary. This halftone image consists of a periodic array of black dots whose sizes vary spatially according to the spatial variation of intensity in the input. This is accomplished by optically adding a halftone screen and the input image and then hard-clipping the resulting image. Nonmonotonic nonlinearities are obtained by employing various Fourier plane filters with an appropriate halftone screen design. The specific nonlinearity will depend on the halftone dot shape and on which diffraction order is passed by the filter.

The second approach is directed toward achieving nonlinearities by relying directly on nonlinear characteristics of electro-optical devices such as real-time spatial light modulators. For example, certain of these devices depend on an electro-optically controlled birefringence to produce a selective linear differential phase retardation along two axes of a crystal. Upon placing the crystal between crossed polarizers, a sinusoidal variation of intensity transmittance with voltage is obtained which can be the basis for many optically controlled nonlinear functions. One such function which has been demonstrated is three-bit optical parallel A/D conversion with a bit rate potential estimated at 1.2×10^8 points processed per second (ref 4).

The third approach, the variable grating mode technique, is based on the fact that under certain conditions a linear, phase grating structure can be established in a liquid crystal, and the period of this grating can be changed by varying an externally applied voltage as illustrated by figure 5. By employing a photoconductor in connection with the liquid crystal, it should be possible to have a grating frequency whose spatial variations correspond to the intensity variations of an image projected onto the photoconductor (ref 5). If the resulting encoded image is input to an optical spatial filtering system (figure 6), the various spatial frequency components would be diffracted to different locations in the frequency plane and could be filtered to produce an output with any desired nonlinear relationship to the input image intensities.

IMAGE ENCODING

With an increased interest in image type operations on behalf of the military comes an increased interest in image transmission. Remotely piloted vehicles and battlefield surveillance are two military operations where image communications will likely play a prominent role. Two definite problems encountered in any long distance transmission of analog image information are limited bandwidth and atmospheric scattering. With regard to the bandwidth problem, real-time image compression schemes are needed. The most severe limitation on existing schemes is the extensive computational burden, a problem for which optics may indeed be able to provide a solution. Research has successfully formulated a modified differential pulse code modulation (DPCM) technique which is suitable for incoherent optical implementation. Referred to as interpolated DPCM, or IDPCM, the technique employs a mask to spatially sample the image. These samples are then quantized and transmitted. In addition, the sampled image is interpolated by a low-pass convolution and a different image is generated by subtracting this interpolated image from the original. This difference image is also sampled, quantized, and transmitted. At the receiver, the image samples are interpolated to form a low-frequency version, and the difference-image samples are added to the interpolator output to reconstruct the original. A simulation of this technique has shown the validity of employing optical processing for bandwidth compression. Efforts are continuing toward expanding optical compression schemes into the realms of interframe and adaptive compression (ref 6).

Another approach being pursued is to employ optical transformation of the image followed by a delta modulation of the transformation. Two analog transform encoding schemes are being considered: one is a coherent optical Fourier transformation while the other is an incoherent optical Hadamard transformation. Real-time linear and adaptive delta modulators operate on the video signal obtained via a TV camera in the output plane of the optical system (ref 7). With regard to the Hadamard system, the image is broken up into a large number of sub-images by a fly's-eye lens, and each sub-image is weighted by a Hadamard mask.

The second problem area, that of atmospheric scattering, may be solvable by employing some novel encoding process such as intensity-to-frequency conversion. This involves using a wavelength-coded source to illuminate the object so that each resolution element (pixel) is illuminated with a different wavelength, thus realizing a spatial-to-spectral conversion of the object information. At the receiver, the collected light is decoded by a spectroscope which displays the various wavelengths at the proper spatial positions so as to reconstruct the original image. Since scattered light does not undergo any wavelength shift, the information on each of the spectral carriers is free to travel any path, either direct or multiply scattered, between the transmitter and the receiver. It may even be possible to use such a technique to transmit three-dimensional images (ref 8).

INCOHERENT IMAGE PROCESSING

Since the discovery of the laser in the early 1960's, coherent optical processing has advanced steadily toward developing an information processing capability with speed-of-light performance. Two major difficulties of coherent processing which have prevented a more rapid advancement are the nonavailability of suitable spatial light modulators and a relatively low dynamic range. Incoherent processing, of course, does not need the incoherent-to-coherent conversion step which the spatial light modulators perform for coherent processors. Furthermore, incoherent processing avoids the problem of coherent noise or speckle which often masks the effects of the desired image processing operation. By lessening the coherence of the system, one is, in effect, increasing the number of information bearing channels, all of which are carrying the same information in parallel. The major result of this redundancy is an increase in the signal to noise ratio. On the other hand, incoherent processing is not without problems, such as a built-up of dc-bias.

Overcoming the problems of incoherent processing, or at least significantly reducing their impact, is the goal of Air Force research in this area. If the fundamental problems can be solved, the ultimate objective will be to realize all optical processing operations with incoherent systems. Not only do incoherent processors offer a significant reduction in cost over coherent systems, but the mechanical alignment problems are much less severe, and this may be a very important point if optical processors are ever to find their way into airborne information systems.

Optical processors use interference to process information; however, with incoherent light, interference is much more difficult to achieve. Consider the formation of a Fourier transform hologram. If the required reference beam does not pass through the Fourier transforming lens, its optical path will not exactly match the object beam path and there will be no interference. But if the reference beam does pass through the lens, it will be Fourier transformed into a point image and will not be able to uniformly cover the object beam. This problem is being investigated using a technique involving a chirp-z transform. This method achieves a Fourier transform in a way basically different from the usual way, which is to place the object on the input side of a lens and take the output from the back focal plane. In the chirp-z method, a zone plate lens overlays the object, producing a compound object. The light then passes through a spatial filtering system consisting of two lenses and a spatial filter, and the resulting output is a Fourier transform. By making the Fourier transform in this manner, the previously noted problem can be avoided and it becomes possible to insert the entire optical system into a three-grating achromatic interferometer. Thus, after achromatizing the Fourier transformation process and introducing, by means of the interferometer, an achromatic coherent reference beam, it becomes possible to produce Fourier transform holograms in completely white light (ref 9).

Another effort is working more directly on conceiving an incoherent matched filter correlator (ref 10). The concept demonstrated to date employs a color-compensating grating which collects correlation-signal energy over a band of wavelengths, which has been dispersed by the matched filter, and concentrates it in a single spot to achieve a much improved S/N for the correlation peak. However, correlator operation still suffers from the very narrow spectral response of the matched filter itself. Various combinations of zone plates and gratings will be tried in an effort to overcome this deficiency and create achromatic systems capable of performing the operations of Fourier optics in white light.

A third approach to incoherent optical processing, while not as universal or flexible as the previous two techniques, has the advantage of being relatively simple to implement. A diffraction grating is employed in the input plane of the optical processor to effect a sinusoidal modulation of the input signal. This results in two off-axis spectral distributions in the Fourier plane of the processor, and these distributions will be dispersed into rainbow color due to the use of incoherent light. The origins of the differently colored signal spectra will be linearly dispersed in a direction perpendicular to the grating. A complex spatial filter for each of a discrete set of wavelengths will be placed in the spatial-frequency plane to produce a set of mutually incoherent filtered signals. The output of this incoherent filtering scheme will be formed by the incoherent addition of the discrete spectral bands (ref 11).

INTEGRATED OPTICS AND ACOUSTO-OPTICS

Spurred on by the tremendous impact that electronic integrated circuits have had, the field of integrated optics has already progressed to the point where complete circuits are being attempted. Such basic elements as optical modulators, coherent light sources, lenses with near diffraction-limited performance, and optical detectors have been demonstrated and may now be combined on a single substrate to perform some practical signal processing operations. In an effort to further expand these processing operations, the Air Force is interested in supporting research that will advance the current state-of-the-art, especially in achieving more compatibility between electronic and optical integrated systems. Much research is still needed in the areas of programmable filters, more simplistic lenses, broader band surface acoustic waves for acousto-optic processors, and higher processing gains.

Investigations are being conducted into Fresnel diffraction in an attempt to fabricate efficient and inexpensive waveguide lenses for integrated optical systems. Current lenses are either geodesic or Luneburg; however, geodesic lenses involve an expensive and time-consuming precision grinding process while Luneberg lenses have very limited focusing capabilities in high index-of-refraction waveguides because of the small change of the effective index that can be obtained from known materials. Fresnel lenses have the potential to outperform both the geodesic and Luneburg lenses. They consist of pads deposited on the waveguide which act to achieve either phase shift or absorption in alternate half-period zones (ref 12).

A recent accomplishment in the area of programmable filtering was the demonstration of a 32-bit, 17 Mbit/sec digital correlator as shown in figure 7. The reference signal is programmed into an array of interdigital electrode sets fabricated on a thin buffer layer on the surface of a planar electro-optic waveguide. The input signal is encoded as one of two possible frequencies of a surface acoustic wave (SAW). If a perfect match exists between the input and reference signals, the optical energy which is first diffracted by the SAW is diffracted a second time by the electro-optic grating produced by the interdigital electrode sets and is focused onto the detector. If a match does not exist, such as the case in the figure, some of the energy is diffracted to another point in space and does not reach the detector (ref 13).

There will always be some loss and degradation due to scattering in coupling light from a lithium niobate waveguide to a detector array formed on silicon whether or not channel waveguides are present. Also, accurate alignment of two structures will always be required. These aspects could be eliminated if layers of single crystal silicon could be grown on lithium niobate. Such growth by conventional epitaxy is not possible. However, based on recent experimental results involving laser-assisted growth of single crystal silicon layers on amorphous substrates and formation of MOS devices on these layers, it may be possible to form silicon photodetector arrays on lithium niobate (ref 14).

Acousto-optics offers a potential for unique integrated optical signal processing devices which, in part, is due to the huge difference between acoustic and electromagnetic propagation velocities. Currently under study are several novel thin-film acousto-optic and magneto-optic devices with applications to wideband multi-channel information processing, high-speed deflection and switching of a guided light beam, optical time-division multiplexing/de-multiplexing, and tunable optical filtering (ref 15).

HYBRID OPTO-ELECTRONIC PROCESSING

Many physical problems, especially in simulation and control, require the real-time solutions to 2D and 3D partial differential equations. Under investigation is a hybrid optical-electronic computer capable of high speed solutions of such equations. The speed and versatility of the hybrid computer will enable it to handle a wide variety of complex problems. It will be especially useful in applications requiring partial differential equations to be solved many times while initial conditions, coefficients, nonlinearities, and nonhomogeneous terms are varied. A confocal Fabry-Perot interferometer forms the basis of the optical portion of the computer which performs the Fourier transformations, the spatial filtering, and the feedback (ref 16).

The digital processor operates in an analysis mode with regard to a digitized version of the optical output and acts as a controller for the mirror position and the laser beam scanner which produces the input image and the spatial filters in real time. The feedback configuration allows the optical system to achieve a filtering dynamic range of approximately twenty times that of a more conventional system without feedback. However, even better performance is now being sought through the addition of gain to the system. By offsetting system losses, even modest amounts of gain incorporated into the Fabry-Perot can lead to dramatic increases in filtering dynamic range. Furthermore, sufficient gain would allow the system to operate as an optical operational amplifier. The technique being investigated involves flashlamp-pumped dye lasing. The dye amplifier is placed within the Fabry-Perot and used to offset losses by coherently amplifying a He-Ne signal. In actuality, a two-stage injection-locked dye laser/dye amplifier arrangement is employed to aid in preserving signal frequency and relative phase which is so important in the feedback system.

The Air Force is not interested at this time in supporting investigations into optical logic or digital computing, but rather those areas in which optics can best complement electronic processing. One such area would be where massive parallelism is desirable to perform computationally intensive operations as, for example, in matrix inversion or eigenvector decomposition. Requirements for matrix inversion, such as solutions of simultaneous equations and various signal filtering operations, have established a need for a fast parallel computational method. The problem of real-time eigenvector and eigenvalue determination from a given matrix is also important in practice. Such operations play a role in pattern recognition. Another area which strongly complements electronic processing is the use of optics in VLSI interchip and intrachip communications. Optics may offer a technique for overcoming a fundamental limitation to device density—that of being able to further reduce the spacing between interconnects without appreciably increasing interference. The practical problems of using optics can be separated into two categories: getting suitable optical sources and detectors onto a chip, and realizing suitable holographic optical elements.

REFERENCES

1. C. Warde, A.D. Fisher, J.I. Thackara, and A.M. Weiss, "Image Processing Operations Achievable with the Microchannel Spatial Light Modulator," SPIE Vol. 252- Smart Sensors II, 25-32 (1980).

2. D. Casasent and D. Psaltis, "Multiple-Invariant Space - Variant Optical Processors," Applied Optics 17, 655-659 (1978).

3. R. Kasturi, T. Krile, and J.F. Walkup, "Multiplex Holography for Space-Variant Processing: A Transfer Function Sampling Approach," Applied Optics 20, 881-6 (1981).

4. A. Armand, A.A. Sawchuk, T.C. Strand, D. Boswell, and B.H. Soffer, "Real-Time Parallel Optical Analog-to-Digital Conversion, "Optics Letters 5 (No. 3), 129-31 (1980).

5. B.H. Soffer, D. Boswell, A.M. Lackner, A.R. Tanguay, T.C. Strand, and

A.A. Sawchuk, "Variable Grating Mode Liquid Crystal Device for Optical Processing," SPIE Vol. 218 - Devices and Systems for Optical Signal Processing, 81-7 (1980).

6. B.R. Hunt and S.D. Cabrera, "Optical Computations for a Spatially Adaptive Image Data Compression System," Optical Engineering 20 (No. 4), 616-20 (1981).

7. G. Eichmann, R. Mammone, R. Stirbl, and J. Keybl, "Hybrid Image Source Encoding for Real-Time Image Transmission," SPIE Vol. 154, 204-9 (1978).

8. S.K. Case, "Wavelength Coding for Image Transmission Through Aberrating Media," Optics Letters 6 (No. 7), 311-3 (1981).

9. E.N. Leith and G.J. Swanson, "Achromatic Interferometers for White Light Optical Processing and Holography," Applied Optics 19 (No. 4), 638-44 (1980).

10. G.M. Morris and N. George, "Matched Filtering Using Band-Limited Illumination," Optics Letters 5 (No. 5), 202-4 (1980).

11. G. Gerhart, P.H. Ruterbusch, and F.T.S. Yu, "Color Encoding of Holographic Interferometric Fringe Patterns with White Light Processing," Applied Optics 20 (No. 17), 3085-8 (1981).

12. W.S.C. Chang and P.R. Ashley, "Fresnel Lenses in Optical Waveguides," IEEE Journal of Quantum Electronics QE-16 (No. 7), 744-54 (1980).

13. C.M. Verber, R.P. Kenan, and J.R. Busch, "Correlator Based on an Integrated Optical Spatial Light Modulator," Applied Optics 20 (No. 9), 1626-9 (1981).

14. J.T. Boyd, S. Dutta, H.E. Jackson, and A. Naumaan, "Reduction of the Effects of Scattering by Laser Annealing of Optical Waveguides and by Use of Integrated Waveguide Detection," SPIE Vol. 269 - Integrated Optics, 125-8 (1981).

15. C.S. Tsai, "Guided-Wave Acousto-Optics - Fundamentals and Wideband Applications," SPIE Vol. 139 - Guided Wave Optical Systems and Devices, 132-8 (1978).

16. J. Cederquist and S.H. Lee, "Confocal Feedback Systems with Space Variance, Time Sampling, and Secondary Feedback Loops," Journal of the Optical Society of America 71 (No. 6), 643-50 (1981).

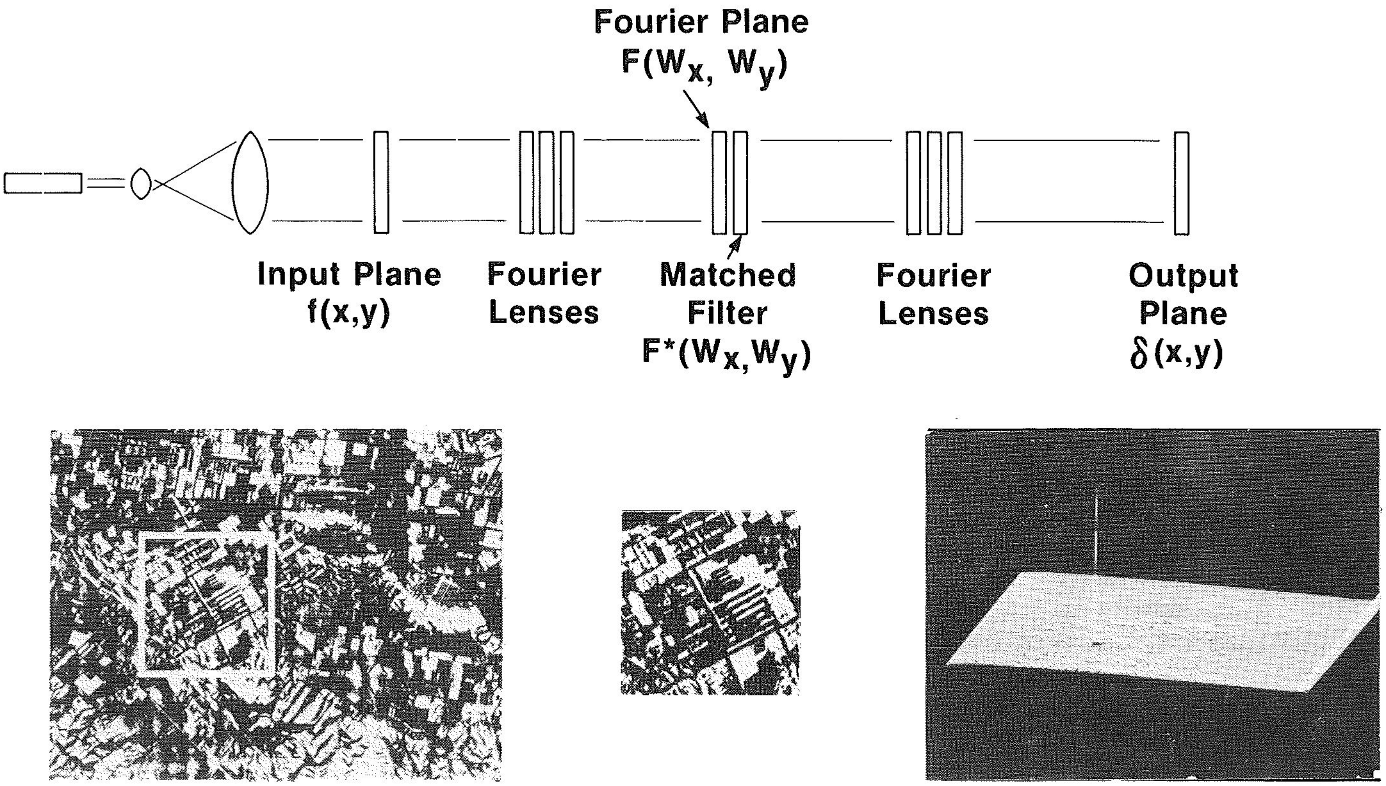


Figure 1.- Optical matched filter for real-time scene matching with output shown as a computer-generated plot of light intensity.

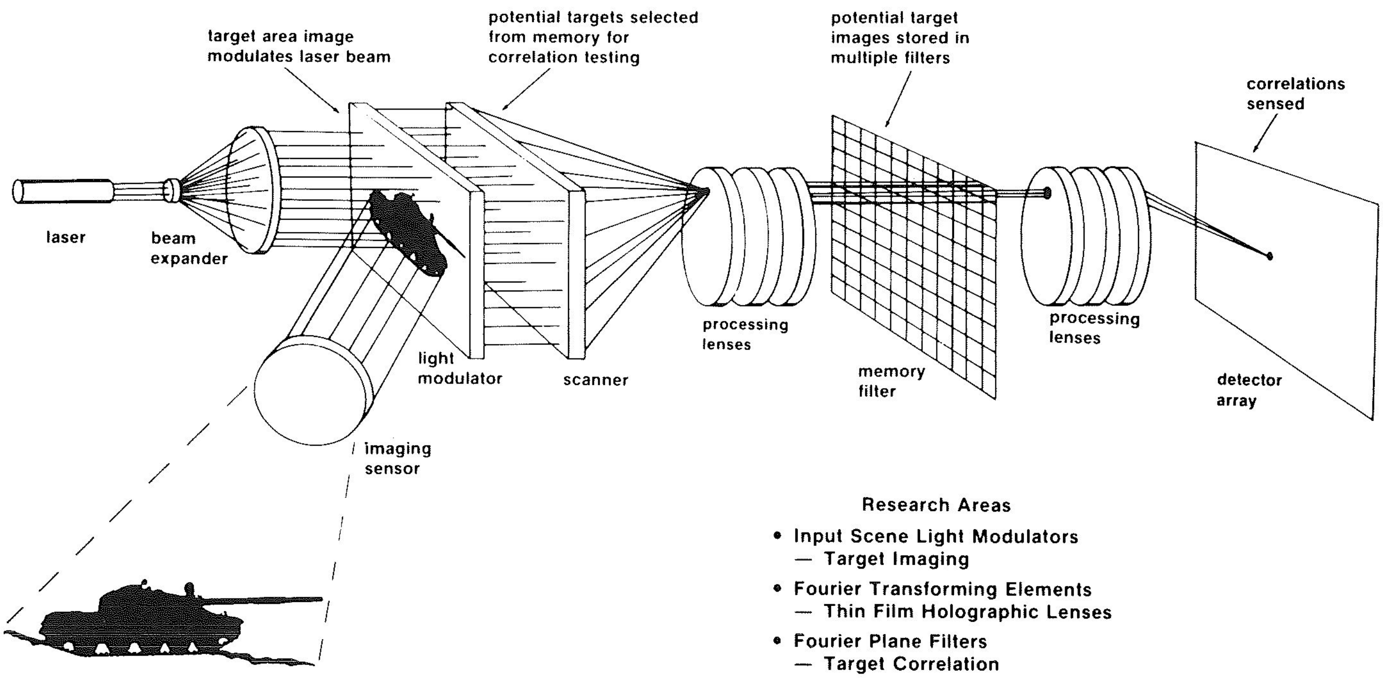


Figure 2.- Optical matched filter used in pattern recognition mode.

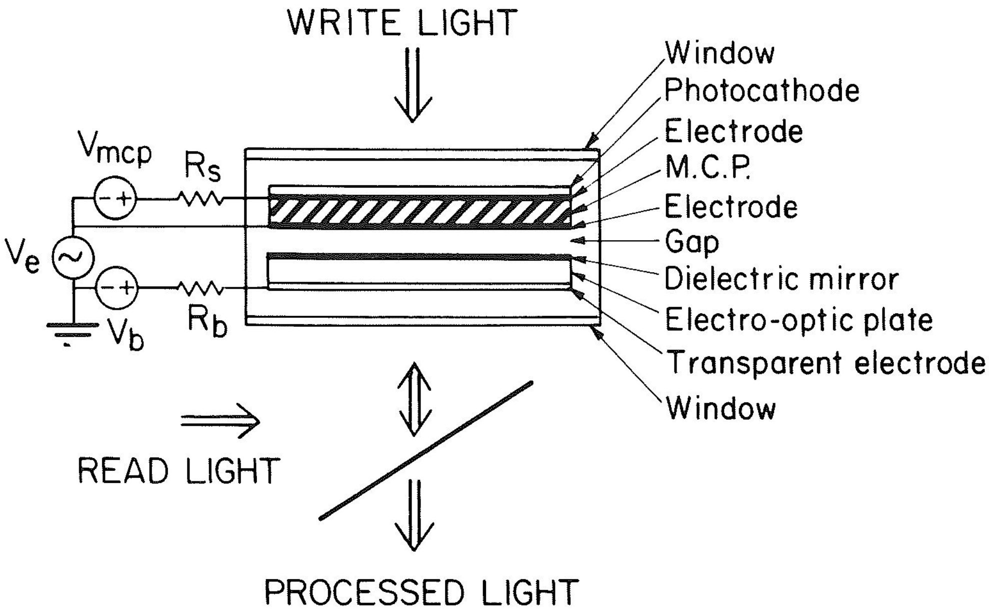


Figure 3.- Microchannel spatial light modulator.

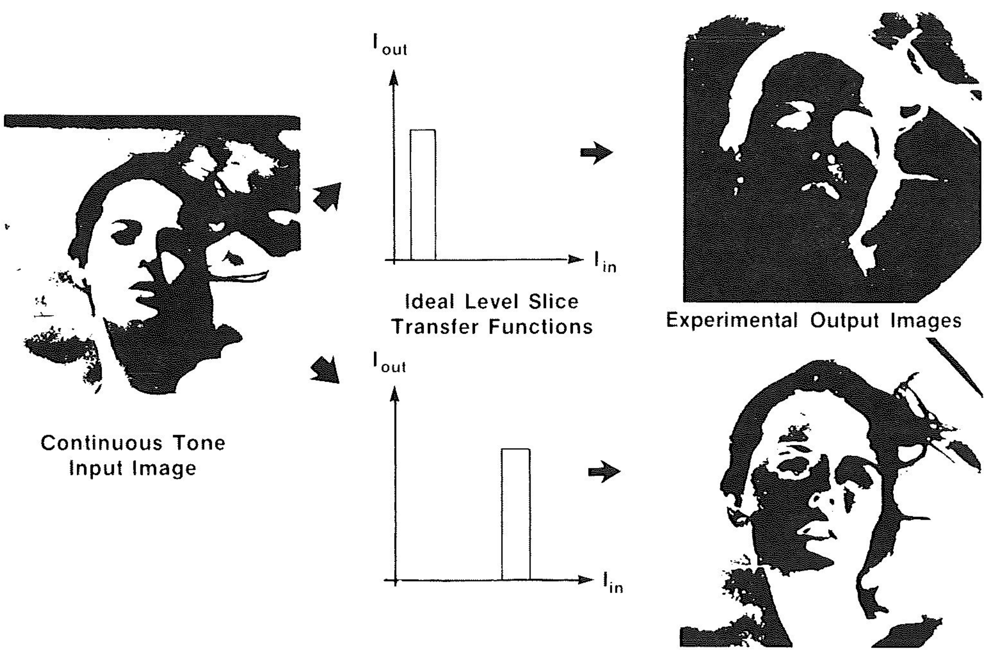
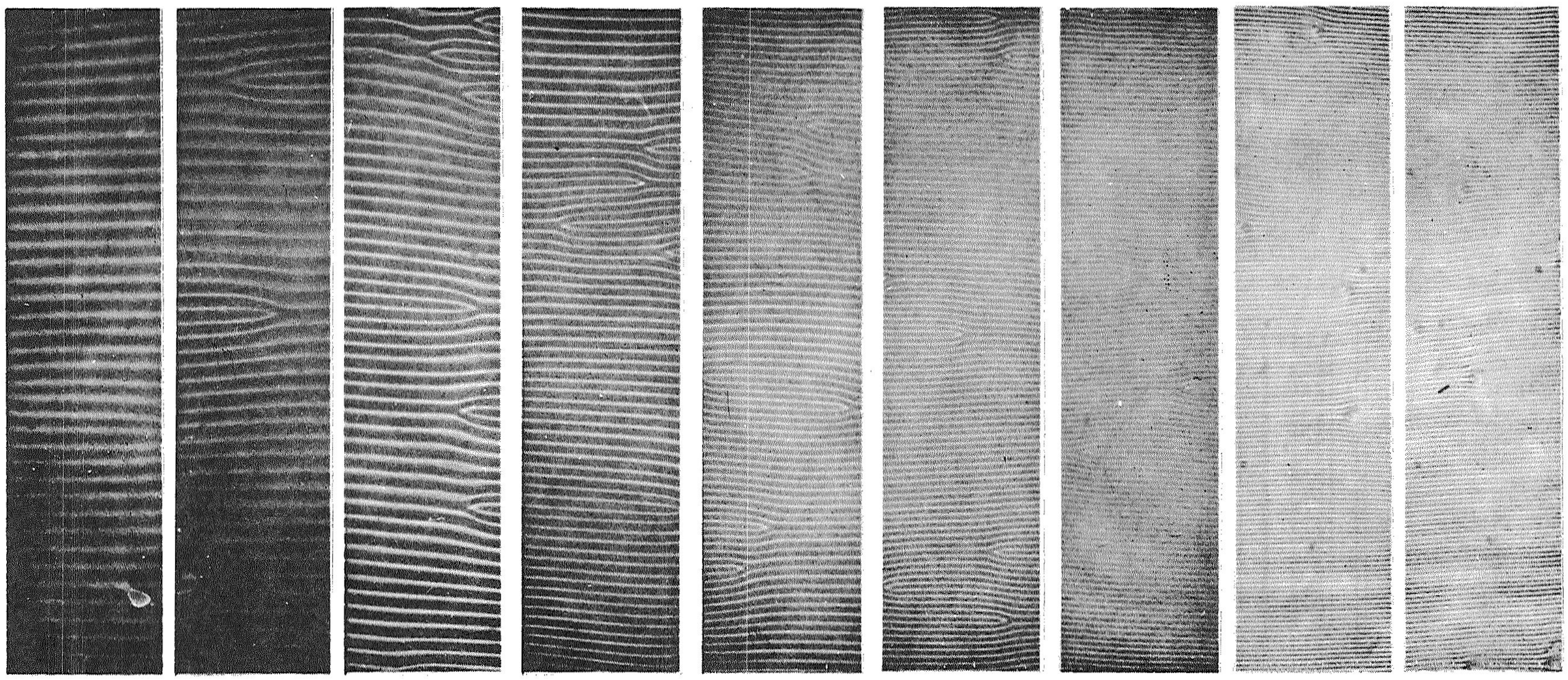


Figure 4.- Level slice operation.



20V 30V 40V 50V 60V 70V 80V 90V 100V

Figure 5.- Variable grating effect viewed through a polarizing microscope.

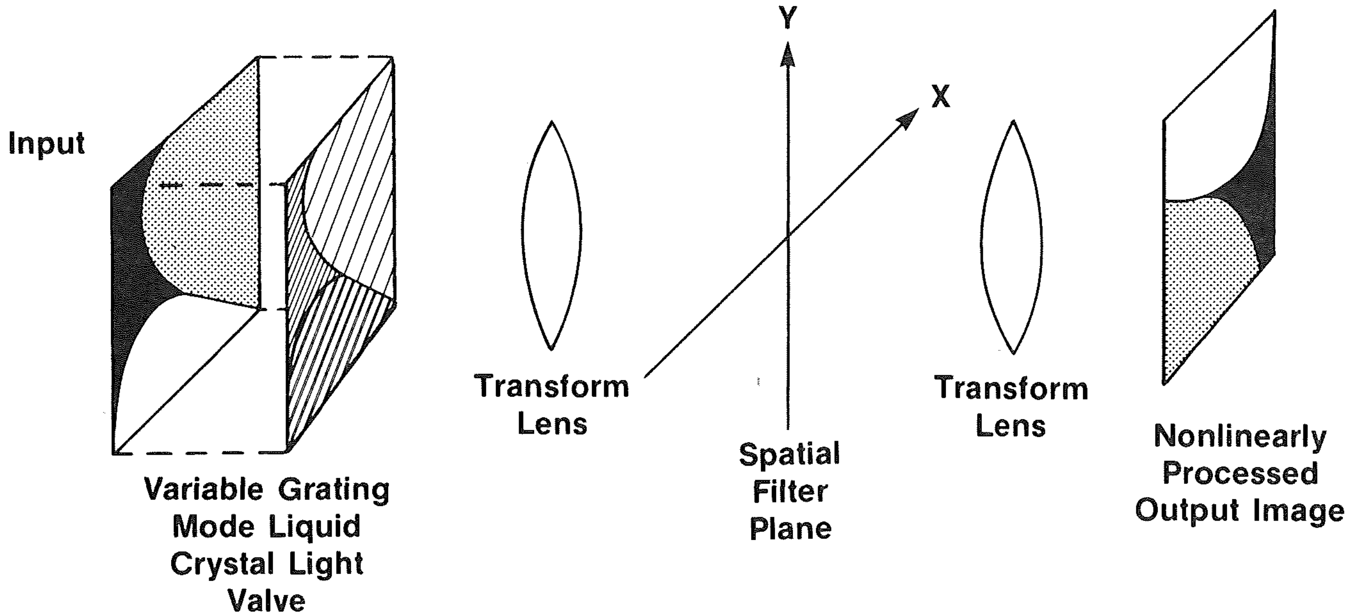


Figure 6.- Variable grating mode image processing.

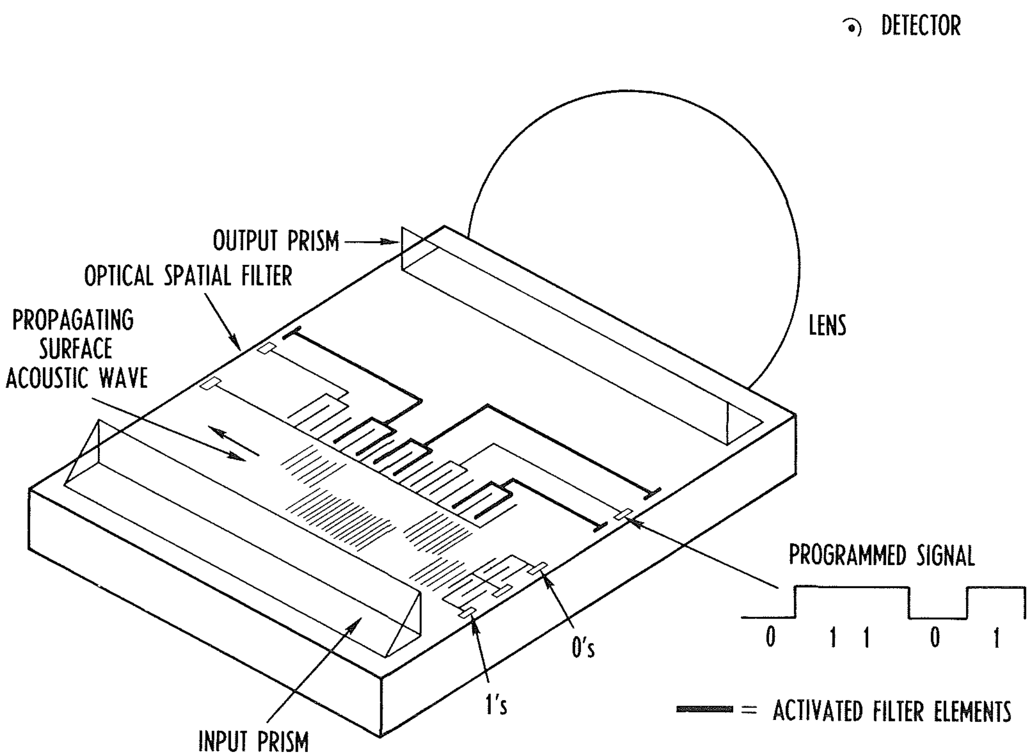


Figure 7.- Programmable optical waveguide spatial filter.