SPACE-VARIANT OPTICAL PROCESSING
WITH ACOUSTO-OPTIC MODULATORS

by

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CHAPTER I

INTRODUCTION

Problem Statement and Previous Work

A two-dimensional (2-D) linear space-variant operation is represented by the 2-D superposition integral [1]

$$g(x,y) = \iint_{-\infty}^{\infty} f(\xi,\eta)h(x,y;\xi,\eta)d\xi d\eta \quad (1-1a)$$

With a change of variables, and using discrete data, this equation becomes

$$g(i,j) = \sum_{n=1}^N \sum_{m=1}^M f(n,m)h(i,j;n,m) \quad \text{for } \begin{matrix} i = 1, \dots, I \\ j = 1, \dots, J \end{matrix} \quad (1-1b)$$

These equations represent a general linear mapping from the 2-D input coordinate system $(\xi,\eta; \text{ or } n,m)$ to the 2-D output coordinate system $(x,y; \text{ or } i,j)$. Different techniques have been used to optically perform 2-D space-variant processing.

One technique of 2-D space-variant processing is described by Walkup [1] using multiplexed holographic filters. Figure 1.1 shows how this is done. The input plane is sampled and is Fourier transformed by L_2 [2]. This output is multiplied by the multiplexed holographic filter and is then Fourier transformed by L_3 , with the output being a close approximation to the desired output. Other work in this area was done by Strand and Sawchuk [3], Case [4], and Carson [5].

Adams [6] investigated a technique that makes use of the wavelength dimension of light by color-encoding the input. By assuming

Figure 1.1. Space-variant processing with multiplexed holographic filters.

Cartesian separability of the 4-D point spread function, $h(x,y;\xi,\eta)$, only three dimensions were needed to perform the image processing instead of the four dimensions implied by Equation (1-1a). The third spatial dimension was changed to a wavelength dimension, as indicated by Figure 1.2. Figure 1.2a shows the first part of the processor. The white light is spread into the color spectrum by L_1 , P_1 , and P_2 . This provides a color-code for the input $f(\xi,\eta)$ by spreading the wavelength λ -dimension so that it occupies the spatial η -dimension. The next set of prisms and lenses (P_3 , P_4 , and L_2) compresses the wavelengths, which have been modulated by the input information in the η -dimension, from the spatial domain to the wavelength domain resulting in the domain-shifted form of the input $f(\xi,\lambda)$. This function varies in the spatial ξ -dimension, the wavelength λ -dimension, and is constant in the spatial x -dimension (previously the η -dimension). The partial result $u(x,\lambda)$ is obtained by integrating the product $f(\xi,\lambda)h_1(x,\xi)$ in the ξ -dimension by means of lens L_3 and the slit.

In the second half of the system, shown in Figure 1.2b, the partial result $u(x,\lambda)$ is spatially spread in the y -dimension (previously the ξ -dimension) by lens L_4 so that it can be multiplied by $h_2(y,\lambda)$. The function $h_2(y,\lambda)$ varies in the spatial y -dimension, the wavelength λ -dimension, and is constant in the spatial x -dimension. Thus, $h_2(y,\lambda)$ is a color filter which has a wavelength transmittance that varies in the y -dimension. The product $u(x,\lambda)h_2(y,\lambda)$ is integrated in the λ -dimension by the detector (e.g., photographic film, photodiode, etc.) to produce the final result $g(x,y)$.

Glaser [7] described a technique using lenslet arrays. The array

Figure 1.2. Optical processor used by Adams: (a) first half of processor; (b) second half of processor; (c) modified second half of processor.

is made up of small lens-like elements all having the same focal length. The input image is focused onto a mask containing the various point spread functions, and the output is summed by a detector array. Another method, as described by Haugen, Bartelt, and Case [8], is similar to Glaser's work, except for the fact that holograms are used. The hologram is actually many holograms (facets) spatially multiplexed on one piece of film. Each facet diffracts a portion of the incident plane wave to a particular place in the output plane, thus resulting in the desired image.

This is a small sample of some of the techniques that have been tried. Each technique is limited to a specific type of problem. Using a holographic filter will, in principle, allow real-time processing, but if a change in one of the point spread functions is desired, it is necessary to produce a different holographic filter. In some image processing situations, it is necessary to first look at the image, and then decide what type of processing is desired.

Acousto-optic modulators (AOM's) have the capability of converting an electrical signal into a spatial index of refraction variation which then diffracts a laser beam (see Chapter 2). By changing the input signal, it is possible to move the laser beam along a straight line in the output plane. Using two AOM's in a crossed fashion (diffraction axes at 90° with respect to each other), it is possible to center the diffracted laser beam at any point in a 2-D output plane. The time required to move the laser beam from one extreme location to the other is typically measured in microseconds. Because of the AOM's speed, it has the potential for being part of a real-time optical processor.

Taking all of this into consideration, the purpose of this research was to develop a technique for real-time space-variant optical processing using acousto-optic modulators.

Outline of the Thesis

Chapter 2 presents the theoretical background of the two major parts of the experiment: space-variant processing and acousto-optic modulators. These two areas form the basis for understanding the experiment. Chapter 3 describes the proof-of-principle experiment that was designed. The equipment used is identified and the development of the computer control is presented. The results are given and a comparison is made between the calculated and the measured results. Chapter 4 goes into the capabilities of the experiment. The physical limitations of the equipment is discussed and some indication of the potential for this design is given. Chapter 5 sums up the experiment and discusses possible areas for future research.

CHAPTER II

THEORETICAL BACKGROUND

Space-Variant Processing

Goodman [9] states that, in order to understand space-variant operations, it is helpful to start with the mathematical formalism used to describe them. He goes on to describe a system as a mapping of a set of possible input functions into a set of output functions which is represented by the operator $L\{\cdot\}$ such that

$$g(x,y) = L\{f(x,y)\} \quad (2.1)$$

This system is linear if it has the two basic properties of additivity and homogeneity, defined respectively by

$$L\{\sum_k f_k(x,y)\} = \sum_k g_k(x,y) \text{ where } g_n = L\{f_n\} \quad (2.2a)$$

$$L\{bf(x,y)\} = bg(x,y) \quad (2.2b)$$

By using the "sifting" formula, the input function $f(x,y)$ can be broken down into a set of impulses, and becomes

$$f(x,y) = \iint_{-\infty}^{\infty} f(\xi,\eta)\delta(x-\xi,y-\eta)d\xi d\eta \quad (2.3)$$

where $\delta(x-\xi,y-\eta)$ is a unit-volume impulse located at $(x=\xi,y=\eta)$. Then, for a linear system,

$$g(x,y) = L\{f(x,y)\} = \iint_{-\infty}^{\infty} f(\xi,\eta)L\{\delta(x-\xi,y-\eta)\}d\xi d\eta \quad (2.4)$$

where $L\{\delta(x-\xi,y-\eta)\}$ is the impulse response of the system.

There are many ways to represent the impulse response [10]. Two of the most useful are

$$L\{\delta(\hat{\xi}-\xi, \hat{\eta}-\eta)\} = h_1(x, y; \xi, \eta) \quad (2.5a)$$

and

$$L\{\delta(\hat{\xi}-\xi, \hat{\eta}-\eta)\} = h_2(x-\xi, y-\eta; \xi, \eta) \quad (2.5b)$$

Equation (2.5a) is such that the impulse response depends on both where the impulse was applied (ξ, η) and where the output occurs (x, y) . Note that $\hat{\xi}$ and $\hat{\eta}$ are input dummy variables. The response to the impulse input in Equation (2.5b) depends on where the impulse was applied (ξ, η) and where, with respect to that point, the output occurs $(x-\xi, y-\eta)$. Using Equations (2.5a) and (2.5b) in Equation (2.4) gives the superposition integrals

$$g(x, y) = \iint_{-\infty}^{\infty} f(\xi, \eta) h_1(x, y; \xi, \eta) d\xi d\eta \quad (2.6a)$$

and

$$g(x, y) = \iint_{-\infty}^{\infty} f(\xi, \eta) h_2(x-\xi, y-\eta; \xi, \eta) d\xi d\eta \quad (2.6b)$$

Space-invariant systems are linear systems where the impulse response (h_1 or h_2) depends only on the difference of coordinates $(x-\xi, y-\eta)$, and the outputs are given by the convolution integral

$$g(x, y) = \iint_{-\infty}^{\infty} f(\xi, \eta) h(x-\xi, y-\eta) d\xi d\eta \quad (2.7)$$

Linear space-variant systems are those systems that cannot be described by Equation (2.7), but must be expressed in the form of Equations (2.6a) or (2.6b). For the purpose of this paper, Equation (2.6a) will generally be used to define space-variant operations.

Acousto-Optic Modulators

A comprehensive review of the characteristics of acousto-optic modulators (AOM's) can be found in the first three chapters of Berg and Lee [11] and in the book by Sapriel [12]. For the purpose of this thesis, the AOM will be thought of as a device that converts an electrical signal into a laser beam diffraction pattern. As indicated in Figure 2.1, the relationship between the angle of diffraction and the input signal is given by

$$\sin\theta = \frac{\lambda}{\Lambda} \quad (2.8)$$

where θ is the angle between the zero order beam and the first order beam, λ is the wavelength of the laser, and Λ is the wavelength of the acoustic wave in the material. Putting this in terms of the acoustic frequency f yields

$$\sin\theta = \frac{\lambda}{v} f \quad (2.9)$$

where v is the velocity of the acoustic wave traveling through the medium. The value of v is determined experimentally and is given in the specifications for the device [13].

Also in Figure 2.1, the relationship between the off-axis distance d and the distance from the AOM, F , is

$$\tan\theta = \frac{d}{F} \quad (2.10)$$

Combining Equations (2.9) and (2.10), and solving for d , yields

$$d = F \tan \left[\sin^{-1} \frac{\lambda}{v} f \right] \quad (2.11)$$

Figure 2.1. Geometrical relationship of the AOM.

Since only small angles are involved, Equation (2.11) can be written as

$$d \approx \frac{F\lambda f}{v} \quad (2.12)$$

This gives a linear relationship between the frequency and the position of the diffracted laser beam. The parameters F , λ , and v are determined by the particular equipment being used, and therefore remain constant. Changes in position are thus proportional to changes in frequency, i.e.,

$$\Delta d = F \frac{\lambda}{v} \Delta f \quad (2.13)$$

This is the relationship that will be used in this thesis.

The magnitude of the diffracted light is proportional to the magnitude of the rf signal in the AOM. For an AOM operating in the so-called Bragg region (only a single diffracted beam), the efficiency (proportion of diffracted light [eff]) is given by

$$\text{eff} = \sin^2 \frac{v}{2} \quad (2.14)$$

where v is the modulation index of the device. The modulation index is a function of the crystal's physical properties, and is given by

$$v = \frac{\pi}{\lambda} \left[\frac{2P n^6 p^2 L}{\rho v^3 b} \right]^{\frac{1}{2}} \quad (2.15)$$

where λ is the laser wavelength, n is the index of refraction, p is the photoelastic coefficient, ρ is the density of the material, v is the acoustic velocity, L is the acousto-optic interaction length, b is the

height of the interaction cross-section, and P is the average rf power [12]. Looking at Equation (2.14), it is possible to obtain 100 percent efficiency whenever v is equal to $(2k-1)\pi$ for positive integer values of k . By knowing how to manipulate the various properties and dimensions of the crystal, it should be possible to design an AOM with 100 percent optical efficiency. The most important point is that the amount of light diffracted into the first order beam is proportional to the average rf power. Combining Equations (2.14) and (2.15) yields

$$\text{eff} = \sin^2 \left\{ 2P \frac{n^6 p^2 L}{\rho v^3 b} \right\}^{\frac{1}{2}} \quad (2.16)$$

This gives the relationship between the input rf power and the amount of light diffracted. The next chapter will describe the development of the proof-of-principle experiment that will prove that the process is capable of performing space-variant operations.

CHAPTER III

THE EXPERIMENT

Description of the Experiment

An experiment was designed to prove that the process being used was capable of truly space-variant processing. In order to simplify the experiment, a 3×3 input and output were chosen and only binary (0 or 1) input values were used. Figure 3.1a shows that the input used was a transparent square with an opaque center. Each box represents a pixel and the value in each box indicates the relative intensity of the transmitted light. The output was to be a cross with relative intensities shown in Figure 3.1b. In order to realize this output, the point spread functions required are shown in Figure 3.2. Since the input is scanned one pixel at a time, it is easier to see what is happening by using the backprojection technique as described by Glaser [7]. Figure 3.3 shows the difference between the conventional way of doing the superposition operation and the backprojection method. In the conventional method, the output value at a particular pixel depends on the projection of the input onto the point spread function. By using backprojection, each input pixel is projected over a particular point spread function. This partial result is stored in the output plane and the next input pixel is then projected over its point spread function. By summing all these outputs, the same results are obtained as in the conventional method. It should be noted that the set of point spread

1	1	1
1	0	1
1	1	1

 $f(n,m)$

(a)

0	2	0
2	4	2
0	2	0

 $g(i,j)$

(b)

Figure 3.1. Input function and desired output:
(a) input function; (b) desired
output.

0	0	0
0	0	0
0	0	0

 $h(1,1;n,m)$

1	1	0
0	0	0
0	0	0

 $h(1,2;n,m)$

0	0	0
0	0	0
0	0	0

 $h(1,3;n,m)$

0	0	0
1	0	0
1	0	0

 $h(2,1;n,m)$

0	1	0
1	0	1
0	1	0

 $h(2,2;n,m)$

0	0	1
0	0	1
0	0	0

 $h(2,3;n,m)$

0	0	0
0	0	0
0	0	0

 $h(3,1;n,m)$

0	0	0
0	0	0
0	1	1

 $h(3,2;n,m)$

0	0	0
0	0	0
0	0	0

 $h(3,3;n,m)$

Figure 3.2. Conventional point spread functions.

(a)

(b)

Figure 3.3. Conventional and backprojection methods of superposition: (a) conventional method of superposition; (b) backprojection method of superposition.

functions are not the same for both systems. The point spread functions required for the backprojection method are shown in Figure 3.4.

For example, looking at $h(i,j;1,1)$ in Figure 3.4, it can be seen that the input signal at $f(1,1)$ will be mapped to output point $g(1,2)$. The input $f(1,2)$ is then mapped to $g(1,2)$ and $g(2,2)$ by $h(i,j;1,2)$, etc. This process continues until all inputs have been scanned and the final result is the summation of all these individual mappings. Thinking in terms of a serial process, it was possible to come up with a table of the mappings that occur. Table 3.1 shows the required mappings between the nine input points and the nine output points, and the order in which they will occur. Figure 3.5 shows the mappings on a time scale. This shows the same thing as Table 3.1, except that it shows what is happening over the period of scan time. The light that shines through pixel 1 will be diffracted to point 2 on the output plane for a period of time equal to t_0 seconds each.

With nine input points and a maximum of two mappings per input pixel, it is possible to do the entire operation in eighteen time units. This was expanded to twenty time units because decade counters were going to be used in the digital logic. This allowed two time units for a starting point.

Figure 3.6 shows a block diagram of the experimental layout. Rather than scanning an actual 3×3 image, a shutter was opened and closed to simulate the scanning of the image. Digital logic was designed to control the shutter, and the input voltage levels to the two VCO's. A single photodetector was used at the output plane. To make measurements, it was moved to the particular output point, and the

0	1	0
0	0	0
0	0	0

 $h(i,j;1,1)$

0	1	0
0	1	0
0	0	0

 $h(i,j;1,2)$

0	0	0
0	0	1
0	0	0

 $h(i,j;1,3)$

0	0	0
1	1	0
0	0	0

 $h(i,j;2,1)$

0	0	0
0	0	0
0	0	0

 $h(i,j;2,2)$

0	0	0
0	1	1
0	0	0

 $h(i,j;2,3)$

0	0	0
1	0	0
0	0	0

 $h(i,j;3,1)$

0	0	0
0	1	0
0	1	0

 $h(i,j;3,2)$

0	0	0
0	0	0
0	1	0

 $h(i,j;3,3)$

Figure 3.4. Backprojection point spread functions.

Table 3.1
Input-to-Output Mappings

Input Point	Output Point(s)
1	2
2	2 and 5
3	6
4	4 and 5
5	none
6	5 and 6
7	4
8	5 and 8
9	8

Figure 3.5. Time sequence relating input to output points.

Figure 3.6. Equipment layout for experiment.

light intensity was measured during the total scan time. The output from the photodetector was in the form of a voltage. This voltage was stored in a RC circuit (integrator) until it could be measured with a voltmeter. The capacitor was then discharged and the photodetector was moved to the next output location.

Equipment

A Lexel Model 95 Argon-ion laser was used for this experiment. The laser power was set at 450 mW at the 514.5 nm wavelength. The laser beam was switched on and off by a Uniblitz Model 262 Shutter [13] powered by the Model 310B Shutter Timer Control. Two Isomet OPT-1 AOM's were used to deflect (by diffraction) the laser beam. The horizontal modulator was driven by a Model rf 805 Amplifier [14] which amplified the signal from the Motorola MC1648P VCO chip. The vertical channel was driven by two Hewlett Packard Model 460 Wide Band Amplifiers hooked up in series. The VCO circuit used is shown in Figure 3.7. The output light intensity was measured using a Bell and Howell 509-50 photodetector. The voltage from the photodetector was stored in an RC circuit consisting of an adjustable 25 k Ω resistor and a 50 μ f capacitor. The voltage across the capacitor was measured with a Radio Shack Model 22-204 Multitester on the 50 VDC scale. For the photographs shown in Figure 3.13 (page 34), Polaroid Type 51 film was used with a Type 545 Land Film Holder.

Development of the Digital Logic

What was needed was a way to simultaneously deliver both a signal

L: 22 turns of 20 guage wire with
1/4" inside diameter.

Figure 3.7. Diagram of VCO circuit.

to the shutter controller and one of three different voltage levels to the two VCO's. With nine input points and a maximum of two mappings, eighteen units of time were needed in order to represent the processor. After considering several possibilities, it was decided that the easiest way to time the experiment was with decade counters. A CMOS 4011 chip was used for a clock (see Figure 3.8). Using a variable resistor in the circuit allowed for easy changes in the clock rate. A count-to-twenty circuit was built using two CMOS 4017 Decade Counter chips and twenty AND gates (CMOS 4081). Using Table 3.1 and Figure 3.5, it was possible to design the necessary logic for the shutter and the two VCO's. Figure 3.9 shows a diagram of the digital logic employed.

Three outputs were needed. Based on Figure 3.5, the shutter needed an "off" signal for the first, second, tenth, and eleventh time periods. This was done by using a CMOS 4002 Quad Nor gate chip. Table 3.2 shows how the horizontal and vertical outputs were chosen using the coordinate system in Figure 3.10. A set of CMOS 4071 and CMOS 4072 OR gate chips were used to realize the outputs for the horizontal and vertical controls. These outputs were tied to six 2N2222 NPN transistors which controlled the voltage drop across the 10 k Ω resistor. This voltage became the input for the VCO's. In this way, it was possible to get three different voltage levels to the VCO's.

In order to make the system more flexible, it was desirable to interface a computer to drive the outputs. An Apple III microcomputer was used because of its availability. The interface was designed by Jones [15] and updated by Chase [16] for use with a Compucolor microcomputer. This equipment was adapted to the Apple III by Brent Boren.

Figure 3.8. Diagram of clock circuit.

Figure 3.9. Digital logic diagram.

Table 3.2
Breakdown of Output Coordinates

Time	Input Point	Output Point	Vertical Point	Horizontal Point
1	0	0	off	off
2	0	0	off	off
3	1	2	A	E
4	1	0	off	off
5	2	2	A	E
6	2	5	B	E
7	3	6	B	F
8	3	0	off	off
9	4	4	B	D
10	4	5	B	E
11	5	0	off	off
12	5	0	off	off
13	6	5	B	E
14	6	6	B	F
15	7	4	B	D
16	7	0	off	off
17	8	5	B	E
18	8	8	C	E
19	9	8	C	E
20	9	0	off	off

VERTICAL
COORDINATES

A	1	2	3
B	4	5	6
C	7	8	9

HORIZONTAL
COORDINATES

D E F

Figure 3.10. Coordinate system for Table 3.2.

Figure 3.11 shows a diagram of the interface. The program was done in BASIC and essentially instructed the 6502 microprocessor chip in the Apple III computer to give digital output signals to the D/A converters in the interface. This was accomplished with the POKE command. It is possible to get one of 256 different voltage levels between zero and 10 VDC. The output time length t_0 is governed by the use of FOR-TO loops. After POKEing a particular voltage level, a time delay is written into the program to control the length of the voltage pulse. It was found experimentally that the fastest time pulses were 9 ms. A sample program is given in the Appendix. The Apple II Emulation software was needed to run this program on the Apple III.

Results

Two measurements and several pictures were made with the equipment described for the proof-of-principle experiment. These values are shown in Figure 3.12. Figure 3.12a shows the desired results, and can be compared with the measured results of Figures 3.12b and 3.12c. As can be seen, the two sets of measured results are close to the desired results. The deviations were due to measurement errors.

It was found that the VCO needed at least 300 ms in order to switch frequencies. Attempting to switch any faster would not allow the VCO to reach the correct output frequency. That made the total input scan time 5.4 s. Because of the long integration time, there was some noticeable leakage in the RC circuit. This was due to the current leaking through the multimeter which was a parallel circuit to the capacitor.

Figure 3.11. Interface diagram.

0	2	0
2	4	2
0	2	0

a) Desired results

0	2.08	0
2.00	4.00	1.75
0	2.29	0

b) 1st measurement

0	1.67	0
2.25	3.43	1.75
0	2.00	0

c) 2nd measurement

Figure 3.12. Desired results, first measurement, and second measurement.

Several attempts were made to record the output on film. Figure 3.13a shows the output with 1.08 mW of incident laser light power as measured with a NRC Model 820 laser power meter. This was measured at the input of the crossed AOM's. Figure 3.13b was taken with 1.35 mW of input light power. The "fragmented" appearance of the output in the top left corner was due to reflections off of the equipment. Figures 3.13c and 3.13d were made with 1.62 mW and 2.16 mW, respectively. Development time was thirty seconds and all pictures were taken at room temperature. Figure 3.14 shows a picture of the equipment layout. The next chapter will consider the capabilities and limitations of this experiment.

(a)

(b)

Figure 3.13. Photographs of the output: (a) 1.08 mW incident power; (b) 1.35 mW incident power; (c) 1.62 mW incident power; and (d) 2.16 mW incident power.

(c)

(d)

Figure 3.13 (Continued)

Figure 3.14. Photograph of equipment.

CHAPTER IV

USES AND LIMITATIONS OF DESIGN

Present System Capability

The Apple III computer using the Apple II Emulation software is capable of running at 9 ms per cycle. This means that the fastest it can change from one voltage level to another is 9 ms. A sample program is given in the Appendix. With the interface described in Chapter 3, the Apple III is able to output one of 256 voltage levels ranging from 0 to 10 V. With the crossed modulators, this gives the capability of addressing a 256×256 point output array. With the current operating capability of the Apple III, it would be able to scan all the points in the array in 9.83 minutes. If the input image is also 256×256 points, it would take 447 days, 9 hrs, 25 m, 5.66 s to map all of the input points to all of the output points. Of course, this would be the worst case situation. If it were not necessary to map each input point to all of the output points, then the processing would be potentially much faster.

The typical maximum integrating time for most CCD arrays operating at room temperature is 5 ms [17]. Thus, in its present state, the system would not be able to use a CCD device for the output.

With the purchase of two Isomet Model D100-1 VCO deflector drivers, it would be possible to change frequencies at a rate of 1 MHz/ μ s. The bandwidth is 30 MHz, so the line rate for this device would be 33,333 lines/s or 30 μ s per line. Considering a 256×256 output array

again, it would take 7.68 ms for one complete scan of the output array, and 8 m, 23 s for a complete mapping of input plane to output plane. Again, this is clearly the worst case situation.

The ultimate capabilities of the AOM's used here have not been tested experimentally because of limitations in the drivers. It is possible to consider some theoretical limits to the modulators' capabilities. The Isomet OPT-1 AOM has a frequency range of 30 MHz to 60 MHz. Consider that it takes at least one full wave period at a given frequency in order to achieve the required diffraction; then it would take about 6 μ s to sweep one line. This was computed by dividing the 30 MHz frequency range into 256 parts and computing the time for one wavelength at each different frequency. It resulted in the following series:

$$T = \frac{1}{30M} + \frac{1}{30M + \frac{30M}{255}} + \frac{1}{30M + 2(\frac{30M}{255})} + \dots + \frac{1}{60M} \quad (4.1)$$

which can be manipulated and reduced to the following form:

$$T = \frac{255}{30M} \sum_{n=0}^{255} \frac{1}{255 + n} \quad (4.2)$$

Solving Equation (4.2) analytically gives about a 6 μ s line sweep time. Considering again the worst case possibility, it would take 1 m, 40.66 s to process a 256 $\times$ 256 input to output mapping. The next section will compare these values to the requirements for real time processing.

Limitations in the System Design

As a real time processor, a television picture is usually considered as the lower limit of resolution. A television picture is made up of 525 lines that change at a rate of 30 frames/s. This implies a line scan time of about 63.5 μ s. Although each line is an analog signal, consider it to be made up of 525 pixels and that each frame is 525 $\times$ 525 pixels. The actual number of lines used in a normal television picture is less than 525 lines because some of the lines are used for the vertical sync signal.

If the input is 525 $\times$ 525 points, then the line time for a total mapping is about 230×10^{-12} s, which is considerably faster than the approximately 12.1 μ s needed for a 525 point line by the AOM. In order to keep the 30 frames/s, the modulator-driver combination would be capable of mapping only a 14 $\times$ 14 input pixel array to a 14 $\times$ 14 output pixel array. A 525 $\times$ 525 pixel input-to-output mapping would take 29 m, 10.9 s based on a 12.1 μ s line sweep time.

The Apple III has an internal clock rate of 2 MHz. Using machine language and allowing ten steps for each voltage shift, it would have a line sweep time of 2.63 ms. Thus, for a 525 $\times$ 525 input-to-output mapping, it would require 4 days, 9 hrs, 30 m, and 45.7 s. A computer would need a clock rate of 84 MHz in order to operate at television frame rate. The Apple III would be capable of doing a 12 $\times$ 12 input-to-output mapping at television frame rates. Also, for the VCO driver to operate in this real-time scheme, it would require a slew rate of about 130,000 MHz/ μ s. In terms of achieving a real-time processor, the equipment available is very limited. The next chapter will consider

all the possibilities and limitations of this design and the conclusions that can be drawn from this experiment. We will also consider some possibilities for future research.

CHAPTER V

CONCLUSIONS AND FUTURE RESEARCH

Based on the results presented in Chapter 3, it has been shown that the processor is capable of space-variant processing and is not limited by separability of the input or the point spread function. In terms of a real-time processor, the calculations in Chapter 4 demonstrated the limitations of the particular hardware used in this experiment. The calculations showed that the AOM was capable of performing at realistic processing times (less than two minutes per picture frame), but improvements are needed in the VCO drivers and the computer.

The biggest problem was the time required to map each of the input points to each of the output points. If the number of required input-to-output mappings is limited, the real-time processing would be possible. For example, if each input of a 525×525 image is mapped to only ten output points, then there would be a total of about 2.8×10^6 mappings as compared to about 7.6×10^{10} mappings in a full input-to-output mapping. This would allow the processor to run about 27,000 times faster.

Several simplifications were made for the proof-of-principle experiment. One of these was the use of binary inputs and point spread functions. For future research, it would be interesting to test the ability of the processor to handle different values of input intensities and point spread functions. This can be done by temporally

changing the input rf power to the AOM. Another area of interest would be to program the Apple III microcomputer in assembly language in order to utilize its 2 MHz operating speed. With this capability and the new Isomet drivers, it should be possible to use the CCD array at the output. It would also be possible to test the physical limits of the AOM. One question that needs to be answered is whether or not the AOM is capable of operating at its theoretical limits. The answer to that question awaits further research.

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APPENDIX
COMPUTER PROGRAM

This program will drive a shutter and both VCO's in order to produce the same results as the digital logic used for the experiment.

```
10 REM VCO DRIVER PROGRAM
15 X=49647:Y=49661:S=49655
17 REM SET STARTING VALUES
20 POKE X,0:POKE Y,0:POKE S,0
22 REM DELAY LOOP
25 FOR I=1 TO 170:NEXT I
27 REM SECOND TIME UNIT
30 POKE X,0:POKE Y,0:POKE S,0
35 FOR I=1 TO 170:NEXT I
37 REM THIRD TIME UNIT
40 POKE X,200:POKE Y,255:POKE S,255
45 FOR I=1 TO 170:NEXT I
47 REM FOURTH TIME UNIT
50 POKE X,0:POKE Y,0
55 FOR I=1 TO 170:NEXT I
60 POKE X,200:POKE Y,255
65 FOR I=1 TO 170:NEXT I
70 POKE X,200:POKE Y,200
75 FOR I=1 TO 170:NEXT I
```

```
80 POKE X,255:POKE Y,200
90 FOR I=1 TO 170:NEXT I
95 POKE X,0:POKE Y,0
100 FOR I=1 TO 170:NEXT I
105 POKE X,155:POKE Y,200
110 FOR I=1 TO 170:NEXT I
115 POKE X,200:POKE Y,200
120 FOR I=1 TO 170:NEXT I
125 POKE X,0:POKE Y,0:POKE S,0
130 FOR I=1 TO 170:NEXT I
135 POKE X,0:POKE Y,0:POKE S,0
140 FOR I=1 TO 170:NEXT I
145 POKE X,200:POKE Y,200:POKE S,255
150 FOR I=1 TO 170:NEXT I
155 POKE X,255:POKE Y,200
160 FOR I=1 TO 170:NEXT I
165 POKE X,155:POKE Y,200
170 FOR I=1 TO 170:NEXT I
175 POKE X,0:POKE Y,0
180 FOR I=1 TO 170:NEXT I
185 POKE X,200:POKE Y,200
190 FOR I=1 TO 170:NEXT I
195 POKE X,200:POKE Y,155
200 FOR I=1 TO 170:NEXT I
205 POKE X,200:POKE Y,155
210 FOR I=1 TO 170:NEXT I
```

215 POKE X,0:POKE Y,0

220 FOR I=1 TO 170:NEXT I

225 GO TO 20