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Development of a Parallel Access Optical Disk System for High Speed Pattern Recognition

by

Christopher Davison B.Eng. (Hons)

A Doctoral Thesis submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy

of

Loughborough University

June 1997

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Nomenclature

a	Photographic grain area
а	Constant
Α	Area
A	Light amplitude
Α	Mueller matrix of LCTV
Ь	Constant
с	Speed of light
d	Length
D	Photographic density
D	Diameter, Aperture width
D	Mean power spectrum (diagonal matrix)
е	Error
E	Eigenvalues
Ε	Exposure
E_{av}	Mean correlation plane energy
E _p	Photon energy
E_l	Energy (per pulse) of pulsed laser
f	Focal length
\mathbf{f}_{co}	Cut-off frequency
f	Function
f_1	Input function in linear system
f_2	Output function in linear system
<i>f/</i> #	f-number
F	Fourier transform of <i>f</i>

-.

8	Reference function
8 av	Mean grain size
G	Constant
G	Fourier transform of g
h _n	Neuron number
h	Impulse response function, Plancks constant
h _c	Coherent impulse response function
H	Filter complex transfer function, Fourier transform of function h
Ι	Intensity
J	Jones vector
k	Constant
ls	Half-the-side-length of diffraction limited spot
L	Length
L	Spatial frequency content of LCTV pixellated structure
m	Constant
М	Constant
n	Constant
n_p	Number of photons
n _{//}	Refractive index parallel to LCTV molecular director
n_{\perp}	Refractive index perpendicular to LCTV molecular director
Ν	Constant
NA	Numerical aperture
р	Pixel size
p(n)	Poisson probability distribution
P _e	Expected power in correlation peak
P_l	Laser power
Р	Phase matrix
r	Radius
r _{min}	Minimum radius
$r_{\rm max}$	Maximum radius

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rs	Radius of diffraction limited spot
R	Reflectivity
R _{fg}	Correlation of functions f and g
R _{fg}	Fourier transform of R_{fg}
R	Vector of correlation peak constraints
$\mathbf{R}(\mathbf{ heta})$	Co-ordinate transformation matrix
S	Linear System
t, <i>T</i>	Time
t _a	Amplitude transmittance
t _i	Intensity transmittance
t _a	Complex amplitude transmittance
(<i>u</i> , <i>v</i>)	Spatial frequencies in (x, y) directions
v _{mn} , w _{mn}	Neuron weighting value between neurons m and n
V	Velocity
V, W	Neuron weighting matrix
W _n	Neural network feature detector
x _o	Mean position of holographic fringe
x	Stokes vector
x _n	Inputs to neural network
Уn	Outputs from neural network
(x, y)	Spatial co-ordinates
(x_u, y_v)	Co-ordinates of spatial frequencies (u, v)
α	Variable describing the angle of a coherent reference beam
β	Constant
δ	Dirac delta function
ε	Angle
ξ	Spatial domain variable in x-direction of linear system
γ	Film gamma
λ	Wavelength

Mean number of photographic grains
Spatial domain variable in y-direction of linear system
Phase angle
Normalised radius
Standard deviation
Population variance
Sample variance
Angle
Light frequency
Optical power transmission efficiency

Abbreviations

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BPOF	Binary Phase-Only Filter
CCD	Charge Coupled Device
CCIR	Comite Consultatif International de Radiodiffusion video standard
CD	Compact Disk
CGH	Computer Generated Holography
CHC	Circular Harmonic Component
CPU	Central Processing Unit
CW	Continuous Wave
DC	Direct Current
DOF	Depth of Field
EASLM	Electronically Addressed Spatial Light Modulator
FFT	Fast Fourier Transform
FT	Fourier Transform
H-D	Hurter-Driffield curve
I/O	Input / Output
JTC	Joint Transform Correlator
LCTV	Liquid Crystal Television
MACE	Minimum Average Correlation Energy
MRHC	Mellin Radial Harmonic Component
MTF	Modulation Transfer Function
MVSDF	Minimum Variance Synthetic Discriminant Function
NA	Numerical Aperture
ND	Neutral Density
NDA	Negative Dielectric Anisotropy
NTSC	National Television System Committee video standard

OFG	Overlay Frame Grabber
PAODS	Parallel Access Optical Disk System

PDA Negative Dielectric Anisotropy

POF Phase-Only Filter

SBP Space-Bandwidth Product

SDF Synthetic Discriminant Function

SLM Spatial Light Modulator

SNR Signal to Noise Ratio

TBP Time Bandwidth Product

TFT Thin Film Transistor

TN Twisted Nematic

TPD Total Phase Difference

WORM Write-Once-Read-Many times

 $\omega_{ij}^{(1)}$

Abstract

Pattern recognition is a rapidly expanding area of research, with applications ranging from character recognition and component inspection to robotic guidance and military reconnaissance. The basic principle of image recognition is that of comparing the unknown image with many known reference images or 'filters', until a match is found. By comparing the unknown image with a large data bank of filters, the diversity of the application can be extended. The work presented in this thesis details the practical development of an optical disk based memory system as applied in various optical correlators for pattern recognition purposes.

The characteristics of the holographic optical disk as a storage medium are investigated in terms of information capacity and signal to noise ratio, where a fully automated opto-mechanical system has been developed for the control of the optical disk and the processing of the information recorded. A liquid crystal television has been used as a Spatial Light Modulator for inputting the image data, and as such, the device characteristics have been considered with regard to processing both amplitude and phase information. Three main configurations of optical correlator have been applied, specifically an image plane correlator, a VanderLugt correlator, and an Anamorphic correlator. Character recognition has been used to demonstrate correlator performance, where simple matched filtering has been applied, subsequent to which, an improvement in class discrimination has been demonstrated with the application of the Minimum Average Correlation Energy filter. The information processing rate obtained as a result of applying 2D parallel processing has been shown to be many orders of magnitude larger than that available with comparable serial based digital systems.

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1

Introduction

1.1 FUNDAMENTALS

The motivation for the increased interest in pattern recognition over the last few decades has come from many different potential applications. From automatic character recognition and component inspection, to robotic guidance and military reconnaissance, the applications are vast; where in general the objective has been to relieve the need for undertaking monotonous or laborious tasks 'by hand'.

When computing speed was a restriction, only relatively simple tasks could be performed in relieving the need for an otherwise manual procedure. For example, external perimeter could be used to discriminate between nuts and bolts in an automated sorting procedure, since the bolts in general may have a larger perimeter than the nuts. If a specific perimeter were used to discriminate between the nuts and bolts, then clearly in some cases a large nut may be classified as a bolt for example, resulting in a classification error. Advances in computing power have allowed the same classification rate, where additional object features have been used to reduce classification error. Using the example above, the area as observed in plan view could be an additional discriminating feature.

The fundamental background to the field of pattern recognition originates from statistical decision theory [1-1, 1-2] - is it a nut, or is it a bolt?; is it an apple, or is it a pear? If many samples are available, the resulting statistical distribution (relating to features such as perimeter, area, colour and shape for example) permits classification

of unknown objects or images on the basis of the known data. The principles behind the identification of an object, or more generally the identification and classification of an object or objects in a scene, are based on feature extraction followed by classification. In the above example, perimeter and area are the feature data extracted from the samples, from which classification can take place. For example if one class of objects is described by a large external perimeter and a small area, this class may be discriminated from another class described by a small perimeter and a large area. When more and more features are used, such as thread diameter and thread pitch, errors can be further reduced, where the classification procedure takes place within multi-dimensional 'feature space'.

Some rather sophisticated pattern recognition algorithms and systems are now in general use as a result of the application of powerful computers and high speed digitising frame grabbers. For application with industrial robots, Ham et al [1-3] have used 'the number of crossing points', width and other distance based features to recognise raised characters on rubber tyres. Distance based features are also used by Scholl [1-4] in order to provide semi-autonomous docking of space craft. The relative positions of various sector-star targets as painted on a space station provide sufficient information from which automatic docking can take place. The space craft can approach from any direction, with any orientation and still be docked successfully.

Further advances in the processing speed of digital systems can only take place with improvements in computer technology. Since images are usually two dimensional, the serial nature of digitisation and subsequent processing will always be restrictive. Optical systems on the other hand, inherently provide a two dimensional processing medium, and as such can provide truly parallel processing, with a fundamentally much greater processing speed. The underlying principles of feature extraction and classification, still however, remain the objective of optical pattern recognition. Feature extraction takes the form of comparing the unclassified scene with many known reference objects (or 'filters') until a match is found. The now known components of the scene permit classification.

Since the advent of the complex matched spatial filter [1-5], much research has taken place regarding optical pattern recognition, and many algorithms originally undertaken serially, are now processed with parallel optical systems. In order to

recognise the numbers 0 to 9 for example, under normal circumstances 10 matched filters would be required. Kamemaru et al [1-6], however, extract 4 characteristic features of the 10 digit set, such that recognition can take place on the basis of only 4 optical matched filters. Other examples of optical pattern recognition include real-time fingerprint recognition [1-7] for use in secure systems and real-time road sign recognition [1-8] for automatic vehicular control. There are many applications of optical pattern recognition within the military, and one such example is the work of Sloan and Small [1-9], where a miniaturised optical correlator has been fitted in the head of a missile for guidance purposes.

This chapter reviews some of the important work undertaken within the field of optical pattern recognition, and describes the importance and the content of the work undertaken here.

1.2 PATTERN RECOGNITION WITH NEURAL NETWORKS

Although pattern recognition using neural networks is not directly related to the work undertaken here, due to the considerable research activity in this field, it deserves brief consideration.

Artificial neural networks were originally modelled on the network of interconnected nerve cells in the brain, and are capable of undertaking calculations and problem solving in parallel [1-10]. Neural networks generally comprise layers of simple processors (neurons), where each neuron is connected to neurons in the adjoining layers. Figure 1-1 illustrates a simple three layered network, with 3 neurons in both the input and output layers, and two neurons in the 'hidden' layer. The (w, v) values are the interconnection weights. Taking a single neuron (h₁) for example; if the sum of the weighted input values $(x_1w_{11} + x_2w_{12} + x_3w_{13})$ is either greater than or less than a predetermined threshold level, then the neuron typically outputs the binary value 1 or 0 respectively. Once the network has been trained such that the weighting values effectively memorise the training data, an input distribution can be mapped to a specific output distribution, resulting in an associative memory for example, where output data is 'recalled' by its association with the input data. Note in Figure 1-1 how

the weights corresponding to each interconnection layer can be represented in matrix form, [W] and [V] for the input and output layers respectively. The network in Figure 1-1 could also be applied as a classifier, where the outputs could represent three different classes for example. The outputs from the classifier are dependent on the outputs from the hidden layer, which in turn are dependent on the matrix of weight values [W]. The vectors $W_1 = \{w_{11}, w_{12}, w_{13}\}$, and $W_2 = \{w_{21}, w_{22}, w_{23}\}$ extract characteristic features of the input data, and relay this information to the final classifying output layer. W_1 and W_2 can therefore be regarded as feature detectors. Trained neural networks thus offer a useful way of automatically selecting feature detectors.

Useful networks for pattern recognition demand hundreds if not thousands of fully interconnected neurons, and as such, the two dimensional parallel nature of optics offers an attractive medium for practical implementation [1-11]. Any one input neuron in Figure 1-1 is mapped to a number of neurons in the hidden layer. This is analogous to generating a 2D object image from a single reference beam in holography, and holograms are indeed used extensively to record the interconnection weights in optical neural networks. By considering each input neuron to be a point source, for example x_1 in Figure 1-1, when used to re-illuminate a hologram, the weighting vector { w_{11} , w_{21} } can be recreated. Similarly the point sources x_2 and x_3 result in producing the vectors { w_{12} , w_{22} } and { w_{13} , w_{23} } respectively, when re-illuminating another two holograms. When all the holograms are multiplexed, the entire weighting matrix [W] is recorded, fully interconnecting the input and the hidden layers. Holographic interconnects are used extensively, where for example, Li et al [1-12] have used a photorefractive crystal to angularly multiplex the weighting values for a network used to recognise human faces in real-time.

In essence, the processing operations undertaken within a neural network are that of multiplication and integration. These are precisely the functions of an optical correlator, and as such, these devices can be used for the practical implementation of some or even all of the neural network pattern recognition task. As stated in Section 1.1, pattern recognition takes the form of comparing the unknown input object with many reference images until a match is found. Agu et al [1-13] have used this idea to perform a multiple matched filtering operation in parallel. A lenslet array is used to

first of all form many duplicates of an input image, subsequent to which a second lenslet array forms individual 2D Fourier transforms of the duplicate images. The Fourier transforms are incident on a 2D array of matched filters, designed to recognise specific features of the input image. The 2D output correlation plane therefore comprises an arrangement of peaks corresponding to features extracted from the input data. The many individual optical correlators therefore undertake feature extraction, where classification takes place in a computer on the basis of the arrangement of correlation peaks.

Optical correlators can also be considered as a specific class of neural network. If the input in an optical correlator is a 2D array of image data, then the output is a 2D array of correlation data, where the distribution of weighting values can be considered to represent the reference images. An important feature of optical correlators is the shift invariance property, and is where a shift in the input gives rise to a proportionate shift in the output. This system can be thought of as a neural network comprising an input and an output layer only, where the weighting values between neurons (m) and (n) satisfy;

$$\mathbf{w}_{mn} = \mathbf{w}_{(m-1)(n-1)} \qquad \text{for all } m,n \qquad (1-1)$$

in providing shift invariance.

Shift invariance has been implemented by Uang et al [1-14] through application of the centring property of the power spectrum. Their network is trained on the basis of spatial frequency domain data, where the unknown input image is also presented in the spatial frequency domain. In this way, character recognition has been achieved regardless of the position of the input data.

The work presented in this thesis relates to optical correlator based pattern recognition, and the remainder of this chapter reviews work relating to such systems. The importance of optical memory systems as required for useful optical correlation systems is also discussed.

1.3 OPTICAL CORRELATION

As stated in Section 1.1, pattern recognition takes the form of comparing the unknown object or image with many reference images (or filters) until a match is found. The correlation function [1-15] gives a measure of the similarity of two images, as a function of their relative position. As such, the identity <u>and</u> position of the unknown object in the input data field can be determined from the location of a peak in the correlation data. Various optical correlation systems have been applied [1-16], and an overview of the early developments is given by VanderLugt [1-17]. The general features of optical pattern recognition have also been reviewed, amongst others by Casasent [1-18, 1-19].

The comparison of object and reference images can be undertaken in the spatial domain through a relative spatial shift of the two images, or in the spatial frequency domain (by application of the convolution theorem), through a multiplication of the object and reference image Fourier transforms. In the former, physical translation of the reference images is required to identify the location of the object, whereas with the latter, coherent light permits positional information to be encoded through the phase of the Fourier transform, where no physical translation is required. The two main systems available for undertaking coherent based correlation are the VanderLugt correlator [1-5], (based on complex matched filtering) and the Joint Transform Correlator (JTC) [1-20].

In essence, the matched filter approach maps the Fourier transform of the unknown input object onto a reference image Fourier transform pre-recorded on a transparency. The light transmitted through the transparency is the multiplication of the object and reference image Fourier transforms, and a further Fourier transformation results in the correlation of the input object and the reference image. The application of many reference images allows identification of the input object. Rapid complex optical information processing is possible with this architecture through placing many matched filters in the spatial frequency plane in quick succession. The main practical problem with the matched filter approach, however, is the need for strict alignment between the input object and the reference matched filter. The need for strict alignment is relieved with the JTC.

In the JTC, the *joint* power spectrum of both the unknown input object and the reference image is recorded on a square-law detector such as photographic film or a Spatial Light Modulator (SLM), and regardless of input alignment, Fourier transformation results in the data being centred. The Fourier transformation of the joint power spectrum results in the correlation of the input object and the reference image. Although the correlation operation can be performed with little regard to the position of the input object and the reference image, the JTC provides only a relatively slow processing speed. The speed of the VanderLugt correlator is limited by the speed with which the pre-recorded matched filters can be placed in the frequency plane, whereas with the JTC, it is for this reason that in general, the VanderLugt correlator is the most important of the two coherent optical processing systems.

The performance of the above optical correlation systems increases as the 'height' (power) of the correlation peak increases, whilst the width reduces. A higher correlation peak results in an improved recognition ability, whilst a reduction in the width improves the accuracy of object positioning. Since the correlation process utilises the Fourier plane, the Fourier transform of the aperture function of the optical system can result in the manifestation of sidelobes in the correlation plane, and if sufficiently high, they can incorrectly indicate the presence of additional input objects. Improvements in filter design therefore generally aim at increasing peak height and reducing peak width, whilst maintaining a maximum peak-to-sidelobe ratio.

In the matched filtering operation, both amplitude and phase information are present on the holographic spatial filter. Phase information is generally encoded by using a spatial carrier frequency (or reference beam) resulting in the requirement for an amplitude-only modulation device. With an amplitude-only recording, the diffraction efficiency of the filtering operation is low, where the maximum theoretical diffraction efficiency of a thin amplitude hologram is 6.25% [1-21]. A thin phase hologram, on the other hand, has a theoretical maximum diffraction efficiency of 34%. It is generally accepted [1-22] that phase information is considerably more important than amplitude information in preserving the visual quality of an image, and this was used by Horner and Gianino [1-23] where they developed the concept of the phase-only matched filter (POF). The POF concept simply matches the input object's phase

distribution, resulting in much higher optical transmissions, with higher correlation peaks. Although the Signal to Noise ratio (SNR) of the POF is lower than that of the classical matched filter, the actual peak height is much larger. This is a useful result, since in some circumstances, other sources of noise in the correlation system may be higher than the peak height available with the classical matched filter, giving a fractional SNR. The higher peak available with phase-only matched filtering can result in a useful SNR, i.e. greater than unity.

A useful model of the POF is that of a conventional matched filter, whose complex characteristics are described by $|\mathbf{H}(u,v)| \exp(-j\varphi(u,v))|$ (where (u,v) are the spatial frequencies) preceded by an amplitude-only filter $|\mathbf{H}(u,v)|^{-1}$ [1-24], resulting in a phase-only response. The reciprocal nature of the amplitude-only filter results in a high pass filtering effect, improving discrimination performance between two similar objects. A drawback of the POF, however, is that high correlation peaks may result from an input which may not look like that image used to generate the filter. This can occur when the phase information of the input is matched to that of the filter, and where the amplitude information may be entirely different. The filter can therefore be poor at rejecting non-similar input objects. Due to the emphasis on high frequency components, a further drawback of the POF is the sharp reduction in correlation peak height when the input image suffers small rotational or scale changes [1-25].

Photographic film has been the most common medium for displaying the matched filter. For a useful pattern recognition system, however, an unknown input object must be interrogated with many reference images in rapid succession. Although SLM's suffer from a limited resolution, a high cost and a questionable reliability, they are often applied to display the classical (amplitude-only) matched filter or the POF with a reasonably high frame rate. Some SLM's operate well in binary mode only, and was the motivation for the development of the binary-phase-only filter (BPOF) [1-26]. As with the POF, the BPOF remains poor at rejecting non-similar input objects. Flannery et al [1-27] however, have proposed the use of a ternary valued (-1, 0, +1) filter, which can be regarded as a product of a binary phase-only (-1, +1) and a binary amplitude-only filter (0, 1). The zero modulation term allows spectral components carrying mainly non-similar input object energy to be blocked. An improvement in the

ability to reject non-similar input objects is obtained at the expense of a decrease in the correlation peak height and an increase in the peak width, since the filter is no longer phase-only.

It is difficult for some SLM's to operate purely as amplitude-only or phase-only modulators with grey scale resolution, and in general they operate in a cross-coupled mode. Farn and Goodman [1-28], however, have developed an optimisation procedure which permits such cross-coupled devices to best display the filter data and give maximum intensity peaks at the centre of the output correlation plane. Similar work has been undertaken by Neto et al [1-29], where an iterative procedure has been used to give the optimum performance from a liquid crystal television (LCTV) SLM as applied to display kinoform data. The need for an ideal amplitude-only or phase-only device has therefore been relieved somewhat, however in applications where the intensity of the correlation peak must be as large as possible, phase-only devices remain desirable.

Pezzaniti and Chipman [1-30] have presented a technique for reducing the crosscoupled amplitude modulation in a LCTV configured to provide phase-only modulation. Mueller matrices [1-31] have been used to describe the effect of the LCTV on the polarization of an input wave. They determine specific input polarisations that are unaffected by the LCTV, such that the polarisation state of the output wave is almost identical to the input, where the former undergoes a phase change only. By describing the input polarization as a Stokes vector (\mathbf{x}), the Mueller matrix of the LCTV (\mathbf{A}) operates on the input such that

 $\mathbf{A}\mathbf{x} = \mathbf{E}\mathbf{x} \tag{1-2}$

where the scalar E gives the eigenvalues of the system. The eigenvalues describe the transmission losses through the LCTV, whilst the corresponding eigenvectors give the 'eigenpolarisation' states that propagate into and out of the device. The eigenpolarisation states are elliptical polarisations, and the elliptical retarder so developed has provided a maximum of 7% cross-coupled intensity modulation.

By viewing the POF as a product of an amplitude-only filter and a classical matched filter, one can consider the reciprocal response of the amplitude-only pre-

filter to be a non-linear operation. Kotzer et al [1-32] use this non-linearity to not only fabricate a POF, but also modify the *input* to be phase-only, resulting in further increases in the optical energy transfer. The main drawback of their proposal, however, is the distortion in the correlation output when multiple (identical) objects are input at regularly spaced intervals. The phase information in such composite input images (when Fourier transformed) comprises that phase information relating to the structure of the individual objects, and the linear phase tilts that give their position. The phase information regarding position is therefore coupled with the phase information resulting from the amplitude distribution. Ignoring the amplitude information can therefore result in neglecting important information regarding the location of the individual input objects, and can result in generating false correlation peaks, or suppressing existing peaks. This phenomenon is not a problem, however, when the objects are distributed randomly in the input image, as is often the case.

The non-linear filtering concept as applied to optical correlation was considered in general by Javidi [1-33], where a k^{th} law non-linearity is imposed electronically on the (linear) matched filter data. For a linear filter transfer function H, the non-linearity results in a thresholded filter function \mathbf{H}' , where $\mathbf{H}' \propto \mathbf{H}^k$. \mathbf{H}' can be considered as a sum of infinite harmonic terms, where the first harmonic retains the correct (linear) phase information of the matched filter function. The amplitude information, however, is modulated in proportion to the k^{th} power. By selecting specific values of k, the first harmonic can have different filtering characteristics, for example inverse filtering (k =-1), phase-only filtering (k = 0), and linear matched filtering (k = 1). All filtering operations can be undertaken without the need for fabricating the individual filters. Gualdron and Arsenault [1-34] have extended the application of non-linear matched filtering by forcing the non-linearity to be a function of spatial frequency. Their 'locally non-linear' matched filter has the properties of an inverse filter at low spatial frequencies, a POF at intermediate frequencies, and a matched filter at high frequencies. In this way, peak sharpness (inverse filter characteristics), noise resistance (POF characteristics), and good class discrimination (matched filter characteristics) are obtained simultaneously.

Similar operations to the ones described above have also been undertaken with the JTC. Javidi [1-35] has implemented non-linear thresholding of the joint power spectrum, resulting again in the option to undertake phase-only filtering or matched filtering operations without the need to fabricate the individual filters. As with the non-linear matched filters, the non-linear JTC has multiple harmonics, where the first harmonic retains the correct phase information of the (linear) matched filtering operation. Javidi [1-36] has also compared the relative performance of the non-linear JTC and the non-linear matched filter in terms of correlation peak power, peak-to-sidelobe ratio, and correlation peak width, as the severity of the non-linearity increases. In essence, his simulations have shown that as k decreases from 1 (linear matched filter) to zero (phase-only filter), for both types of correlator the correlation peak width reduces. Since the non-linearities are imposed on both the input object and reference images in the JTC, the improvements in the correlation signal are greater than that with the matched filter, where the non-linearities only affect the reference filter.

1.4 DISTORTION INVARIANCE WITH OPTICAL CORRELATORS

As considered in the previous section, by placing an emphasis on the higher spatial frequencies of an input object, improved recognition can result. Taking the POF as an example, although improved recognition between similar objects is available, the filter is very intolerant to any form of distortion in the input object, such as changes in the scale or the orientation of the object [1-25]. For example, a tank may easily be recognised with a filter designed to recognise the tank with its barrel pointing to the left. If the tank were to move, however, it may not be recognised. This is an extremely important issue in pattern recognition, and is why targets such as the 'sector-star' [1-4] are popular, due to its scale and rotational invariance properties. This section considers some of the important work surrounding distortion invariant pattern recognition.

The simplest way of obtaining distortion invariance is to interrogate the unknown input object with reference images subject to all possible distortions. Taking the example of recognising a tank, invariance is achievable by comparing the image of the tank with reference images comprising all possible rotations, scales and other geometric distortions. This process demands a very large memory system, and can be a time consuming process. An improvement is available by forming a composite filter, where for example, each filter may comprise a combination of the distorted reference images. A single correlation operation is then capable of identifying the input object subject to the class of distortions recorded within the single filter. The Synthetic Discriminant Function (SDF) [1-37] is such a composite filter and is a weighted linear combination of a set of reference images. The weights are selected such that the correlation output at the origin is the same for all input images belonging to the class of reference images used to generate the filter. Since an input is filtered with a linear combination of reference filters, and never a single reference filter however, the output is always a cross-correlation, and never an autocorrelation. The phase terms would cancel with the latter operation, giving the highest possible correlation output peak at the origin. The cross-correlation can result in spurious phase information spreading the data in the correlation plane, thereby reducing the correlation peak level at the origin.

A further drawback of the SDF was that noise was not considered in the original formulation. Vijaya Kumar [1-38], however, developed the 'Minimum Variance SDF' (MVSDF) which considers input images corrupted by additive noise. The output from the SDF filtering operation would be the desired output corrupted by a noise component. The MVSDF filter minimises the variance of the noise in the correlation plane, improving SNR.

Both the SDF and the MVSDF control the correlation value at the origin only, and therefore have difficulty in recognising objects shifted by unknown amounts. As such, Mahalanobis et al [1-39] developed the Minimum Average Correlation Energy (MACE) filter to combat this problem. This filter is not only capable of controlling the output correlation peaks, but also minimises the average energy in the correlation plane occurring from the correlations between the input image and all of the images within the composite filter structure. The minimised correlation energy results in an improvement in the SNR of the correlation signal, although the light efficiency is reduced somewhat due to the pre-whitening effect of the filter - see Chapter 5. The interested reader is referred to the review paper by Vijaya Kumar [1-40], where the above composite filters are considered in more detail.

A specific class of distortion is that of 2D in-plane rotation. This is a frequent problem in pattern recognition, where for example, the inspection of components on a conveyor belt can take place with fixed imaging conditions. As such, the principal distortion is that of 2D in-plane rotation. Much research effort has taken place developing rotationally invariant filters, and other than the SDF and subsequent variants, an important development was based on the circular harmonic expansion [1-41]. By expressing the complex Fourier series in polar co-ordinates, an image described by $f(r,\theta)$ can be considered to be composed from a sum of harmonics given by;

$$f(r,\theta) = \sum_{M=-\infty}^{\infty} f_M(r) \exp(jM\theta)$$
(1-3)

where M is the order of the harmonic, and where;

$$f_M(r) = \frac{1}{2\pi} \int_0^{2\pi} f(r,\theta) \exp(-jM\theta) d\theta$$
(1-4)

If Equation 1-3 describes a reference image, where a rotated version of the reference image, i.e. $f(r, \theta + \varepsilon)$, is used as the input object in an optical correlator, then the centre correlation output value can be shown [1-41] to be;

$$R(\varepsilon) = 2\pi \sum_{M=-\infty}^{\infty} \exp(jM\varepsilon) \int_{0}^{\infty} r \left| f_{M}(r) \right|^{2} dr$$
(1-5)

When a matched filter is synthesised on the basis of only one circular harmonic component (CHC) M = M' say, there is no summation in Equation 1-5, and the output *intensity* is independent of input object rotation, giving the desired result of both shift and rotational invariance. It is noted that the phase of the centre correlation value is a function of input object rotation (ε), however this is not a problem since

recognition is usually based on output intensity. Note that a phase detection system would allow the actual rotational position of the input object to be evaluated.

As a result of the CHC filter being comprised from only a small proportion of the input data, poor discrimination ability is obtained. An improvement in the filter's performance was demonstrated by Yau and Chang [1-42] through a simulation of the phase-only filtering principle. In addition, Yau et al [1-43] give a practical demonstration of phase-only CHC filtering through application of computer generated holography (CGH). Both papers demonstrate sharper correlation peaks whilst maintaining rotational invariance. Clearly the best way to improve the performance of the CHC filter, however, is to utilise more than one harmonic component. From Equation 1-5, the correlation output would, in this case, be a coherent sum of multiple complex vectors (phasors), where the final output intensity would depend on rotation angle, such that invariance to rotation would diminish. By synthesising many independent CHC filters, each matched to a different order, the multiple output correlation intensities could be added to improve performance [1-44], whilst maintaining rotational invariance. The disadvantage of this technique, however, is the requirement to measure the output from each harmonic separately.

Rotational invariance is an important sub-set of distortion invariance in general. There are also many applications that demand invariance to input object size or scale, for example in recognising different sized characters in printed text, or in guiding selfpropelled robotic machines. Similarly to the decomposition of an image into circular harmonics, an image can be decomposed into Mellin radial harmonics [1-45];

$$f(\rho,\theta) = \sum_{M=-\infty}^{\infty} f_M(\theta) \rho^{i2\pi M - 1}$$
(1-6)

where;

$$f_{M}(\theta) = \frac{1}{L} \int_{e^{-L}}^{1} f(\rho, \theta) \rho^{-i2\pi M - 1} \rho d\rho$$
(1-7)

M is the order of the harmonic, $\rho = r/r_{max}$ is the normalised radius, and $L = \ln(r_{max}) - \ln(r_{min})$, where r_{min} and r_{max} are the minimum and maximum radii respectfully. Again, similarly to the CHC filter, if a filter is matched to a single Mellin Radial Harmonic component (MRHC), scale invariance is achieved [1-45]. The correlation output peak intensity remains constant regardless of input scale, where the correlation peak phase gives a quantitative measure of input scale. The limitations of the CHC and MRHC filters are directly analogous, as are the techniques used to improve performance (such as applying the POF principle).

An alternative technique for providing distortion invariant pattern recognition applies co-ordinate transformation to map a change of scale or rotation in the input object into a translation of the correlation output peak. Mendlovic et al [1-46] have performed a co-ordinate transformation that transforms the co-ordinates x and y into x' and y' respectively such that;

$$x' = \ln(x)$$

$$y' = \ln(y)$$
(1-8)

When the original co-ordinate system is scaled by a factor of a, Equation 1-8 gives;

$$x' = \ln(ax) = \ln(a) + \ln(x)$$

$$y' = \ln(by) = \ln(b) + \ln(y)$$
(1-9)

If a function f(x', y') were input in an optical correlator, Equation 1-9 shows that (by application of the shift theorem) a scaling in the original co-ordinate system would result in a proportionate shift in the correlation output peak. If a 2D shift in the original co-ordinate system were to take place, the transformed co-ordinates would be given by;

$$x' = \ln(ax + d_x) = \ln(d_x)[\ln(a) + \ln(x)]$$

$$y' = \ln(by + d_y) = \ln(d_y)[\ln(b) + \ln(y)]$$
(1-10)

When f(x', y') is now input in an optical correlator, the scaling would result in a proportionate shift in the correlation peak as before, however the multiplicative factor in Equation 1-10 results in an output dependent on the shift in the input.

A pre-processing step is therefore required, where the power spectrum of the input image undergoes the co-ordinate transformation, and is used as the input data in an optical correlator. In this way, any shift in the input image is centred by the Fourier transformation, resulting in a system with shift and scale invariance. Since the power spectrum of the input image is formed, however, positional information is lost, and the location of the object in the input data field remains unknown.

Other co-ordinate transformations are possible, where for example Casasent and Psaltis [1-47] have described a logarithmic-polar transformation which results in simultaneous scale and rotational invariance. The co-ordinate transformation takes the form;

$$x' = \ln(r) = \ln(x^{2} + y^{2})^{1/2}$$

$$y' = \theta = -\tan^{-1}\left(\frac{y}{x}\right)$$
(1-11)

Similarly to the work of Mendlovic et al [1-46], scale invariance is achieved through the logarithmic transformation, where a scale change in the input object results in a proportionate shift in the correlation peak along one of the correlator output coordinates. Since any rotational change in the input object can be considered as a translation of the (θ) co-ordinate (as input to the optical correlator), such a translation results in a proportionate shift of the correlation peak along the other correlator output co-ordinate. Scale and rotational invariance are thus achieved simultaneously through this logarithmic-polar co-ordinate transformation. Again however, since the power spectrum is used as the input data, positional information is lost. In addition, some discrimination ability is lost, since some objects can have similar power spectra.

Casasent and Psaltis [1-47] implemented the co-ordinate transformation (as given in Equation 1-11) using a two stage process, where subsequent to the optical

Fourier transformation of the input object in cartesian co-ordinates, the geometric transformation was undertaken electronically. Mendlovic et al [1-46] however, utilise CGH techniques to optically implement the full transformation in a single stage process. This latter technique was also adopted by Casasent et al [1-48] who optically implemented the co-ordinate transformation given in Equation 1-11. In essence the optical implementation takes the form of multiplying the input object by a phase-only CGH, where upon subsequent optical Fourier transformation yields the desired co-ordinate transformation.

This section has presented a brief review of the most important techniques used for obtaining distortion invariant pattern recognition. Although the review is in no way exhaustive, it does present the main principles of the techniques available. Application of CHC or MRHC filtering techniques provide rotational and scale invariance respectively, whilst retaining positional information. Since both techniques utilise only a single harmonic component of the input object in performing recognition, typically discrimination ability is poor. Multiple harmonic components can be applied in succession to improve performance, however, such that the final correlation output value is the sum of the individual correlations [1-44]. This technique clearly requires a memory system so that the filters matched to various harmonic orders can be stored, and recalled in rapid succession.

Techniques which use co-ordinate transformation of the power spectrum utilise a much higher proportion of the information relating to the input object, and although scale and rotation invariance can be available together, positional information is lost. Ideally, a pattern recognition system should be capable of identifying *and* locating an input object with a high SNR when subject to geometric distortions such as scale or rotation. From this review, it is clear that the ideal recognition algorithm can not be achieved from a single filtering operation in an optical correlator. For example, an input may first of all be classified (without knowing the exact location of the object in the input data field) when subject to distortion such as scale or rotation. When the input scale and orientation have been assessed quantitatively, a memory system could place, in the filter plane, the filter correctly matched to the scale and orientation of the input object. A final matched (or perhaps phase-only) filtering operation would then identify the location of the object in the input data field. In general, multiple filtering operations will therefore be required for a useful pattern recognition system, where the optical memory will be a very important component of the system. The following section discusses optical-memory systems for use with pattern recognition systems.

1.5 OPTICAL MEMORY SYSTEMS

Digital memory is an advanced technology, and can be applied with optical systems, where an electronically addressable SLM (EASLM) can be used to display image data as held in a computer. The serial processing nature of digital systems, however, places a restriction on the speed of retrieving 2D image data. Truly parallel access optical memories are thus the subject of a great deal of research. A short introduction regarding the applications of optical memory systems is given by Neifeld et al [1-49], where their importance when used in an optical correlator has been indicated in the preceding sections.

A major area of development with regard to optical memories is that of the holographic multiplexed memory [1-50 to 1-53]. A hologram is recorded as an interferogram of an object beam and a reference beam. The object beam can only be recalled successfully if an exact duplicate of the reference beam illuminates the pre-recorded hologram. By changing the angle [1-50], the wavelength [1-51] or the spatial phase distribution [1-52] of the reference beam, many holograms can be multiplexed, or 'overlaid' on the same area of film. An object image can subsequently be recalled by illuminating the hologram with the appropriate reference beam. These techniques have been used to record as many as thousands of holograms on the same area of film. The diffraction efficiency of the individual holograms is, however, generally quite small.

If a thin layer of holographic emulsion is used to multiplex N images, the recording medium's dynamic range (and therefore SNR) is split into N, and therefore the maximum SNR that could be obtained by recording a single image is reduced by a factor of N. Normally a thick recording medium is used, such that many holograms can be recorded throughout the volume of the medium, where Bragg selectivity allows independent retrieval of an individual image. The diffraction efficiency of each stored

image generally reduces in proportion to the square of the number of holograms recorded [1-21, 1-52], and as such, in maintaining a usable diffraction efficiency, the maximum number of multiplexed images is limited.

A further drawback of holographic multiplexing is associated with recording multiplexed Fourier transform holograms, and applying the hologram in the spatial frequency plane of an optical correlator. Curtis and Psaltis [1-53] angularly multiplex many matched filters by changing the angle of the reference beam. When an unknown input is interrogated with the multiplexed matched filters, it is recognised if one of the multiplexed filters is identical to that input image. At this point, the specific reference beam used to record that matched filter is holographically recreated, and when brought to a focus, gives the correlation between the input image and the image used to synthesise the matched filter. If the input image shifts, however, the resulting linear phase tilt destroys the Bragg condition, destroying shift invariance in one direction. An arrangement of cylindrical lenses has been used [1-53], however, to overcome this problem, giving the 2D shift invariance property.

In general, holographic multiplexing results in storing images with a reduced SNR, and if this parameter is of concern, 'spatial multiplexing' is the simplest solution. By recording individual images on different regions of film, although larger areas of film are consumed, and some form of spatial addressing is required, a maximum SNR is maintained. Yu et al [1-54] present an addressing technique that uses a rotatable grating on a LCTV to direct the position of the recording beam, whereas Kirsch et al [1-55] improve addressing speed through the use of an acousto-optic deflector. Perhaps the most conceptually simple device for addressing spatially multiplexed images or matched filters is that of the parallel access optical disk. Disk based optical memories have the potential for recalling data at a very high rate and are discussed in the following paragraphs.

Jutamulia and Gregory [1-56] have proposed the application of a Kodak photo-CD (Compact Disk) player to download images (held on the CD) onto a LCTV as one of the inputs in a JTC. The underlying serial processing of the photo-CD system however restricts the rate of correlations to only 1 in every 2 seconds. Yu et al [1-57] proposed the application of a truly parallel access optical disk in a JTC, where images are stored in the spatial domain. Since scratches or specks of dirt on the disk could

potentially destroy correlation data, Yu et al [1-58] proposed storing the image data as Fourier transform holograms. In this way, dirt and scratches merely reduce the overall SNR rather than destroying correlation data. Kutanov and Ichioka [1-59] have also recorded images as Fourier transform holograms for use in an image plane correlator. An unknown image is displayed on a LCTV, and the reference data (as held on the optical disk) is inverse Fourier transformed and imaged onto the LCTV. As such, the transmitted light represents the correlation between the unknown image and the reference images. The system is illustrated in Figure 1-2, and shows how the conjugate reference image $g^*(x, y)$ is correlated with the unknown image f(x, y) as displayed on the LCTV. Since the reference images are imaged from a Fourier transform hologram, the centring property of the Fourier transform images $g^*(x, y)$ onto f(x, y) at (x=0, y=0) only, with the result that shift invariance is not available.

Psaltis et al [1-60] have made a significant contribution to the development of a parallel access optical disk memory based on a commercially available Sony Write-Once-Read-Many times (WORM) optical disk. Data is recorded on the Sony disk by the heating effect of focused laser spot. The heat causes two 2-element alloys deposited on the disk surface to form a single 4-element alloy. Binary data is retrieved from the disk due to the differences in reflectivity (R) of the unaffected 2-element alloy (R=5%) regions and the single 4-element alloy (R=12%) regions produced through the heating effect. The applications of the optical disk were that of storing the interconnection weights in a neural network, and storing both spatial domain data and Fourier transform holograms as reference data in image plane and VanderLugt based correlators respectfully. They note that their image plane (incoherent) correlator can only process unipolar information, and that their system is capable of 400 correlations per second on the basis of 100x100 pixel images.

In order to utilise more than a single track of images on an optical disk, in general a moving optical pick-up head is required. Marchand et al [1-61], however, have developed a 'motionless head parallel readout optical disk system'. By taking 1D slices of an image and computing the 1D Fourier transform holograms, these hologram slices are shifted relative to one another such that the 2D Fourier transform hologram is effectively elongated and positioned along a single radial line. The entire disk is
comprised of elongated 2D Fourier transform holograms positioned adjacent to one another on radial lines around the disk. Fast data processing is possible since all of the data on the disk can be retrieved in a single revolution. The drawbacks of the system, however, are the time taken to calculate the binary CGH's and the time taken to serially record the disk.

1.6 PREFACE

Pattern recognition is an expanding area of research, with much work undertaken within algorithm and filter development. Distortion invariance is a particular problem, which must be fully overcome before an all encompassing recognition system, capable of identifying an input object subject to any distortion, can be developed. At present, the usefulness of pattern recognition systems is generally limited to the identification of input objects subject to a limited set of distortions, such as shift and 2D in-plane rotation. The preceding sections of this chapter have discussed the nature of current distortion invariant algorithms, and have identified the importance of a large memory. The memory system is required not only for comparing an unknown input with many different images, but also for maintaining a high SNR whilst providing distortion and shift invariance.

This thesis presents work regarding the practical development of a high speed optical pattern recognition system, which uses a parallel access optical disk as the optical memory system. The work does not attempt to add to the already large area of research regarding filter design, but rather concentrates on the engineering issues associated with a practical solution, which have until now, been regarded as rather a secondary issue.

Chapter 2 presents the optical disk, where fabrication techniques and the nature of the data recording process are considered. The optical disk can be applied not only as an image store, but also as a means for processing information, and as such, the nature of the recording medium is investigated with regard to SNR and the information carrying capacity.

The practical issues surrounding the design and application of a parallel access optical disk system are considered in Chapter 3. A fully automated opto-mechanical control system has been developed, where automatic disk recording and the means for controlling the flow of reference image identification and correlation signals are all incorporated within the computer controlled system.

An important device used with the parallel access optical disk system is that of the optical input medium, the SLM. In this case, a commercially available LCTV was applied. Chapter 4 considers the issues surrounding the use of the LCTV as a complex light modulation device. The physical structure and the effects of the limited resolution are also considered.

In essence, Chapters 2,3 and 4 are concerned with specific practical issues of the pattern recognition system. In Chapter 5, the parallel access optical disk system is applied in various configurations of optical correlators for pattern recognition purposes. The configurations investigated use the optical disk not only as a memory store, but also as a means to process the input data in parallel, thereby maintaining high rates of information processing. An image plane correlator capable of processing both unipolar and bipolar data is considered, and subsequent to which two coherent based processors, that of the VanderLugt and anamorphic correlators, are also considered. The high rates of information processing available with optical systems are emphasised in Chapter 5, and are seen to be many orders of magnitude higher than those currently available with digital systems.

2

The Optical Disk Medium

An important aspect of the pattern recognition system developed here, is the device used for storing reference information - the optical disk. In order to maximise the data storage capacity of any optical storage medium, it is important to understand the physical and optical characteristics of the medium. There are many photo-sensitive materials available for data storage, all with different photo-chemical responses, resulting in a variety of physical and optical characteristics. These materials include silver halides, photopolymers, dichromated gelatin, photorefractives, azo-polymers and bacteriorhodopsin, whose characteristics have been well documented elsewhere [2-1, 2-2, 2-3]. As a result of the high optical sensitivity, stability, and commercial availability of Silver Halide photographic emulsions, this material was chosen as the storage medium for the optical disk. The specific emulsion chosen was that of Agfa-*Gevaert 8E75HD*, whose specification is given in Appendix A.

This chapter is concerned with describing the fabrication of the optical disk, and the measurement of pertinent photographic parameters. Since the optical disk is applied in information processing systems, the SNR is an important parameter, and is considered in some detail in the latter part of the chapter.

2.1 OPTICAL DISK FABRICATION

Agfa 8E75 holographic emulsion is the basis of the optical disk, and two different techniques of disk fabrication were investigated. In order to obtain a relatively flat recording medium, the first technique was merely to purchase commercially available holographic plates, comprised of 8E75 emulsion on 4mm (or 2mm) float glass, and cut into a circular shape. As the glass cutting process had to be undertaken under dark room conditions, however, it was deemed impossible to cut a central hole in the disk, which would have made the design of the disk holding mechanism relatively simple. As a result of using a solid glass disk, it was thus necessary to permanently bond a steel bracket to the rear surface of the disk, thereby permitting attachment to the disk holding mechanism. Figure 2-1 gives a photograph of an optical disk fabricated with this technique.

The alternative technique used for fabricating optical disks was based upon laminating Agfa 8E75 holographic *film* onto a Perspex (Methyl Methacrylate) substrate, pre-cut by a CO_2 laser. The CO_2 laser permits intricate shapes to be cut, and with a central hole, a simple 'nut and bolt' type holding mechanism can be applied. This eases mechanical design (as considered further in Chapter 3), however the lamination process does introduce some additional noise due to irregularities from trapped particles. An evaluation of disk noise is undertaken in Section 2.3.

As the laminated disk was the technique adopted in the applications discussed in Chapter 5, it is worth while briefly describing the lamination process used for fabricating the optical disks. Having pre-cut the Perspex disk to the desired shape, the central cut-out is retained, and temporarily taped back into place. Following the removal of one of the protective polyester liners, pressure rollers allow the *Flexmark* DFDA - *Double faced polyester film laminate* (supplied by the *FLEXcon Company* UK) to be adhered onto the Perspex disk. The second protective polyester liner is then removed and the 8E75 film is adhered onto the polyester laminate again with the pressure rollers. Excess 8E75 film is trimmed off, and then the film now covering the central hole in the disk is removed. A large hole cutting drill-bit was used to cut through the 8E75 and laminate from one side of the disk, with care taken not to penetrate the Perspex, and then finger pressure from the opposite side of the disk

allowed the central hole to be popped out, leaving the finished disk. Figure 2-2 gives a photograph of the optical disk so produced. Without clean room conditions, dust and other air-borne particles can be trapped in the lamination, and without sufficient care, air bubbles may also be trapped during the lamination process. It is important to avoid these bubbles, as they would act to shroud any data stored in that section of the film.

Following exposure of the disks, the 8E75 holographic film requires wet processing [2-4, 2-5], and depending on the application, one of two alternative development strategies were available. First of all the normal negative photographic development process was utilised to obtain 'black images on a white background' from a single photographic exposure. Secondly, at times it was desirable to undertake a reversal chemical development procedure which produced 'white images on a black background' still on the basis of a single photographic exposure. These two chemical procedures are now briefly explained.

The normal negative processing technique is well known and in essence, when exposed to light, a silver halide grain undergoes a complex photochemical change resulting in the manifestation of a few atoms of metallic silver, this being referred to as a development centre. Chemical *development* (*Kodak D19 in this case*) would eventually reduce all of the silver halide to silver, however, the presence of a few silver atoms acts as a catalyst in the chemical reaction, and thus speeds up the process. By developing over a short period of time, only the development centres undergo the amplification process, changing the entire silver halide grain into black metallic silver. The subsequent *fixing* process (*Kodak Unifix*) changes the unexposed silver halide into a soluble compound which can be washed away from the glass or film substrate, leaving the regions of black metallic silver behind.

The reversal development procedure is undertaken with a *Kodak T-MAX 100* Direct Positive Film Developing Outfit. In essence, the first developer performs the same function as that for normal negative processing. The film is then bleached which acts to remove the metallic silver, whilst leaving the unexposed silver halide behind. By redeveloping with a stronger developer, the originally unexposed regions are chemically reduced thereby forming metallic silver.

It is important to isolate the various chemical reactions, otherwise the transfer of the smallest amounts of one chemical into a bath of another can significantly affect the result. Extensive rinsing in fresh water in between steps was therefore strictly observed.

2.2 PHOTOGRAPHIC RECORDING PARAMETERS

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Conventional photography can be considered as a means to permanently record visual data in a manner akin to the response of the retina. Generally it is desirable to linearly map the incident light intensity into a printed image of corresponding intensity. This process is undertaken in two stages, where an initial exposure forms the photographic negative, subsequent to which a positive is formed by exposing a second piece of film with light transmitted through the first. Note that this two-stage process of forming a positive is not to be confused with the single stage reversal development procedure as considered in Section 2.1.

A widely used description of the response of the photographic emulsion is that of the Hurter-Driffield (H-D) curve [2-6], which relates the inverse of the intensity transmittance to exposure on a logarithmic scale. Figure 2-3 illustrates this relationship, where the full linear section of the curve is applied in conventional photography, thereby obtaining a large dynamic range for visual impact. The linear section of the curve can be described by;

$$D = \gamma \cdot \log(E) - D_o = \gamma \cdot \log(IT) - D_o$$
(2-1)

where γ is the film 'gamma', *E* is the exposure, *I* is the incident intensity occurring over an integration period *T*, and D₀ is the value of D that occurs where the straight line crosses the vertical axis. Since

$$\mathbf{D} = \log\left(\frac{1}{t_i}\right),\tag{2-2}$$

Equation 2-1 can be re-written as;

$$t_i = G. I^{-\gamma} \tag{2-3}$$

where t_i is the intensity transmittance of the film, and G is a constant. The mapping of incident intensity to the transmitted intensity of the photographic negative is thus non-linear for a positive gamma. The intensity transmittance of the photographic negative alone can be described by;

$$t_{i1} = G_1 \cdot \Gamma^{\gamma_1} \tag{2-4}$$

If this film is then placed adjacent to a second piece of unexposed film and both are illuminated with intensity I_o , then the intensity incident on the second film is $t_{i1}I_o$. The resulting intensity transmittance of the second film so formed is given by;

$$t_{i2} = G_2 (t_{i1} I_o)^{-\gamma_2} = G_2 (G_1 I^{-\gamma_1} I_o)^{-\gamma_2} = G_2 G_1^{-\gamma_2} I_o^{-\gamma_2} I^{\gamma_1 \gamma_2} = G_3 I^{\gamma_1 \gamma_2}$$
(2-5)

where γ_1 and γ_2 are the gamma values for the first and second pieces of film respectfully, and where G_1 , G_2 and G_3 are constants. Equation 2-5 shows that a linear mapping of intensity is possible with the two stage process when the overall gamma product (for *both* pieces of film) is unity.

In coherent based optical processing systems, the transmitted complex amplitude is of more interest, and it is thus more appropriate to consider the relationship between complex amplitude transmittance and exposure. By neglecting any phase irregularities in the emulsion substrate, the positive square root of the intensity transmittance can be taken as the (non-complex) amplitude transmittance, i.e.

$$t_a = (t_i)^{\frac{1}{2}}$$
(2-6)

Appendix A gives Agfa's measurement of t_a 'v' E and Figure 2-4 gives the experimental measurements of both the intensity and amplitude transmittances undertaken here. Note how the measured amplitude transmittance shows reasonable linearity over the range of exposures considered and that the intensity transmittance shows some non-linearity.

Similarly to the mathematical description for the linear section of the H-D curve, the t_a 'v' E curve as measured in Figure 2-4 can be approximated by a straight line over the range of exposures considered, and can be described by;

$$t_a = \beta . E + t_{ao} = \beta' . |A|^2 + t_{ao}$$
(2-7)

where the incident light distribution has an amplitude given by A. β and β' are constants, and t_{ao} is the value of t_a that occurs where the straight line crosses the vertical axis. Equation 2-7 indicates the 'square-law' behaviour of photographic film, in that the transmitted amplitude after development is linearly proportional to the exposure, which in turn, is proportional to the incident amplitude squared.

Although the measured data is in close agreement with that reported in the specification, differences in the choice of developer, temperature, concentration and development time, all contribute to variations in the amount of metallic silver so produced during chemical development. It is these factors which are expected to account for the discrepancies between the two measurements.

It is interesting to note that in general, the t_a 'v' *E* curve remains linear over a region of relatively high transmission, occurring close to the toe of the corresponding H-D curve. When exposures higher than those considered here are applied, both the intensity and amplitude transmittance curves become increasingly non-linear. This essentially states that further blackening of an already black film requires an exposure level greater than that anticipated through the assumption of a linear response. Images recorded to give a linear mapping of incident intensity to complex amplitude transmittance after development, thus look rather under-exposed when compared to conventional photographic images, and have a relatively small dynamic range.

In addition to the linearity of the photographic recording, there are other, more fundamental parameters, which affect the quality of the recorded data. The granularity of photographic film results in a random fluctuation superimposed on the information being recorded, and can be considered as a noise component controlling the SNR of the recorded information. The SNR is very important with regard to information processing, and is considered in Section 2.3 in some detail. The granularity also dictates the theoretical maximum resolution by application of the Nyquist sampling theorem, however, there are some effects which occur during the photographic exposure and development which alter the theoretical maximum resolution [2-4, 2-7]. These effects include the light scattering by silver halide grains resulting in a spreading of the 'ideal' incident light distribution, and 'halation', where reflections can produce halos around small bright regions. Holographic plates or film are, however, generally supplied with antihalation backing to prevent this particular effect. These two effects can reduce the theoretical maximum resolution as dictated by granularity, and therefore degrade visual quality.

In addition to the above effects, 'tanning' and 'edge-effects' can occur, which may act to improve visual quality. The tanning effect is where highly developed regions absorb less water and therefore dry quicker, shrinking and drawing in moist and flexible neighbouring regions, potentially sharpening the image. A relief image is produced however, and results in variations in the thickness of the developed emulsion in proportion to the incident light distribution, and can be a source of non-linearity as considered later. Edge-effects occur where the distribution and subsequent diffusion of developing reagents about an edge can increase the sharpness of an image, and is explained as follows. During the development process there is an excess of developing reagents on the side of an edge where exposure was low. These reagents tend to diffuse towards the highly exposed side of the edge, developing the grains in this region even further. As a result of this diffusion, there is less reagent available to develop the side of the edge where exposure was low, reducing the quantity of developed grains. As stated above, the effect of this phenomenon is to increase the sharpness of the edge.

Edge-effects and the tanning effect are examples of non-linearities that can occur during the photographic development process. The Modulation Transfer Function

(MTF), however, is a parameter that describes the film as a linear recording medium. The MTF plots the *maximum* diffraction efficiency obtained with fringes (of *maximum* modulation depth) recorded on the film, as a function of the spatial frequency of the fringes. For Agfa 8E75, the MTF has been shown [2-1] to be reasonably flat over a large bandwidth, where a maximum resolving power of approximately 5000 lines/mm is quoted in the specification (Appendix A). Features such as the MTF and diffraction efficiency depend not only on the characteristics of the film, but also on exposure and on the conditions of development.

When film is used to record data as considered above where there is a linear mapping between the incident intensity and the transmitted amplitude after development, it is important to maintain the mean (bias) exposure at the midpoint of the t_a 'v' E curve, and not allow the modulating term of the exposing light distribution to extend far beyond the linear region. If this occurs, non-linearities may be recorded with the photographic process [2-6], with saturation occurring around regions of high exposure. Under these conditions, Equation 2-7 may be written as;

$$t_a = t_{ao} + \beta_1 E + \beta_2 E^2 + \dots$$
(2-8)

If holographic recording of an incident object signal (f) and a reference signal (g) takes place, as in the coherent optical correlators considered in Chapter 5, then the amplitude transmittance is given by;

$$t_a = t_{ao} + \beta_1 T |f + g|^2 + \beta_2 T |f + g|^4 + \dots$$
(2-9)

As a result of saturation, the holographic fringes are 'clipped', giving higher order frequency components in the recorded data. The high order non-linear terms in Equation 2-9 can be considered as noise in the transmitted wavefront [2-1, 2-8], and result in a halo surrounding the required transmitted light distribution.

When an image is recorded linear with respect to amplitude transmittance, there still remains the possibility of non-linearity due to the manifestation of a relief image

through the tanning process. Since the magnitude of relief is directly proportional to the incident intensity, the *complex* amplitude transmittance can be modelled as;

$$\mathbf{t_a} = \exp(jkI) \cdot \left(t_{ao} + \beta TI\right) \tag{2-10}$$

where k is a constant. Assuming the phase component to be small, Equation 2-10 can be expanded to give;

$$\mathbf{t_a} = (1 + jkI) \cdot (t_{ao} + \beta TI) = (1 + jk|f + g|^2) \cdot (t_{ao} + \beta T|f + g|^2)$$

= $t_{ao} + (\beta T + jkt_{ao})|f + g|^2 + jk\beta T|f + g|^4$ (2-11)

which, again with a holographic recording, is seen to include the same form of nonlinearity as that in Equation 2-9.

The non-linearities as considered above can be thought of as noise in an otherwise linear system. In order to minimise the non-linearities, care should be taken to maintain correct exposure levels. With regard to the linear processing of complex amplitude, as considered above, the mean exposure level should be set at the midpoint of the linear region of the amplitude 'v' exposure curve.

2.3 SIGNAL TO NOISE RATIO OF DISK MEDIUM

2.3.1 Introduction

There are various sources of noise inherent in the design of the optical disk as considered above, and in general they act to limit the storage capacity, and consequently reduce the rate of information processing. When viewed through a microscope, the granularity of the film is apparent, as are the imperfections in the lamination introduced largely through air-borne particles. These noise sources modulate the mean level of the transmitted light, and are accompanied by sources of phase noise, which are of concern when the disk is applied in coherent optical processing systems. Irregularities in the Perspex substrate, the polyester laminating film, and the holographic film, all contribute to an uneven optical recording surface. A further source of phase noise is that associated with the relief of the developed image caused by the tanning process, as considered in the previous section. In an effort to evaluate phase noise independently of amplitude noise, it is tempting to remove amplitude modulation through a bleaching process. This is futile, however, since the bleaching converts the relief image into a so-called index image, where fluctuations in refractive index encode the data, giving further phase modulation. To reduce phase noise, a liquid gate can be applied [2-9], however, this is not appropriate with the optical disk system developed here.

Data is usually introduced into an optical system in either a transmissive or reflective mode. The optical disk developed here operates in transmission, and therefore the output light distribution is proportional to the incident light distribution multiplied by the disk attenuation. Any element of noise present on the multiplicative transmission mask thus results in a multiplicative noise component superimposed on the ideally transmitted light distribution. A 'number' can therefore be recorded on the optical disk as a mean amplitude transmittance + noise, or as a mean intensity transmittance + noise.

The SNR of the recorded number is dependent on the magnitude of the recorded signal. Since the SNR of devices such as the CCD camera are quoted at half maximum peak-to-peak voltage, for comparison, the SNR of the optical disk medium will be considered on the basis of a signal corresponding to half maximum (amplitude or intensity) transmittance. From Figure 2-4 it is apparent that the required exposure for film corresponding to $t_a = 0.5$ is greater than that corresponding to $t_i = 0.5$. With reference to Figure 2-4, Equation 2-7 can be approximated as;

$$t_a = \beta \cdot E + 1 \tag{2-12}$$

and for $t_a = 0.5$, the required exposure is given by;

$$E_{t_a=0.5} = \frac{-0.5}{\beta}$$
(2-13)

From Equation 2-6, the intensity transmittance is proportional to the square of the amplitude transmittance. The exposure $E_{t_i=0.5}$ required to give an intensity transmittance of 0.5 is defined by the relation;

$$\left(\beta E_{t_1=0.5} + 1\right)^2 = 0.5 \tag{2-14}$$

which results in;

$$E_{t_i=0.5} = \frac{-0.3}{\beta}$$
(2-15)

By comparing Equations 2-13 and 2-15, the exposure required to give $t_a = 0.5$ is 1.7 times greater than that required to give $t_i = 0.5$. Assuming the number of developed grains is proportional to exposure, film exposed to give $t_a = 0.5$ will have approximately 1.7 times more developed grains per unit area than film exposed to give $t_i = 0.5$. In Section 2.3.3 it will be shown that the SNR is proportional to the mean number of developed grains per unit area, and as such a number recorded in amplitude transmittance is expected to have a greater SNR than a number recorded in intensity transmittance.

In Sections 2.3.4 and 2.3.6, the SNR of numbers recorded in amplitude transmittance and intensity transmittance respectively are measured.

2.3.2 Evaluation of SNR

Regardless of whether data is recorded in amplitude or intensity transmittance, the signal is given by the mean transmittance, and the noise is given by the fluctuations about the mean level. The power ratio definition of SNR applies here, where;

$$SNR = 20.\log_{10}\left(\frac{\text{mean signal}}{\text{rms noise}}\right)$$
(2-16)

As indicated above, the SNR depends on the number of developed grains, and therefore on the area within which the data is recorded. When data is stored on only a small region of film, a limited number of grains are available to record the data. When more and more grains are available, the accuracy of the recorded data increases. As such, a larger area of film permits a larger SNR, and a relationship exists between SNR and film area. Sampling many identical areas of film allows a 'sample mean' transmission to be obtained for each sample area. By evaluating the variance of the sample mean values, the fluctuating or 'noise' term can be calculated, thereby evaluating the SNR for the specific area of film being considered. The SNR is thus evaluated through a consideration of variations in the mean transmittance of an ensemble set of statistically identical films, all exposed and developed identically. It may be sufficient for a number to be stored with an 8-bit system specification for example - in line with other system components such as an 8-bit digitising frame grabber. Each pixel would therefore have to be recorded on an area of film resulting in a SNR of $20\log_{10}(256/1) = 48dB$, such that accuracy is obtainable to ± 1 grey level.

By evaluating the SNR over a specific sample area, the recorded data has a maximum bandwidth whose cut-off frequency is defined by the Nyquist sampling theorem such that;

$$\mathbf{f}_{co} = \frac{1}{2d} \tag{2-17}$$

where f_{co} is the cut-off frequency and where *d* is the sample length. This definition of bandwidth gives the cut-off frequency for a signal recorded in *one dimension* on the film. The Time Bandwidth Product (TBP) of an electrical system gives a measure of the information that can be processed in 1D. Similarly, in 2D, the Space Bandwidth Product (SBP) gives a measure of the information capacity of a 2D storage medium. In general, the SBP is given by the product of the area and the bandwidth squared.

As a consequence of Parseval's theorem [2-6], the SNR can also be evaluated when the power spectrum of the signal is formed, resulting in;

$$SNR = 10.\log_{10}\left(\frac{\text{signal power}}{\text{noise power}}\right)$$
(2-18)

where the 'noise power' is taken over the bandwidth as given by Equation 2-17. For small and large bandwidths, the noise powers are small and large, and Equation 2-18 gives high and low SNR's respectively. Note that small and large bandwidths have correspondingly large and small areas of film available to record the data, thus confirming the above discussion of SNR based in the spatial domain.

Figure 2-5 illustrates data as held in the spatial and spatial frequency domains, and shows that if a carrier frequency is applied to encode data through fringe modulation depth, the SNR can be evaluated in the frequency plane in one of two locations. Since in general, the noise in optical systems is multiplicative, by the convolution theorem [2-6] the noise spectrum appears at the location of each delta function in the frequency plane, where the magnitude of each is proportional to the area under the corresponding delta function. In Figure 2-5, the SNR can thus be evaluated at the location of the DC (area ratio a/b) or at the location of the carrier frequency (area ratio c/d). In Section 2.3.6, the SNR is evaluated at the location of the carrier frequency.

Similarly to evaluating the SNR in the spatial domain, the SNR can be determined about the carrier frequency in the spatial frequency domain by evaluating the variance in the sample mean values of peak signal power as obtained from an ensemble set of statistically identical films, all interferometrically exposed and developed identically. An approximate value for the SNR can, however, be evaluated on the basis of a single piece of film. This alternative procedure takes the peak signal power available from a single set of fringes, and assumes that any variations in this peak level, (as would be obtained from many different sets of fringes), can be approximated by the noise spectrum surrounding the peak. As discussed above, SNR is dependent on the area of film used to record the data, or rather on the bandwidth, and thus the power spectrum easily permits the noise per bandwidth of interest to be evaluated.

It is important to distinguish between additive and multiplicative noise at this point, since different sources of noise may be introduced depending on the measurement conditions. The distinction is best illustrated in the frequency plane where a white noise spectral density is assumed over the bandwidth of interest. When a signal is described by a mean transmittance, noise is introduced through a multiplication of the ideal signal and the disk noise. Figure 2-6(a) illustrates this situation, indicating that the noise is purely multiplicative. When a signal is encoded through fringe modulation depth, however, the noise spectrum is dealt out at the location of each delta function in the frequency domain, as in Figure 2-6(b). As such the noise surrounding the carrier frequency delta function is composed from the noise spectrum dealt out there and an additive component associated with the noise spectrum dealt out at the location of the DC. Depending on the bandwidth of the noise spectrum and on the frequency of the carrier signal, the noise at the carrier frequency may be multiplicative and/or additive. This is an important issue when the SNR is being evaluated in the spatial frequency domain, and can result in a reduction in the measured value.

2.3.3 A Theoretical Model of Intensity Transmittance

A useful model for photographic film is that of the overlapping circular grain model [2-10, 2-11]. Figure 2-7 illustrates the layout of the grains in the photographic film, and in essence the model assumes that the grains are circular, of equal size, and are randomly distributed in an area with Poisson statistics. If the mean number of developed grains in any area (A) is given by (μ) , then the probability of there being (n) developed grains in a particular sample area (A) is given by the Poisson distribution function;

$$p(n) = \frac{\mu^n . \exp(-\mu)}{n!}$$
 (2-19)

From this model it is possible to evaluate the mean intensity transmittance through an area of film as a function of the number of developed grains. The model assumes that a grain is either perfectly transparent or opaque, and an integration of the point by point transmission over the area (A) results in an expression for the mean intensity transmittance [2-11];

$$t_i = \exp\left(\frac{-\mu . a}{A}\right),\tag{2-20}$$

where (a) is the area of a single grain. Figure 2-8 plots Equation 2-20 for a/A = 0.0001, and shows that at first, the intensity transmittance decreases almost linearly with the increasing number of grains, up until grain overlapping begins to occur, where the transmittance decreases non-linearly with the mean number of grains. Over the linear section of the curve, the Poisson model states that the variance in the mean number of grains, as measured from many different sample areas, equals the mean number of grains [2-12]. From Equation 2-16, the SNR can therefore be evaluated as a function of the mean number of grains used to record the data, and is given by;

SNR = 20.log₁₀
$$\left(\frac{\mu}{\sigma}\right)$$
 = 10.log₁₀ $\left(\frac{\mu}{\sqrt{\mu}}\right)^2$ = 10.log₁₀ (μ) , (2-21)

where σ^2 is the variance in the sample mean values, and where σ is the standard deviation. It can be seen that the SNR is proportional to the mean number of grains used to record the data, and assuming that the grains are distributed in 2D, and that the film emulsion has zero depth, the SNR is proportional to area, as considered earlier.

In order to record a number in intensity transmittance corresponding to $t_i = 0.5$, the mean number of developed grains in an area (A) is expected to be approximately half the total number of grains in that area. In Appendix A, the mean grain size is approximately 35x35nm, and therefore the theoretical value for a SNR corresponding to $t_i = 0.5$ is given from Equation 2-21 as approximately;

SNR_{*t_i*=0.5} = 10 log₁₀
$$\left(\frac{A}{(2)(35 \times 10^{-9})^2} \right)$$
 (2-22)

Equation 2-22 thus gives the theoretical relationship between SNR and Area for an intensity transmittance corresponding to $t_i = 0.5$.

As discussed in Section 2.3.1, a number recorded to give an amplitude transmittance of $t_a = 0.5$ requires an exposure approximately 1.7 times greater than that required to record the equivalent number in intensity transmittance. Assuming the number of developed grains to be proportional to exposure, Equation 2-21 gives the SNR of the data corresponding to $t_a = 0.5$ to be $10\log_{10}(1.7) \approx 2 \,\mathrm{dB}$ greater than that corresponding to $t_i = 0.5$.

The linear Poisson model is based on relatively high intensity transmittances, where the mean number of developed grains is low. Non-linearities appear when the mean number of grains increases, and grain overlapping occurs. This condition has been considered earlier in Equation 2-8, where the presence of non-linear terms would give additional blackening of the film, reducing the transmittance.

Figure 2-6 has illustrated the multiplicative nature of the noise when data is recorded as a mean transmittance. With the Poisson model, the noise is given by the standard deviation, and as the mean number of grains increases, the noise also increases, again indicating the multiplicative nature of the noise for high overall transmittances.

2.3.4 Measurement of Intensity Transmittance SNR

In the following, the spatial domain is used, and Equation 2-16 is applied in evaluating the film SNR. A microscope fitted with a 100x objective is used in conjunction with a frame grabber to obtain 2D images of the film. The frame grabber used throughout the course of this work was a VISION*plus* 8-bit '*Imaging Technology Inc. ITEX Overlay Frame Grabber (OFG)*' [2-13]. The image data is analysed in order to obtain values of the mean transmittance and the rms of the variations in the mean values (the standard

deviation). By taking many square sub-sections of area (A), side length (L), from the digitised image, the mean transmittance can be evaluated for each of the sub-sections and the rms of the variation in the mean values can also be determined. This data permits the SNR to be evaluated for a 1D bandwidth with a cut-off frequency given by Equation 2-17, where in this case d = L.

Film exposed at the mid-point of the t_i 'v' *E* curve was used as the basis of the measurement. By initially viewing an exposed film whose intensity transmittance was maximum, the microscope illumination intensity was set to obtain near saturation of the digitised image, thereby utilising the full dynamic range of the frame grabber. A piece of film with $t_i = 0.5$ was then observed through the microscope, resulting in an image with approximately half maximum grey level.

The procedure for calculating the SNR for a specific area (and therefore bandwidth) of film is described with reference to Figure 2-9. N different images are digitised, and therefore N different 'data cells', each of area (A) exist at co-ordinates (x, y). By evaluating the mean grey level of each data cell $A_n(x, y)$, N mean levels are known. This data set of size N gives sufficient information with which to evaluate a single number for the SNR of a specific area (A). By performing this exercise for all co-ordinates (x, y), many SNR values are returned from which an average value can be obtained. This exercise can be repeated for different sized areas, thereby obtaining a relationship between SNR and film area.

A simpler procedure for obtaining the same data could be undertaken with only a single image, by merely using different areas of the image to obtain the data set of size *N*. This simpler procedure, however, cannot account for low frequency noise components across any single image resulting from an uneven illumination intensity or noise within the microscope objective. The simpler procedure would therefore give inaccurate results due to artificial broadening of the spread of the mean grey levels held within the data set, giving a low SNR.

The measurement undertaken here utilises 10 different images, i.e. N=10, where Figure 2-10 shows one such digitised image. A plot of SNR(dB) 'v' $\log_{10}(Area)$ obtained with this method for 8E75 film is given in Figure 2-11, where for comparison, the theoretical response as described by Equation 2-22 is also given. By

extrapolation, Figure 2-11 can be used to evaluate the SNR that would be available from any film area. For example, if a number is to be recorded with an 8-bit dynamic range, then a SNR of 48dB is required. From the experimental results in Figure 2-11, a piece of film measuring approximately 0.044 by $0.044 = 1.9 \times 10^{-3} \text{mm}^2$ is required for a SNR of 48dB, where the 1D bandwidth is therefore limited to 11.4 cycles/mm by Equation 2-17.

The experimental results are thought to differ from the theoretical response due to the shape of the noise spectral density obtained with the experimental measurement. The linear Poisson model randomly distributes grains over the film, resulting in a uniform 'white' noise spectral density, whereas the measured data comprises mainly low frequency noise, as considered later. The reasons for the white noise spectral density in the model are given as follows. The Poisson model has a linear response up until grain overlapping begins to occur. At this point, the developed grains can be considered to be positioned directly adjacent to one another, thereby obtaining a maximum bandwidth of $(1 / 2g_{av})$ by the Nyquist sampling theorem, where g_{av} is the mean grain size. Across this bandwidth, the noise spectrum is approximately white since the autocorrelation theorem [2-6] gives the power spectrum as the Fourier transform of the autocorrelation of g_{av} . Since g_{av} is small, the spectrum is wide-spread and approximately white, with a bandwidth corresponding to $(1 / 2g_{av})$.

As stated above, the measured data comprises mainly low frequency noise. This can be observed by calculating 1D Fourier transforms across the rows of the image given in Figure 2-10. The mean 1D Fourier transform so obtained is given in Figure 2-12, where the DC component of the spectrum has been removed to show the non-flat nature of the noise spectral density. With regard to the Poisson model, when the area doubles (and the mean number of grains per area is fixed), the 1D bandwidth reduces by a factor of $\sqrt{2}$, and due to the uniform noise spectral density, the total noise power (in 2D) reduces by a factor of 2. Equation 2-18 therefore gives a 3dB increase in the SNR. Due to the non-flat noise spectral density of the measured data, however, the total noise power does not reduce by a factor of 2, and the SNR thus increases at a lower rate.

There are a number of reasons why the data obtained largely comprises low frequency sources of noise. First of all there is an effect that occurs in real film, known

as 'clumping' [2-4]. Due to the random distribution of grains across an area of emulsion and indeed throughout the depth of the emulsion, a number of grains may lie close together resulting in a 'clump' or conversely, where the grains are sparse, a 'hole'. This clumping effect results in the manifestation of an excess of low frequency noise components.

The main reason for an excess of low frequency noise in the image data is, however, thought to be due to the characteristics of the imaging conditions being applied. First of all, the transfer function of the microscope objective lens is considered. Since the 8E75 film has a maximum resolution of 5000 lines/mm, the spatial bandwidth of the film extends to a theoretical maximum of 2500cycles/mm. In conjunction with the 100x microscope objective, the OFG (512x768 pixels) used to digitise the images of the film can be seen, from Figure 2-10, to permit observation of a maximum spatial frequency of 384/0.0906 = 4240 cycles/mm. Note, however, that the CCD array, whose dimensions are 4.8x5.7mm comprises 582x752 pixels. The bottom 70 (582-512) rows of the CCD image are therefore not displayed on the digitised image, In the horizontal direction, however, the 752 pixels are spread over the 768 pixels, so in actual fact the maximum spatial frequency is 376/0.0906 = 4150cycles/mm. This is clearly more than sufficient to observe information which utilises the full spatial bandwidth of the film. The numerical aperture (NA) of the microscope objective, however, imposes a limitation on the maximum spatial frequency entering the imaging system. For monochromatic illumination, the coherent transfer function of the lens is rectangular with a cut-off frequency given by;

$$f_{co} = \frac{NA}{\lambda}$$
(2-23)

where λ is the wavelength. The microscope used here, however, illuminates the film with incoherent (white light), and the *incoherent transfer function* dictates the maximum spatial frequency entering the imaging system.

In a linear imaging system (see Chapter 5) illuminated with coherent light, the distribution of complex amplitudes in the input is linearly mapped to a distribution of complex amplitudes in the output. For a single point (impulse) of amplitude in the

input, the output is given by the coherent impulse response function (h_c) . In an incoherently illuminated system, however, the distribution of intensities in the input is linearly mapped to a distribution of intensities in the output. For a single point (impulse) of intensity in the input, the output is therefore given by $h_c \cdot h_c^* = |h_c|^2$. Since the transfer function is given by the Fourier transform of the impulse response function, then the (monochromatic) incoherent transfer function is proportional to the autocorrelation of the coherent transfer function. For a more thorough mathematical treatment of this result, the reader is referred to Goodman [2-6].

For a microscope objective (NA = 0.9) illuminated with coherent light of wavelength λ =520nm (corresponding to the mid-point of the visible spectrum), Equation 2-23 gives a rectangular (in 1D) coherent transfer function with a bandwidth of 1750 cycles/mm. The corresponding (monochromatic) incoherent transfer function (in 1D) is therefore triangular with a bandwidth of 3500 cycles/mm. Note that the 2D autocorrelation of a circular aperture is only approximately triangular in cross section, where the high spatial frequencies are in actual fact attenuated more than the lower. Also note that for a truly incoherent light source, such as the white light source used here, due to components from all of the visible spectrum, the incoherent transfer function is not a perfect triangle. As illustrated in Figure 2-13, the incoherent transfer function is composed from the individual (monochromatic) triangular transfer functions resulting from the different wavelengths. The overall affect is that the high spatial frequency content of the real film noise spectrum is attenuated by the incoherent transfer function, resulting in the domination of low spatial frequencies in the data obtained by the CCD, giving a noise spectrum such as that observed in Figure 2-12.

In addition to the incoherent transfer function's attenuating effect, since the Depth of Focus (DOF) of the microscope is many times smaller than the thickness of the emulsion, some planes of grains are imaged out-of-focus. The out-of-focus planes can be considered as ideal image data whose noise spectrum has been low pass filtered, and as such they contribute additional low frequency components into the final image.

A final effect of the microscope imaging system is that associated with any aberrations that may be present. An ideal (approximately triangular shaped) incoherent transfer function can only be obtained with a diffraction limited imaging system. In general, aberrations can reduce the high frequency components of the data, and therefore reduce the effective bandwidth [2-6].

The measured data can be thought of as that predicted by the Poisson model subject to the low pass filtering effect associated largely with the transfer function of the incoherent imaging system. Figure 2-14 illustrates the *expected* differences between the measured data and the Poisson model of SNR 'v' Area. The Poisson model shows a linear response as a result of the uniform noise spectral density. The film area A₁ corresponds to the 1D bandwidth $\frac{1}{2\sqrt{A_1}}$, and is the bandwidth of the noise spectrum obtained with the measured data. As this area reduces, the bandwidth increases, and since the measured noise is zero beyond this bandwidth, the SNR remains constant. The film area A₂ corresponds to the 1D bandwidth $\frac{1}{2\sqrt{A_2}}$, and

is the bandwidth below which the noise spectrum of the measured data and the model are assumed to be both uniform. Above this area, the SNR 'v' Area relationship is the same for both the measured data and the Poisson model. The actual data in Figure 2-11 is similar to that of Figure 2-14, however Figure 2-11 indicates that the measured noise spectrum does not become uniform as the bandwidth reduces (as the area increases). The theoretical and measured responses in Figure 2-11 cross at an area corresponding to a 1D bandwidth of approximately 170 cycles/mm, and from Figure 2-12, the spectrum is not uniform. The differences in the theoretical and measured responses of Figure 2-11 are, as stated earlier, thought to be largely due to the low pass filtering effect of the imaging system. As will become clear, SNR's above 41dB are of interest, and for the purposes of calculation, the measured data in Figure 2-11 will be used throughout in providing a worst case estimate for the area of film required for a specific SNR.

In order to compare photographic film with a CCD camera / frame grabber as image storage mediums, it is first necessary to quantify the SNR available with a typical CCD/frame grabber system. As stated earlier, the SNR of a CCD camera is

generally quoted at half maximum peak-to-peak voltage or half maximum grey level, and most modern systems are specified as having SNR's in the region of 48-52dB. Assuming the quantisation error introduced in the analogue to digital converter is the main source of noise in the OFG, then for an 8-bit dynamic range, the SNR can be

approximated [2-14] as SNR =
$$20.\log_{10}\left(\frac{256}{1/\sqrt{12}}\right) = 59 \,\text{dB}$$
. The actual SNR

available from the CCD/OFG system used here was measured, however, in order to obtain a realistic value for such a storage medium. An extended, diffuse light source illuminated the CCD and was used to provide a variable mean grey level as captured with the OFG. By evaluating the mean and the rms of each image as the grey level is increased, a graph of SNR versus mean grey level can be plotted. Figure 2-15 gives such a plot, and shows how a SNR of approximately $20\log_{10}(112) = 41$ dB is available at half maximum mean grey level. The amount of film required to record an image whose quality is equal to that of a realistic digital system can now be evaluated. As a brief aside it is interesting to compare this SNR with the likes of the CD [2-15]. Typically 90dB are available with 16-bit systems, and the improvement due to applying digital technology is clear.

From the measured data in Figure 2-11, each pixel can be recorded with a SNR of 41dB when 8.9×10^{-5} mm² of 8E75 film are used (approximately $9.5 \times 9.5 \mu$ m). For a 'TV quality' image of 512x768 pixels, a piece of film measuring 4.8×7.2 mm is required, which is actually slightly greater than the size of the CCD sensing element that would comprise the same number of pixels (4.2×5.8 mm). From these measurements, in terms of SNR and area, the typical CCD element has improved performance over the 8E75 film. Note that the Poisson model predicts a lower area of film for this value of SNR, i.e. approximately 2.8x4.3mm.

As a final consideration, it is worth while appreciating how other monochrome films perform in comparison to Agfa 8E75 in terms of storage capacity. The analysis undertaken in this section was repeated for both 'Kodak Technical Pan' and 'Ilford FP4 Plus' monochrome films. Figure 2-16 illustrates the different responses of the three films for comparison. First of all it is clear that, for a certain sized piece of film, the SNR increases with the film resolution; the resolution of the Ilford, Kodak, and Agfa films being specified as 180, 320 and 5000 lines/mm respectively. Similarly to

the previous calculation for Agfa film, a 512x768 pixel / 41dB image can be recorded on 101x152mm of Kodak film, and on 108x162mm of Ilford film, and one can conclude that these two films are not useful for recording large amounts of data with a high SNR.

2.3.5 Measurement of Phase Flatness

Section 2.3.6 gives an evaluation of the SNR available with a number recorded in amplitude transmittance with coherent light. Since the phase is an important factor in coherent systems, a measurement of the overall phase flatness of the optical disk is considered in this section.

When coherent light is used to record a multiplicative transmission mask, the incident light *intensity* is recorded. Normal photographic development techniques permit the subsequent modulation of incident amplitude information, however if the emulsion is bleached, it is possible to modulate the phase of the incident coherent light. When amplitude-only modulation is required, as is the case here, it is important not to modulate phase, otherwise the cross-coupled modulation could provide sources of additional noise. Any phase modulation would scatter the ideally transmitted light distribution, broaden the diffraction limited spot size, and can be considered as noise when an image is to be recovered from the recording medium, or indeed when the medium is to be used as a means for processing complex data.

As a first approximation, the phase flatness can be quantitatively assessed by viewing the affect on parallel fringes when the disk is placed in one arm of a Mach-Zehnder interferometer. Figure 2-17 gives a typical result showing how the mean fringe position is shifted, as measured with a He/Ne laser of wavelength $\lambda = 633$ nm. From the figure, the disk is seen to be optically flat to approximately two wavelengths of light across the height of the image, i.e. a gradient of 0.15mm in 1m on average. Across an image area of 1.5mm say, the disk is therefore flat to approximately $\lambda/3$. It must be noted that this measurement of phase flatness is a macro measurement, giving some idea as to the overall flatness of the disk, and thus the differences in the relative phase transmission from one side of the disk to the other. With regard to the spatial frequency distribution of the phase modulation, the interferometer can not be applied

easily for obtaining such information. Forming the power spectrum in the back focal plane of a convex lens is the best method for obtaining the required data, however, the amplitude spectrum accompanies the phase spectrum, and the two are difficult to separate [2-9]. Throughout the course of this work, no attempt has been made to observe the phase spectrum independently, however Figure 2-18, as discussed in Section 2.3.6, gives an illustration of the optical power spectrum obtained with the film. This figure indicates the relatively low spatial frequency content of the phase spectrum [2-9], whose phase noise power is very small in comparison to the signal peak.

2.3.6 Measurement of Amplitude Transmittance SNR

In the following, the spatial frequency domain is used, and Equation 2-18 is applied in evaluating the film SNR. Two off-axis coherent beams are used to illuminate 8E75 film, thereby recording interference fringes, such as those considered in Figure 2-5. Both beams are of equal intensity, with the exposure of each corresponding to the midpoint of the t_a 'v' E curve in Figure 2-4. Sinusoidal fringes of maximum modulation depth are thus recorded linearly, resulting in only a single frequency component in the Fourier Transform, where a maximum diffraction efficiency of approximately 3% has been measured. The frequency of the fringes was measured as approximately 780 cycles/mm, and as can be seen in Ref.[2-1], the MTF remains close to the maximum for frequencies well in excess of that recorded here. The diffraction efficiency is therefore approximately the maximum that can be obtained. By re-illuminating the developed film with one of the original incident beams, a Fourier Transform lens is used to form the power spectrum on a CCD camera. Assuming a linear relationship between incident power and the grey level of the 8-bit digitised image subsequently obtained, the power spectrum can be evaluated in terms of grey level. The CCD is centred on the peak in the power spectrum corresponding to the frequency of the sinusoidal fringes.

Ideally, in order to obtain a direct comparison with the previous result, variations in the signal power obtained through an ensemble set of fringes, recorded under identical conditions, on different areas of film, should be measured. These variations

could therefore be used to evaluate the SNR as before, where it is important to take into consideration the area of the film that is illuminated. As considered in Section 2.3.2, however, an approximation can be obtained on the basis of a single set of fringes. Equation 2-18 is applied in evaluating SNR, where the noise power is taken as the *mean* noise power summed across the bandwidth of interest.

Essentially two different images of the signal are grabbed from the CCD camera as held in the frequency plane. First of all, maximum available light power is utilised in order to saturate the CCD sensing element, thereby allowing the noise power to extend into and form a grey level distribution within the 8-bit dynamic range of the OFG. Secondly, a neutral density (ND) filter is applied in order to reduce the incident light power to such an extent that the signal peak can be measured within the dynamic range of the CCD/OFG. Taking the transmission characteristics of the ND filter into account (in this case $t_i = 0.1\%$), the signal power can be calculated in terms of grey level.

Figure 2-18 gives 1D plots of the power spectrum obtained with and without the ND filter present, where the frequency is given with respect to the frequency of the sinusoidal fringes. Note that a lens of focal length f = 40mm is used in forming the Fourier Transform on the CCD element (whose dimensions are 4.8x5.7mm). The figure plots a single row of the 2D image, where the maximum spatial frequency u_{max} across the row is determined by the size of the CCD and the size of the Fourier transforming lens and is given by;

$$u_{\text{max}} = \frac{x_u}{\lambda f} = \frac{\left(5.7 \times 10^{-3}/2\right)}{\left(633 \times 10^{-9}\right) \cdot \left(40 \times 10^{-3}\right)} = 112 \text{ cycles/ mm}$$
(2-24)

where x_u is the location of the spatial frequency u in the power spectrum. Note also that the 1D plot in Figure 2-18 is for illustrative purposes alone, and that the calculation is undertaken in 2D. Figure 2-18 also shows that the signal power is largely limited to a very narrow spike, where the radius of the diffraction limited spot is given by;

$$r_s = 1.22 \frac{f \lambda}{D} \tag{2-25}$$

where D is the diameter of the illuminating beam. For D = 4 mm, f = 40 mm, Equation 2-25 gives the radius of the diffraction limited spot as 7.7µm, which from Section 2.3.4 closely matches the mean resolution available with the CCD (7.9µm). The plot of noise power in Figure 2-18 shows how some of the noise is associated with a spreading of the diffraction limited spot as a result of phase noise. The mean noise power is calculated on the basis of all of the noise as distributed either side of the diffraction limited spot. For a direct comparison with the previous result it is necessary to evaluate the effect of the illuminating beam area. The 4mm diameter beam has an area of 12.6mm², and as an approximation, a square side length of $\sqrt{12.6}$ mm results in a 1D bandwidth of 0.14cycles/mm from Equation 2-17 The noise power is therefore taken as the mean noise power summed across this bandwidth. With the above considerations, the SNR available with a number recorded as $t_a = 0.5$ on 12.6mm² of film has been calculated as approximately 76dB.

2.3.7 Comparison in the Measured Values of SNR

In Section 2.3.4, the SNR has been evaluated as a function of area, for a number recorded in intensity transmittance as $t_i = 0.5$. With reference to Figure 2-11, extrapolation from the measured data to an area of 12.6mm² gives a SNR of 69dB, whereas the Poisson model suggests 97dB. The 69dB is underestimated since it is expected that the measured data would follow the Poisson model for large areas.

In Section 2.3.6, a number recorded in amplitude transmittance as $t_a = 0.5$ has resulted in a SNR of 76dB, again for 12.6mm² of film. The coherent based measurement technique was an approximation since the *mean* noise power was taken over the bandwidth of interest, resulting in some phase noise being included in the calculation. Additive noise may also have been present in the measurement (see Section 2.3.2). These two sources of additional noise give an underestimated approximation for the SNR. It is difficult to obtain an accurate comparison of film SNR from the two techniques considered. The measured and theoretical values of SNR for a number recorded as $t_i = 0.5$ are only similar where the two responses cross in Figure 2-11, where the corresponding 1D bandwidth is around 170 cycles/mm. The sampling interval for such a frequency is given from Equation 2-17 as approximately 3µm. Using the coherent based measurement technique to obtain a comparative value of SNR, a set of fringes measuring 3x3µm would have to be interrogated, which is not practically possible. A SNR of around 41dB is of interest in recording TV-quality data, and since the measured data in Figure 2-11 matches the theoretical response well, the former will be used throughout for the purposes of calculation.

In the applications in Chapter 5, data is recorded in both intensity and amplitude transmittance. From Section 2.3.3, a number recorded as $t_a = 0.5$ is expected to have a SNR only 2dB higher than a number recorded as $t_i = 0.5$. As such, the calculations in Chapter 5 regarding data recorded as both amplitude and intensity transmittance will be based on the measured results in Figure 2-11.

2.4 SUMMARY OF DISK SPECIFICATION

The optical disk developed and applied throughout the work described in this thesis utilises Agfa-Gevaert 8E75HD holographic emulsion as the recording medium. The recording area of the optical disk is limited by a minimum radius as well as the physical size of the disk. The minimum radius is set by the closest position the final imaging lens (microscope objective) can be positioned next to the central hub of the disk holding mechanism, and corresponds to $r_{min} = 37$ mm, with an outer radius $r_{max} = 75$ mm. This results in an active area of 13370mm².

If the disk were to be applied for the storage of binary data, the maximum resolution of 5000 lines/mm could apply. The full active area therefore permits the storage of approximately 3.34×10^{11} bits of information, which theoretically corresponds to 41.78Gbyte. The optical systems as described in Chapter 5, however, are analogue, and a minimum SNR dictates a minimum size of the recorded data.

Across a region of approximately 1.5mm, the disk is flat to $\lambda/3$, and as such phase noise is not considered to be a problem. Grain noise dominates, and in order to record a pixel with a SNR of 41dB (approximately 7-bit), an area corresponding to approximately 9.5x9.5µm, i.e. $8.9x10^{-5}$ mm² is required. This corresponds to a disk capacity of approximately 130Mbyte.

Some of the recording area is required for data labelling however, and in some applications (see Chapter 5), each image block must be separated by a space corresponding to the size of an individual image. The maximum storage capacity of the disk is thus reduced, and the optical disk medium therefore offers no advantage in storage capacity over commercially available memory systems such as the CD [2-15] or the magneto-optic [2-16], where the maximum capacity is in the region of 650Mbyte. The parallelism of the system developed and applied here, however, fundamentally offers large increases in the data access and processing rates [2-17].

3

Parallel Access Optical Disk System Design

In order to provide a useful memory system, it is desirable to record as much data on the chosen medium as possible, as a larger memory can be applied in many more widespread and diverse applications of pattern recognition and optical processing. As considered in Chapter 2, the optical disk has the potential for storing large amounts of data, and consequently an automated recording and 'playback' system was developed. This chapter is concerned with describing and analysing the limitations of the mechanical and system design parameters associated with the Parallel Access Optical Disk System (PAODS) so developed.

3.1 MECHANICAL DESIGN

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3.1.1 Opto-Mechanical Considerations

In order to hold as much data as possible, ideally the PAODS should utilise the full theoretical SBP available with the recording medium, thereby maximising disk capacity. The SBP is governed by the disk recording area and the maximum spatial frequency that can be recorded. As considered in Chapter 2, however, as the spatial frequency of the recorded data increases, not only does the diffraction efficiency

decrease (as described by the film MTF), but the SNR of the data also decreases. This is because there are fewer grains available to record the fluctuations in high frequency data. In preserving a minimum SNR, each pixel of the recorded data must utilise a minimum number of grains, and therefore a minimum area of film. In general it is therefore not possible to utilise the full SBP available with the film whilst maintaining a minimum SNR over the bandwidth of the recorded data.

For data recorded with a SNR equivalent to that of a CCD / frame grabber 'TVquality' image (i.e. 41dB), Chapter 2 dictates a requirement of $8.9 \times 10^{-5} \text{mm}^2$ (approximately 9.5x9.5µm) of film for each pixel. This pixel size imposes restrictions on the imaging conditions that are required to faithfully record such small resolvable regions. By the Nyquist sampling theorem (Equation 2-17), the minimum pixel size gives a maximum spatial frequency of 53 cycles/mm. In order to capture and record such a frequency, Equation 2-23 dictates a minimum NA of 0.033, where a wavelength of $\lambda = 633$ nm has been assumed. The NA of an imaging system is an important parameter as it controls the DOF, where a small DOF occurs when high demagnification optics apply, giving small images on the disk. Positioning the disk in a plane perpendicular to the optical axis (i.e. the vertical plane) allows data to be recorded on different regions of the disk, simply through disk rotation. If the disk wobbles as it rotates, a small DOF may result in some images being recorded out-offocus. In order to ensure that all images on the disk remain in focus, it is important to maintain a DOF greater than the lateral displacement of the disk as caused by wobble. A common engineering term for disk wobble is that of 'run-out', and is used here.

A simple approach in evaluating DOF applies geometrical optics, where the DOF is evaluated as that distance along the optical axis moved (in either direction) from the ideal point of focus, such that rays meeting at this point are a maximum of $\pi/2$ radians out of phase. This 'Rayleigh quarter-wave limit' [3-1] gives the DOF as approximately;

$$DOF = 4\lambda \cdot \left(f/\#\right)^2 = \frac{\lambda}{\left(NA\right)^2}$$
(3-1)

where the relationship;

$$f/\# \approx \frac{1}{2.NA} \tag{3-2}$$

has been applied. For a NA = 0.033, the DOF is thus evaluated from Equation 3-1 as approximately 580µm. In contrast to commercially available Compact Disk (CD) systems [3-2], due to the relatively large DOF, no auto-focusing was deemed necessary. A fixed focus system is therefore the basis of the PAODS design.

When the application of the optical disk memory demands an increase in the number of images stored, or in the rate of information processing, smaller and smaller images must be recorded, (along with increases in the rotational speed of the disk). In obtaining smaller images, higher de-magnification optics must be applied, which increases the *NA*, thereby reducing the DOF. Disk run-out and SNR are two features which control the minimum size of image data that can be recorded on the disk. The DOF must always be larger than disk run-out, and in order to record smaller and smaller images, run-out must be kept to a minimum. With regard to SNR, as image size is reduced, the pixel size becomes smaller, and therefore the number of grains used to record the pixel data is reduced. For a specific minimum SNR, the minimum size of recorded image data is therefore fixed.

A fundamental issue surrounding the mechanics of applying the optical disk in an optical correlator is that of image alignment. In simple terms, the optical correlators considered in Chapter 5 operate by casting incident light from a LCTV onto data prerecorded on the disk, and where the correlation signal is derived from the transmitted light. It is important that the incident distribution is aligned with the data held on the disk, otherwise reduced or false correlation signals can occur. Misalignment (or 'eccentricity') occurs when a disk is replaced in the PAODS following chemical development, and where there is a positional error between the initial (recording) circular track position and the 'playback' track position. In obtaining an alignment accuracy of 1 pixel, the maximum eccentricity that can be tolerated is given by the pixel size of the recorded data. Conversely, for an eccentricity fixed by manufacturing tolerances, the minimum pixel size must be made to be equivalent to the magnitude of eccentricity.

Chapter 5 discusses correlators that use the optical disk with data recorded in both the spatial and spatial frequency domains. With data recorded in the spatial domain, an increased eccentricity can be accounted for by increasing the size of the pixels recorded on the disk, thereby reducing the SBP of the recording. With data recorded in the spatial frequency domain, an increased eccentricity can be accounted for, again, by increasing the size of the pixels recorded on the disk. This can be accomplished by reducing the size of the aperture in the input (spatial) domain, before Fourier transformation takes place, where again, the SBP of the recording becomes smaller.

In essence, the PAODS was designed and manufactured in order to provide a minimum of eccentricity and disk run-out with currently available CNC machinery. Two disk clamping designs were investigated, where both the initial and final designs allow multiple tracks of images to be recorded through the use of two motors, one to turn the disk, and one to move the entire rotating disk on a linear translation stage. As stated earlier, the optical disk has the potential for storing large amounts of data, and consequently an automated recording and 'playback' system is required. The adopted technique utilises an 'image label' concept, whereby individual images on the disk are labelled with rectangular 'tick' marks adjacent to the images. A subsequent tick counting procedure enables image identification, where the features of this procedure are considered further in Section 3.3

3.1.2 Initial Design of the PAODS

The initial design of the PAODS concentrated on achieving a minimum of disk runout, which would result in the potential for storing a large amount of data, as the small DOF would permit the application of high magnification lenses. The design was developed on the basis of the optical disk medium, which in this case, as mentioned in Chapter 2, was holographic (glass) plates cut into disks. In principle, this medium provides the best method for obtaining a minimum run-out, since float glass is specified flat to within 10µm. The two critical design factors, that of disk run-out and

eccentricity, were minimised through the design feature as sketched in Figure 3-1. Disk run-out was minimised by pressing the disk firmly against a machined datum surface, as a result of spring pressure being applied through angular contact bearings, a holding plate and a centring bracket. A combination of bearing tilt and a rubber 'O' ring ensured that it was only the machined surface which corrected the position of the disk in the vertical plane. A maximum run-out of approximately 20µm at a disk radius of 70mm was measured, giving an 'angular deviation' of approximately 0.015°. It is interesting to note that the commercially available CD is specified with a maximum angular deviation of 0.6°, 40 times worse than that achieved here. In Figure 3-1, a sliding fit between the holding plate and the centring bracket maintained a minimum of eccentricity. Figure 3-2 shows a photograph of the first system, where the motor, normally connected via a belt, has been disconnected. Clearly, the small run-out only requires a DOF of similar size, and from Section 3.1.1, the de-magnification of the recording optics could be increased substantially, thereby increasing the number of images stored on the disk. The SNR limitation, however, restricts the ultimate minimum size of recorded data.

Although a very small run-out was achievable with this design, there were some inherent drawbacks worth noting here. First of all, disk fabrication was not easy, where both glass cutting and the concentric bonding of a steel centring bracket to the rear face of the disk had to be undertaken under dark room conditions. Secondly, when the PAODS was used in an optical processor, it was observed that upon disk replacement, the error associated with eccentricity was significant.

A further drawback of the initial design was that the image labelling unit was fixed to, and thus traversed with the optical disk clamping system when a new track of images was to be recorded. This resulted in only a single track of labels being recorded on the outskirts of a disk that could comprise many tracks of images. In order for the image labelling system to function, a radial distribution of labelled images had to be recorded as is indicated in Figure 3-3. This configuration significantly reduces the number of images that can be recorded on a single disk. In order to improve image packing density, the final design incorporated a labelling system that provided each image with its own label, where the labelling system is considered further in Section 3.3.3.

3.1.3 Final Design of the PAODS

The final design of the PAODS incorporates features which alleviate the problems of the initial design, and improve concentricity on disk replacement. The fundamental difference between the initial and final designs is that the latter utilises holographic film laminated onto Perspex disks as the storage medium, as mentioned in Chapter 2. Figure 3-4 gives a photograph of the PAODS manufactured to accommodate the new optical disks. For reference, Figure 3-5 gives the three views of the PAODS, originally drawn in 3rd angle orthographic projection.

The central hole in the optical disk relieves the need for any centring bracket, and has been carefully designed to assist in obtaining concentricity on disk replacement. Figure 3-6 illustrates how the three point positioning rests on the tapered shaft of the PAODS, and that a keyway has been incorporated to ensure that, when replaced, any disk sits in a predetermined rotary position. As the large nut and washer are tightened into place, the tapered shaft begins to retract through the action of a spring hidden in the bearing housing. The tapered shaft is fully retracted when the optical disk is pressed firmly against the machined datum surface, as in the initial design, thereby controlling run-out. Approximately 40µm of run-out at a disk radius of 70mm was present with this design, corresponding to an angular deviation of 0.03°, still much improved over that available with commercially available CD systems. The increased value of run-out with this final design is attributable to the use of Perspex sheets. The Perspex is not supplied perfectly flat, and the heat from the CO₂ laser may result in additional warping. Note, however, that this run-out is well within the DOF restriction considered in Section 3.1.1. An eccentricity of $\pm 13\mu m$ has been measured with this design, and in maintaining alignment to an accuracy of 1 pixel, the effect of eccentricity is an increase in the required pixel size to 26µm. As considered in Section 3.1.1, the SBP of the recorded data must therefore be reduced in order to account for this eccentricity. The resolution of the data recorded (either in the spatial or in the spatial frequency domains) on the disk must be restricted in order to maintain an alignment accuracy of 1 pixel.

A further point of interest is that this design incorporates in-line coupling between the stepper motors and the two driven shafts. This reduces the overall size of
the device, and the nature of the coupling devices passively reduces the transmission of any vibration from the motors to the disk.

3.2 SYSTEM CONTROL

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When the PAODS is used in a practical processing system, considerable automation is required. Figure 3-7 gives a schematic of the main components of the generalised system. The PC is the central feature, and controls all aspects of the system, giving a fully automated recording procedure with correlation output signal monitoring and control. Many images are held within the PC as a source of reference data to be recorded on the disk. The OFG relays the image data to an EASLM, in this case a '*Casio TV5100*' LCTV. During the recording phase, the electronic shutter is opened to relay the image from the LCTV, via demagnification optics to the disk, and obtain the correct image exposure. Simultaneously, the laser diode in the image labelling unit is fired appropriately to record the image label on the disk. Following an index of the stepper motor to the adjacent image position, or the next track, the frame grabber downloads the next image to be recorded, and the process repeats.

An 'Amplicon Liveline PC14AT' [3-3] digital input/output board is used as the interface for controlling the laser diode and the electronic shutter, and indeed for monitoring and controlling the image label and correlation signals, through on-board digital counters. For reference, Figure 3-8 gives a more detailed sketch of the input/output configurations associated with the PC14AT board. Once the reference data has been recorded on the disk, the PC merely performs software polling of the D-type flip-flop latch output, until a correlation signal (above a pre-determined threshold level) arrives. At this point, the image label count value is latched, thereby identifying which of the reference images gave the high correlation peak. Subsequent to this, the flip-flop is reset, ready for any further correlation signals. When applied with the spatial domain correlator, as described in Chapter 5, the above procedure requires only a single correlation peak photodiode, where the correlation signal is a one-dimensional function of time alone. When a 2D correlation output signal is obtained, for example with the VanderLugt correlator in Chapter 5, a 2D output detector is required, and the

individual detector pixels must be thresholded in parallel. The generalised system in Figure 3-7 is therefore not directly appropriate for a 2D correlation signal. In such applications, however, the image labels are used to time the firing of a pulsed laser, as considered in the following section.

3.3 IMAGE LABELLING

3.3.1 Signal Analysis

An important aspect of the PAODS is that of the image labelling system. For example, if the PAODS were to be utilised merely as an image store, and the 250th image of the 35th row were to be recalled, then clearly an automated labelling system would be required. Alternatively, when applied as a source of reference data in an optical correlation system, it is important to know which reference image resulted in a high correlation output signal. Figure 3-9 illustrates the main features of the labelling system, and in essence, a laser diode illuminates a rectangular (razor blade) aperture, and a microscope objective forms a de-magnified image of the aperture on the disk, thereby forming the image label. During the recording phase, an image and its label are recorded simultaneously, where the rectangular labels have been measured as approximately 780x90µm. During 'playback', as the disk rotates, the laser diode permanently illuminates the disk, and the black (or 'white') sharp image labels cross the path of the laser beam. Since the disk is illuminated with an image of the aperture, a triangular shaped waveform is obtained from the photodiode. The first graph in Figure 3-10 gives a typical example of the signal obtained when the labels are recorded 'black on a white background'. This analogue signal must be conditioned and converted into digital form before the PC14AT on-board digital counters can give the individual reference images a count value. Figure 3-11 illustrates the required signal processing, and in essence, the objective is to pick out the leading edge of the image label - line A-A. The noisy analogue signal is added to a variable DC offset, thereby shifting the signal to clamp any voltage above line B-B to 5V. Following amplification, the signal is compared with a variable DC voltage level - line C-C, to

threshold the signal, resulting in a 0/5V square waveform. The signal is then fed through a timer to allow variable output pulse widths to be obtained. For reference, Figure 3-12 gives the circuit diagram for the electronic system used.

In general, the triangular waveform is not perfect, as exaggerated in Figure 3-11, and contains a noise component which fluctuates from tick to tick. The point in time at which the voltage line C-C (in Figure 3-11) thresholds the signal therefore varies, depending on the nature of the noise. Clearly, the 'squarer' the original signal, the less of an effect is the noise component on the image locating accuracy. After the image labels have been recorded, replacing the original microscope objective with one of higher magnification results in the photodiode signal looking more like a square waveform. The second graph in Figure 3-10 shows a typical signal obtained with a 'playback' microscope objective 3 times the magnification of the recording objective. Figure 3-13 models these illuminating conditions in order to estimate the maximum image locating error associated with a non-square unconditioned image label signal. Taking a worst case SNR of 5:1, the maximum timing error is given in Figure 3-13 as $\pm e$, where 2e corresponds to one fifth the width of the illuminating beam. With a 90µm wide image label, the illuminating beam is 30µm, and therefore the maximum image locating error is approximately $\pm 3\mu m$, which from Section 3.1.1 is seen to be less than the size of an individual pixel.

3.3.2 Timing Principles

As previously considered, the images stored on the disk are labelled with a count value from the digital counter on the PC14AT board. The input to the counter is a square waveform, as generated from the conditioned image labelling unit photodiode signal. The 16-bit programmable down-counting timer/counters on the PC14AT board are primarily used to identify images. If one track of a disk holds say 500 images, then a counter could be programmed to count from 65535 to 65035, where a single pulse from the photodiode down-counts by one. When the last programmed count value has been reached, the next pulse (i.e. the first pulse), acts to reset the counter and start counting from 65535 once more. To recall the 250th image say, the motor would turn

whilst the counter is monitored, and when the appropriate count value has been attained, the motor would stop.

For application in the spatial domain correlator configuration (see Chapter 5), where the correlation signal is a 1D function of time alone, a further use of the counter/timer is possible. By running a fast timer in between adjacent image labels, it is possible to use the timer value to interpolate across the input field and identify when, and thus where, in the input field (in one dimension) is the object you are trying to identify. For example, in Figure 3-14, counter 1 pulse train gives the image number, in this case images 58, 57 and 56. When this waveform is fed to the gate of counter 2, set up as a timer with a high frequency clock input signal (4MHz in this case), each gate input pulse resets the counter to the original starting count value. As the disk rotates, and the optical processor performs a 1D cross correlation between say image 58 and the input image, the correlation peak may occur at any point between counter 2 values of say, t_1 =55000 and t_2 =37000, depending upon where, in the input field, is image 58. The value latched and returned for counter 2 allows a spatial interpolation across the input field to accurately determine the position of image 58 in the input data field. The spread of counter 2 values (t_1-t_2) , and indeed the accuracy of interpolation, depends on the relative position between the reference images and their labels, the counter frequency, and on the rotational speed of the disk. A calibration of the system is therefore necessary before successful operation, which can, however, be accomplished within the controlling software, assuming the relative position between the tick marks and the images is known. This interpolation in one dimension gives a single dimensional shift invariance property associated with the input, purely as a result of disk rotation., i.e. if the input moves a certain amount, the interpolative count value shifts in proportion to the input image shift.

3.3.3 The Effects of Different Disk Image Configurations

In the conventional CD player, control circuitry dictates the rotational speed of the disk motor, and maintains a constant linear track velocity of between 1.2 and 1.4ms^{-1} , with a mean speed of $1.3 \pm 0.01 \text{ms}^{-1}$. This and timebase correction electronics maintain a steady data output rate from the disk itself, regardless of track position, thus ensuring

that the data is read and output correctly. It is equally important to be able to control the flow of data from the PAODS developed here, and this depends on the configuration of images on the disk, the image labelling system, and indeed on the nature of the optical system the PAODS is applied in.

In general, the image label count alone can be utilised regardless of the rotational speed (and thus the linear track velocity) of the disk. When the application demands use of the interpolative count, however, it is important to control the linear track velocity at any track radius to an extent that the relative time (and therefore position) between images and labels is known. This is necessary in order to successfully interpolate across any image on the disk when applied in the spatial domain correlator, or indeed when any image on the disk is to be recalled and positioned accurately within imaging optics, for example when the system is applied as a memory store. Depending on the relative position between the image and label, and on rotational speed, a timing calibration is necessary before the interpolative count can be used effectively.

As mentioned previously in Section 3.1.2, the initial design of the PAODS could only support images configured in a radial distribution on the disk, and that only a single track of image labels are present on the outskirts of the disk. Regardless of whether a constant angular velocity or a constant linear track velocity mode were to be applied, some timing calibration is required to determine the start (t_1) and stop (t_2) count values obtained with the interpolative counter/timer, as these values are dependent on the track radius. Knowledge of this spread of counter values allows a spatial interpolation across any image and Figure 3-15 illustrates the timing scenario for this configuration of images. For an image at radius rl, the spread of interpolative counter values is $(t_{1(r1)} - t_{2(r1)})$, whereas at radius r2, the spread of count values is $(t_{1(r2)})$ - $t_{2(r_2)}$). For a constant linear track velocity, calibration would require the values t_1 and t₂ to be determined for all radii. Driving with a constant angular velocity removes the need for elaborate motor control circuitry, however, a timing calibration is still required for all radii. It is possible, however, to utilise the known geometry of image layout and the known disk speeds in order to calculate the expected start / stop times for the interpolative count for any radius. Due to the inaccuracies associated with disk speed and imperfect image positioning, however, a more accurate timing calibration is achievable through experimental measurement.

As briefly mentioned in Section 3.1.2, the final design of the PAODS permits each image to have its own label, resulting in the potential for an increased image packing density. The final design has its image recording optics spatially separate from the image labelling optics, and in contrast to the initial design, both are fixed with respect to any motion of the disk. Figure 3-16 illustrates this configuration for one track of images. Since the optics are separated from the motion of the disk, each image can be seen to have its own label, regardless of track position. It is noted, however, that although each image has an adjacent image label, this specific label is that label associated with an image some distance away.

The final system design permits the relative position between an image and its label to be constant regardless of track position, and in order for only one timing calibration to be necessary a constant linear track velocity is required. A constant linear track velocity is accompanied with a variable angular rotational speed, and as such, motor control circuitry is required to accurately control the angular velocity of the disk depending upon which track of images is being utilised. As an illustration of the accuracy of spatial interpolation, with a linear track velocity of 1.3ms⁻¹, the 4MHz counter/timer permits interpolation across an image height of 1.36mm with a positional accuracy of 0.325µm. From Section 3.1.1, the interpolation resolution is therefore less than the size of an individual pixel.

3.4 FURTHER TIMING CONSIDERATIONS

When the PAODS is applied in the spatial domain correlator, a further positional inaccuracy can occur as a result of the software based polling of the latch in Figure 3-8. If a correlation peak were to occur immediately subsequent to a software poll, the counter values are latched at a later time, that corresponding to the time between polls. This introduces an error in the interpolative count value so obtained, resulting in a positional inaccuracy of the correlation peak. By incorporating a hardware latching

process, however, as soon as the correlation peak arrives, the counters would be immediately latched, giving virtually zero positional error of this kind.

Again, due to the use of software based polling, there is a restriction in how close two adjacent identical images can be in the input data field, if they are both to be recognised and located appropriately. In the first instance the separation is, of course, limited by the size and resolution of the SLM. When the interpolative count is applied to obtain their location, the minimum separation is also dictated by the polling frequency. The minimum separation can be inferred from the speed of the disk and the time taken between subsequent polls, and can be reduced by increasing the polling frequency, (through improvements in the hardware/software interfacing).

In coherent systems such as the VanderLugt correlator, it is the resolution of the 2D output signal detector and the diffraction limited correlation spot size which limit the separation between adjacent images in the input data field. The separation can be minimised here through improvements in optical design and by applying a high resolution 2D detector. The frame-rate of the 2D detector is also very important with regard to information processing speed, and can result in a restriction of the disk rotational speed, and thereby affect the required speed of the interfacing hardware/software and indeed the necessary laser power in obtaining an easily detectable number of photons in the output correlation peak.

In the VanderLugt correlator, an entire 2D image is input in parallel, and as such a pulsed laser is required. When the PAODS is applied with such a system, it is the image label signal which triggers the Q-switch of the laser, thereby illuminating that image associated with the image label causing the laser pulse. It is important that the triggering signal fires the laser at exactly the correct time, otherwise a misaligned image may be 'clocked' into the optical system. Correct timing depends on the relative position between the images / image labels / laser beam, and on the speed of the disk and the track position. There is, however, a delay between the generation of a pulse from the image labelling system and the actual firing of the laser. This delay occurs as a result of the speed of the signal conditioning electronics, the time taken for communication, and the response time of the electronics used to control the acoustooptic crystal used in the Q-switching operation. The set-up of Figure 3-17 allows this delay to be measured. Photodiode D1 gives the image label signal, and after being

passed through the signal conditioning unit, is relayed to both the oscilloscope and the external input of the laser to control the Q-switching. The signal subsequently obtained from the second photodiode D2 as the laser fires is also fed to the oscilloscope. A comparison of the two scope traces gives the delay, and has been measured as 1.06msec. For a disk turning with a linear track velocity of 1.3ms⁻¹, this timing delay corresponds to a positional error of approximately 1.4mm. This error could give severe misalignment, however, certain measures can prevent any error at all. Depending on the rotational speed of the disk, careful positioning of the laser can account for the misalignment, or alternatively, electronic hardware can give an additional time delay before the laser is fired, resulting in the laser illuminating the neighbouring image. This results in the associated image label count number shifting by one, which can, however, be accounted for within the controlling software.

3.5 SUMMARY OF PAODS SPECIFICATION

The PAODS was designed and manufactured in order to provide a minimum of eccentricity and disk run-out with currently available CNC machinery. An eccentricity of $\pm 13\mu$ m was present with the final design which dictated a minimum pixel size of 26µm in maintaining an alignment accuracy of 1 pixel. A run-out of 40µm at a disk radius of 70mm was also present. With regard to locating recorded data, the timing system as considered in Section 3.3 gave a positional accuracy ($\pm 3\mu$ m) of less that one pixel.

Throughout this thesis a linear track velocity of 1.3ms⁻¹ has been assumed in order to compare data access rates and processing power with commercially available CD systems. The system developed here, however, revolved with a mean linear track velocity of approximately 3ms⁻¹, thus giving a proportionately higher processing speed.

4

Spatial Light Modulation with a Liquid Crystal Television

In general, SLM's are used as either incoherent to coherent image converters, or indeed to actually perform complex processing of incident coherent light. Electronically addressable SLM's are the most useful, as different images can be displayed easily, in rapid succession. These devices are typically purpose built, however, and can therefore be prohibitively expensive, and are quite often unreliable. Due to the commercial exploitation of LCTV's, their price and reliability has generated much interest in applying these devices as SLM's.

A LCTV has been applied in the work undertaken here, specifically a Casio TV-5100. In the optical correlators discussed in Chapter 5, the LCTV is used to display information through intensity transmittance, where this data is used to record reference images on the optical disk, and to display unknown objects for subsequent recognition. In general however, the LCTV could be used to display complex data, when positioned in either the input plane or the filter plane of an optical correlator. It is for these reasons that this chapter is concerned with evaluating the characteristics of the LCTV in terms of amplitude and phase modulation. An examination of the effects of the pixelated structure and the limited resolution when applied in an optical system is also undertaken.

4.1 LIGHT MODULATING CHARACTERISTICS

4.1.1 Liquid Crystal Physics

The chemistry and physics of liquid crystals are well documented by Goodman [4-1], and are summarised as follows.

Liquid crystals are a class of materials that exist in a mesomorphic state, that is they have a definite ordered structure, but have a viscosity comparable to that of liquids. Substances which form liquid crystals are almost always organic and are composed of molecules which possess a high degree of asymmetry - long thin molecules or flat planar ones. Due to the shape of the molecules, the physical properties (such as refractive index, dielectric constant, and thermal conductivity) tend to be anisotropic, however the application of an external stimulus can render the material isotropic, which is important for display technology.

Liquid crystals can be categorised into three groups - *nematic*, *smectic* and *cholesteric*, and Figure 4-1(a) illustrates their structure. In nematic liquid crystals, the molecules tend to be parallel, but their positions are random. In smectic liquid crystals, the molecules are parallel, and are stacked in parallel layers within which they have random positions. The molecules cannot move between layers. In cholesteric liquid crystals, the structure is similar to that of the nematic phase, however, the molecular orientation undergoes a helical rotation about an axis.

An important parameter associated with all liquid crystals is that of the *molecular director*. This parameter gives the average orientation of the long molecular axis and is about which properties such as the dielectric constant and refractive index are defined. For instance, the two dielectric constants are defined parallel and perpendicular to the molecular director. A material whose parallel dielectric constant is greater than the perpendicular dielectric constant is said to have positive dielectric anisotropy (PDA). Similarly, a material whose parallel dielectric constant is less than the perpendicular director also gives the local orientation of the optic axis of an individual molecule.

For reasons such as speed and increased viewing angle, *twisted nematic* (TN) liquid crystal devices have become the most popular and commercially advanced for display purposes, where a twist angle of 90° is normal. The structure of the TN liquid crystal cell is given in Figure 4-1(b). In essence the TN liquid crystal can be considered as being similar in structure to the cholesteric phase, except that the helical twist in the TN is an imposed condition brought about by the orientation of the two boundary layers. By placing the liquid crystal material between two glass plates polished in perpendicular directions, the long axes of the molecules tend to align with the rubbing directions, thereby forming the helical twist through the thickness of the liquid crystal layer.

Twisted nematic liquid crystal televisions (TN-LCTVs) are well developed and are the devices used throughout the course of the work described in this thesis. Figure 4-1(c) shows the general structure of such a device, and consists of a TN liquid crystal material (in this case of PDA) sandwiched between polaroids P₁ and P₂, orientated at angles θ_1 and θ_2 with respect to the input plane molecular director. Various polaroid orientations are possible, but for amplitude modulation, a typical configuration is the crossed condition whereby the input and output polaroids are parallel and perpendicular to the input plane molecular director respectively, i.e. P(input, output) = P(θ_1 , θ_2) = P(0, 90).

When a maximum voltage is applied across the cell, the molecular director aligns parallel with the electric field (when the liquid crystal material is of PDA), as shown in Figure 4-1(c). This creates a medium which is isotropic in the x-y plane. The crossed output polaroid therefore transmits no light, turning the LCTV 'OFF'. When a minimum voltage is applied, the twisted structure returns, and in general, elliptically polarised light emerges from the cell due to a combination of birefringence and polarization rotation. This results in some light passing through the output polaroid, turning the LCTV 'ON'. Depending on the applied voltage, different states of ellipticity result, giving different output light intensities, required for displaying grey scale images.

4.1.2 Jones Matrix Model of a TN-LCTV

TN-LCTV's can, in some circumstances be regarded as waveguides that merely rotate the input polarization by 90° and impose a variable phase change on the guided waveform [4-2], thereby operating as phase only modulators. This can generally be the case when liquid crystal materials of high birefringence are used, or where a thick sandwich of liquid crystal material is applied. As commercially available devices are required to operate at a TV frame rate speed of 25Hz, their design (e.g. thin layer of material) generally prevents their application as waveguides without significant modification [4-3, 4-4]. Under normal operation, the elliptically polarised output light results in a combination of amplitude <u>and</u> phase modulation when passed through the output polaroid, and an analysis of the modulating properties of LCTV's is best undertaken through the application of Jones Matrices [4-5].

The TN-LCTV can be considered as a stack of N positive uniaxial crystal layers whose optic axis rotates gradually in a helical manner. In the model developed here, a left-handed helical twist is applied, where the total helical twist is θ_N . Each layer can therefore be considered as being rotated by an angle $\theta_n = (\theta_N/N)$ with respect to the previous layer. If the Jones vector $\mathbf{J}_1 = \begin{cases} A_{x1} \\ A_{y1} \end{cases}$ represents the complex input waveform associated with a single crystal layer in co-ordinate system (x_1, y_1) of Figure 4-2, then the output from a single uniaxial crystal layer in the new co-ordinate system of (x_2, y_2) is obtained by taking appropriate geometric components of \mathbf{J}_1 , and imposing a phase change due to birefringence. The resultant output is given by;

$$\mathbf{J}_{2} = \begin{bmatrix} \exp(j\varphi_{n}) & 0\\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos(\theta_{n}) & -\sin(\theta_{n})\\ \sin(\theta_{n}) & \cos(\theta_{n}) \end{bmatrix} \cdot \mathbf{J}_{1} = \mathbf{P} \cdot \mathbf{R}(\theta_{n}) \cdot \mathbf{J}_{1}$$
(4-1)

where;

$$\varphi_n = \frac{2\pi d}{\lambda} \cdot \left(n_{1/} - n_{\perp} \right) \tag{4-2}$$

is the phase advancement introduced in the x-direction of this positive uniaxial crystal, and where d is the thickness of a single layer. n_{ll} and n_{\perp} are the refractive indices parallel and perpendicular to the optic axis (x-axis) respectively. For N layers of the material, Equation 4-1 becomes;

$$\mathbf{J}_{2} = \left[\mathbf{P} \cdot \mathbf{R}(\boldsymbol{\theta}_{n})\right]^{N} \cdot \mathbf{J}_{1}$$
(4-3)

As the co-ordinate system has rotated through a total angle of θ_N , in order to make the input and output co-ordinates concurrent, it is necessary to impose a further transformation matrix to complete the model. As such, the light transmitted through the device is described by;

$$\mathbf{J}_{2}^{\prime} = \mathbf{R}(-\theta_{N}) [\mathbf{P}.\mathbf{R}(\theta_{n})]^{N} . \mathbf{J}_{1}$$
(4-4)

This final transformation is not, however, illustrated in Figure 4-2, where A_{xN} and A_{yN} represent the output field components as they would actually appear. For the model to be mathematically correct, the final transformation converts the drawn components A_{xN} and A_{yN} into $-A_{yN}$ and A_{xN} respectively, resulting in the input and output axes being concurrent in the mathematical model. Equation 4-4 is the basis with which the polarization of the output waveform can be obtained for any given input polarization, with an arbitrary total twist angle and birefringence. Note that when φ_n is zero, this represents an isotropic medium in the (x,y) plane, where the LCTV is supplied with a maximum voltage, fully untwisting the helical TN structure. At any non-zero value of φ_n , the LCTV is in the general condition where some molecular twisting will be present, and where elliptically polarised output light will result.

This model has been used to plot the variations in ellipticity of the transmitted light for a 90° TN-LCTV, with varying levels of 'total phase difference' (TPD) between the x and y components of the transmitted light. The TPD is the sum of the phase differences incurred as a result of the birefringence of the individual layers, i.e.

 φ_n [in Equation 4-2] x N. These ellipses are given in Figure 4-3 for incident light linearly polarised parallel to the input plane molecular director, i.e. the x-axis, for a total phase difference of between zero and 18 radians. The equivalent ellipses are given in Figure 4-4 for incident light linearly polarised perpendicular to the input plane molecular director.

The model also permits an evaluation of the normalised intensity and phase of the transmitted light for any input / output polaroid orientation, simply by taking appropriate geometric components of the orthogonal complex components of the transmitted light. Figure 4-5 gives these plots for polaroid configurations P(0,0) and P(0,90), and Figure 4-6 gives these plots for polaroid configurations P(90,0) and P(90,90), both for a total phase difference of between zero and 18 radians. These two figures show the normal operating configurations of a LCTV when used as an amplitude modulator for television purposes, specifically between zero and approximately 5 radians total phase difference, where the cross-coupled phase modulation accompanying the amplitude modulation is seen to be significant in general.

It is interesting to note in Figures 4-3 and 4-4 that for the left-handed helical twist model used, the major axes of the polarization ellipses rotate to the right (clockwise) as TPD increases, which intuitively, is somewhat unexpected. If the output field from N crystal layers is described by the components A_{xN} and A_{yN} (without having undergone the final co-ordinate transformation described in Equation 4-4), then from Figure 4-7, it is only possible for the polarisation ellipses to rotate to the right if the phase difference between A_{xN} and A_{yN} is at least $\pi/2$ radians. This is exactly the situation that results with TN-LCTV's, and the phenomenon can be explained with a closer look at the changes in the orthogonal complex components of the waveform as they propagate from layer to layer.

First of all, taking the previous example of $\varphi_n = 0$, A_{xn} merely reduces in amplitude as n increases, until 90° have been turned at which point $A_{xN} = 0$. Simultaneously, A_{yn} increases in amplitude until $A_{yN} = A_{x1}$. This indicates that the incident linearly polarised light is unaffected by the liquid crystal material, and propagates freely through and out of the device. This is to be expected, however, since

with no birefringence, the LCTV is isotropic in the x and y directions, as considered earlier.

In general when $\varphi_n \neq 0$, however, $A_{xN} \neq 0$, and $A_{yN} < A_{x1}$, as is indicated in Figure 4-2, and elliptically polarised light emerges. It remains to be shown that, in the limit as $\varphi_n \rightarrow 0$, A_{xN} is advanced by $\pi/2$ radians with respect to A_{yN} , and that as φ_n increases, the phase difference increases even further. This phenomenon can initially, however, be observed in Figure 4-5 when the TPD tends to zero.

Considering the n^{th} layer of the crystal, there are two incident components, $A_{x(n-1)}$ and $A_{y(n-1)}$. A_{xn} and A_{yn} can therefore be obtained by expanding Equation 4-1 to give;

$$A_{xn} = \left[A_{x(n-1)} \cdot \cos(\theta_n) - A_{y(n-1)} \cdot \sin(\theta_n) \right] \exp(j\varphi_n)$$

$$A_{yn} = A_{x(n-1)} \cdot \sin(\theta_n) + A_{y(n-1)} \cdot \cos(\theta_n)$$
(4-5)

where $\exp(j\varphi_n)$ describes the phase advancement due to birefringence. Figure 4-8 gives a pair of phasor diagrams illustrating Equation 4-5, and a comparison of the two shows that the phasor A_{xn} rotates further than the phasor A_{yn} for any one layer in the liquid crystal. The changes in both phasors A_{xn} and A_{yn} as they propagate through the layers of the liquid crystal can be obtained by applying the above procedure as n increases.

Figures 4-9(a) and 4-9(b) illustrate how these phasors change from layer to layer for both small and large values of φ_n respectively. It can be observed in Figure 4-9(a) that for very small values of φ_n , the amplitudes of A_{xn} and A_{yn} do indeed reduce and increase respectively as stated earlier for the condition $\varphi_n = 0$. Again for small φ_n , the phase of A_{yn} remains close to zero for all n, such that the components $-A_{y(n-1)} \cdot \sin(\theta_n)$ in Figure 4-9(a) reduce the magnitude of A_{xn} , whilst turning the phasor through > $\pi/2$ radians. In the limit when $\varphi_n \rightarrow 0$, the magnitude of A_{xn} , i.e. $|A_{xn}| \rightarrow 0$, whilst the phase of A_{xn} becomes advanced by $\pi/2$ radians. Again as stated earlier, as φ_n increases, Figure 4-9(b) shows how the phase difference between A_{xN} and A_{yN} increases beyond $\pi/2$ radians. This phenomenon explains why, in a 90° TN-LCTV, a left-handed helical twist results in the major axes of the elliptical output polarization rotating clockwise, as A_{xN} in Figure 4-2 has been shown to be always at least $\pi/2$ radians advanced with respect to A_{yN} .

A further interesting phenomenon shown in Figures 4-5 and 4-6 is that of the π radian phase jumps for parallel input / output polaroid configurations, coinciding with zero intensity transmission. As considered above, the A_{xn} phasor rotates further than the A_{yn} phasor for any one layer in the liquid crystal. For a certain level of birefringence, the condition will arise that the $(n-1)^{\text{th}}$ layer of the liquid crystal has its $A_{x(n-1)}$ phasor advanced by π radians with respect to the $A_{y(n-1)}$ phasor, as illustrated in Figure 4-10. These two components are then incident on the n^{th} layer of the liquid crystal, and appropriate geometric components are taken in forming A_{xn} and A_{yn} . At the point where $A_{x(n-1)}$ is advanced by π radians with respect to the $A_{y(n-1)}$, Equation 4-5 gives the magnitude of the phasors A_{xn} and A_{yn} as;

$$|A_{xn}| = |A_{x(n-1)}| \cdot \cos(\theta_n) + |A_{y(n-1)}| \cdot \sin(\theta_n)$$

$$|A_{yn}| = |A_{x(n-1)}| \cdot \sin(\theta_n) - |A_{y(n-1)}| \cdot \cos(\theta_n)$$
(4-6)

As can be seen in Figure 4-9, in general the magnitude of the phasors A_{xn} and A_{yn} decrease and increase respectively as *n* increases, such that there will come a point when $|A_{y(n-1)}|\cos(\theta_n) > |A_{x(n-1)}|\sin(\theta_n)|$ in Equation 4-6. At this point, the sign of the phasor A_{yn} will change, resulting in a phase jump of π radians. At this point, linearly polarised light occurs, and the whole process of splitting the linearly polarised incident light into two components (one parallel and one perpendicular to the optic axis of the subsequent liquid crystal layer) starts once more. When used as an amplitude modulator (see Figures 4-5 and 4-6), the thickness and/or the refractive indices of the birefringent liquid crystal material should be chosen to give the condition of linearly polarised light at the output from the N^{th} layer, at which point 90° will have been

turned. This point should coincide with applying the minimum (bias) voltage across the liquid crystal. In this way, maximum dynamic range is achieved for amplitude modulation.

If the specific level of birefringence required to obtain linearly polarised light were increased, the phases of A_{xn} and A_{yn} would have similar values at first, however phasor A_{xn} would again rotate further than phasor A_{yn} . This phasor rotation mechanism would continue if the level of birefringence were to continue increasing, and would lead to the oscillatory phenomenon seen in Figures 4-3 to 4-6.

If a highly birefringent or thick layer of liquid crystal material is utilised in a LCTV configured with either parallel or perpendicular input / output polaroids, a 90° twist would result in the LCTV operating in the region at the right hand side of Figures 4-5 and 4-6. A relatively high minimum (bias) voltage would therefore have to be applied in order to establish the threshold level for the onset of amplitude modulation. If, however, the LCTV is operated in the voltage regime below this 'optical threshold' [4-6, 4-7, 4-8], little amplitude modulation would result. The configuration P(0,90) is ideal, as high overall transmission occurs with a linear phase ramp. LCTV's are, however, designed to work in the voltage regime above the optical threshold, as amplitude modulation is required for television purposes. Some design modifications to the commercially available LCTV's are therefore usually required if near phase only modulation is to be obtained in the above described manner. By modifying the drive electronics [4-3], the bias voltage (originally controlled with the LCTV's brightness control), can be altered to permit the LCTV to work in the 'low voltage regime', below the optical threshold. Specific modifications to the choice of liquid crystal material, or indeed other design parameters [4-4] again permits operation in the low voltage regime.

Through the course of this work, near phase only modulation has been achieved without the need for modification, whilst operating the LCTV under normal conditions above the optical threshold. This is achievable merely through a realignment of the input / output polaroids and an appropriate setting of the brightness control [4-9, 4-10, 4-11]. With incident light polarised parallel and then perpendicular to the molecular director, Figure 4-11 shows the variation in the elliptically polarised

output light that occurs between zero and 3.5 radians TPD. By placing the output polaroid normal to one of the dotted lines in the figure, little amplitude modulation would occur over the dynamic range being considered. Figure 4-12 summarises these potential configurations for phase only modulation as modelled with Jones matrices, and shows configuration P(0,120) to be optimum for obtaining maximum phase only modulation.

4.1.3 Experimental Validation of the Jones Matrix Model

It is clear that any 90° TN-LCTV can be modelled by Jones Matrices if the relative refractive index $n_{11} - n_{\perp}$ and thickness d of the device in Equation 4-2 are known. Following many attempts, it was deemed impossible to obtain reliable manufacturer's data regarding such parameters. Experimental measurements were therefore undertaken in order to validate the results obtained with the model. Experimental measurements of the ellipticity of the output polarisation states, and thereby the normalised intensity transmittance were possible, which allowed a comparison with the modelled data in Figures 4-3 to 4-6.

Techniques of ellipsometry can be applied to evaluate the orientation of the major / minor axes of the elliptically polarised output states, and indeed the normalised amplitudes of the major and minor axes. Figure 4-13 illustrates the basis of the technique used to determine these parameters, where Figure 4-13(a) illustrates a generalised ellipse, and where Figure 4-13(b) illustrates the adopted technique. By placing a quarter-wave ($\lambda/4$) plate, whose axes are parallel to the major / minor axes of the ellipse, the elliptically polarised light is converted into linearly polarised light. An appropriately orientated polaroid therefore allows a null to be established. The orientation of the $\lambda/4$ plate determines the inclination of the major / minor axes of the elliptically polarised light (ε° from the x-axis), and the orientation of the polaroid allows the 'intensity normalised' amplitudes of the major / minor axes to be determined. Since the normalised intensity of the elliptically polarised light is given by;

$$A_{maj}^{2} + A_{min}^{2} = 1 \tag{4-7}$$

and since;

$$\tan(\theta) = \frac{A_{\min}}{A_{mai}}; \tag{4-8}$$

where A_{maj} and A_{min} are the amplitudes of the major and minor axes of the ellipses respectively, and where θ is determined from the orientation of the polaroid, Equations 4-7 and 4-8 can be solved in order to evaluate A_{maj} and A_{min} .

Light was polarised parallel to the input plane molecular director of the Casio TV-5100, and was supplied with a 50Hz CCIR (Comite Consultatif International de Radiodiffusion) video signal from the 8-bit OFG. The LCTV's brightness control was set to give maximum observable contrast when in the P(0,90) configuration, and different grey levels were supplied to the LCTV which effectively varied the voltage applied across the liquid crystal cell. The changes in the ellipticity of the light output from the LCTV were measured with the above technique, and Figure 4-14 gives a plot of these measured polarisation states as the grey level was increased from 0 to 255, i.e. as the TPD was increased, or indeed as the voltage applied across the liquid crystal cell was reduced. Similarly with the Jones matrix model, it is possible to take geometric components of the output light in order to evaluate the normalised intensity transmittance from any orientation of output polaroid. Figure 4-15(a) gives this plot for configurations P(0,0) and P(0,90), where the maximum contrast ratio when operating in this mode as an amplitude modulator has been measured as approximately 25. A comparison of Figure 4-15(a) with Figure 4-5 shows how the Jones matrix model from zero to approximately 3.5 radians TPD models the Casio TV-5100 well. Similar observations are made when the modelled ellipses in Figure 4-11 (for a dynamic range of zero to 3.5 radians) are compared with the measured ellipses given in Figure 4-14.

It is noted from Figure 4-15 that with a low or a high bias voltage setting, i.e. when the brightness control was set to its maximum or its minimum respectively, the

intensity transmittances are correspondingly high and low. This can also be inferred from the elliptical polarisation states in Figure 4-3, where the output ellipses are close to being orientated with their major axes 90° to the input plane molecular director for a high intensity transmittance, and at 0° for a low intensity transmittance, where the corresponding values of TPD are low and high respectively.

4.1.4 Phase Modulating Characteristics

A Mach-Zehnder interferometer was used in order to evaluate the phase modulating properties of the Casio LCTV. Figure 4-16 shows the experimental arrangement, where the $\lambda/4$ plate gives circular polarization, permitting the polaroids P1 and P2 to be orientated at any angle. The LCTV held a single 'white' stripe on a black background, and the fringe shift between these 'on' and 'off' regions was investigated. In Section 4.1.2, it was stated that when the LCTV is operated normally, above the optical threshold, cross-coupled phase modulation accompanies the amplitude modulation. Figure 4-17 shows the output from the interferometer with the polaroid configuration P(0,90), and shows how both amplitude and phase modulation occur simultaneously. Amplitude modulation with a contrast ratio of 25 has therefore been observed with a cross-coupled phase modulation of approximately $\pi/2$ radians. Note how it is difficult to observe the fringes in the black regions, as little light is being passed by these regions of the LCTV.

The Jones matrix model predicted the configuration P(0,120) for providing maximum phase modulation. With the brightness control set to give maximum observable contrast when in the P(0,90) configuration, the configuration P(0,114)achieved near phase only modulation, and Figure 4-18 shows how approximately π radians phase difference occurs between the 'on' and 'off' regions under consideration. This result corresponds well to that predicted in the model. Note also, that when the brightness control was set to minimum and then maximum, the respective configurations P(0,106) and P(0,149) also provided near phase only modulation, and near phase only modulation could also be found for all intermediate configurations.

From an inspection of Figure 4-11, some amplitude cross-coupled modulation is to be expected when the LCTV is configured in the phase-only configuration. The P(0,90) amplitude-only configuration was compared with the P(0,106), P(0,114) and the P(0,149) configurations with regard to output light intensity as a function of applied grey level. The entire LCTV screen held a constant grey level and a power meter recorded the transmitted light intensity from an incident Helium Neon laser. Figure 4-19 displays the results and shows that P(0,114) has a cross-coupled amplitude modulation which varied by approximately 10% over the majority of the useful range. The near phase-only configurations investigated here have an intensity transmittance less than the maximum attainable with the P(0,90) amplitude modulation configuration. This is simply because the output polaroid is aligned along the general line of the minor axes of the ellipses, as seen in Figure 4-11. The Jones matrix model gives an intensity transmittance approximately 25% of the maximum, as seen in Figure 4-12 for the configuration P(0,120), whereas in Figure 4-19, the experimental measurement is seen to give approximately 50% of the maximum. Due to the interpixel dead region, and that the LCTV is illuminated with monochromatic light, the maximum intensity transmittance is << 1. The maximum intensity transmittance available with the LCTV has been measured as approximately 5%, when a grey level of 255 is displayed on the LCTV configured as P(0,90). As such the reduction to around 2.5% when operating as a phase only modulator is not of major concern.

The linearity of the P(0,90) amplitude modulation configuration as a function of grey level is seen in Figure 4-15(a) and Figure 4-19. In order to evaluate the linearity of phase-only modulation, the Mach-Zehnder interferometer was aligned to produce high frequency fringes normal to the orientation of the on/off stripes as displayed on the LCTV. By obtaining amplitude and phase spectrums for the on and off regions' fringes, the phase of the central 'on' stripe could be determined for various grey levels with respect to the 'off' region. This allowed a measurement of the linearity of phase-only modulation. Figure 4-20 shows that P(0,106) with minimum brightness setting gives best linearity.

Further to the testing of a single LCTV with a Mach-Zehnder interferometer, two LCTV's were cascaded [4-12], whereby a $\lambda/4$ plate and a polaroid sheet sandwiched between the LCTV's allowed them both to be configured as P(0,114). Figure 4-21 shows the progression of the fringe positions in the middle 'on' stripe as the grey level of the video signal supplied to both LCTV's is increased. 2π phase modulation is seen to be produced from this tandem arrangement, and as such an arrangement of three appropriately configured LCTV's could provide independent control of the phase and amplitude of a transmitted wavefront.

4.2 LCTV STRUCTURE AND OPERATION

The previous sections have considered the phase and amplitude modulating properties of the LCTV, which are important with regard to application in coherent optical systems. There are, however, a number of other properties of the Casio TV-5100 LCTV that affect their practical application. These properties are considered as follows.

4.2.1 Specification of the Casio TV-5100 LCTV

The LCTV used in this work is a commercially available Casio TV5100. This TN-LCTV has a colour active matrix screen, incorporating Thin Film Transistor (TFT) technology. The general specification of the device is summarised as follows.

- * Screen size 27.2 x 36.5 mm, (1.8" diagonal).
- * 220 x 280 pixels, with an overlaid RGB colour filter mask.
 (Pixelation period : ≈ 124µm vertically, ≈ 130µm horizontally)
- * A/V connection for CCIR (50Hz) standard video.

The colour filter mask has been designed such that the pixels are arranged in groups of three, comprising red, green and blue pixels. Figure 4-22(a) gives a magnified picture of the LCTV, and Figure 4-22(b) illustrates that when monochromatic light is used, the pixel layout is not merely rectangular in nature, but rather a structure of two interleaved fields, each comprising 110 rows by 93 columns of pixels. With regard to image display, however, the resolution can be considered as being approximately 220 x 187 pixels, as seen through further considerations of the pixel structure in Section 4.2.3.

4.2.2 Diffraction from the Pixelated Structure

As you would expect from the pixelated structure, the Fourier Transform of any image displayed on the LCTV screen comprises a number of spatially separate diffracted orders, distributed at locations corresponding to the pixel spatial frequency. Again with monochromatic illumination, considering the red pixels, the LCTV can be viewed as two separate interleaved 'fields' of pixels, as illustrated in Figure 4-22(b). If the LCTV holds a constant grey level across all pixels, the spatial frequency content of the first field of pixels can be described (in 1D) by;

$$\mathrm{FT}\{f(x)\} = \mathbf{F}(u_x) \tag{4-9}$$

and the spatial frequency content of the second field of pixels can be described (again in 1D) by;

$$FT\{f(x - d/2)\} = F(u_x) \exp(-j2\pi[u_x \cdot d/2])$$
(4-10)

by the shift theorem; where FT represents Fourier Transformation, u_x is the spatial frequency, and d is the separation of adjacent red pixels. The total spatial frequency content is therefore given by;

$$\mathbf{L}(u_x) = \mathrm{FT}\{f(x) + f(x - d/2)\} = \mathbf{F}(u_x)[1 + \exp(-j2\pi[u_x \cdot d/2])]$$
(4-11)

For the 'zeroth' (dc) order, $u_x = 0$, and $\mathbf{L}(u_x) = 2.\mathbf{F}(u_x)$. For the fundamental diffracted order; $u_0 = \frac{1}{d}$, and $\mathbf{L}(u_x) = 0$. For the 1st harmonic diffracted order, $u_1 = \frac{2}{d}$, and $\mathbf{L}(u_x) = 2.\mathbf{F}(u_x)$, etc.

As a result of the two fields of pixels (in 'anti-phase'), not all of the diffracted orders are visible in the Fourier Transform. Only the dc order and the 1st, 3rd, 5th, etc.

harmonic diffracted order components are visible. This is an important result when optically measuring the pixel separation with diffraction techniques. The extra separation between adjacent orders is also a useful result if the pixelated structure is required to be removed through spatial filtering techniques, as considered in Section 4.2.5. When all but one of the diffracted orders are removed, the monochrome pixel data is spread out over the entire pixel period which encompasses both the actual pixel and the neighbouring inter-pixel 'dead' region.

4.2.3 Resolution Limitations

The Casio LCTV is comprised of 220 rows of pixels, where each row holds 280 coloured pixels, as considered above. As the source of the image data is a video signal from the OFG comprising 512 rows by 768 columns of pixels, the information content in the signal must be reduced before being displayed on the LCTV screen. This results in a 2D pixel mapping from the high resolution video signal to the relatively low resolution of the LCTV. The OFG video signal only provides black and white picture information, and as such, each colour pixel on the LCTV is fed with the same luminance signal. The pixel mapping is dependent on the video specification, the number of LCTV pixels, and on the design of the LCTV electronics. For application as a SLM, the precise positioning of data on the LCTV must be known, which is why a thorough understanding of the pixel mapping is necessary. First of all, the video signal being utilised must be considered.

The Casio TV-5100 is a Japanese device designed on the basis of the NTSC (National Television System Committee) video standard, re-tuned to the CCIR (I) PAL system for sale in the UK. The CCIR (50Hz) system comprises 625 lines, of which a total of 49 lines are used for the vertical retrace of both interlaced fields, resulting in 576 usable lines [4-13]. The OFG has been designed on the basis of the CCIR video standard, and supplies the LCTV with an 8-bit video signal. Experimental investigation has shown that the 512 lines of OFG data (as is typical in image processing systems for ease of manipulation, i.e. a power of 2) are positioned in the middle of the 576 usable lines in the full CCIR video signal, resulting in the LCTV receiving 576 video lines, of which the top and bottom 32 [(576-512)/2] lines are

blank. Figure 4-23 compares these video signals for a single interlaced field only. The actual mapping of these 576 OFG video lines to the 220 rows of LCTV pixels is now described in more detail:

In essence, the LCTV receives two interlaced video fields, each comprising 288 lines of data. Following the electronic removal of certain lines of data, the remaining lines from each field are displayed, in turn, on the single 'field' of LCTV pixels comprising 220 rows of pixels, at a rate of 50Hz. Experimental analysis of the mapping has shown that in each interlaced field, one in every six lines of video data are electronically removed, as illustrated in Figure 4-24 for both odd and even interlaced fields. The 'dashes' in Figure 4-24 represent the lines of video signal that are removed by the LCTV electronics. Note that two different mappings have been observed, where each one can be made to occur at random by repeatedly switching the LCTV off and on. Depending on which mapping occurs, the video lines can be placed on different rows of LCTV pixels. It is therefore important to know which mapping occurs, for example when the exact location of a pixel in the video signal, as displayed on the LCTV, is required. These different mappings are thought to occur as a result of the LCTV not demodulating the field synchronisation pulses correctly, resulting in the LCTV assuming that the odd video field is the even field and vice-versa. When this occurs, the even field lines are fed into the section of the LCTV electronics that removes one in every six lines, where the 'video line removal logic' assumes that the signal is the odd field data, and vice-versa. Through an analysis of the two mappings in Figure 4-24, Mapping 2 is seen to be identical to Mapping 1, when the latter mapping's odd and even fields are switched, and are shifted by one line. Mapping 1 is the most regular of the two mappings, and can always be made to occur through experimental verification after the device is turned on.

Figure 4-24 shows a further experimental observation, in that the first 10 rows of LCTV pixels are blank when the OFG video signal is input. The first 16 lines of the OFG video data in any field are blank, as is indicated in both Figures 4-23 and 4-24, and therefore it seems that the LCTV obtains vertical synchronisation 3 (single field) video lines after the start of the useful CCIR video data (for Mapping 1). The (single field) video signal that is passed to the LCTV from the OFG therefore comprises 13 blank lines, 256 lines of data, and then a further 16 blank lines, as is indicated in

Figure 4-23. If all the 256 lines of OFG video data are to be displayed with the LCTV pixels, then the LCTV must first display the 13 blank lines and then the 256 lines of OFG data, i.e. a total of 269 lines. Since one in every six video lines are removed, there remains approximately 224 lines of video data to be displayed on the 220 rows of LCTV pixels. The bottom 4 lines of each field of OFG video data are therefore not expected to be displayed on the LCTV. Figure 4-25 gives an illustration of Mapping 1 in both the vertical and horizontal directions, where it is seen that the OFG video lines 509, 510, 511 and 512 are not displayed on the LCTV. The OFG video data held within the region bounded by rectangular pixel number co-ordinates (9-722, 1-508) is relayed to rows 11 to 220 of the LCTV, encompassing all LCTV pixels in any one row.

The mapping of the pixels in the horizontal direction is not as precise as the above mapping of the OFG video data in the vertical direction. In essence, the horizontal line of video data can be considered to be low pass filtered before being displayed by the horizontal pixels of the LCTV. The low pass filtering effect reduces the information content of the video signal, in order to display the data on the reduced number of pixels available on the row of LCTV pixels. Figure 4-26 illustrates the mapping when a single vertical line is displayed on the OFG video signal. The video signal is averaged over approximately 4 OFG pixels (713/187 \approx 4 - see Figure 4-25) and the resultant is relayed to and displayed by 1 LCTV pixel. Note from Figure 4-26 that depending on the horizontal pixel location of the single vertical line in the OFG video signal, the low pass filtered signal can result in two adjacent vertical lines of LCTV pixels being partially illuminated. Although the number of monochrome pixels in any one row is approximately 93, from Figure 4-26, the resolution in the horizontal direction with regard to image display can be considered as 187 pixels, as mentioned in Section 4.2.1.

The mapping of any pixel in the OFG video signal to the corresponding LCTV pixel is well defined in the vertical direction, and although the mapping in the horizontal direction is not as precisely controlled, from the above discussion the locating error can be considered as approximately $\pm 1/2$ LCTV pixel. As considered earlier, it is important to know the precise positioning of data on the LCTV when applied as a SLM, and this is therefore achievable with pixel accuracy.

4.2.4 Analysis of Liquid Crystal Response Time

Monitoring the transmitted intensity through the LCTV allows the response time of the liquid crystal material to be analysed. If, for example, the video signal supplied to the LCTV held a single horizontal line in the even interlaced field, at the mid-point in the vertical direction say, then Figure 4-27(a) illustrates the expected transmitted intensity as a function of time, where a fast response time has been assumed. When the mid-point in the vertical direction is reached, the line of pixels is turned on, and the transmitted intensity is non-zero. Since the LCTV uses TFT technology, the maximum intensity is expected to remain constant until the odd field (containing zero data) overlays the even field, resulting in zero transmitted intensity, etc. Experimental investigation has shown, however, that regardless of the vertical position of the horizontal line in the even field, the transmitted intensity takes the form of Figure 4-27(b). Note also that Figure 4-27(c) gives the same result for a single line in the odd field. These latter two figures suggest that the LCTV incorporates memory which 'clocks' an entire field of data at the beginning of the field, and also indicate that the response time of the liquid crystal material approaches the period of an individual frame, i.e. 20msec.

If the video source held more even field lines than odd for example, then a 25Hz modulation in the transmitted light would occur. In a general image however, the total number of illuminated pixels in the even field is approximately equal to that in the odd field, and any modulation would be insignificant. To ensure zero modulation, the video signal could, if necessary, be made to hold the same image in the even field as in the odd field, such that the same data would be fed to the LCTV pixels every 20msec, giving no modulation in the transmitted light.

When the LCTV is required to display many images in rapid succession, the intensity transmittance will vary depending upon when the transmitted light is observed. To ensure that the mean intensity transmittance associated with each image remains constant, the transmitted light should be observed at the same point in time for each video frame. This could be implemented in practice with a pulsed laser, where each frame is illuminated just before the next video frame arrives. In this way, the pixels will have been fully turned on when the laser pulse is fired. Note that by

using a pulsed laser, each video field could display a different image, and the LCTV could therefore display different images at a rate of 50Hz.

4.2.5 Other Limitations

When the Casio LCTV is applied in an optical processing system, there are other sources of 'noise', not previously considered, which may corrupt the output signal.

First of all, if the LCTV is to be used as an amplitude modulator, it is desirable to have no or negligible phase modulation. The polaroid sheets laminated to either side of the LCTV are a source of phase irregularities, and their removal results in an improved SLM. Their function can be replaced with an appropriately orientated linearly polarised laser as the source of illumination, and a high quality polaroid sheet in the output field.

Optical information processing systems typically use coherent light, and this itself can be the source of noise, due to diffraction effects associated with dirt on lenses for example. The liquid crystal material is trapped between two thin glass plates, and due to thickness variations, the transmitted light can become corrupted with phase errors, similarly with the optical disk as considered in Chapter 2. The phase errors associated with the glass LCTV are significantly less than those associated with the Perspex optical disk, and are therefore not problematic in the applications considered here. The use of an index matched liquid gate can, if needed however, help remove this source of noise.

A further problematic effect associated with using LCTV's is the manifestation of Moiré fringes resulting from the pixelated structure. If, for example, the LCTV is used in an image plane correlator [4-14], and is applied not only to record a reference image on photographic film for example, but also as the source of the input object, then the optical correlation of the two images results in moving Moiré fringes being superimposed on the correlation signal. These Moiré fringes are a direct consequence of recording the pixelated structure of the LCTV. This effect can, however, be removed by spatially filtering the pixelated structure of the LCTV. Care must be taken here, however, as it is easy to remove high frequency information from any single order being passed by the spatial filter. This would result in a blurred image, reducing the information processing capacity of the system.

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Optical Pattern Recognition Systems

The main purpose of the work described in this thesis was the practical investigation and development of optical correlators based on the PAODS. This chapter documents such an investigation, where three different configurations of optical correlator have been investigated. In all three configurations, the optical disk is used not only as a memory device, but as a parallel processing element, since the input object distribution is modulated by the disk transmission function. The matched filtering operation has been used to demonstrate the processing capability, where the bipolar MACE filtering operation [5-1] has been used to illustrate the capability of undertaking more generalised processing operations based on synthetic filters.

A brief review of some important theoretical principles is undertaken, subsequent to which, the results obtained from the three different correlators are presented. The data storage capacity of the disk and the rate of information processing are also considered. Finally, the important practical issues surrounding the work are considered.

5.1 THEORETICAL CONSIDERATIONS

5.1.1 Review of Linear Systems Theory

Goodman [5-2] considers the theory of linear systems, and is summarised in this section in order to establish the notation used here, and to define the optical convolution and correlation operations mathematically.

A linear system (S) is a system that obeys the principle of superposition, in that the response of the system to a sum of inputs is equal the sum of the individual responses. When a function $f_1(x_1, y_1)$ is input into a linear system, the output can be described by;

$$f_2(x_2, y_2) = S\{f_1(x_1, y_1)\}$$
(5-1)

where (x_1, y_1) and (x_2, y_2) are the input and output co-ordinates respectfully. By the sifting properties of the Dirac delta function (δ) , the input function can be given as the decomposition;

$$f_{1}(x_{1}, y_{1}) = \int_{-\infty}^{\infty} f_{1}(\xi, \eta) \delta(x_{1} - \xi, y_{1} - \eta) d\xi d\eta$$
(5-2)

where $f_1(\xi, \eta)$ is an elementary component of $f_1(x_1, y_1)$ at spatial co-ordinates $(x_1 = \xi, y_1 = \eta)$. Substituting Equation 5-2 into 5-1 yields;

$$f_{2}(x_{2}, y_{2}) = \int \int_{-\infty}^{\infty} f_{1}(\xi, \eta) S\{\delta(x_{1} - \xi, y_{1} - \eta)\} d\xi d\eta$$
(5-3)

since the system (S) is linear. Equation 5-3 can be re-written as;

$$f_2(x_2, y_2) = \int \int_{-\infty}^{\infty} f_1(\xi, \eta) h(x_2, y_2; \xi, \eta) d\xi d\eta$$
(5-4)

where $h(x_2, y_2; \xi, \eta)$ is the response of the system at output co-ordinates (x_2, y_2) to a delta function an input co-ordinates (ξ, η) , and is referred to as the impulse response function. Optical imaging systems fall into the special class of linear systems known as linear shift-invariant systems, where the impulse response function depends only on the distances $(x_2 - \xi)$ and $(y_2 - \eta)$. Shift invariance is the property that a shift in the input of a linear system results in a proportionate shift in the output. In this case, Equation 5-4 can be written;

$$f_2(x_2, y_2) = \int \int_{-\infty}^{\infty} f_1(\xi, \eta) h(x_2 - \xi, y_2 - \eta) d\xi d\eta$$
(5-5)

and as such, the output from a linear shift-invariant optical imaging system can be described by the convolution of the input function with the impulse response function, which in shorthand notation is given by;

$$f_2 = f_1 \oplus h \tag{5-6}$$

By the convolution theorem, the Fourier transformation of Equation 5-6 is given by;

$$\mathbf{F}_{2}(u,v) = \mathbf{F}_{1}(u,v)\mathbf{H}(u,v)$$
(5-7)

where (u, v) are the spatial frequencies, and where the Fourier transform of the impulse response function is the transfer function **H** of the system.

From the discussion given in Chapter 1, pattern recognition takes the form of comparing the unknown object with many reference images until a match is found. The *correlation* operation gives a measure of the similarity of two images as a function of their relative position. If the correlation output is higher than a predetermined threshold level, then the unknown input object is classified as being

identical to that particular reference image being used to interrogate the input. As such, the identity and position of the unknown object in the input data field can be determined from the location of a thresholded peak in the correlation data. The 2D complex cross-correlation between a function f(x, y) and a reference function g(x, y) is defined by;

$$R_{fg} = \int \int_{-\infty}^{\infty} f(\xi, \eta) g^*(\xi - x, \eta - y) d\xi d\eta$$
(5-8)

which in shorthand notation is given by;

$$R_{fg} = f \otimes g^* \tag{5-9}$$

By comparing Equations 5-5 and 5-8, the correlation operation can be undertaken in a linear shift invariant optical system by placing, in the frequency domain, a filter whose impulse response function has the form;

$$h(x, y) = g^{*}(-x, -y)$$
(5-10)

The corresponding transfer function is given by $\mathbf{G}^*(u, v)$, and if the input to the optical system were g(x, y), then in the frequency domain the output would be given from Equation 5-7 as $\mathbf{G}(u, v)\mathbf{G}^*(u, v)$, where the filter $\mathbf{G}^*(u, v)$ is said to be matched to the input. The output from the optical correlator in this matched condition is therefore given by;

$$\mathrm{FT}\left\{\mathbf{G}(u,v)\mathbf{G}^{*}(u,v)\right\} = g \otimes g^{*}$$
(5-11)

which is the autocorrelation of g, (FT represents Fourier transformation). This results in a high intensity correlation peak, above the threshold level, and thus identifies the input function as being identical to that function used to synthesise the matched filter.

5.1.2 MACE Filtering

The bipolar MACE filtering operation has been used to illustrate how the correlators considered here are capable of undertaking more generalised processing operations using synthetic filters. This section presents a brief theoretical treatment of the MACE filter.

The MACE filter is a composite filter H(u, v) designed on the basis of a training set of N images f_1, \ldots, f_N , to provide distortion invariant pattern recognition. The correlation between the training set images and the composite filter is constrained to satisfy;

$$R_{fh}(x=0, y=0)_{n} = \iint \mathbf{F}_{n}(u, v) \mathbf{H}(u, v) \exp(-j2\pi(xu+yv)) dudv$$

$$n = 1, 2, ..., N$$
(5-12)

such that the central correlation output values obtained from an in-class input object $f_n(x, y)$ are controlled. It is usual to constrain the central output of an in-class object to be 1, and an out-of-class object to be 0. In addition, the MACE filter aims to minimise the mean correlation plane energy, which by Parseval's theorem [5-2], is given by;

$$E_{av} = \frac{1}{N} \sum_{n=1}^{N} \iint \left| \mathbf{F}_{n}(u, v) \right|^{2} \left| \mathbf{H}(u, v) \right|^{2} du dv$$
(5-13)

Since the MACE filter is synthetic and generated in a computer, the discrete composite filter so obtained is given in matrix-vector notation by [5-1];

$$H = D^{-1}F(F^{+}D^{-1}F)^{-1}R, \qquad (5-14)$$

where + indicates the conjugate transpose, and where F is now a matrix comprised of \mathbf{F}_n as its n^{th} column vector (i.e. the 2D image matrices are scanned into vectors of length m). D is a diagonal matrix whose m^{th} diagonal entry is the average of the m^{th}

values of the column vectors $|\mathbf{F}_n(u,v)|^2$ taken over all *n*, i.e. the average power spectrum of the 1D training images. **R** is a vector comprising the correlation peak constraints.

The result of minimising the average correlation plane energy is to whiten the spectrum of the composite filter, such that the DC component and all spatial frequencies contribute equally to the recognition process, thereby providing an easily recognisable peak. Although this 'pre-whitening' effect improves recognition ability, the transmission efficiency is reduced due to a reduction in the relative magnitude of the low frequency components of the filter, and the filter's ability to reject noise is impaired.

5.2 SPATIAL DOMAIN CORRELATOR

5.2.1 General Description

The first correlator studied performs spatial domain correlation by an image casting method. In this configuration the unknown input object is imaged onto the reference images stored on the optical disk as multiplicative intensity transmission masks, where the transmitted light is incident on a photodetector, as illustrated in Figure 5-1. The disk is rotated to interrogate the unknown input object with the many reference images in rapid succession. The system therefore performs fast parallel processing of an input light distribution, where the disk acts as a memory store and as a processing element. As a result of disk rotation, the relative spatial shift between the input object and the reference images takes place in 1D, and therefore with regard to pattern recognition, the system is capable of identifying an unknown input object and reference image intensity distributions, then the output photodetector has the form;

$$R_{fg}(y) = \int \int_{-\infty}^{\infty} f(\xi, \eta) g(\xi, \eta - y) d\xi d\eta$$
(5-15)

where only one dimension of shift invariance is available, in this case in the ydirection.

Noting that f and g must be positive and real valued functions, in general the main limitation of spatial domain correlators is the inability to deal with bipolar reference images or bipolar impulse response functions. The system developed here, however, is capable of processing bipolar data by separating the positive and negative components of the bipolar reference images. Equation 5-16 is the basis of the technique, where the positive and negative components of the bipolar reference image have been separated, indicating that two spatially separate signals are processed;

$$R_{fg}(y) = \int \int_{-\infty}^{\infty} f(\xi,\eta) g_+(\xi,\eta-y) d\xi d\eta - \int \int_{-\infty}^{\infty} f(\xi,\eta) g_-(\xi,\eta-y) d\xi d\eta \quad (5-16)$$

The bipolar correlation signal is obtained through a subtraction of the two spatially separate signals.

5.2.2 Opto-Mechanical Considerations

Since the correlation operation assumes a linear translation of the reference images, and that the disk provides a circular motion, there exists a fundamental constraint regarding the size of the image blocks that can be recorded on the disk in maintaining an alignment accuracy of 1 pixel. An object in an input data field of size L can be identified if constrained to move (from a nominal central position) in the vertical direction by a maximum distance of $\pm (L/2)$. Figure 5-2 therefore indicates that since the data on the disk translates through a circumferential track, a horizontal misalignment occurs between the input as imaged onto the disk, and the pre-recorded data on the disk. For small angles, simple geometry allows the misalignment to be estimated as;

$$x \approx \frac{L^2}{8r} \tag{5-17}$$
where L is the length (in the y-direction) of the block of data recorded on the disk, and where r is the track radius. Alignment is dictated by block size and radius, and if alignment is to be achieved to 1 pixel (where for 41dB, the minimum pixel size \approx 9.5µm) regardless of track radius, the maximum misalignment that can be tolerated is $x_{max} = 9.5$ µm. At a minimum radius of $r_{min}=37$ mm, the misalignment is the highest, and in order to maintain alignment to pixel accuracy, Equation 5-17 gives the maximum permissible block size as $L_{max} = 1.67$ mm, resulting in a maximum resolution of 175 pixels, where each pixel is recorded with a SNR of 41dB. Ideally, the block size should be as small as possible in order to store many images on the disk, however, if the block size is smaller than 1.67mm, the resolution and/or the SNR will be reduced.

The LCTV's dimensions are 27.2x36.5mm, and in order to obtain the maximum permissible block size at the minimum radius, a de-magnification factor of approximately 16 is required. In order to reduce the size of the images on the disk even further, thereby increasing the total number of images on the disk, a de-magnification factor of 20 was chosen. The LCTV was therefore reduced to a disk image size of approximately 1.36x1.83mm, where this reduction occurs at the expense of the SNR. The LCTV effectively comprises 220 x 187 pixels, where each pixel therefore occupies an area of film corresponding to approximately 6.2x9.8 μ m = 6.05x10⁻⁵mm². From Chapter 2, this results in each pixel being recorded with a SNR of approximately 40dB.

Under these latter imaging conditions, the sampling interval of $6.2\mu m$ results in a maximum spatial frequency of 81 cycles/mm, by Equation 2-17. From Equation 2-23 and Equation 3-1 respectively, the maximum spatial frequency results in a minimum *NA* of 0.051 and a DOF of 240 μm . The DOF is still seen to be much greater than disk run-out (40 μm).

In the above analysis, eccentricity is assumed to be negligible, however as stated in Section 3.1.3, an eccentricity of $\pm 13\mu$ m is present, which demands a minimum pixel size of 26µm in the radial direction (the x-direction of Figure 5-2). For such a pixel size, Equation 5-17 permits a much larger maximum block size whilst maintaining an alignment accuracy of 1 pixel. The 1.67mm maximum block size is used here, however, in order to record many blocks of data on the disk. The 20x de-magnification results in the 26 μ m pixel size corresponding to a 520 μ m pixel size in the LCTV input plane. The maximum resolution is therefore set at approximately 70 (36.5mm / 520 μ m) pixels. The LCTV was therefore used with a maximum pixel resolution of 64x64, since it is a power-of-two which scales conveniently with the 512x768 resolution of the OFG video output. The pixel size as recorded on the optical disk was therefore approximately 21x29 μ m, which corresponds to a SNR of 45dB. With unipolar filtering operations, the full 64x64 pixel resolution was available, however bipolar filtering operations required pairs of identical input images, and as such only 32x32 pixel resolution was available per image.

In Figure 5-2, any misalignment associated with the rotation of the filter has been neglected, and is approximated in the following. Figure 5-3 illustrates this rotational misalignment, where in this case the misalignment in the x-direction has been neglected. The rotation of the filter results in a maximum vertical misalignment (y) at the extreme ends of the block of data, which in comparison to Equation 5-17, can be approximated by;

$$y = \frac{L}{2}\sin(\Delta\theta) = \frac{L^2}{4r}$$
(5-18)

The maximum and minimum values of y occur with minimum and maximum radii respectively, and are approximately $y_{max} = 19\mu$ m, and $y_{min} = 9\mu$ m for a block size L=1.67mm. The effect of rotational misalignment is to reduce correlation peak levels, where the reduction is greater for large L values. If L/2 gives the shift of the unknown object in the input data field, then an increased rotational misalignment reduces the extent of vertical shift invariance. Equation 5-17 gives a misalignment associated with all pixels across the width of the data block, whereas Equation 5-18 gives a misalignment that occurs only at the extreme ends of the filter, reducing linearly towards the centre. For this reason Equation 5-17 has been used as the basis for evaluating the maximum block size.

5.2.3 Experimental Results

The optical configuration of the spatial domain correlator developed here [5-3] is given in Figure 5-4. Although an incoherent source could have been used to illuminate the LCTV, a laser source was chosen because it could be shuttered conveniently. The use of this source also allowed easy identification of the pixelated structure which resulted in high order diffracted components in the back focal plane of the field lens, L. This structure was removed using a spatial filter element before imaging the LCTV onto the disk with microscope objective M2 A second microscope objective M1 relays the light transmitted through the disk to a photodiode arrangement, whereby the photodiode(s) current has the form of Equation 5-15.

For unipolar filtering systems, Equation 5-15 applies and only one of the two photodiodes (P1, P2) in Figure 5-4 is used. For bipolar filtering systems, Equation 5-16 applies and two independent signals must be processed. Under these latter conditions, the disk holds pairs of filter functions side by side, corresponding to the positive and negative components of the bipolar reference function. The LCTV inputs pairs of identical images, and following multiplication by the disk filter functions, beam splitting optics allow the two spatially separate signals to be conveniently split, and the resulting photodiode signals are subtracted with an electronic subtraction unit to realise Equation 5-16 in real time.

Various in-plane rotations of the letters M, A, C, and E were imaged and recorded on the disk, resulting in a bank of filters with which an input object could subsequently be interrogated and identified. Each of the letters at 10° intervals from 0° to 140°, and at 20° intervals from 160° to 340° were recorded twice on the disk as adjacent pairs of binary images. Hereafter, the letter E at 100°, for example, will be referred to as filter E100. The reversal chemical development procedure (as discussed in Section 2.1) was applied here, resulting in 'white images on a black background'. In this way, noise scattered from non-filter regions of the optical disk was eliminated, where the correlation signal was proportional to the intensity of the transmitted light. Figure 5-5 illustrates the quality of the filters held on the disk.

First of all, unipolar filtering operations were investigated. Image C280 was held on the LCTV and was input to the correlator. The resulting oscilloscope time trace from the single photodiode P1 of Figure 5-4, is given in Figure 5-6. The largest peak was identified as that resulting from the filter matched to image C280. The two filters C340 and E0 were masked from the disk in aiding interpretation of the trace. The ratio of the maximum correlation peak to the mean of the non-similar image correlation peaks for this particular arrangement was found to be approximately 1.5. Peaks of significant amplitude were also produced from filters matched to the letter E in a similar orientation to that of C280, i.e. E280. In order to provide improved class discrimination between the letters C and E, and to illustrate the bipolar processing capability of the system, a MACE filter was synthesised for the recognition of C280 and suppression of E280.

For ease of application and illustration, the MACE filter function was displayed on the LCTV, and was correlated with the images pre-recorded on the disk. The two components of the 32x32 MACE filter are illustrated in Figure 5-7. It can be observed that the MACE filter utilises prominent features of the training set data, where in this simple application the edges of the C280 image are prominent. The output from the electronic subtraction unit is given as an oscilloscope time trace in Figure 5-8, and again shows a maximum peak resulting from the correlation between the input MACE filter and the image C280 held on the disk. The ratio of the maximum correlation peak to the mean of the non-similar image correlation peaks for this particular arrangement was found to be approximately 5.3. Bipolar processing has been demonstrated with the spatial domain correlator, and it is clear that the application of the MACE filter results in a substantial improvement in class discrimination. It can be seen from a comparison of Figures 5-6 and 5-8, however, that the correlation signal amplitude is significantly reduced due to the pre-whitening effect of the MACE filter.

Automatic correlation peak identification was possible by applying the control system summarised in Section 3.2. The time traces in Figure 5-6 and Figure 5-8 were thresholded with the signal conditioning unit given in Figure 3-12, and the resulting correlation signal was fed into the computer via the PC14AT I/O board (see Figure 3-8). The correlation peak latch was polled in software, such that a number was assigned to that filter on the disk giving the high correlation peak. In the work undertaken here, approximately 100 disk filters were recorded on one circumferential track. The work was not extended to multiple tracks, nor were the PC14AT digital counters used to

interpolate across any one image. As such, the disk was driven with a constant angular velocity, where no timing calibrations (as discussed in Chapter 3) were required.

5.2.4 Simulated Results

The theoretical performance of the spatial domain correlator was compared with the experimental results by undertaking digital correlations between images C280, E280 and the MACE filter. The images were taken as the 'perfect' images as stored in the computer, and Figure 5-9 gives the theoretical performance of the unipolar filtering operation, through digital correlations between the input image C280, and the filters C280 and E280. The theoretical performance of the bipolar filtering operation was obtained through digital correlations between the MACE filter and the 'input' images C280 and E280. These results are given in Figure 5-10. The term 'input' is given in quotes here to emphasise that the actual input in the real system was the MACE filter. The same result would have been achieved, however, if the positive and negative components of the MACE filter were held on the disk, and the images C280 and E280 were input.

The simulated results given in Figures 5-9 and 5-10 show good agreement with the experimental results given in Figures 5-6 and 5-8 respectfully. Again, the improvement in class discrimination, and the reduction in signal amplitude as a result of pre-whitening, are both apparent from the simulation. Correlation peak sharpness is also seen to be improved upon with MACE filtering.

5.2.5 Information Processing

This section considers the ideal maximum disk capacity and the rate of information processing available with the PAODS when eccentricity is neglected and where SNR is the only limiting factor with regard to minimum pixel size. The reduction in the performance of the system as a result of eccentricity is also noted.

Section 5.2.2 has shown that a fundamental issue concerning the use a rotating optical disk is that of filter alignment as the filters translate through the input object (as imaged onto the disk). Equation 5-15 indicates a linear translation of the filter,

however, the actual system can be considered to approximate to this ideal linear translation only when filter alignment is maintained to an accuracy of 1 pixel. From Section 5.2.2, a maximum block size of 1.67mm in length is available at the minimum radius of 37mm. Each pixel occupies 9.5x9.5 μ m such that a SNR of 41dB is available per pixel (approximately 7-bit), and therefore an image block of 1.67x1.67mm has 175x175 pixel resolution. Between the minimum and maximum radii of 37mm and 75mm respectively, a recording area of 13370mm² is available, and in terms of area alone, approximately 4800 images can be recorded. The maximum information storage capacity of a concentric disk is therefore 1.03x10⁹ bits, or 130Mbyte. As will be discussed in Section 5.5, however, in order to ensure that each correlation operation is independent, adjacent filters must be separated by a distance equal to the block size. This reduces the effective data storage capacity to approximately 65Mbyte.

Taking eccentricity into account, and using the actual LCTV image block size of 1.36x1.83mm, each image block comprises 64x64 pixels, where each is recorded with a SNR of 45dB (greater than 7-bit). Again in terms of recordable area, when adjacent blocks of data are separated appropriately, the effective disk capacity actually obtained is approximately 10Mbyte.

The rate of information processing is limited, above all, by the angular velocity of the disk, and the detectability of the output correlation peak [5-4]. The system developed here uses a 5mW He/Ne laser, where for comparison, the disk is considered to turn with a speed corresponding to the mean linear track velocity of the CD player [5-5], i.e. 1.3ms⁻¹. In this configuration of optical correlator, an elementary 'signal' to be processed can be considered to be a single pixel at half maximum grey level. The number of photons per correlated pixel arriving at the correlation plane photodiode in Figure 5-4 can be obtained from;

$$n_p = \frac{P_e \cdot T}{E_p} = \frac{P_l \cdot \chi \cdot T}{h\upsilon}$$
(5-19)

where P_e is the expected power of the correlation peak, occurring over a time period T, and where $E_p = hv = \frac{hc}{\lambda}$ is the photon energy, with v the light frequency, c the speed of light, and h being Plancks constant. P_l is the laser power, and χ is the optical power transmission efficiency of the system in Figure 5-4 for a single pixel. The photon energy is immediately calculable as 3.14×10^{-19} J for red He/Ne light. The 'dwell' time (T) is the time over which n_p photons pass through the single LCTV pixel as the disk rotates, and is approximated, with reference to Figure 5-11 as;

$$T = \frac{p}{V} = \frac{9.5 \times 10^{-6}}{1.3} \approx 7.3 \mu \,\text{sec.}$$
(5-20)

where p is the pixel size, and V is the linear track velocity of the disk. The transmission efficiency can be approximated by considering the losses occurring through the components of the system in Figure 5-4. In the figure, the incident laser power suffers a reduction due to reflections from a minimum of 10 air/glass interfaces (96% transmission - where the Perspex disk is assumed to be glass). A large transmission inefficiency is that associated with the LCTV as configured in the P(0,90) mode when operating with monochromatic light, which from Section 4.1.4 has been measured as 5%. For a single red pixel, the light intensity is attenuated further by a factor of (3/61600), where the total number of pixels is 61600, and since the signal of interest is a single pixel at half maximum grey level, there is an additional attenuation factor of 0.5. The total system transmission efficiency is therefore approximated as;

$$\chi = (0.96^{10}) \cdot (0.05) \cdot \left(\frac{3}{61600}\right) \cdot (0.5) = 8.1 \times 10^{-5} \%$$
(5-21)

Substituting Equations 5-20 and 5-21, and the photon energy into Equation 5-19, results in approximately 10^5 photons per correlated pixel. In general, an image is comprised of many hundreds of pixels, and as such, the correlation peak comprises a sufficient number of photons, easily detectable with modern silicon photodiodes. The number of photons can, if necessary, be increased by increasing laser power, reducing the speed of the disk, or with the application of an LCTV with improved transmission characteristics.

Taking the ideal case of no eccentricity, the disk comprises 1.67×1.67 mm blocks of 175×175 pixels, each recorded with 7-bit accuracy. With a linear track velocity of 1.3 ms^{-1} , each block of data is accessed in approximately 2.6msec on average (approximately 8 times faster than video), and as such, the data access rate is approximately 0.08×10^9 bits/sec, or 10Mbyte/sec. The capacity and data access rates for the concentric disk are thus 65Mbyte and 10Mbyte/sec respectively. Taking eccentricity into account, similarly to the above calculation, each 1.36×1.83 mm / 64×64 pixel block of data results in a disk capacity and a data access rate of 10Mbyte and 1.7Mbyte/sec respectively. These figures can be compared with a typical CD system, whose capacity and data access rate are around 650Mbyte and 0.16Mbyte/sec respectively. The data access rate is clearly much improved upon due to the parallelism offered by the system developed here. Note that CD-ROM systems typically specify an increased data access rate by revolving the disk at speeds greater than the industry standard of $\sim 1.3 \text{ms}^{-1}$ for audio CD systems. At speeds of up to 24 times the basic speed, modern CD-ROM drives thus offer around 3.8Mbyte/sec.

Not only does the parallel access optical disk provide a means for fast data access; when used as a multiplicative mask in a correlator, the system undertakes multiplication and accumulation operations simultaneously with data access. In the spatial domain correlator developed here, one dimension of shift invariance is available, and each of the 175 pixels in one column of input data are multiplied by the 175 pixels in the corresponding column of data on the disk. Since there are 175 columns, 175^3 multiplication and accumulation operations take place in the time taken for the disk filter to translate the entire input image, i.e. 2.6msec. Multiplication and accumulation is therefore performed at a rate of 2.1×10^9 7-bit operations per second. Taking eccentricity and the actual LCTV block size into account, 64^3 operations are undertaken in 2.1msec, i.e. 0.13×10^9 7-bit operations per second.

5.3 VANDERLUGT '4f' CORRELATOR

5.3.1 General Description

The VanderLugt or '4f' correlator [5-6] is based on complex matched spatial filtering in the spatial frequency domain, where the correlation operation is derived from a multiplication in the spatial frequency domain.

Figure 5-12 illustrates the optical set-up of the VanderLugt correlator, and illustrates why the system is often referred to as the '4f' correlator. Consider the correlation of an input object $f(x_1, y_1)$ and a reference function $g(x_1, y_1)$, whose Fourier transforms are $\mathbf{F}(u, v)$ and $\mathbf{G}(u, v)$ respectively. In order to record the spatial frequency domain multiplicative mask (i.e. $\mathbf{G}(u, v)$), a *complex* SLM would be necessary [5-7]. VanderLugt [5-6] however, pioneered an alternative technique which requires an amplitude-only modulation device, where the phase of the complex transform is encoded by using a spatial carrier frequency. Figure 5-13 illustrates the recording geometry, where a coherent reference wave acts as the frequency carrier, and is incident, along with $\mathbf{G}(u, v)$, on photographic film. According to the Fourier transforming properties of lenses [5-2], the photographic film records an intensity distribution proportional to;

$$I \propto \left| \frac{1}{\lambda f} \mathbf{G}(u, v) + \exp(-j2\pi\alpha x_u) \right|^2$$

$$\propto \left| \frac{1}{\lambda f} \mathbf{G}(u, v) + \exp(-j2\pi\alpha\lambda f u) \right|^2$$
(5-22)

where Equation 2-24, relating the spatial frequency u to its co-ordinate x_u , has been applied, and where;

$$\alpha = \frac{\sin(\theta)}{\lambda} \tag{5-23}$$

with θ giving the inclination of the reference beam in Figure 5-13. Since the amplitude transmittance is proportional to the recorded intensity, Equation 5-22 describes the complex transfer function of the matched filter H(u, v), and when expanded gives;

$$\mathbf{H}(u, v) \propto 1 + \frac{1}{(\lambda f)^{2}} |\mathbf{G}(u, v)|^{2} + \frac{1}{\lambda f} \mathbf{G}(u, v) \exp(j2\pi\alpha\lambda f u) + \frac{1}{\lambda f} \mathbf{G}^{*}(u, v) \exp(-j2\pi\alpha\lambda f u)$$
(5-24)

Once the complex matched filter is replaced in the spatial frequency domain, an input object $f(x_1, y_1)$ can be interrogated. The reference beam is removed, and the Fourier transform of the input object is incident on the matched filter. The light emerging from the filter is given by;

$$\mathbf{R}_{\mathbf{fg}} \propto \frac{1}{\lambda \mathbf{f}} \mathbf{F} + \frac{1}{(\lambda \mathbf{f})^3} |\mathbf{G}|^2 \cdot \mathbf{F} + \frac{1}{(\lambda \mathbf{f})^2} \mathbf{G} \mathbf{F} \cdot \exp(j2\pi\alpha\lambda \mathbf{f} u)$$

$$+ \frac{1}{(\lambda \mathbf{f})^2} \mathbf{G}^* \mathbf{F} \cdot \exp(-j2\pi\alpha\lambda \mathbf{f} u)$$
(5-25)

By taking a further optical Fourier transformation as in Figure 5-12, Equation 5-25 becomes;

$$R_{fg} \propto f(x_2, y_2)$$

$$+ \frac{1}{(\lambda f)^2} \Big[g(x_2, y_2) \oplus g^*(-x_2, -y_2) \oplus f(x_2, y_2) \Big]$$

$$+ \frac{1}{\lambda f} \Big[g(x_2, y_2) \oplus f(x_2, y_2) \oplus \delta(x_2 + \alpha \lambda f) \Big]$$

$$+ \frac{1}{\lambda f} \Big[g^*(-x_2, -y_2) \oplus f(x_2, y_2) \oplus \delta(x_2 - \alpha \lambda f) \Big]$$
(5-26)

The first two terms of Equation 5-26 can be considered as noise centred on the optical axis. The third term, however, is the convolution of f and g, centred at $x_2 = -\alpha\lambda f$. The fourth term is of most interest as it is the complex cross-correlation of f and g, centred at $x_2 = \alpha \lambda f$. Note that the signal output from the VanderLugt correlator is obtained on a photodetector, and since intensity is measured, the actual output has the form of the square of Equation 5-26.

When the input object $f(x_1, y_1)$ is Fourier transformed and is incident on the complex spatial filter, the filter is said to be matched to the input when the transfer function is the conjugate of the incident light distribution (i.e. \mathbf{F}^*). If the matched filter were originally synthesised from an object $f(x_1, y_1)$, then \mathbf{F}^* would be present in the fourth term of Equation 5-24. In essence, the light transmitted by the matched filter is proportional to the product of the input transform (**F**) and the transfer function of the matched filter (\mathbf{F}^*). Under these matched conditions, an amplitude modulated plane wave emerges from the frequency plane, and is brought to a sharp focus by the second Fourier transforming lens, indicating a high correlation. Viewed alternatively, the filter is essentially a Fourier transform hologram of an image, and thus when the Fourier transform of the image is incident on the correctly positioned hologram, the reference beam is reproduced, which is planar, and is brought to a sharp focus by the second Fourier transforming lens.

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Similarly to the spatial domain correlator, the disk is rotated to interrogate the unknown input object with the many complex matched filters (as recorded on the optical disk as amplitude modulation) in rapid succession. The system therefore performs fast parallel processing of an input light distribution, where the disk effectively acts as a memory store and as a *complex* processing element. In this case, disk rotation merely acts to position the matched filters appropriately in the frequency plane. Any relative shift of the input object appears as a linear phase tilt in its Fourier transform, whereupon a further Fourier transformation gives a proportionate shift in the correlation output signal, i.e. the system inherently provides 2D shift invariance without the need for any physical translation of the reference images. In practice, a pulsed laser is used to strobe each matched filter in turn, interrogating the unknown input object in parallel.

5.3.2 Experimental Results

The optical configuration of the VanderLugt correlator developed here is given in Figure 5-14, where a photograph of the actual set-up is given in Figure 5-15. A diode pumped, solid-state Nd:YLF (Neodymium : Yttrium-Lanthanum-Fluoride) pulsed laser is used to illuminate the LCTV and to provide the coherent reference beam. The laser can operate with both internally or externally triggered Q-switching at a rate of 0-20kHz, and has a wavelength of 523nm and a power of approximately 100µJ per pulse. In Figure 5-14, a lens of focal length f_1 forms the Fourier transform of the input object as held on the LCTV, and the complex matched filter is recorded on the disk with the coherent reference beam. A second lens of focal length f_2 performs a further Fourier transformation on the light transmitted through the disk and results in the output as described by Equation 5-26. A CCD camera is located in the output correlation plane to observe and capture typical output results. Note that the original polaroids laminated in the crossed condition either side of the LCTV cell were removed in order to eliminate excessive phase distortion. The polarisation of the laser and a rotatable polaroid allowed the necessary input/output polarisation configuration to be retained.

Since the VanderLugt correlator inherently provides 2D shift invariance, there is no need for a physical translation of the reference filter. As such, in contrast to the spatial domain correlator, there is no set maximum with regard to the data block size that can be applied (see Section 5.2.2). Any sized data block can be recorded, large or small, however the minimum pixel size that can be recorded remains limited by eccentricity and ultimately by SNR. Assuming zero eccentricity, in maintaining 41dB, the pixel size is approximately $9.5x9.5\mu$ m, as before. Resolution in the spatial frequency domain is given by the radius of the diffraction limited spot, as defined by the size of the input aperture. As such, the diffraction limited spot radius obtained from the Fourier transforming lens (of focal length f_1) in Figure 5-14 must be no less than 9.5 μ m in maintaining 41dB per recorded spot in the Fourier transform. For a square input aperture of width *D*, Equation 2-25 can be re-written to give 'half-theside-length' of the diffraction limited spot as;

$$l_s = \frac{f_1 \lambda}{D} \tag{5-27}$$

and for $l_s=9.5\mu$ m, $\lambda = 523$ nm, and D = 36.5mm, Equation 5-27 gives the minimum required focal length of the Fourier transforming lens as $f_1 = 660$ mm. With eccentricity taken into account, the pixel size must be a minimum of 26 μ m. This can be accomplished through reducing the SBP of the recorded data, as considered in Section 3.1.1. By reducing the input aperture in the spatial domain, the diffraction limited spot, and thus the minimum pixel size is increased. In the experimental investigation undertaken here, the full aperture of the LCTV was used in order to investigate the extent of shift invariance available, and so a minimum pixel size of 26 μ m was not achieved. Eccentricity remains a problem with the VanderLugt system so developed, and is not considered in the calculations in Section 5.3.3. A diffraction limited aplanatic doublet lens of focal length 650mm was used in the VanderLugt correlator.

Figure 5-16 shows one image used to form a complex matched spatial filter on the disk, and Figure 5-17 shows an image of the filter as viewed under the microscope. Note how high magnification permits the holographic carrier fringes to be observed. For comparison, Figure 5-18 gives the digitally calculated power spectrum of the letter 'A', where the optical and digital power spectrums show a great deal of similarity. Since the filter is an interferogram, the correlation output is independent of the chemical development procedure used, and in this case, normal (negative) development was applied. When the holographic matched spatial filter as given in Figure 5-17 is correctly positioned in the frequency plane of the VanderLugt correlator, and when the input is that image used to synthesise the filter (i.e. Figure 5-16), then the output from the correlator is given in Figure 5-19, showing a high intensity correlation peak. Further illustrations of input / output obtained with the VanderLugt correlator are given in Figures 5-20 and 5-21, where 2D shift invariance is seen to be available across the entire input aperture (i.e. the LCTV screen). Note that the outputs from the correlator as given in Figures 5-19 and 5-20 were obtained with a high magnification, whereas the output as given in Figure 5-21 was obtained with a

low magnification. This was necessary in order to view the correlation peaks in detail on the CCD element, and also to illustrate the full shift invariance capability of the system.

The results presented above show fringes across any one correlation peak. These fringes are produced directly as a result of recording multiple diffracted orders from the LCTV. When the Fourier transform of the input object is incident on the filter, the light emerging from the filter comprises multiple holographically recreated reference beams, one from each of the LCTV diffracted orders as recorded on the filter. This light distribution undergoes a second Fourier transformation, which results in the fringes, whose spacing is inversely proportional to the distance between the diffracted orders on the filter. These fringes may introduce difficulties when the centre of the correlation peak is to be established. Recording only one diffracted order through spatial filtering techniques removes this problem, however, and Figure 5-22 gives an illustration of the output available with the VanderLugt correlator set up in such a manner. Note that a spatial filter of approximately 2mm in diameter was used and was positioned as indicated in Figure 5-14.

The above results are all based on the input being matched to and accurately aligned with the filter. As an illustration of the output signal obtained with an unmatched filtering operation, Figure 5-23 gives the result where the input was a letter 'C' at 90° to the vertical, and where the filter was that matched to a vertical letter 'A'. The output as given in Figure 5-23 clearly shows no observable peak, as to be expected. An interesting result is obtained, however, when the filter becomes misaligned with the input. Figure 5-24 shows the input image and output correlation plane data from such a filtering operation, where it can be seen that the input image is partially reformed as a pair of faint images in the output correlation plane. Brief explanations for this phenomenon are given as follows.

The DC component of a matched filter is generally overexposed in order to increase the exposure of high frequency components, thereby improving object recognition ability. Due to this overexposure, however, holographic fringes are only formed on the 'outskirts' of the enlarged 'DC region', where the amplitude of the object transform component of the filter is reduced. When the filter is misaligned, some of the DC and low spatial frequency components of the incident transform are

incident on these fringes, and the diffracted light is Fourier transformed by the second lens in the 4f system, partially reforming the original input image. The output as given in Figure 5-24, however, shows a faint *pair* of images. This pair of images could only be reproduced if the filter contained a multiplicative low frequency modulation term, where Fourier transformation results in the output image being convolved and thus dealt-out at the location of two closely separated delta functions, (as the pair of images were observed to be separated by only a small distance). Since the filters are overexposed, the film is not operating in the linear region of the amplitude transmittance curve, and it is possible that intermodulation terms are introduced due to the non-linearity of the recording process [5-8], as mentioned in Section 2.2. These terms may result in the multiplicative low frequency modulation term and thus produce the ghost images in the output correlation plane. Note that the image of the output correlation plane as given in Figure 5-24, has been obtained by imaging the output correlation plane through a single lens element, magnifying the image to fill the CCD element appropriately, whilst performing a co-ordinate inversion. Since the two Fourier transforming lenses also produce a co-ordinate inversion, the two faint images of the letter 'C' occur with the same orientation as the input object. By comparing the correlation plane outputs given in Figures 5-19 and 5-24, however, the intensity of these ghost images (as produced with the unmatched filtering operation) at any one point is much lower than the correlation peak obtained with the matched filtering operation, and thus the effect is not problematic, and is of general interest only.

In order to compare the results obtained with the spatial domain correlator, bipolar processing was again illustrated here with the MACE filtering operation. As discussed in Section 5.2, the spatial domain correlator demanded certain practical measures to be taken in order to process bipolar information. Due to the application of coherent light with the VanderLugt correlator, however, it is possible to utilise phase to encode the bipolar data, where no elaborate experimental modifications are required.

The bipolar MACE filter was displayed on the LCTV by first of all adding a DC bias term. Under normal circumstances, the MACE filter would be recorded in the frequency plane (on the disk), by Fourier transforming the data as held on the LCTV. Over-exposure would result in saturating the DC component, thereby recording the

correct filter transfer function. Similarly to the spatial domain correlator, however, Fourier transform holograms of the individual images were pre-recorded on the disk, where the MACE filter was input via the LCTV. The holograms on the disk were over-exposed, however, such that the correct correlation function was still obtained on the CCD array.

The filter matched to a vertical letter 'A' was held on the disk in the frequency plane of the VanderLugt correlator. A MACE filter was synthesised for the recognition of image A0 and the suppression of image C300. Figure 5-25 gives the input MACE filter and the output from the correlation operation. Since the bipolar data is displayed as a single image on the LCTV, the dynamic range of the LCTV is a limiting factor, however only 1 bit of accuracy is lost in enabling the LCTV to display the bipolar information.

Finally, it is noted that the results described in this section were obtained with a CCD for illustrative purposes only. In a real, computer controlled system, it would be necessary to threshold the 2D output detection device in parallel, thereby obtaining recognition and location data automatically, whilst preserving the information processing rate made available with the optical system. This has not been undertaken here, largely due to the unavailability of the high speed, parallel thresholdable detection device. Recent advances in Smart Camera [5-9] technology, however, give an attractive solution to rapid (programmable) parallel thresholding, where 256x256 resolution images can be processed in the region of 500 frames per second.

5.3.3 Information Processing

As stated in the previous section, any sized data block can be used with the VanderLugt correlator. For comparison with the spatial domain correlator however, a block size of 1.67×1.67 mm comprising 175×175 pixels will be considered, where the ideal case of no eccentricity is assumed and where the pixel size is limited by SNR alone. From Section 5.3.2, this data block size can be recorded by taking the Fourier transformation of a 36.5×36.5 input object comprising 175×175 pixels, with a lens of focal length $f_1 = 660$ mm.

Due to the holographic recording, each pixel records both amplitude and phase information. Figure 5-26 illustrates how the mean number of developed photographic grains over the area of the 'complex pixel' gives the amplitude information, whereas the position of the fringe encodes the phase information $(0 < \varphi < 2\pi)$. Since the mean number of developed grains remains approximately the same as that for an amplitude-only pixel, from Equation 2-21, the mean noise associated with the amplitude component of the complex data recording remains unchanged.

The mean noise (and therefore SNR) associated with the amplitude component of the complex pixel is evaluated on the basis of the variation in the sample mean transmittance values as obtained from many identically recorded pieces of film (see Chapter 2). The noise associated with the phase component of the complex pixel could similarly be evaluated from a set of identically recorded fringes, however an estimation is available by considering the fringe as a statistical distribution of grains about a mean position.

An ideal 'correctly' positioned fringe can be considered to be made up of N grains, where each grain is distributed about the mean central position (φ_o) , with a 'population' variance (σ_p^2) , as indicated in Figure 5-26. The variance of the central position of many sample fringes is dictated by the number of grains in each sample, and is given by [5-10];

$$\sigma_s^2 = \frac{\sigma_p^2}{N} \tag{5-28}$$

and therefore the noise associated with the phase component of the complex pixel is given by;

$$\sigma_s = \frac{\sigma_p}{\sqrt{N}} \tag{5-29}$$

The SNR associated with the position of the fringe is therefore given by;

$$\operatorname{SNR}_{p} = 20 \log_{10} \left(\frac{\varphi_{o}}{\sigma_{s}} \right) = 20 \log_{10} \left(\frac{\sqrt{N} \cdot \varphi_{o}}{\sigma_{p}} \right)$$
$$= 10 \log_{10} \left(\frac{N}{N} + 20 \log_{10} \left(\frac{\varphi_{o}}{\sigma_{p}} \right) \right)$$
(5-30)

The first term in Equation 5-30 is seen to be identical to the SNR associated with the amplitude component of the recording, as given by the Poisson model in Equation 2-21. The second term in Equation 5-30 is seen to depend on the value taken for φ_o , however in the above example of a single fringe across the complex pixel, the second term is small. In a matched filter, the phase component of the complex data is therefore seen to be recorded with approximately the same SNR as the amplitude component. In this case, the amplitude and phase information are both recorded with an accuracy of approximately 7-bits. For 1.67x1.67mm blocks of data, each comprising 175x175 complex pixels (7-bit for both amplitude and phase), 4800 blocks are recorded on a disk of recordable area 13370mm². The disk therefore has an information storage capacity corresponding to approximately $2x10^9$ bits or 260Mbyte.

As with the spatial domain correlator, the rate of information processing is ultimately limited by the detectability of the output correlation peak. In contrast to disk speed and the associated 'dwell time' of the spatial domain correlator, in the VanderLugt correlator it is the energy of a single pulse from the laser which dictates the maximum number of photons that arrive at the detector. Taking the 'elementary signal' once more as a single pixel on the LCTV at half maximum grey level, the number of photons arriving at the detector can be found by re-expressing Equation 5-19 as;

$$n_p = \frac{E_l \cdot \chi}{E_p} \tag{5-31}$$

where E_l is the energy of a single pulse from the laser. χ can be approximated by considering the losses occurring through the system as given in Figure 5-14. By

comparing Figures 5-4 and 5-14, Equation 5-21 can be evaluated for the VanderLugt correlator as;

$$\chi = (0.96^{10}) \cdot (0.05) \cdot \left(\frac{3}{61600}\right) \cdot (0.5) \cdot (0.03) = 2.4 \times 10^{-6} \%$$
 (5-32)

where the diffraction efficiency of the holographic filter as mentioned in Section 2.3.6 is taken to be typically 3%. With a single laser pulse providing 100μ J, Equation 5-32 can be substituted into Equation 5-31, along with a photon energy of 3.8×10^{-19} to evaluate the number of photons per correlated pixel arriving at the detector as approximately 6.3×10^{6} , resulting in an easily detectable correlation peak.

With regard to the data access rate available with the VanderLugt correlator, a disk revolving with a linear track velocity of 1.3ms^{-1} , with $1.67 \times 1.67 \text{mm}$ blocks of complex pixels, as detailed above, results in a data access rate of approximately 0.33×10^9 bits/sec or 41Mbyte/sec on average.

Similarly to the spatial domain correlator, data processing takes the form of multiplication and accumulation operations. Two dimensions of shift invariance are inherently available with the VanderLugt correlator, and as such, each of the 175x175 pixels in the input image are correlated with each of the 175x175 pixels in the reference image. This results in 175^4 7-bit operations taking place in 1.3msec on average, due to the application of a pulsed laser. Multiplication and accumulation is therefore performed at a rate of 7.2×10^{11} 7-bit operations per second.

In summary, when considering equal sized blocks of data, the VanderLugt correlator results in an information capacity and a data access rate around four times that available with the spatial domain correlator, due to the extra dimension (phase) of storage. With regard to information processing, due to the extra dimension of processing power (i.e. <u>2D</u> shift invariance), the VanderLugt correlator results in around two orders of magnitude improvement over the spatial domain correlator. These conclusions are based on a concentric disk, where the performance of the VanderLugt correlator would clearly reduce when eccentricity is taken into account through a reduction in the SBP. In general, however, the VanderLugt correlator is far superior to the spatial domain correlator with regard to information capacity, data

access rate and the rate of information processing, when considering equal sized blocks of data. A practical means for reducing the eccentricity of the system developed here is discussed in Section 6.2, which would allow the maximum performance figures to be achieved in practice.

Finally, as mentioned in Section 5.3.2, the above discussion of performance depends on the 2D output detector of a real system being capable of handling such high data rates, whilst undertaking a parallel thresholding operation. Such a device was not available here, and was the reason why a fully operational system was not implemented. In the following section, however, an anamorphic based processor is described which relieves the need for a 2D high speed output detection device, whilst still preserving full 2D shift invariance.

5.4 ANAMORPHIC CORRELATOR

5.4.1 General Description

The main disadvantage with the VanderLugt correlator is that a very high frame rate, 2D parallel thresholdable output detector is required. It is possible to relieve the need for such a detector, and modify the VanderLugt architecture, resulting in the requirement for a 1D thresholdable detector. Although these devices are not generally available, in principle they could be fabricated by modifying a linear bank of independent photodiodes, and incorporate independent thresholding electronics.

The optical processor in Figure 5-27 can be considered as a combination of the spatial domain and VanderLugt architectures. Anamorphic optics are used (cylindrical lenses) to map the spatial frequency onto the disk in the x-direction (horizontal) whilst maintaining an imaging condition in the y-direction [5-11]. In a similar manner to the spatial domain correlator, the variable y in Equation 5-15, is derived from the temporal characteristics of the signal from each photodiode element, where the variable x is derived from the photodiode position - as in Equation 5-26. The full two dimensional complex filtering operation given by the form of Equation 5-5 can thus be implemented resulting in 2D shift invariance.

The cylindrical lenses as illustrated in Figure 5-27 are positioned to give a 1:1 imaging condition in the vertical direction, and since the optics on either side of the disk are identical, any shift in the input object results in an identical shift in the output correlation peak. The actual choice of optical components depends on the minimum size with which the filters on the disk are to be recorded, as dictated by SNR and eccentricity. The size of the output detector is also an important parameter with regard to optical design. Large output photodiodes, for example, may be desirable in easing the fabrication of thresholding electronics attached to each photodiode element.

As the information regarding input object position is obtained in exactly the same way as the spatial domain correlator (i.e. the *time* when a correlation peak occurs), a CW (continuous wave) illumination source should be used.

5.4.2 Experimental Results

The aim of this study was to investigate the feasibility and practicality of the configuration. As such, the fabrication of the linear thresholdable detector was not undertaken here. Similarly to the work concerning the VanderLugt correlator, a CCD camera was located in the output correlation plane to observe and capture typical output results.

First of all, it is interesting to observe the characteristics of the anamorphic matched filters, where they are Fourier transforms in only one direction. Figures 5-28 and 5-29 illustrate some input / filter pairs, where multiple orders from the LCTV are observable as the multiple vertical (DC) 'bars'. The first input / filter pair in Figure 5-28 is perhaps the most illustrative, and shows how the vertical positional information of the input images is maintained in the filter. These images are merely the 1D power spectrums of the input objects, and it is noted that when the actual filters are recorded on the disk, a carrier frequency is used in exactly the same way as with the VanderLugt correlator in order to encode the phase of the Fourier transform. Figure 5-30 gives an example of the filter matched to a vertical letter 'A', as recorded on the optical disk, where the holographic fringes cannot be observed due to the low magnification used. The co-ordinate inversion in the vertical direction can also be observed in Figures 5-28, 5-29 and 5-30, due to the imaging condition maintained.

Some typical correlation output results as obtained with the CCD camera are now presented. These results were obtained when the cylindrical lens in the output optics was removed, where the reason for this modification will become clear. The following results are based on an anamorphic filter matched to a vertical letter 'A', as held on the optical disk, where the input is spatially filtered allowing the passage of only a single diffracted order from the LCTV. Figure 5-31 shows the output correlation peak obtained when the input to the correlator was a vertical letter 'A' in the centre of the LCTV data field, and as expected, a high correlation peak was obtained. Figure 5-31 also shows the output obtained when the input was a vertical letter 'M', where a low output signal is expected and is achieved. Figure 5-32 illustrates the shift invariance property available in the horizontal direction through multiple input objects.

An illustration of the shift invariance available in the vertical direction would only be possible by placing the linear output detector in the correlation plane and viewing the temporal signature. The cylindrical lens in the output optics 'squeezes' any correlation peak in the horizontal direction into a vertical line. Only a section of a sheet laser beam is thus incident on the output detector, and as such, the time at which the laser sheet is incident on one of the photodiodes gives the information required to interpret the vertical position of the input object. Figure 5-33, however, illustrates this phenomenon without the cylindrical lens present in the output. The input to the anamorphic processor is that given in Figure 5-33(a), and with this system, one would expect a correlation output peak, first of all when the filter on the disk becomes aligned with the top input object. At this point (time t_1), a vertical line would strike an output photodiode towards the left hand side of the linear bank of photodiodes. Figure 5-33(b) illustrates the correlation peak obtained under these conditions. Similarly, when the disk rotates further to a point corresponding to time t_2 , Figure 5-33(c) illustrates the output correlation peak. As expected, no correlation peak occurs at this time, as there is no input object at the location in the input corresponding to time t_2 . Finally, when the disk rotates to a point such that the filter aligns with the bottom input object, the correlation peak as given in Figure 5-33(d) occurs at a time t₃. Shift invariance has therefore been demonstrated in the horizontal direction in exactly the same manner as achieved with the VanderLugt correlator, and in the vertical direction in exactly the same manner as achieved with the spatial domain correlator.

5.4.3 Information Processing

In this section, the effective data storage capacity and the rate of information processing available with the ideal anamorphic correlator (with no eccentricity) are considered.

The anamorphic correlator is capable of recording complex data, and for 175x175 complex pixels stored in 1.67x1.67mm blocks, the maximum data storage capacity is given in Section 5.3.3 as approximately 260Mbyte. Since the anamorphic correlator suffers from the fact that adjacent blocks of data must be spatially separate (as discussed in Section 5.5), then the effective data storage capacity is reduced to approximately 130Mbyte.

With regard to the rate of information processing, 2D shift invariance is available, and from Section 5.3.3, 7.2×10^{11} 7-bit operations per second can be performed when the disk revolves with a linear track velocity of 1.3 ms^{-1} , and where the blocks of data are adjacent to one another. For the spatially separate data blocks in the anamorphic correlator, approximately 3.6×10^{11} 7-bit operations per second can be undertaken.

5.5 PRACTICAL CONSIDERATIONS

Information processing is a well established field, where the noise tolerance of digital systems has allowed sophisticated algorithms to be used with great success. Although optical information processing offers truly parallel processing, its analogue nature generally results in difficulties with regard to practical implementation. The main practical issues concerned with applying the PAODS in the above optical information processing systems are summarised in this section.

Care in the general optical system design is required for a number of reasons. For example, a diffraction limited optical system was required in order to achieve shift

invariance across the full aperture of the LCTV. Aberrations can effectively reduce the extent of shift invariance in an optical system, and can be introduced through lenses, mirrors, and other optical components. The overall size of an optical system is often reduced through the use of adjustable mirrors to steer the laser beam appropriately. If anything other than an unexpanded laser beam is incident on the mirrors, magnitude and phase modulations can be introduced and thus superimposed on an otherwise flat beam profile. Careful optical design utilising lenses designed to minimise aberrations was undertaken here. The disadvantage of such an optical system is the physical size, where in the VanderLugt correlator developed here for example, a Fourier transforming lens of focal length 650mm was used in order to provide shift invariance over the 50mm lens aperture. In contrast to the spatial domain and VanderLugt correlators, the anamorphic correlator used cylindrical lenses to provide imaging and Fourier transformation operations. Since well corrected cylindrical lenses are not generally available, laboratory standard plano-convex cylindrical lenses were used, and as such, shift invariance was not obtained across the full input aperture.

When bipolar signals are being processed with the spatial domain correlator, two spatially separate signals are subtracted to give the correct output signal. Due to the differences in the response of the two photodiodes in Figure 5-4, and in the differences in the noise levels associated with the two images stored on the disk, the two photodiode signals obtained are not ideal. It is very important to match the relative gain and DC offset of the two signals, otherwise serious error in the correlation output signal may result. An electronic subtraction unit was designed and built in order to undertake such an operation in real-time. An alternative technique would have been to use a split photodiode with common electronics, however such a device was not available here.

An issue surrounding the operation of all three correlators is that of the minimum separation between two images of the same class in the input data field. Primarily, it is the resolution of the input SLM which dictates the minimum separation, however there are other factors which can affect the separation. With regard to the spatial domain correlator, as considered in Section 3.4, the disk speed and the frequency with which the correlation peak latch is polled also dictate the minimum separation between adjacent objects in the input data field. Taking the

simplest object as a single pixel, the maximum resolution of the LCTV dictates the minimum separation of two adjacent objects as 6.2µm in the plane of the optical disk. With a linear track velocity of 1.3ms⁻¹, the time between adjacent objects is approximately 5µsec. In order to resolve two such objects in the vertical direction, the counter latching process must therefore take place with a minimum frequency of approximately 400kHz by application of the Nyquist sampling theorem. This sampling frequency is easily achievable with commercially available PC based systems. In order to make sure the correlation signal itself is not undersampled, 400kHz also corresponds to the minimum bandwidth required for the single photodiode in the spatial domain correlator, and for each element in the anamorphic correlator's linear bank of photodiodes. The photodiode used with the spatial domain correlator has a 10MHz bandwidth, and therefore far exceeds the requirement.

The minimum separation between two images of the same class in the input data field of the VanderLugt correlator is dictated not only by the resolution of the input SLM, but also by the resolution of the 2D correlation plane output detector. If, for example, the SBP of the output detector were lower than the SBP of the input data, then two input images of the same class would result in two closely spaced correlation peaks, not resolvable with the low SBP output detector. In simple terms, for both the VanderLugt correlator, and (one dimension of) the anamorphic correlator, the SBP of the output detector should match that of the input data.

When undertaking multiple correlations through disk rotation, it is important that the input object is interrogated by one filter at a time, otherwise an output signal may comprise multiple (non-separable) correlations between the input and two or more of the matched filters as held on the disk. This would introduce serious sources of error, and can only be avoided by separating the matched filtering operations appropriately. The VanderLugt correlator uses a pulsed laser to strobe the input, such that the input data is interrogated by a single filter in a single pulse of the laser. In this way, the matched filtering operations are independent, where filters can be recorded adjacent to one another whilst avoiding cross-talk between adjacent filters. This is in contrast to both the spatial domain and anamorphic correlators, where CW light is used, and where the correlation operation requires physical translation of the matched filters. As is illustrated in Figure 5-34, each filter must be separated by a minimum distance equal to the length (L) of the filter, thus ensuring that the output signal comprises only a single correlation term. As a result of this separation, the disk capacity and the rate of information processing associated with both the spatial domain and anamorphic correlators are reduced, emphasising the advantage of using the VanderLugt architecture.

The main practical limitation of applying the PAODS in optical correlators is that of disk eccentricity. As discussed in Section 3.1.1, eccentricity dictates a minimum pixel size, whilst maintaining a filter alignment accuracy of 1 pixel. The affect of sub-pixel filter misalignment has been considered by VanderLugt [5-12], however for simplicity, only pixel size alignment has been considered here. The pixel alignment accuracy has been considered for data recorded in both the spatial and spatial frequency domains. With regard to data recorded in the spatial domain, in general a misalignment of 1 pixel would have serious affects on the correlation signal obtained with small images only. With large images, a misalignment of 1 pixel would have little effect on the light transmitted through the disk, and thus on the correlation signal. The opposite is true for data recorded in the spatial frequency domain. For small images, in general a lot of information is spread out over many spatial frequencies giving a broadened spectrum. As such, a misalignment of 1 pixel has little affect on the correlation signal. For large images, the data in the spatial frequency domain is largely DC, and a misalignment of 1 pixel can have significant effect on the light transmitted by the matched filter, significantly affecting the correlation signal. Clearly, the effect of filter misalignment is very much dependent on the recorded data. In general however, as eccentricity increases, alignment can be maintained to an accuracy of 1 pixel by reducing the SBP of the recorded data, (as considered in Section 3.1.1). In the system developed here, an eccentricity of $\pm 13\mu m$ has resulted in a maximum resolution of approximately 64x64 pixels whilst maintaining alignment to an accuracy of 1 pixel.

Due to the complex data recording, the option to place filters adjacent to one another, and no effect with regard to rotational filter misalignment, the VanderLugt correlator is the superior of the correlators investigated here. Disk capacity, data access rates, and the rate of information processing are all greater with the VanderLugt correlator, and with kinematic positioning (as discussed in Chapter 6), the

performance could be improved upon even further. The disadvantage with the VanderLugt correlator is the need for a high frame rate, parallel thresholdable 2D detection device. The smart camera [5-9], however, is a recently developed device that allows high frame rate operations, and may be a solution to this problem.

6

Conclusions and Further Work

6.1 CONCLUSIONS

Since the first demonstration of linear filtering operations using optical methods, much research effort has been directed to the design of synthetic filters that permit shift, rotation and scale invariant pattern recognition. It is clear from the literature that it is not possible to identify an unknown object, locate its position when subject to geometric distortion, *and* maintain a high SNR, all in a single linear filtering operation. It is therefore attractive to consider recognition via the (non-linear) combination of many linear filtering operations. Such a system needs considerable memory and processing power above and beyond what is currently available. The work described in this thesis was initiated with the objective of providing such a system based on a parallel access optical disk.

A new form of optical disk has been fabricated by laminating Agfa 8E75 holographic (silver halide) film on a Perspex substrate. Two dimensional grey scale data can be stored as modulations in the amplitude or the intensity of light transmitted through the disk.

The relationship between SNR and area of the recording medium has been investigated with regard to evaluating the minimum area required to record data with a specific dynamic range. Experimental measurement was undertaken to obtain such data, and an approximate theoretical model based on Poisson statistics was compared with the experimental data. The two sets of data compare well in the region of

approximately $1x1\mu m$ to $25x25\mu m$, i.e. that corresponding to SNR's of approximately 30-50dB, which includes information recorded up to and including an accuracy of 8bit. Due to limitations in the imaging system used to analyse the film, good comparison between the theoretical and experimental results was obtained over the 30-50dB range only. Comparisons over a larger region could only be undertaken by modifying the experimental technique.

The SNR of the recording medium has been compared with a digital system comprising a CCD camera and a frame grabber. The SNR of such a digital system has been measured as 41dB per pixel (approximately 7-bit), and in order to record data on the optical disk with the same SNR, an area of 9.5x9.5µm has been shown to be required. The optical disk developed here has a recording area of 13370mm², and therefore the maximum data storage capacity in terms of amplitude or intensity transmittance is approximately 130Mbyte. The dimensions of the 512x768 pixel CCD camera were approximately 4.2x5.8mm, and in order to record the same amount of information, approximately 4.8x7.2mm of Agfa film is required. In comparison to alternative memory systems such as the CD or a CCD / frame grabber system, the Agfa film therefore has a lower storage capacity. The research work undertaken here, however, is focused on the data access rate and the rate of information processing available with parallel optical systems, and has been shown to be far superior to that available with serial based systems.

The maximum spatial frequency corresponding to the 9.5µm pixel size dictates a minimum numerical aperture, which in turn dictates a specific DOF. A DOF of approximately 580µm was available whilst recording such a pixel size. As a result of this relatively large DOF, no auto-focusing was necessary, and a fixed focus system was the basis of the disk holding mechanism. The mechanical device designed and subsequently manufactured resulted in a disk run-out of approximately 40µm at a disk radius of 70mm, thus presenting no problems with regard to out-of-focus images.

Due to the large data storage capacity of the optical disk, and the potentially high rates of information processing, significant automation was required. A PC based control system has been developed not only to automate the recording of the reference data on the optical disk, but also to monitor thresholded correlation signals, resulting in a fully automated pattern recognition machine. A simple, yet effective image

labelling system has been incorporated into the control system, such that each reference image on the disk has an associated reference label, also recorded on the disk. The timing signal obtained from the image labels has been shown to locate the position of an image to an accuracy of less than one pixel. A further use of the image labels has been discussed, that being the spatial interpolation across any image. A high speed (4MHz) timer allows image interpolation with a resolution of $<1\mu$ m when the disk revolves with a linear track velocity of 1.3ms⁻¹. Image size, radius, disk speed, and the configuration of the images on the disk have all been considered with regard to the correct interpretation, calibration and use of the timing signal.

A Casio LCTV has been used not only to display reference data during the disk recording procedure, but also to input unknown object data in the optical correlators investigated. In order to make sure the optical systems are performing the desired correlation between the input object and the reference images, it was necessary to examine the accuracy with which the LCTV displays the pixels of image data. The LCTV was supplied with a CCIR video signal as the source of image data held in a computer. Due to the differences in the resolution of the video signal and the LCTV, certain lines of video were seen to be removed by the LCTV electronics before the remainder were displayed on the LCTV pixels. Two different pixel mappings have been observed, where the difference has been shown to be due to errors in establishing field synchronisation. Simple experimental verification of which mapping occurs has permitted exact pixel registration in the vertical direction. The pixel mapping in the horizontal direction has also been examined, and pixel registration is available with an accuracy of $\pm 1/2$ pixel.

The complex light modulating properties of this specific LCTV have also been investigated here. A theoretical model has been used alongside experimental observation to evaluate the complex modulating characteristics of the crossed and parallel polaroid configurations. Two interesting features of this type of light modulation have been observed and explained in physical terms. As the grey level supplied to the LCTV is increased from 0 to 255, the elliptically polarised output light has been shown to rotate in a direction opposite to the helical twist. This has been shown to be due to a minimum of a $\pi/2$ phase difference between the orthogonal complex components of the output polarisation when the grey level is zero. The

second interesting phenomenon is that of the π radians phase jumps that coincide with zero output light in the parallel polaroid configuration. This effect has been explained in terms of the changes in the complex polarisation phasors as they propagate from layer to layer. This effect has not been observed in practice, however, due to the relatively low birefringence of the LCTV used here.

With regard to amplitude modulation, a crossed polaroid configuration has resulted in a contrast ratio of approximately 25, where a cross-coupled phase modulation of approximately $\pi/2$ radians has been observed. Since the LCTV used here has a relatively low birefringence, phase-mostly modulation was investigated with a procedure involving the careful re-alignment of the input / output polarisation state. Phase-mostly modulation is achieved with this latter procedure by positioning the output polaroid parallel to the mean line of the major (or minor) axes of the elliptical output polarisation states that occur over the dynamic range of the LCTV. A phase modulation of between 0 and π radians has been obtained with the Casio LCTV, where a cross-coupled amplitude modulation of 10% across the useful range has been measured. Two Casio LCTV's have been placed in tandem and correctly configured for phase-mostly modulation, resulting in 2π phase modulation. The use of three correctly configured LCTV's has been suggested in order to obtain a stand-alone complex light modulation device.

The main contribution of the work described in this thesis is the practical investigation and development of three disk based optical correlators, where character recognition has been used as the basis for demonstrating their performance. A spatial domain correlator has been demonstrated that is capable of recognising an unknown input object when constrained to move in one direction only. The 1D shift invariance property was made available through disk rotation. The main drawback of spatial domain correlators in general is the inability to process bipolar data. A new technique for providing a bipolar processing capability with disk based correlators has been demonstrated here, where the MACE filtering operation was the basis of the demonstration. By recording pairs of filters on the disk, where each filter corresponds to the positive and negative components of the bipolar impulse response function, two spatially separate signals are processed. An electronic subtraction system has allowed the bipolar correlation signal to be obtained in real-time.

It has been shown that the spatial domain correlator is capable of processing data with a maximum block size of 1.67×1.67 mm, and where adjacent blocks of data must be separated by a distance equal to the size of an individual block. With this block size, 175×175 pixels can be recorded with a SNR of approximately 41dB per pixel. This has resulted in a data storage capacity of approximately 65Mbyte. The parallel processing nature of the spatial domain correlator has shown that when the disk revolves with a linear track velocity of 1.3 ms^{-1} , multiplication and accumulation operations can be performed at a rate of 2.1×10^9 7-bit operations per second on average.

The second correlator that has been demonstrated is the VanderLugt correlator. This correlator inherently provides 2D shift invariance, and through careful optical design, shift invariance has been achieved over the entire LCTV input aperture. The processing of bipolar impulse response functions has again been demonstrated with the MACE filter. Bipolar MACE filters are recorded by displaying the filter in intensity transmittance with a DC bias, and then overexposing the Fourier transform.

Since the VanderLugt correlator is a truly complex processor, in the most general sense a *complex input object* could be recorded. The complex input could be entered into the optical system by using independent amplitude and phase modulating devices. Since light modulating devices generally provide some cross-coupled modulation, an optimisation procedure (as considered in Chapter 1) for recording the best matched filter would have to be undertaken.

Unlike the spatial domain correlator, any sized block of data can be processed with the VanderLugt correlator, where the blocks of data can be recorded adjacent to one another, and where the maximum size is ultimately limited by the size of the disk. For comparison, 1.67x1.67mm blocks of 175x175 complex pixels are considered, resulting in a disk capacity of approximately 260Mbyte. The processing speed is limited by the frame rate of the 2D output detector, however due to the 2D shift invariance property, the VanderLugt correlator has the potential for undertaking $7.2x10^{11}$ 7-bit multiplication and accumulation operations per second, again when the disk revolves with a linear track velocity of 1.3ms^{-1} .

An anamorphic correlator has been demonstrated to relieve the need for a high speed 2D output detector, whilst maintaining 2D shift invariance. Similarly to the

spatial domain correlator, the anamorphic correlator can only process (complex) data blocks with a maximum size of 1.67×1.67 mm comprising 175×175 pixels. This correlator also suffers from the fact that adjacent images must be spatially separate in the same manner as the spatial domain correlator. In comparison to the spatial domain and VanderLugt correlators, the anamorphic correlator is therefore capable of applying an optical disk whose data capacity is approximately 130Mbyte, where the rate of information processing is approximately 3.6×10^{11} 7-bit operations per second.

Aplanatic doublet lenses were required with the VanderLugt correlator in order to provide shift invariance across the entire LCTV input aperture. In order to provide the same performance in the anamorphic correlator, compound cylindrical lenses would be required. Uncorrected plano-convex cylindrical lenses were used in the anamorphic correlator developed here however, which reduced the extent of shift invariance available.

The main problem associated with all of the disk based correlators is that of eccentricity. Disk eccentricity has been shown to limit the minimum pixel size that can be processed, thereby restricting the data storage capacity. Further work is clearly necessary to implement a system providing tracking in both the x- and y-directions, and has been suggested in order to utilise the full SBP of the recording medium. This work is outlined in the following section.

The VanderLugt correlator is not susceptible to the rotational filter misalignment problem, and complex data blocks of any size can be positioned adjacent to one another on the optical disk. Assuming eccentricity to be zero, the VanderLugt correlator can undertake complex information processing with an optical disk whose data storage capacity is limited by SNR alone. Of the three disk based optical correlators investigated, the VanderLugt correlator is thus optimal in terms of data storage capacity and the rate of information processing.

The advantage of using optical parallel processing can be made clear by comparing the processing rates of the VanderLugt correlator with the likes of a modern super-computer. With 1.67x1.67mm blocks of 175x175 pixels, a disk revolving with a linear track velocity of 1.3ms^{-1} results in approximately 780 (175x175 pixel) 2D correlations per second. In a digital computer, the correlation between two functions is generally performed through a multiplication of the

respective Fourier transforms. Implementing the FFT (Fast Fourier Transform) algorithm in the mathematical software Matlab [6-1] has resulted in a 175x175 pixel correlation operation requiring approximately $15x10^6$ floating point operations. If this procedure were to be undertaken with a modern super-computer capable of around $3x10^9$ floating point operations per second [6-2], then approximately 200 (175x175 pixel) 2D correlations per second could be undertaken.

The correlation operation undertaken within the super-computer may be 32-bit or even 64-bit however, whereas only 7-bit correlation has been undertaken with the VanderLugt correlator. Nevertheless, the processing rate available with the relatively straight forward experimental apparatus used here is seen to be rather substantial, especially when one considers that the cost of such a super-computer is in the region of £0.5M.

6.2 FURTHER WORK

The main drawback of the PAODS developed here is that associated with eccentricity when the disk is replaced in the holding mechanism following chemical development. Ideally, the disk should be replaced in the exact same position as that used during exposure, giving zero eccentricity. With this condition, data could be stored in the minimum area as dictated by SNR. This could be accomplished by undertaking the development procedure in-situ, without removing the disk from the holding mechanism, and by rotating the disk through the various chemical baths. This would give the desired zero eccentricity for that specific disk, however, if an input object had to be interrogated with another disk, disk replacement would give eccentricity.

In order for any disk to be replaced in the holding mechanism with zero eccentricity, a modification to the current design is suggested by incorporating two orthogonal micro-linear-positioners. These positioners would permit any pre-recorded disk to be located in a precise 2D kinematic position on the drive shaft. The required movement of each positioner must be measured on the basis of data recorded on the disk. It is therefore suggested to focus a laser beam onto the outskirts of the disk during the recording phase, and thereby record a very fine 'alignment circle' around

the disk. The use of a photodiode on the opposite side of the developed disk would allow the transmitted light intensity to be measured as the disk rotates. A maximum (uniform) signal obtained with the photodiode would indicate that the disk is positioned in the same position as that used during the recording phase, and eccentricity will have been minimised. A feedback control loop from the photodiode to tracking motors would also permit the operation to be undertaken automatically.

The relationship between SNR and area has only been measured around a relatively large bandwidth, since it is of interest to record data on very small areas of film. Unfortunately, the high magnification microscope objective used for this analysis gave an incoherent transfer function approximately triangular in shape. The nonuniform noise spectral density that resulted gave discrepancies between the theoretical model and the experimental data, and a good comparison was only obtained over a region where the measured noise spectral density was approximately uniform. In order to improve the measured data, it is suggested to use a measuring system whose transfer function is either uniform, or whose non-uniform transfer function could be accurately evaluated and accounted for in a calibration stage. In order to extend the region of measured data, smaller bandwidths could be considered by using microscope objectives of lower magnification, where the effect of the transfer function of each could be calibrated. Care would have to be taken, however, to ensure that the mean intensity as recorded by the CCD remains constant for each of the microscope objectives.

The overall system SNR associated with the optical correlators investigated is dependent not only on the SNR available with the recording medium, but also on the SNR of the OFG used to supply the LCTV with the video data, the SNR of the output detector(s), and indeed on the SNR of the LCTV itself. Since the LCTV is used not only to record data, but also as a means to display the input object, the SNR of this device is especially important. It is therefore suggested that an investigation into the SNR available with the LCTV is undertaken. By focusing a laser beam on an individual pixel of the LCTV (at half maximum grey level), the transmitted intensity could be measured with a photodiode. By moving the LCTV such that the laser is incident on many different pixels, the variations in the transmitted light would allow an evaluation of the SNR associated with maximum spatial bandwidth. The use of a smaller, monochrome LCTV with higher resolution (and improved transmission efficiency) is also suggested, since these devices are becoming more readily available at affordable prices. The reduced size would relieve the need for obtaining diffraction limited performance over a large aperture, and since lenses of a reduced focal length could be applied, a smaller optical system would result. Using the previously mentioned linear positioners to minimise eccentricity, the full SBP of a higher resolution modern LCTV could be utilised. The maximum disk capacity (and rate of information processing) as dictated by SNR could therefore be attained. A full analysis of the new LCTV, such as that undertaken here for the Casio TV-5100, would also be required. An LCTV with a VGA input would also be recommended to ensure a 1 to 1 pixel mapping.

The LCTV has been applied here to display data in intensity transmittance only, where in the VanderLugt correlator, spatial frequency domain data is recorded on the optical disk. As stated in the previous section, in the most general sense, the VanderLugt correlator is capable of processing complex data, and that independent amplitude and phase modulating devices could be used to enter the complex input into the optical system, from which the complex matched filter could be recorded. Due to the cross-coupled nature of such devices, it is difficult to record the desired complex filter response on the basis of the information held on the LCTV's. An area of further work is therefore to investigate how cross-coupled LCTV's could be used most appropriately in displaying amplitude and phase data, from which a matched filter giving optimised performance could be recorded.

The spatial domain correlator developed here suffers from the need to spatially separate adjacent filters on the optical disk. A limitation of this architecture is therefore the small disk capacity when compared to the likes of a CD. In order to increase the storage capacity, research into the feasibility of recording binary data is suggested. From communications theory, the (minimum) mean SNR associated with each of the signals '0' and '1', required to ensure a bit-error-rate of 10^{-9} , is approximately 6 [6-3]. Clearly, binary data could be recorded on a much smaller area of film. In a communications system, the transmitted data is thresholded by the receiver in order to give a truly binary system. When film is required to record binary
data, a highly non-linear recording medium (e.g. lithographic) is therefore necessary to provide a threshold.

Since an 8-bit reference function g can be split into a sum of its binary components;

$$g = g_1 + 2g_2 + 4g_3 + \dots + 128g_8 \tag{6-1}$$

where g_1 and g_8 are the least and most significant bits respectively, the correlation between an input object f and the reference function can be described by;

$$f \otimes g = f \otimes g_1 + 2f \otimes g_2 + 4f \otimes g_3 + \dots + 128f \otimes g_8 \tag{6-2}$$

A grey scale input image can therefore be processed by interrogating with 8 independently recorded bit-plane data blocks. Although the disk capacity may well be increased substantially, the processing speed may, however, be reduced due to the need for storing 8 independent sets of correlation data, where subsequent digital processing would be required in order to complete the 8-bit correlation operation described by Equation 6-2.

The Fourier transformation of Equation 6-1 gives the individual transfer functions associated with the spatial domain bit-plane data blocks. Taking G as the Fourier transformation of g, it is clear that the decomposition;

$$\mathbf{G} = \mathbf{G}_1 + 2\mathbf{G}_2 + 4\mathbf{G}_3 + \dots + 128\mathbf{G}_8 \tag{6-3}$$

does not comprise binary transfer functions. Filters with a binary transfer function have been implemented with great success elsewhere, however, where one example is the BPOF. For a given recognition problem, it is therefore likely that an optimal solution exists using a combination of the outputs obtained from filters with binary transfer characteristics. Similarly to the work of Farn and Goodman [6-4], an area of further work is therefore the development of an optimisation algorithm with regard to the decomposition of a complex transfer function into a sum of transfer function's with binary amplitude characteristics.

It is now clear that, of the three correlators investigated, the VanderLugt correlator provides the best performance in terms of disk capacity, data access rate and the rate of information processing. The VanderLugt correlator developed here was not fully automated, however, due to the lack of an appropriate output detector. An important area of practical research is therefore the development of a fully automated disk based VanderLugt correlator, where a device such as the smart camera could be applied to threshold the 2D output correlation signal in parallel and at high speed.

Once eccentricity is removed through an automated tracking procedure, and the improvements to the VanderLugt correlator have been undertaken, a fully automated disk based optical correlation system will be available. The system will be capable of storing 260Mbyte of data, and with a linear track velocity of 1.3ms⁻¹, will have a data access rate of around 41Mbyte/sec. The system could then be used for undertaking many alternative pattern recognition tasks, where sophisticated, memory intensive algorithms could be applied.

Appendix A

NDT Info

IDT/Holography

. Introduction

hotographic materials for holography

hotographic materials for holography must meet specific equirements. Since the dimensions of the structure of ne interference pattern to be recorded are usually of ne order of magnitude of the wavelength of the light used or exposure, a very high resolving power is essential. high speed is also desirable to allow short exposures.

lowever, high resolving power and high speed are omewhat incompatible properties, which makes it ecessary to arrive at a compromise of the highest ossible efficiency. The nature of the subject will letermine whether the ideat solution of this problem will re slanted towards high speed or high resolving power.

ccording to the above principles, Agfa-Gevaert has
 leveloped 4 types of HOLOTEST photographic materials:
 10 E 75 High sensitivity - size of grain approx.

High sensitivity - size of grain approx. 90 nm, resolving power approx. 3000 lines/mm, to be used with red light emitting lasers.

- 10556 Same properties as the 10 E 75 material, but to be used with green light emitting lasers.
- 8 E 75 HD Size of grain approx. 35 nm, very high resolving power of approx. 5000 lines/mm, lower sensitivity than 10 E 75, to be used with red light emitting lasers.
- 8 E 56 HD Same properties as the 8 E 75 HD material, but to be used with green light emitting lasers.

2. Amplitude holography

2.1. Density and amplitude transmission curves

The relation between density D and exposure E is usually represented by the characteristic curve. Fig. 1 shows these curves for HOLOTEST emulsions 8 E 75 HD and 10 E 75 for red laser light, 8 E 56 HD and 10 E 56 for blue and green taser light respectively.





Exposures of HOLOTEST 8 E 75 HD and 10 E 75 were effected with 627 nm, and of 8 E 56 HD and 10 - E - 56 with 514 nm.

Processing was carried out in G 282 (1 + 2) for 4 minutes at 20°C. After an intermediate rinse in water (1 minute at 20°C), fixing was carried out in Agfa-Gevaert fixing bath G 321 for 4 minutes, followed by washing for 15 minutes. The density of the developed emulsion layers was measured by parallel light. Characteristic curves contain useful information in the case of certain holographic exposures, but in general amplitude transmission curves are preferred, because a hologram acts as a diffraction screen to the incident wave front, where not the local density but the local amplitude transmission is the more important consideration. Amplitude transmission is defined as the ratio between the amplitudes of a monochromatic plane wave after and before passing through the photographic emulsion. This is usually a complex quantity; in other words, not only the amplitude but also the phase of the incident radiation is affected. However, in the case of processed emulsions, for measuring amplitude transmission IT_a1 the only easily measured quantity is intensity transmission $T_i = T_a T_a^*$. where T_a * represents the complex conjugate of T_a. This quantity is expressed as a function of the exposure of HOLOTEST 8 E 75 HD and 10 E 75 at a wavelength of 627 nm, and of HOLOTEST 8 E 56 HD and 10 E 56 at a wavelength of 514 nm respectively, in Fig. 2.



ie energy per unit surface that corresponds to 1 = 0.5 can be regarded as an indication of e sensitivity. pproximate values of light intensities for $|T_n| = 0.5$

orresponding to D = 0.6) are

0.5 μJ/cm² for 10 E 75
 10 μJ/cm² for 8 E 75 HD

 $^{\prime}$ 1 $\mu J/cm^2$ for 10-E-56

· 25 µJ/cm² for 8 E 56 HD

hese values will also be slightly affected by re processing conditions.



12. Colour sensitivity

IOLOTEST holographic emulsions 8 E 75 HD and 10 E 75 ire specially sensitized for wavelengths between 600 and '50 nm, and are intended for use with the He-Ne laser 333 nm) and the ruby laser (694 nm). On the other hand, IOLOTEST holographic emulsions 8 E 56 HD and 10-E-56 ire suitable for exposure to wavelengths up to 560 nm krypton and argon lasers). The density and amplitude ransmission curves given in Section 2.1 apply to he wavelength of the He-Ne laser of 633 nm and those of he krypton laser of 476 and 521 nm. To enable one to convert the exposure to other wavelengths, the absolute ipectral sensitivities are shown in Fig. 3.





Fig. 3

Absolute spectral sensitivity. Curves to obtain a D = 0.60 above fog.

2.3. Image quality

An optical diffraction method was used to determine the image quality of the holographic emulsion. A double-beam interference exposure enabled us to examine the resultant diffraction screen. Fig. 4 shows in schematic form both the exposure and the reconstruction.



Fig. 4

Schematic representation of exposure and reconstruction of doublebeam interference.

During exposure, two plane waves having intensities I_1 and I_2 were incident on the photographic plate, each at the same angle to the normal. Representing the angle between the two rays by θ , spatial frequency f is given by

$$f = \frac{2}{\lambda} \sin \frac{\theta}{2}$$

where λ = wavelength in air (633 nm for the He-Ne laser). With θ = 90°, a spatial frequency of 2,235 lines/mm will then result. The separation between adjacent lines will then be the inverse of the spatial frequency equal to approx. 0.45 micron.

Modulation m depends on the polarization of the laser radiation and intensity ratio I_1/I_2 . In the case described, lasers with linearly polarized radiation were used.

he electric vector was normal to the plane of incidence. he intensity ratio l_1/l_2 amounted to 0.5, corresponding to modulation of 0.94. In general the modulation caused by ne polarization considered here is

$$n = \frac{2 \sqrt{l_1 l_2}}{l_1 + l_2}$$

Reconstruction took place as shown in Fig. 4. Ray I, was used for reconstructing ray I₂'. Intensity I₂' was a diffraction of the first order and hence ratio I₂'/I₁ is is tependant on angle θ , modulation m, and the exposure. Fig. 5 shows ratio I₂'/I₁ against exposure.





Dependence of diffraction efficiency on exposure

This function has a definite maximum. Ratio l_2/l_1 can be considered as a measure of the quality of a screen and is therefore called diffraction efficiency. Fig. 6 and 7 show the optimum diffraction efficiency $(l_2'/l_1)_{max}$ as a function of the spatial frequency for HOLOTEST emulsions 10 E 75 and 10 E 56 respectively. Intensities I1 and I2' have not been corrected for Fresnel reflection, because the latter corresponds to the practical applications of holography. The actual diffraction efficiency of the photographic emulsion for the polarization used is higher still, especially at large values of angle θ . We should mention that the material was over-modulated by using the large modulation values of 0.94 or 1. In other words, this is not a case of linear transfer; intensities of higher orders of diffraction are also obtained. In order to compare the diffraction intensity to noise I_N at various spatial frequencies, exposures were carried out with a single laser beam of the same overall intensity, and the photographic plates were all processed and measured under identical conditions. The resultant ratio I_N/I_1 is also shown in Figs 6 and 7.



Fig. 6

Maximum diffraction efficiency against spatial frequency, E-vector normal to plane of incidence; modulation 0.94.



Fig. 7

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16

Maximum diffraction efficiency against spatial frequency, E-vector normal to plane of incidence; modulation m = 1.

2.4. Reciprocity behaviour

Q-switch lasers with pulsewidths of 10 to 50 ns are used for short exposures. In this case, the reciprocity behaviour of HOLOTEST emulsions is obviously important. To obtain densities $D \leq 2$, the exposure of HOLOTEST materials must be multiplied 2 to 4 times when Q-switch lasers are used.

Processina

kroom illumination

ommended Agfa-Gevaert safelight filters: nplete darkness for HOLOTEST 8 E 75 HD and Ξ 75.

(dark red) for HOLOTEST 8 E 56 HD and 10 E 56.

relopment

both transmission and reflection holograms) minutes in REFINAL - 20°C or min in GP 61 - 20°C (see composition § 3.1)

ina

inutes in G 321 (dilution 1 + 4) or in 34 (dilution 1 + 4).

Phase holography

. Transmission holography

ere theoretically the maximum diffraction efficiency t may be achieved with an amplitude hologram will be 5% at the utmost, theoretically 100% may be nieved with phase holograms.

chnical literature describes a great number of cessing systems that, with the highest possible raction efficiency enable the noise to be kept as low as ssible.

e exposure doses that are required for making a good ase hologram amount to ~ 50 μ J/cm² for \pm emulsion 8 E 56 HD, and to ~ 25 μ J/cm² for emulsion 8 E 75 HD, as a relatively high density tween D = 1.5 and D = 2.5 proves to be necessary. r the Agfa-Gevaert HOLOTEST 8 E 56 HD and E 75 HD emulsions (as the HOLOTEST 10 E 75 and E 56 emulsions after bleaching produce more noise

in the 8 E HD types, they are not recommended for ase holography) the following processing is proposed:

Development:

min. in REFINAL (20°C), or min. in GP 61 (20°C) made up as follows:

² 61			1140
ater	700	ml	(7)%
ETOL	6	g	
droquinone	7	ġ	
enidone	0.8	3 g	
503	30	ğ	
1,CO3	60	ġ	
łr	2	ğ	
LEDTA	1	ģ	
iter to make 1 litre		÷	

Intermediate rinsing in running water: 2 min. mperature 20°C ± 2°C).

Fixing in Agfa-Gevaert G 321 (1 + 4) rapid fixing bath, r 2 min. (temperature = $20^{\circ}C \pm 2^{\circ}C$).

Intermediate rinsing in running water: 2 min. mperature 20°C ± 2°C).

5. Bleaching in a bleaching bath made up as follows:

GP 431

Water	600	ml
Fe (NO ₃) ₃ .9H ₂ O	150	g
KBr	30	9

300 mg of phenosafranin dissolved in 200 ml of ethanol. water to make 1 litre.

To be used in a dilution of: 1 part GP 431 + 4 parts of water (temperature = $20^{\circ}C \pm 2^{\circ}C$).

The keeping quality of the ready-to-use bleaching bath in closed bottles is limited (approx. 1 week).

6. Rinsing in running water: 5 min.

7. Rinsing in demineralized water with 1 part of AGEPON for 200 parts of water, for 2 min. at 20°C.

After the treatment, the water should be evenly distributed over the surface of the glass plate or film.

If there are still drops being formed on the surface of the emulsion, the treatment in the AGEPON solution is to be extended.

When there is no demineralized water available, rinsing may also be carried out in a solution of 1 part of AGEPON for 100 parts of water.

8. The films and plates are to be dried in a vertical position and in a dustfree room, until the emulsion is completely dry. A forced drying system must not be used and the plates must not be turned around in the course of the drying process. Irregular drying or remaining water drops may cause stains being formed.

3.2. Reflection holography

Though theoretically emulsion layers of a thickness of 20 μ m are necessary for reflection holography so as to achieve reflection holograms of top quality, it is still recommended to use the materials 8 E 56 HD and 8 E 75 HD with a thickness of the emulsion layer of 7 μ m, as with these materials the distortion of the Bragg planes after processing will be smaller. This is why it is also possible to achieve high-quality reflection holograms on thinner emulsion layers.

The following processing is proposed:

v

I. Processing when the colour of the hologram has to approximate as closely as possible to that of the laser light.

1. Development: 2 min. at 20°C in a developer of the following composition: CD CO

GP 02			
Part A		Part B	
water	700 ml	water	700 ml
✓METOL	15 g	Na ₂ CO ₃	60 g
√pyrogalloi	7 g	demineralized	-
Na ₂ SO ₃	20 g	water up to	1000 ml
√KBr	4 g		
Na, EDTA	2 g		
water up to	1000 ml		
Use:	•		
1 part A + 2 p	parts of water	r + 1 part B	
Parts A and B	keep well as	separate solution	s.

The ready to use solution can be used for a limited time only (1 to 2 hours).

herefore parts A and B should be mixed immediately efore use.

lemark: Pyrogallol is a hardening developing substance hat may affect the skin. Therefore always wear rubber loves when working with this developer. So as to achieve ood reflection holograms, a density between D = 1.5nd D = 2.5 is to be reached.

. Intermediate washing in running water: 2 min. emperature = $20^{\circ}C \pm 2^{\circ}C$).

. Bleaching: till completely clear in a bleaching bath of ne following composition:

iP 432

/ater	700	ml
(Br	50	g
oric acid	1.5	g
vater up to	1000	ml
honzogulogo	at 0 a/lit	to bo

-benzoquinone* 2 g/lit. to be added just before use. he life of the ready to use bleaching bath in a well topped bottle is limited to 1 week.

emperature of the bleaching bath: $20^{\circ}C \pm 2^{\circ}C$.

. Washing in running water: 5 min. temperature = $20^{\circ}C \pm 2^{\circ}C$).

Washing in demineralized water with 1 part of AGEPON
 200 parts of water for 2 min. at 20°C.

after treatment the water must be evenly spread on the surface of the glassplate or film.

I there is still a formation of drops on the emulsion surface the treatment in the AGEPON solution must be rolonged.

Vhen no demineralized water is available, washing can ossibly be done in a solution of 1 part of AGEPON to 00 parts of water.

3. Drying should take place upright, in a dust-free room intil the emulsion is completely dry. Do not use forced lrying and never turn the plate during drying. Jneven drying or drops of water which remain on the emulsion will give rise to stains.

I. Colour shifting to a longer wavelength:

To obtain an image in which the colour has been shifted o a longer wavelength than that of the laser light, procedure 1 may be applied. The bleaching bath, nowever, should be replaced by the following one:

GP 433		
vater	700 mi	
</td <td>30 g</td> <td></td>	30 g	
poric acid	3 g	
water up to	1000 ml	
Add 2 g/lit. of	b-benzoguinone* just before	e
The belographi	a alatura abtainad in this u	

The holographic picture obtained in this way is slightly ess sharp than the one of procedure I. The colour, nowever, has been shifted to longer wavelengths.

use.

Caution: The odour of p-benzoquinone in powder form is very rritating and inhaling it may be injurious to health. The following safety measures are to be observed: Always wear rubber gloves when working with this bleaching bath. Wear a mask and ensure that the room is well ventilated.

III. Colour shifting to a shorter wavelength:

1. To obtain a holographic picture with a shorter wavelength than that of the laser light the developing bath G 3 p (developing time 2 min. at 20°C), REFINAL (developing time 5 min. at 20°C) or GP 61 (developing time 2 min. at 20°C) is to be used in procedure I. The further course of the processing is the same as that of procedure I.

2. The colour of reflection holograms that are processed the same way as transmission holograms will also shift towards a shorter wavelength.

Example of lay-out for reflection holography

beam splitter with adjustment of the intensities of both beams and of the polarization.



important notes

1. The ratio between the object beam and the reference beam should be $1 \cdot 1.5$ to 2.

The polarisation of the two beams must be equal.
 Scattered light that could reach the plate must be avoided.



P.S. The angle of 45° of the reference beam was chosen so that with reconstruction of the hologram, the beam of white light will not reach the eye by reflection.

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Figure 1-1 Simple Feed-Forward Neural Network

RECORDING:



'PLAYBACK' / CORRELATION :







Figure 2-1 Photograph of (Float Glass) Optical Disk



Figure 2-2 Photograph of (Perspex) Optical Disk







Figure 2-4 Measured Intensity and Amplitude Transmittance 'v' Exposure for 8E75 Film

SPATIAL DOMAIN

FREQUENCY DOMAIN





Figure 2-5 SNR in Spatial and Spatial Frequency Domains



Signal is the DC Level :

Signal Encoded as Fringe Modulation Depth :



Figure 2-6 Multiplicative and Additive Noise



Figure 2-7 Overlapping Circular Grain Model



Figure 2-8 Poisson Model of Film Intensity Transmittance



Figure 2-9 Evaluating SNR from Digitised Images







Figure 2-11 Theoretical and Measured Values of SNR 'v' Area for $t_i = 0.5$





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COHERENT TRANSFER FUNCTION

(MONOCHROMATIC) INCOHERENT TRANSFER FUNCTION



Truly Incoherent Transfer Function is the Normalised Linear Supposition of the (monochromatic) Incoherent Transfer Functions

Figure 2-13 Truly Incoherent Transfer Function



Figure 2-14 SNR 'v' Area - An Illustrative Comparison of the Theoretical and Measured Results



Figure 2-15 CCD/Frame Grabber SNR 'v' Mean Grey Level



Figure 2-16 Comparison of Agfa, Kodak and Ilford Films



Figure 2-17 Disk Phase Flatness




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Figure 3-1 Disk Holding Mechanism



Figure 3-2 PAODS Initial Design



Figure 3-3 Radial Distribution of Images



Figure 3-4 PAODS Final Design



Figure 3-5(a) Engineering Drawings of PAODS



Figure 3-5(b) Engineering Drawings of PAODS



Figure 3-5(c) Engineering Drawings of PAODS



Figure 3-6 Three-point Positioning on Tapered Shaft



- MD Motor Drivers
- FG Frame Grabber
- SLM Spatial Light Modulator
- IL Image Labelling System
- D Photodetector
- M Motor
- SC Signal Conditioning
- E Electronic Shutter

Figure 3-7 System Configuration



Figure 3-8 PC14AT Input/Output Configuration



Figure 3-9 Image Labelling System

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Figure 3-10 Photodiode Signals with Different Illumination Magnification



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Figure 3-11 Signal Conditioning



Figure 3-12 Circuit Diagram for Signal Conditioning Unit



Figure 3-13 Error due to non-ideal Leading Edge



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Figure 3-14 Interpolative Count Value



Figure 3-15 Timing Considerations for Radial Distribution of Images



Figure 3-16 Relative Position between Image and Label

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- ILImage Labelling SystemD1,D2Photodiodes
- Motor Μ
- Signal Conditioning SC





Nematic

Smectic

Cholesteric

(a)



(b)



(c)





Figure 4-2 Propagation of Orthogonal Complex Components



Figure 4-3 Model of Elliptical Output Polarisations for Incident Light Polarised Parallel to Molecular Director (x-axis)



Figure 4-4 Model of Elliptical Output Polarisations for Incident Light Polarised Perpendicular to Molecular Director (y-axis)



Figure 4-5 Model of Transmitted Intensity and Phase for Incident Light Polarised Parallel to Molecular Director



Figure 4-6 Model of Transmitted Intensity and Phase for Incident Light Polarised Perpendicular to Molecular Director



NB/

Vectors A_{xN} and A_{yN} are drawn as they would appear in the O/P field and not as in the mathematical model, where a transformation matrix is applied in the latter to make the I/P and O/P axes concurrent.

Figure 4-7 Illustrative Phase Relationships between Output Field Vector Components



(a)









Figure 4-9 Changes in Phasers of Propagating Light for (a) low, and (b) high birefringence

An before additional phase advancement due to birefringence $-A_{y(n-1)}\sin(\theta_n)$ Ay(n-1) 'Ayn Ax(n-1) Axn

Figure 4-10 π radians Phase Jump



Figure 4-11 Changes in Elliptically Polarised Output Light for Limited Dynamic Range



Figure 4-12 Potential Configurations for Phase-Only Modulation



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(a)



(b)

Figure 4-13 Ellipsometry Measurements



Figure 4-14 Measured Ellipticity of Light Output from LCTV



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Figure 4-15 Normalised Intensity Transmittance for (a) Maximum Observable Contrast, (b) Minimum Brightness, (c) Maximum Brightness



Figure 4-16 Mach-Zehnder Interferometer BS, Beam Splitter P1,P2 Polaroids










Figure 4-19 Phase Modulation : Cross-coupled Amplitude Modulation



Figure 4-20 Linearity of Phase-Only Modulation



(d)

(e)

(f)





220 Rows of RGB Pixels

-Hig. 123 - See - 1 德一楼 **7**94 1

Figure 4-22(a) Structure of Casio LCTV Pixelation



Figure 4-22(b) Separate 'Fields' of Pixels



V.R.I. : VERTICAL RETRACE INTERVAL

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Figure 4-23 A Comparison of the Vertical Structure of the CCIR and OFG Video Signals

MAPPING1 MAPPING2



Figure 4-24 Mapping of OFG Video Signal to Rows of LCTV Pixels



LCTV DISPLAY

OFG VIDEO DATA















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Figure 4-27 Liquid Crystal Response Time







Figure 5-2 Misalignment due to Circular Path of Data Pre-recorded on Disk

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Figure 5-4 Spatial Domain Correlator Configuration : P1-P3, photodiodes; M1-M4, microscope objectives; S, spatial filters; P, polaroid; LCTV, liquid crystal television; L, lens; B, beam splitting optics



Figure 5-5 Recorded Image Quality





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Figure 5-9 Simulated Correlation between C280 and (a) C280, (b) E280



Figure 5-10 Simulated Correlation between MACE Filter and (a) C280, (b) E280



Figure 5-11 Illustration of Dwell Time







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Figure 5-14 The Practical VanderLugt Correlator



Figure 5-15 An Experimental Disk Based VanderLugt Correlator





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Figure 5-19 Example of Output from VanderLugt Correlator with Filter Matched to the Input

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Figure 5-20 Example of Input / Output obtained with VanderLugt Correlator : Letter 'A' as Input / Filter

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Figure 5-21 Example of Input / Output obtained with VanderLugt Correlator : Random Grey Level Input / Filter





Figure 5-22 Example of Input / Output obtained with VanderLugt Correlator whose Matched Filter Comprises a Single Diffracted Order





Figure 5-23 Example of Input / Output obtained with VanderLugt Correlator whose Filter is NOT Matched to the Input



Figure 5-24 Example of Input / Output obtained with VanderLugt Correlator whose Misaligned Filter is NOT Matched to the Input



Figure 5-25 MACE Filtering with VanderLugt Correlator (Upper Image : Impulse response function of MACE Filter Lower Image : Correlation Output)


of Fringe E Phase

Figure 5-26 Illustration of Amplitude and Phase Information Recorded on a Single Pixel of a Complex Matched Filter



Figure 5-27 The Anamorphic Correlator





















Figure 5-31 Examples of Output from the Anamorphic Correlator





Figure 5-32 Illustration of Horizontal Shift Invariance Property as Obtainable with the Anamorphic Correlator

(a) Input Object



(b) Correlation at time t_1



(c) Correlation at time t_2



(d) Correlation at time t_3



Figure 5-33 Illustration of Vertical Shift Invariance Property as Obtainable with Anamorphic Correlator



Figure 5-34 Separation of Adjacent Filters

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