OPTICAL CORRELATION

Final Report

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ABSTRACT

Pattern recognition may supplement or replace certain navigational aids on spacecraft in docking or landing activities. The need to correctly identify terrain features remains critical in preparation of autonomous planetary landing. One technique that may solve this problem is optical correlation. Correlation has been successfully demonstrated under ideal conditions; however, noise significantly affects the ability of the correlator to accurately identify input signals. Optical correlation in the presence of noise must be successfully demonstrated before this technology can be incorporated into system design.

An optical correlator is designed and constructed using a modified 2f configuration. Liquid crystal televisions (LCTV) are used as the spatial light modulators (SLM) for both the input and filter devices. The filter LCTV is characterized and an operating curve is developed. Determination of this operating curve is critical for reduction of input noise. Correlation of live input with a programmable filter is demonstrated.

INTRODUCTION

The ability to safely perform an autonomous planetary landing is critical in NASA's continuing exploration of our solar system. Round trip communication transmission from Earth to Mars require tens of minutes, depending upon the relative positions of the planets in their orbits. An unmanned craft must be independently capable of terrain identification and hazard avoidance. Pattern recognition techniques offer a possible solution to this problem.

Several approaches to this problem are currently under investigation at NASA. These include fuzzy logic, neural networks, fractal characterization and optical correlation. Although these approaches are at various stages of development, the optimum approach, or combination of approaches, has yet to be determined.

Optical correlation offers two distinct advantages over other more computationally intensive techniques: speed and weight. The essence of the optical correlator, the lens, computes the Fourier transform of an image in real time. Proper filtration of that transform and re-transformation with another lens allows for near real time recognition of visual scenes.

BACKGROUND

The origins of Fourier optics can be traced to Abbe and Porter in 1893 and 1906, respectively. Their efforts involved the modification of image information through spatial filtering in the Fourier plane. In 1931 Goldberg was granted a U.S. patent for his application of Fourier optics to character recognition.[1]

A textbook example of an optical correlator is the "4 f correlator." This configuration consists of two lenses, an input plane, filter plane and correlation plane. For lenses of focal length f, the total length of the correlator is four times f (figure 1). For a given object in the input plane and the corresponding filter in the filter plane a correlation peak will be detected in the correlation plane.

Early work with the 4 f correlator used photographic plates as input images. Matched filters were developed for each image and these filters were also placed on photographic plates. Although correlators of this type can adequately recognize a letter, they are sensitive to size and orientation variations.

Detection limitations due to this sensitivity have led to increased investigation in filter design. Variations of the matched filter include phase, amplitude and binary filters.

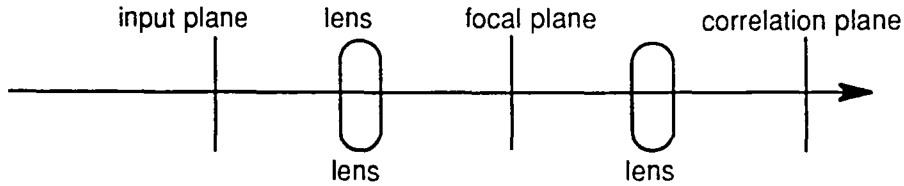

Figure 1. Collimated light enters from the left. The lenses are two focal lengths apart. The input, focal and correlation planes are one focal length from the nearest lens.

Ultimately the filter design must accommodate any limitations of the filter medium, the spatial light modulator (SLM). An SLM modulates amplitude, phase, or a combination of both amplitude and phase. The earliest SLMs were light blocks and photographic film. Deformable mirror devices (DMDs) have been used in the modulation of light. Low cost and ready availability have recently increased interest in the liquid crystal televisions (LCTVs) as a suitable SLM in either phase or amplitude mode.

Though any physical device is constrained to an operating curve and never truly has access to every point of a region on the complex plane (fully complex modulation), filter design and filter characterization have focused on either phase or amplitude and not both. Juday has developed an algorithm to select the point on a device operating curve that best incorporates the phase and amplitude information of the desired point on the complex plane.[2]

Other authors have noted both phase and amplitude modulation in LCTVs; however, none have attempted to operate in both phase and amplitude modulation.[3] With Juday's work a significant increase in signal to noise ratio (SNR) may be obtained by operating in phase and amplitude modulation.

In addition to developing a programmable filter on an LCTV, our research goals included providing live input to the correlator. A second LCTV, driven by an external camera, provided a logical course of action. In this configuration input images could easily be varied and filters could be rapidly changed.

EXPERIMENTAL CONFIGURATION

The LCTV uses a twisted nematic that rotates the polarization of incident light. The amount of rotation is dependent upon the alignment of the liquid crystal molecules. Molecular alignment is controlled through application of a voltage across the LCTV. The brightness control knob on the

Epson projector applies a bias voltage between the two surfaces of the LCTV. The potential difference across individual pixels is controlled via gray scale (0-255) application of additional voltages.

In normal operation, a dichroic sheet polarizer is placed in front of the LCTV and another crossed polarizer is place in back of the LCTV. The amount of polarization rotation induced by the LCTV then determines the total throughput.

The LCTVs used were removed from an Epson Crystal Image Video Projector. This projector uses three LCTVs; red, green and blue. The red LCTV was selected to serve as the filter and the green was selected to serve as the input SLM. Each of these LCTVs was mounted onto conventional optical mounts. Three foot extension cables were fabricated for ease of mounting. For convenience, the input and filter LCTVs were placed orthogonally in the optical path.

The service manual accompanying the projector reported the LCTVs to consist of 70400 pixels (320x220) arrayed in a 1.27 inch diagonal area with an aspect ratio of 4(H):3.1(V). The pixels were in rows and columns uniformly spaced 0.008 cm. and 0.009 cm. respectively. Filters were to be sent to the Epson via a PIP-1024-A Frame Grabber/Buffer. Digital images, 512 x 480 on the PIP, were converted to analog video, sent to the Epson and then converted back to digital and displayed on the LCTV. Careful analysis of the data transfer from the PIP to the LCTV revealed that the 480 rows were sent to the 220 LCTV rows in the following manner: the top 19 rows were not sent to the LCTV, the next 440 rows were sent in an overlapping manner; that is, the first PIP row was written on the first LCTV row, then the second a PIP was written on top of the first LCTV row. This was repeated over the entire LCTV surface, and the bottom 21 rows were not sent to the LCTV. From left to right, the first 13 rows on the PIP were not sent to the LCTV, the next 493 were sent in a fractional manner with 1.5085 PIP columns transferring to 1 LCTV column; the final six columns on the PIP were not sent to the LCTV.

In normal operation of the LCTV 0 gray scale corresponds to black (minimum transmission) and 255 gray scale corresponds to white (maximum transmission). The Epson service manual states that the minimum contrast ratio for each pixel will be 40:1. We found a contrast ratio of 63:1 on the LCTV.

We chose to operate our input LCTV in the conventional mode; however, we decided to run our filter in a white-black-white configuration. The most satisfactory results were found with the corresponding gray scales of 0-127-255. A maximum contrast ratio of 100:1 was found. The data are plotted in figure 2.

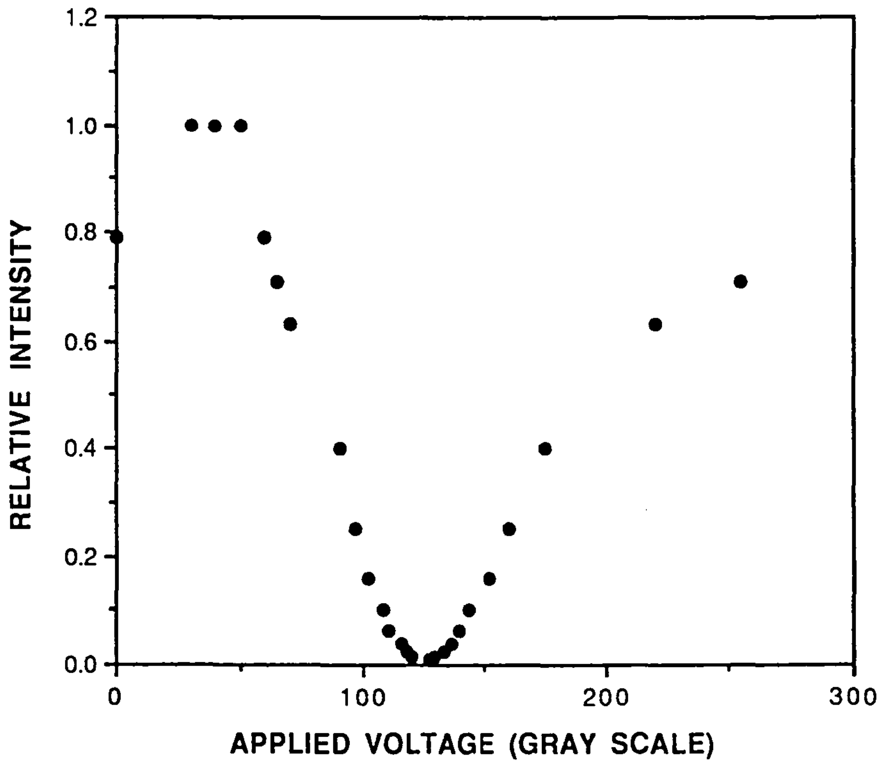

Figure 2. Intensity as a function of voltage

A procedure was developed for determining the optimum setting of the three control variables: input polarizer, output polarizer and brightness knob. The LCTV was divided into three sections, each with a different gray scale setting. The edge sections were set to 0 and 255, respectively, and the center section was set to 127. A trace of the intensity, running across each of the three sections, was displayed on a scope. The input polarizer was rotated until the intensity of the 0 and 255 was even. Using the output polarizer the center section intensity was minimized. Further minimization of the center section was accomplished by adjustment of the brightness knob. These three adjustments were then systematically repeated, minimizing the intensity of the center section, while maintaining equal intensity on the end sections. After the settings had been determined and recorded, all of the adjustment knobs were randomly set and the procedure was repeated several times to insure that the optimum set of adjustments had been determined.

Phase variation as a function of gray scale was determined using a Mach-Zehnder interferometer. Measurements were made with the LCTV and both polarizers in place, at the settings determined during the contrast optimization procedure. To make the phase measurements the LCTV was divided into two sections on one side the gray scale was set at 255 and the other side was interactively varied in increments of 5. The fringe variation was observed the entire time, noting a smooth transition, and data points were recorded every 1/4 fringe. Although only five data points were recorded, the curves displayed are accurate descriptions of the phase variation as a function of voltage (figure 3).

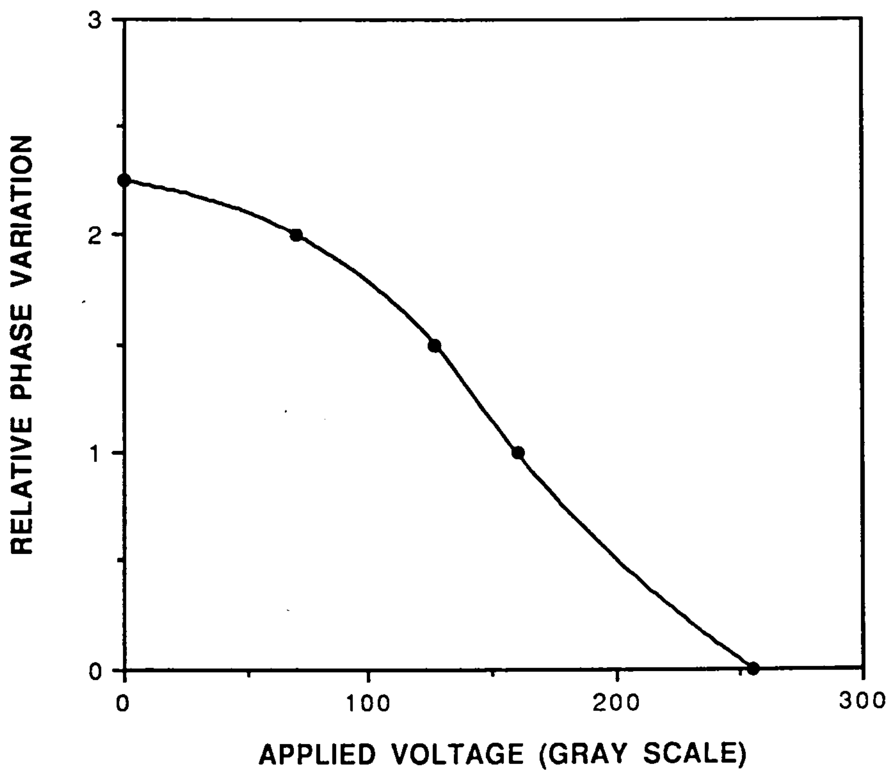

Figure 3. Phase as a function of voltage.

The coupled curve was then modeled using the five phase data points and their corresponding intensity measurements. Amplitude (E) was modeled as though the polarization rotation leading to its variation were affine with phase, with

$$E = A\cos(k\theta - \beta) \qquad (1)$$

for A=0.9803, k=0.4578 and β=0.5295.

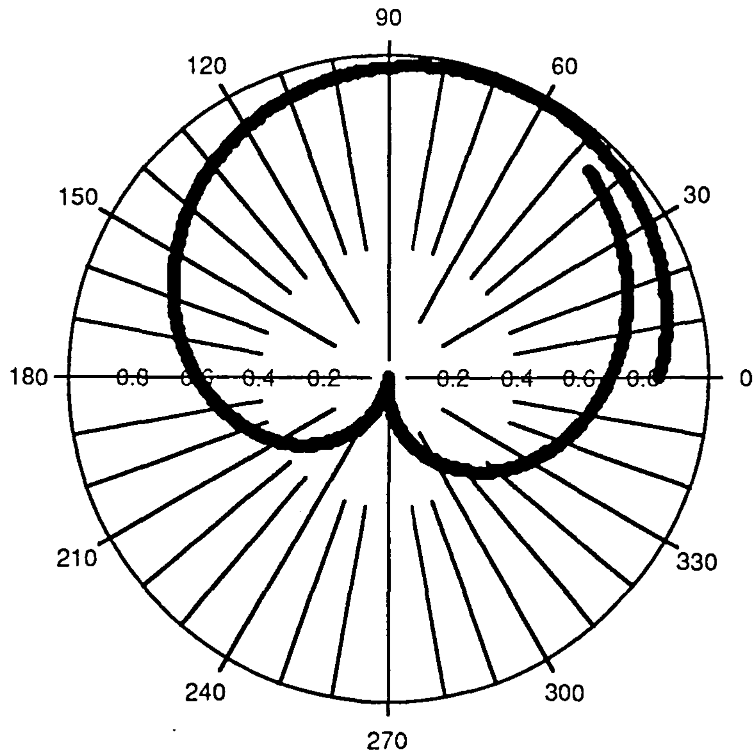

Figure 4. Operating Curve for maximum contrast.

The operating curve of the LCTV (phase vs intensity) is at figure 3. It is this curve that is used in the selection of optimal filter values. Corresponding voltage for any point on the operating curve can readily be found from Table 1.

TABLE 1. PHASE, AMPLITUDE AND VOLTAGE RELATIONSHIPS

$\theta=2.2652-3.7813 \times 10^{-3}V-2.0530 \times 10^{-5}V^2$

$I=-1.7090+1.6889 \times 10^{-2}V-2.8835 \times 10^{-2}V^2$ for $V>127$

$I=0.78755+1.6658 \times 10^{-2}V-2.9384 \times 10^{-4}V^2-9.9441 \times 10^{-8}V^3$
$+7.8447 \times 10^{-9} V^4$ otherwise

$A=0.89283+7.1321 \times 10^{-3}V-1.1596 \times 10^{-4}V^2$ otherwise

$A=-4.0612+5.3474 \times 10^{-2}V-1.9376 \times 10^{-4}V^2+2.3299 \times 10^{-7}V^3$ for $V>127$

$V=102.29+288.48A-687.5A^2+656.58A^3$ for $V>127$

$V=116.82-11.796A-56.913A^2$ for $40<V\leq127$

$V=125.91+245.35I-605.85I^2+725.02I^3$ for $V>127$

$V=116.96-70.353I-5.9588I^2$ otherwise

$V=251.08-46.990\theta-27.495\theta^2$

Where A is the amplitude (relative, scaled from 0 to 1, ±0.05), I is the square of the amplitude, V is the gray scale voltage (±2.5) and θ is the relative phase ($\pm0.12\ \pi$).

Of additional importance in characterization of LCTVs is the orientation of the director. The director is the longitudinal axis of the molecular dipole at the front surface of the LCTV. To determine the orientation of the director linearly polarized light is sent into the LCTV (with no voltage applied) and the polarization of the throughput is analyzed. The input polarization is systematically rotated and the throughput analyzed until settings are determined where the input and throughput light are both linearly polarized. This will only occur when linearly polarized light that is either perpendicular or parallel to the director enters the LCTV. At any other orientation, linearly polarized light will be converted to elliptically polarized light after passing through the LCTV.

Linearly polarized light that enters the LCTV perpendicular to the director will not experience a phase shift, regardless of voltage applied to the LCTV, whereas, linearly polarized light that enters the LCTV parallel to the director will experience a phase shift as varying voltages are applied to the LCTV. This information, combined with the settings determined above, can be used to uniquely determine the orientation of the director. For the filter LCTV the director was found to be 73 degrees from the vertical on the LCTV.

Optimum lens selection for a 4 f correlator requires frequency matching of the input and filter SLMs. For a pixelated input SLM, optimum filtering occurs when one diffraction order from the input image just fits onto the filter. This occurs when:

$$f=Y/dl \qquad (2)$$

where f is the transform lens focal length, Y is the diameter of the filter, d is the Nyquist frequency of the input SLM and *l* is the wavelength of light used.[1]

For a 128 x 128 input image, a 128 x 128 phase only filter was calculated and sent from the PIP to the filter LCTV. Using the PIP to LCTV mapping determined earlier and equation 1, an appropriate focal length of 195 cm. was selected.

A 195 cm. lens was not available; had it been a 4f correlator it would then extend nearly eight meters, an unacceptable long length for our laboratory. To overcome these two problems a 2f modified correlator was designed using the lenses available in the lab (figure 5).[4]

A step by step procedure was developed for lens selection and placement in development of the 2f modified correlator. This procedure is presented below.

1. Lens 1 is selected by image pixel spacing, width of filter and wavelength (eqn 2.).

2. Input plane and lens 2 are selected for convenience and image size.

3. Lens 3 is selected such that $1/f_3=1/d+1/f_2$, where d is the distance from the input plane to the filter plane.

4. The correlation plane is positioned a distance s' from the filter plane such that $1/f_3=1/d+1/s'$.

5. Lens 4 is selected such that $1/f1=1/f4+1/x$, where x is the distance from the spatial filter to lens 4.

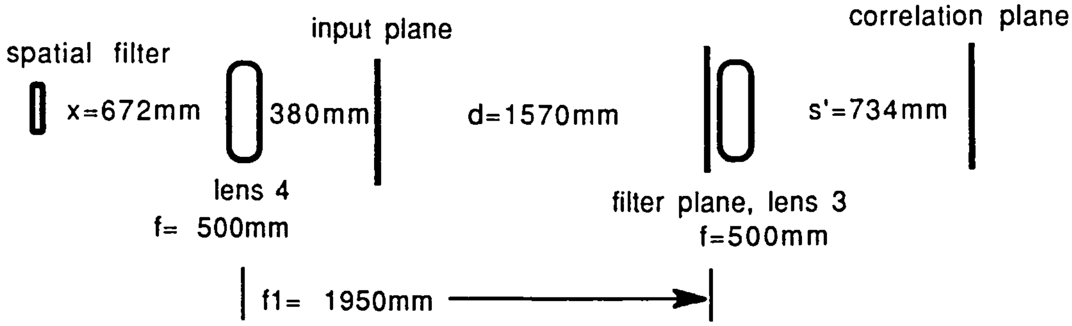

Figure 5. Final correlator configuration.

CONCLUSIONS

Procedures for characterization of LCTVs necessary to determine phase and amplitude cross coupling were developed. These procedures can be applied for optimization of filter design. An Epson-Epson correlator, with video input and phase only filter operated successfully on simple geometric objects. Correlation of live input was accomplished with a phase only filter displayed on the filter SLM. SNR in excess of 25:1 were recorded (figure 6).

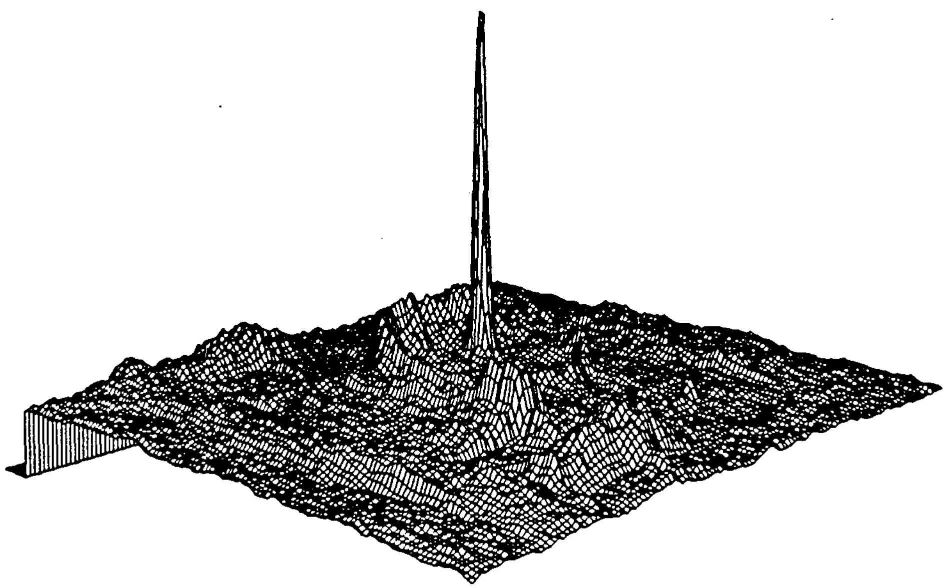

Figure 6. Intensity distribution in the correlation plane.

REFERENCES

1. J. Goodman, *Introduction to Fourier Optics* (McGraw-Hill, San Francisco, 1968).

2. R. Juday, "Correlation with a spatial light modulator having phase and amplitude cross coupling," Applied Optics **28**, 4865-4869 (1989).

3. D. Gregory et al., "Using the hybrid modulating properties of liquid crystal television," Applied Optics **30**, 1374-1378 (1991).

4. K. Fielding et al., "Optical correlator architectures re-examined," SPIE **1295**, 59-66 (1990).