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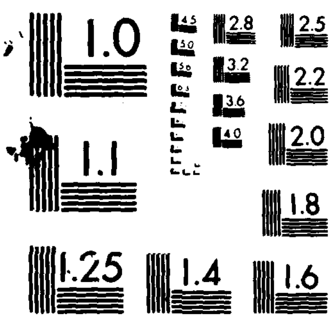

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OPTICAL SYSTEMS and STATISTICAL OPTICS

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Rochester, New York 14627

Annual Report to AFOSR on

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Attention: Dr. John Neff

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Theoretical and experimental research is being conducted in the field of opto-electronic systems. The goal is to contribute solutions to problems of basic research importance which also have an underlying significance in practical applications that involve automatic pattern recognition and remote sensing. Excellent progress is reported on our study of image recognition in white light illumination. We are studying a new type of holographic frequency plane filter that

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20. Abstract (continued)

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OPTICAL SYSTEMS and STATISTICAL OPTICS

Nicholas George

Principal Investigator

ABSTRACT

Theoretical and experimental research is being conducted in the field of opto-electronic systems. The goal is to contribute solutions to problems of basic research importance which also have an underlying significance in practical applications that involve automatic pattern recognition and remote sensing. Excellent progress is reported on our study of image recognition in white light illumination. We are studying a new type of holographic *frequency plane filter* that operates over a broad spectrum in the visible. The concept of an achromatic Fourier transform system has also been reduced to practice in a variety of optical configurations. Secondly, a raytracing theory is being formulated for the analysis of sandwich-type holographic optical elements, and high quality elements are being fabricated. Related studies are reported on optical subtraction, optical metrology of fibers and machined surfaces, and the automatic assessment of image quality.

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OPTICAL SYSTEMS and STATISTICAL OPTICS

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OPTICAL SYSTEMS and STATISTICAL OPTICS

1.0 INTRODUCTION

In this annual report, brief descriptions are made of major results obtained on our program of research on "Optical Systems and Statistical Optics" which is sponsored by the Air Force Office of Scientific Research. Publications resulting from this research are also cited (see Section 3 for cumulative listing), and the Abstracts are contained in the text of this report as part of the technical discussion. Reprints of these articles have been compiled and forwarded separately (listed as Addendum A); hence, they are not repeated in this report.

An Addendum B to this annual report has also been prepared. It consists of a briefing booklet containing prints of slides and captions, prepared by Dr. G.M. Morris, as a summary of his recent oral presentation at the annual meeting of the Optical Society of America. A second-generation achromatic Fourier transform configuration has been developed. From theory and experiments, it has been shown to exhibit greatly improved invariance of transform size with wavelength. The achromatic Fourier transform appears to be useful in a wide variety of applications besides matched filtering.

This report also contains a description of personnel and recent equipment added to facilitate our research in the visual aspects of robotics.

2.0 TECHNICAL PROGRAM

Our long term goal is to contribute solutions to problems having basic research importance which have as well an underlying significance in the practical applications of lasers and optics. Two relevant themes underlie our interest in the research being pursued. These are:

Robot vision systems using hybrid optics; and

Noise limitations in remote optical sensors.

Since 1970 in optics, there has been a host of problem areas which have arisen as various laser applications have been attempted. One such problem area is speckle or coherent optical noise. It is now recognized that speckle is likely to be deleterious in every coherent optical system. Thus, one might ask the question: Is a coherent optical system actually necessary for a given application? If the answer is yes, then the problem of speckle will have to be considered. It is clear that many fundamental problems in speckle have only recently been recognized and that there is much basic work remaining that will contribute to our understanding. On the other hand, coherent noise can be greatly reduced or even eliminated in a system that uses spatially and/or temporally noncoherent light. Thus from the point of view of noise, a noncoherent system can be an attractive alternative. In addition to the noise-reduction feature, noncoherent optical processing is of considerable importance due to the fact that outside the laboratory common light sources, for example the sun, are spatially incoherent, of finite size, and typically possess a wide range of wavelengths.

During the past year, we have had considerable success in broadbanding matched-filter systems. Still there are many basic concepts remaining to be investigated. In Sec. 2.1 Image Recognition in White Light Illumination, we review the field and describe our progress during the past year.

Stimulated by our interest in making broadband Fourier transform systems, we have embarked on the major study in Sec. 2.2, Holographic Optical Elements. This appears to be the type of problem where students at The Institute of Optics are uniquely qualified to make a contribution. This research requires a strong background in physical optics, as well as a thorough understanding of large-scale optical design programs.

In Sec. 2.3 we describe our current research on the assessment of image quality in an operator-independent manner. In Sec. 2.4 we describe a simple, rapid method for remotely measuring surface roughness of machined surfaces. The theoretical basis for this rests on speckle theory. This method has attracted much interest on the part of various industrial visitors, and it is expected to have widespread applications.

Three interim scientific reports are briefly extracted in Sec. 2.5. One is on the resolution in a color metric of an automatic color-sorting opto-electronic hybrid. Then there are two reports on separate methods of subtraction for optical images. These are both suited to images with fine detail, say of 5 or 10 μm; and they operate with white light illumination.

2.1 Image Recognition in White Light Illumination

Approaches to a general problem in pattern recognition can be classified according to the tree structure shown in Fig. 1. Since the implementation often differs greatly depending upon the approach, it is helpful at the outset to decide whether or not a "transform method" is likely to be important in the decision process. This matter has been studied in prior years, and it is generally agreed that the domain which permits one to sample coarsely and still to make recognition decisions to an acceptable accuracy is the more appropriate. For example, in facial recognition a coarse sampling of the direct image, say with 200 pixels, is adequate. Thus, direct processing of a sampled image using a digital computer is a reasonable approach.

Alternatively, the optical transform method is preferable when imagery of larger space-bandwidth and high frame rates needs to be sorted. Aerial reconnaissance photographs are representative of this case, particularly when one wants to make a simple assessment such as to count numbers of vehicles in a complex frame or to decide in an operator-independent manner whether or not a frame is cloud obscured. Likewise automatic quality assessment, largely independent of scene content, is probably best accomplished using an optical transform method.

In our research we are particularly interested in pattern recognition when large numbers of pixels are involved, hence in the optical transform approach. It is important to state this

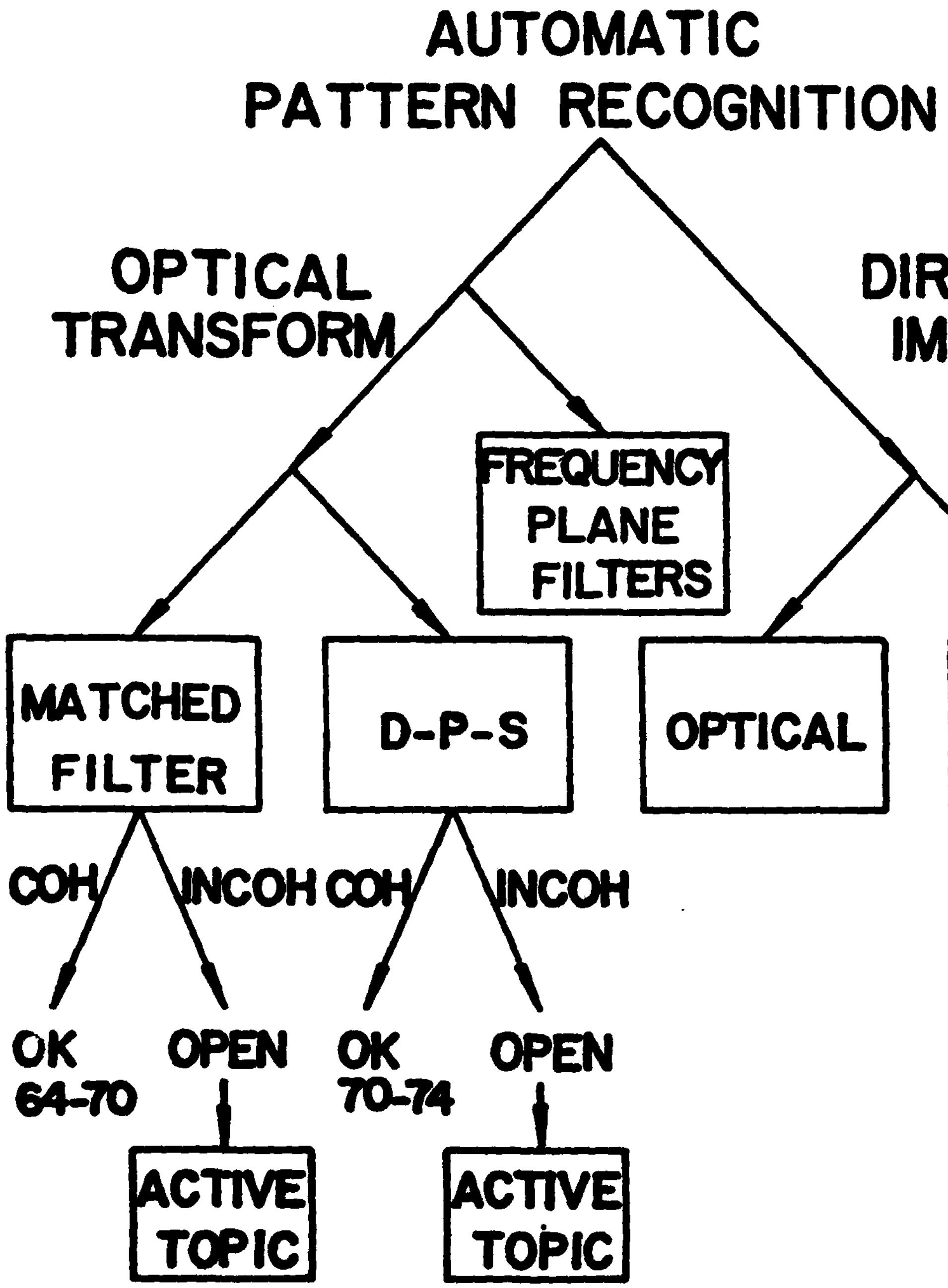

Fig. 1. Family tree showing main approaches in automatic pattern recognition: direct image processing or optical transform methods. Optical transform methods are advantageous when the frame rate and the space-bandwidth product of a frame are very large. With noncoherent illumination, both matched filtering and diffraction-pattern-sampling pose significant problems of current research interest.

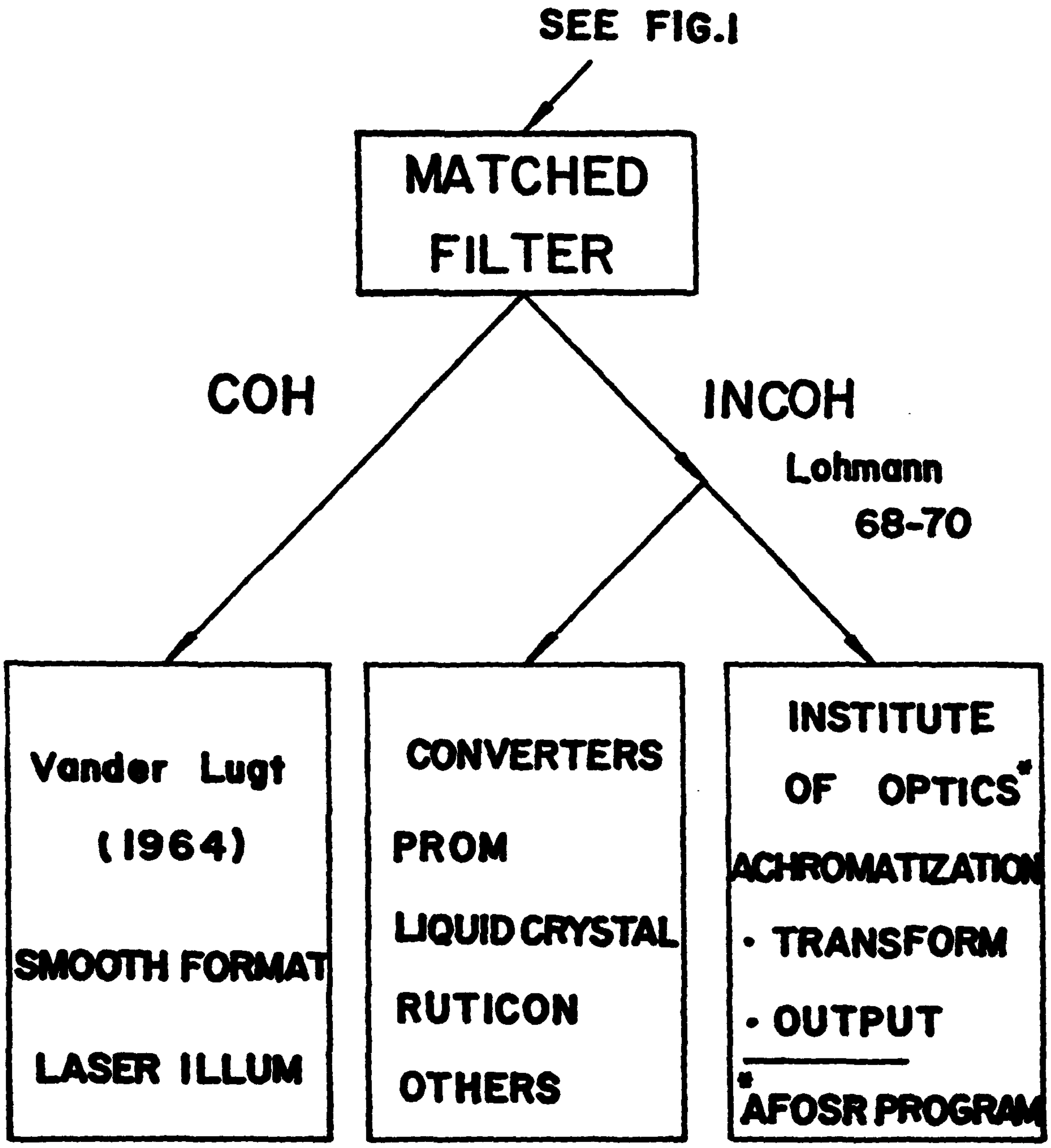

Fig. 2. A continuation of the family tree in Fig. 1 showing the matched filter both with coherent and incoherent illumination. In 1980-82 at The Institute of Optics, the achromatization of the matched filter has been accomplished in the subject program under AFOSR sponsorship. An increasing effort is planned now on diffraction pattern sampling using spatially incoherent illumination.

qualification explicitly. Then in reviewing our study of optical transform systems, one can readily understand our emphasis on systems that will work to diffraction limits. Inherently these will be capable of working with high resolution imagery or detailed objects. On the other hand, the geometrical optics class of transform devices probably are not suitable for pattern recognition of detailed objects or high resolution imagery.

Let us review optical transform methods. There are the ad-hoc systems of frequency plane filters. Special solutions for specific problems. The phase contrast microscope is a good illustration of this category. Then there is the matched filter approach. For coherent illumination and with optically smooth input formats, this problem was solved with the elegant work of A. Vander Lugt (1964).* Much research effort was expended on this type of system during the period from 1964 to 1970. Now this technique must be viewed as mature and well understood; so that at this point in time, it is not active as a field of basic research. Hence the labeling "OK."

For matched filtering in incoherent illumination, Lohmann (1968) and others** made a noteworthy observation that a holographic matched filter in amplitude is also (another) matched filter in

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* VanderLugt, A.B., "Signal Detection by Complex Spatial Filtering," IEEE Trans. Inform. Th., IT-10, 2(1964).

**Lohmann, A., 1968, "Matched filtering with self-luminous objects," Applied Optics, 7, 561-563.

Lohmann, A. & Warlich, U., 1971, "Incoherent matched filtering with Fourier holograms," Applied Optics, 10, 670-672.

Lowenthal, S. & Werts, A., 1968, "Filtrage des frequences spatiales en lumiere incoherente a l'aide d'hologrammes," Comptes Rendus de l'Academie des Sciences de Paris, 266, Serie B, 542-545.

intensity. However, practical applications of white light matched filter systems did not materialize, since it was generally thought that the illumination had to be very narrow-band temporally. With hologram systems of that date (1970), this was quite true. In fact many experiments were reported using a laser beam made spatially incoherent by transmission through a rotating ground glass diffuser. Thus, the application of matched filters when the illumination is incoherent is labeled as an open, and important, field meriting current research.

Before discussing the current research in matched filtering, let me trace the field of diffraction pattern sampling. As an alternative to the holographic matched filter, much research effort was expended on photodiode arrays placed in the optical transform plane. The field of opto-electronic hybrid processors evolved using this configuration. Practical applications of this technique have been made in many fields. A detailed account of this research and the resulting applications would carry me too far afield, and the interested reader is referred to two articles by Thompson.* In a somewhat provincial vein though, I will add that there is a considerable expertise in this field at The Institute of Optics with Thompson in particulate analysis and George with ring-wedge detector applications. Also our long-term effort in this field is expanding.

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* Thompson, B.J., "Hybrid Processing Systems--An Assessment," IEEE Proceedings 65, 62-76, 1977. and "Optical Transforms and Coherent Processing Systems--With Insights from Crystallography" Ch. 2, Topics in Applied Optics 23 (Ed. by D. Casasent, Springer-Verlag, Berlin, Heidelberg, New York 1978), pp. 17-52.

However, in diffraction-pattern-sampling too, the successes have been limited to coherent illumination and a smooth input format. A very basic question remains. Namely, how to use diffraction-pattern-sampling when the input object is rough and three-dimensional and the illumination is spatially incoherent. In our family tree, the D-P-S incoherent limb is labeled as "open"--meaning that this is an important area where active research is merited.

Two major goals of our research program sponsored by AFOSR can be stated in the context of Fig. 1. For the past two years we have studied how

I. To demonstrate achromatized matched filtering of high efficiency using incoherent illumination and rough objects and;

II. To demonstrate diffraction pattern sampling in an opto-electronic hybrid that also uses white light illumination.

2.1.1 Accomplishments in Matched Filtering

For incoherent illumination, there are two basic approaches to matched filtering (see Fig. 2). The use of an incoherent-to-coherent interface device is what one could properly term the standard approach. In this field, there has been much excellent research on new devices at various laboratories. However, there is still no one device that fully meets the need. While we have conducted experiments using liquid crystal devices and Xerox's Ruticon, this is not our principal thrust.

Since 1980 we have been studying an idealization of the matched filter system that is wavelength independent. This required two basic modifications to the conventional holographic matched filter:

1) Achromatic Fourier Transform Optics

   This has been realized using a combination of glass and holographic elements

2) Imaged Filter and Grating Compensation

   This has been achieved using a diffraction-limited imaging of the Fourier plane followed by a grating compensator.

The following paragraphs are abstracts of published papers* describing our results on this major problem. All of this research was carried out under the subject contract with the Air Force Office of Scientific Research.

Opt. Lett. 5, 202-204 (1980):

Matched filtering using band-limited illumination

G.M. Morris and Nicholas George
The Institute of Optics, University of Rochester

A holographic matched filter and an achromatic-fringe interferometer are combined to form an optical correlator that works with nonlaser sources. Pattern-recognition capabilities using band-limited illumination are illustrated in a dollar-bill-recognition experiment.

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* The letter (A) is used following the page citation if the reference is to "Abstract only", i.e., not a paper.

Opt. Lett. 5, 446-448 (1980):

Frequency-plane filtering with an achromatic optical transform

G.M. Morris and Nicholas George
The Institute of Optics, University of Rochester

A holographic matched filter has been recorded in the frequency plane of an achromatic optical transform configuration. Sandwich-type zone plates and an achromatic doublet are used to form the transform system, which is in cascade with the hologram filter and an achromatic-fringe interferometer. Correlation experiments are reported in which a large space-bandwidth and broad spectral range are obtained.

Appl. Opt. 19, 3843-3850 (1980):

Space and wavelength dependence of a dispersion-compensated matched filter

G.M. Morris and Nicholas George
The Institute of Optics, University of Rochester

A technique to eliminate the lateral dispersion in the correlation signal from a holographic Vander Lugt filter is described. Both spatially coherent, and spatially noncoherent, object illumination are considered; and expressions for the color-corrected correlation intensity are written in each case. Experimental results of the correlation plane intensity are shown using laser and spatially noncoherent white-light illumination. The latter is seen to be useful to search automatically for object scale.

J. Opt. Soc. Am. 70, 1613A (1980):

Achromatized Matched Filtering

Nicholas George, G.M. Morris, T.W. Stone
The Institute of Optics, University of Rochester
and B.D. Guenther
Army Research Office, Triangle Park, N.C.

A holographic matched filter has been recorded in the frequency plane of an optical transform configuration that is not highly wavelength-dependent. This zone-plate and lens transform configuration is followed by an achromatic fringe interferometer consisting of imaging lenses, a frequency plane block, a compensation grating, and a simple lens. This cascade provides a correlation system that can be used with coherent or noncoherent illumination. Studies of the correlation intensity and its dependence upon wavelength and spatial coherence are reported. Using light of low spatial coherence, we have obtained good results in a pattern recognition experiment with currency, i.e., ten dollar bill versus false test objects. A conclusion of this study is that optical pattern recognition is practical in a system which contains neither an incoherent-to-coherent converter nor a laser.

In Image Analysis Techniques and Applications, edited by P.N. Slater and R.F. Wagner, SPSE Conf. Proc. (SPSE, Washington, D.C., 1981), p. 87-90:

Image Recognition Using Noncoherent Illumination

G.M. Morris
The Institute of Optics, University of Rochester

There are two principal reasons for studying noncoherent optical information processing. One, optical noise (arising from dust, scratches, or other system imperfections) is reduced compared to that found in coherent (or laser) processing systems. Two, outside the laboratory common light sources, for example the sun or an incandescent light bulb, are both spatially and temporally noncoherent.

In this paper, two matched filter configurations, which operate with either spatially coherent or spatially noncoherent white light illumination, are described. In each case the matched filter is recorded using laser illumination. However, during reconstruction a broad-spectrum illumination source is used.

Appl. Opt. 20, 2017-2025 (1981):

Diffraction theory for an achromatic Fourier transformation

G.M. Morris
The Institute of Optics, University of Rochester

A three-lens achromatic Fourier transform system is analyzed in the context of paraxial Fresnel diffraction theory. From the analysis a general solution for the required wavelength dependence of the various lenses is found. A particular arrangement of the general system is then considered. Using first-order lens design principles, it is shown that each dispersive lens can be fabricated using a holographic zone lens and glass element cascade. The paraxial chromatic aberrations of the resulting system are calculated. It is found that this system design yields an achromatic transformation that is well corrected (paraxially) over the entire visible spectrum.

Current Trends in Optics (Taylor and Francis, London, 1981), pp.80-94:

Optical Matched Filtering in Noncoherent Illumination

N. George and G.M. Morris
The Institute of Optics, University of Rochester

The holographic matched filter discovered by A. Vander Lugt (1964) provides a singular contribution to optical pattern recognition. Using coherent illumination, one is able to sort transparencies of very large space-bandwidth with an extreme degree of selectivity. Williams (1964) studied the application of matched filters and the use of spatially-coherent, but temporally broadband, illumination; and many workers in holography also contributed to the field of frequency plane filtering. In a review paper on coherent optical processing, Vander Lugt (1974) describes the two-dimensional complex-valued spatial filter and its applications in detail. Lohmann (1968) made the initial observation that a filter matched on an amplitude basis for a coherent system is also matched for a corresponding incoherent system; and together with Warlich (1971) conducted a significant series of experiments to demonstrate matched filtering in noncoherent illumination. Studies of illumination efficiency and the effect of various degrees of spatial coherence have been made by Lowenthal and Wertz (1968) and by Watrasiewicz (1969). In many of these early studies, spatially incoherent illumination was obtained using a laser source and a rotating glass diffuser. In these experiments one does not encounter the highly dispersive effects either in the transform or in the hologram filter.

More recently the holographic matched filter has been studied using broadband sources and interest in correlation systems with nonlaser illumination has greatly increased. The principle of dispersion compensation has been applied to matched filtering problems. Goedgebuer and Gazeu (1978) reported a 1-D multiplexing correlator using Fourier holograms; and Ferrière, Goedgebuer, and Viénot (1979) extended this technique to record and decode Fourier holograms in polychromatic light. Almeida, Case, and Dallas (1979) have discussed a technique to eliminate the lateral dispersion from a computer-generated hologram filter. Guenther, Christensen, and Upatnieks (1979) have studied filter multiplexing to relax orientation requirements; Duthie, Upatnieks, Christensen, and McKenzie (1980) have demonstrated cross-correlation and tracking of vehicles using a diode injection laser source whose output is spatially modulated with a liquid crystal light valve. Case (1979) has studied pattern recognition and wavelength multiplexed filters using noncoherent illumination. Bartelt, Case, and Hauck (1981) have written a textbook chapter on incoherent optical processing that contains an extensive analytical framework and a reference list of about 50 papers that are beyond our present scope of summary.

In noncoherent optical processors, the early work of Leith and Upatnieks (1967) on achromatic-fringe systems leads to useful concepts about imaged gratings. Katyl (1972) studied hologram-lens compensating systems, including the achromatic Fourier transform. Morris and George (1980) describe three improvements to matched filtering: the use of an achromatic Fourier transform to record the frequency plane filter and then an achromatic-fringe interferometer to eliminate the direct beam and finally a grating-lens combination to focus the output of the matched filter. Morris (1981) has used diffraction theory to obtain constraints on a broadband Fourier transform configuration.

In the present paper an idealized matched filter system is described. It consists of a wavelength-independent Fourier transform, a frequency-plane filter, an imaging system, a compensation grating, and another wavelength-independent Fourier transform. Using diffraction theory, we show that the amplitude impulse response for this system does not vary with wavelength. This makes the system ideally suited for use with illumination from broadband spatially-incoherent sources.

Opt. Commun. 39, 143-147 (1981):

An Ideal Achromatic Fourier Processor

G.M. Morris
The Institute of Optics, University of Rochester

Paraxial solutions for the dispersive lens powers that are needed to achromatize the image in a spatially-coherent achromatic Fourier processor are derived using diffraction theory. The operational features of a specific processor layout are illustrated with a paraxial ray trace.

J. Opt. Soc. Am., 71, 1600A (1981):

Achromatic Fourier Transformation: *Theory and Practice*

G.M. Morris, R.E. Hopkins, T.W. Stone
C. Brophy, and J. Oschmann
The Institute of Optics, University of Rochester

An achromatic Fourier transform system that uses spatially coherent, white light illumination has been constructed. In this system, two highly dispersive lens groupings are used to form an optical transform that is not sensitive to the illumination wavelength. Each lens grouping consists of a holographic zone lens in cascade with a glass element. In the first grouping, the glass element is an achromat. In the second lens grouping, the glass element is a specially designed doublet. The first-order layout for this system was obtained by matching, as closely as possible, the dispersive power of each thin lens with the ideal paraxial lens power. The higher-order aberrations of the actual lens system were then optimized by using computer lens design techniques. Studies of the transform plane intensity and its dependence on wavelength and spatial coherence are reported. It is found that the system yields an achromatic transformation that is well corrected over the visible spectrum.

2.1.2 Progress in Diffraction-Pattern-Sampling

Statement of the Problem and Objectives

Both in pattern recognition and in metrology, optical transforms have proven useful in a variety of applications. Particularly, the optical transform is preferable to processing the image directly whenever the recognition depends on fine scale image features. The reason for this is that it is advantageous to sample the data coarsely, whichever space is involved, before computer processing. This greatly reduces the amount of computer capacity required.

Our objective in this phase of the research is to demonstrate image recognition in white light using a diffraction pattern sampler. We are investigating several configurations for taking the noncoherent optical transform of the object intensity. It should be emphasized that by themselves the achromatized Fourier transform configurations are not appropriate for this when the illumination at the object is spatially incoherent. Having once established an appropriate transform configuration, we will record sampled transform data; and pattern separability will be established using existing pattern recognition software. With a broadband transform and noncoherent illumination, a map-matching system or an automatic vehicle control can be foreseen operating without need for an incoherent-to-coherent converter.

Several transform configurations have been studied in co-work with a doctoral scholar S. Wang and in consultation with Professor Robert E. Hopkins. A thesis proposal is being prepared with several novel configurations for taking an optical transform of intensity. It is emphasized that it is not a Fourier transform. No publications have been made on this topic, but it will be fully described in a forthcoming report.

2.2 Holographic Optical Elements

The long-term usefulness of our research in which we stress the importance of an achromatic Fourier transform configuration in matched filtering in diffraction-pattern-sampling and in many other applications is critically dependent on the performance of lens and hologram components. Certainly lens elements of predictable design characteristics are well-established. On the other hand, hologram optical elements are not nearly so well understood. In these optical processing or opto-electronic hybrid applications, it is particularly important to be able to characterize efficiency over the aperture, isolation of the direct beam and efficiency vs wavelength.

During the past year, excellent progress has been made theoretically and experimentally to understand better the hologram optical element. An internal report has been prepared on this topic by a doctoral student, Thomas W. Stone. Briefly he has shown that it is possible to adapt major optical design programs to handle the holographic element. The earlier work of B.J. Chang and separately of R. Alferness indicated to us that a sandwich-structure was probably the best choice for superior optical performance. It is this element which we are emphasizing in our current study.

In our research a recent finding of major significance is that the bandwidth of the holographic optical element is considerably larger than one would expect by a consideration based on the simple "grating model." We have found that the fall-off in efficiency due to Bragg-thickness-effects is compensated for at the blue end of the spectrum by an increase in the scattering efficiency due to film grain size effects. The increased efficiency is due to a coherent Rayleigh-like scattering. T.W. Stone is currently preparing a publication describing this effect. The Abstract of his thesis proposal is reported directly below.

THESIS PROPOSAL

Holographic Optical Elements

Thomas W. Stone

Advised By

Dr. Nicholas George

15 June, 1981

Abstract

Research directed toward extending and improving the existing theory of holographic optical elements is proposed. Diffraction theory is combined with geometrical optics in the analysis of generalized holographic elements. A theoretical analysis of the cascade design, which consists of a diffraction grating in contact with an off-axis holographic element, will be made including broad-spectrum effects. Dialyte configurations of such cascades will be characterized, and extended to hybrid (hologram and lens) cases. Theory is proposed for the analysis of thickness-related aberrations, which are shown to be significant in practical broad-spectrum holographic elements, and may impose resolution limits in such cases. By applying diffraction theory such as the method of thin grating decomposition to the problem of ray transfer through a thick holographic element, an exact holographic raytracing theory is sought. Practical monochromatic and broad-spectrum applications will be considered.

2.3 Automatic Assessment of Image Quality

Statement of the Problem and Objectives

The ability to automatically judge the quality of an image is very important in the field of image evaluation. What is required is a criterion to judge image quality that is reliable and independent of scene content over a wide range of imagery. We propose to study image quality using an electro-optic hybrid with a special, easy-to-fabricate, degradation filter. We propose a parallel computer simulation on the digital image processing facility of The Institute of Optics. Initial pattern recognition research will center on a study of frequency moments and increments in the frequency moment as measured in the optical transform plane. Our objective is to establish a method for automatically sorting imagery which is capable of being implemented at high rates.

2.3.1 Review of Image Quality Criteria

An important aspect in the field of image evaluation is the question of image quality. What is desirable is a criterion for image quality that is independent of image content and is highly reliable. The value of such a criterion is readily evident in application to high volume photographic processing. An automatic image evaluation system would be highly useful for quality control, saving time and money. A second possible application would be for real-time automatic correction of satellite camera systems by evaluating the quality of the transmitted images.

To perform these operations a useable criterion must be determined. Herein we briefly review image quality criteria that have appeared in the literature. One early criterion is the Strehl Intensity Ratio[1] defined by:

$$SIR = \frac{\text{Peak of Aberrated Impulse Response}}{\text{Idealized Peak Value}}$$

---

1. N. George, Optical Systems Summer School Notes, University of of Rochester, 1980.

This criterion measures only the system response of a point source; it is not a measure of the quality of an image of arbitrary structure content.

Other criteria, based on mean square differences[2] where I is the test image and σ denotes the ideal image, include:

$$\text{FIDELITY:} \qquad \Phi = 1 - \frac{<(I-\sigma)^2>}{<\sigma^2>}$$

$$\text{STRUCTURE CONTENT:} \qquad T_G = \frac{\iint I^2 dxdy}{\iint \sigma^2 dxdy}$$

$$\text{CORRELATION QUANTITY:} \qquad Q = \frac{\iint \sigma I dxdy}{\iint \sigma^2 dxdy}$$

Perhaps the best current criterion for measuring image quality is that reported by Nill[3,4]. This criterion is a low order moment function of the power spectra as measured in the optical transform plane, given by:

$$M = \frac{\iint_{\nu_a}^{\nu_b} \nu^2 \, GG^* df_x \, df_y}{\iint_{\nu_a}^{\nu_b} GG^* df_x \, df_y}$$

where $G(f_x, f_y)$ represents, the Fourier transform of the aberrated object distribution. The spatial frequency ν is given by $\nu^2 = f_x{}^2 + f_y{}^2$ with f_x and f_y as the customary spatial frequencies corresponding to the x and y axes.

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2. E. H. Linfoot, Fourier Methods in Optical Image Evaluation, Focal Press, London, 1964.

3. N. Nill, Scene Power Spectra: The Moment as an Image Quality Merit Function, Appl. Opt. 15, 2846 (1976).

4. N. Nill, Contrast Effect on Imagery Power Spectra, Appl. Opt. 18, 2147 (1979).

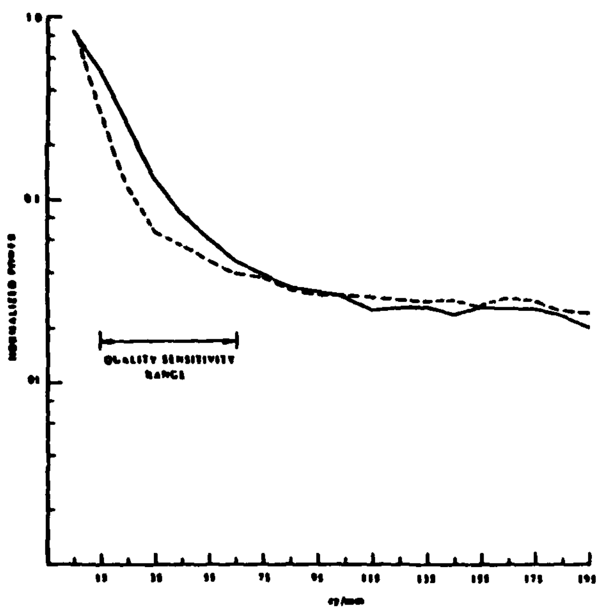
The high frequency content of an image, i.e. sharp lines and edges, is a measure of the image quality. Typically, the integrated power spectrum is dominated by the low frequency content which is relatively insensitive to poor quality. The low order moment is a means of weighting the high frequency content to increase the sensitivity of the technique. Figure 1(b) shows the correlation between the merit function and photointerpreter results. The linear relationship indicates good agreement. This merit function is used typically over a limited range to avoid the very low frequency range and the frequencies above the design cutoffs of the image system. In Figure 1(a) the scene corresponding to the solid curve was judged by trained photointerpreters to be of higher quality then that of the dotted curve. The sensitivity range is marked. Note that above this range the curves invert and below this region the curves join.

Proposed Research

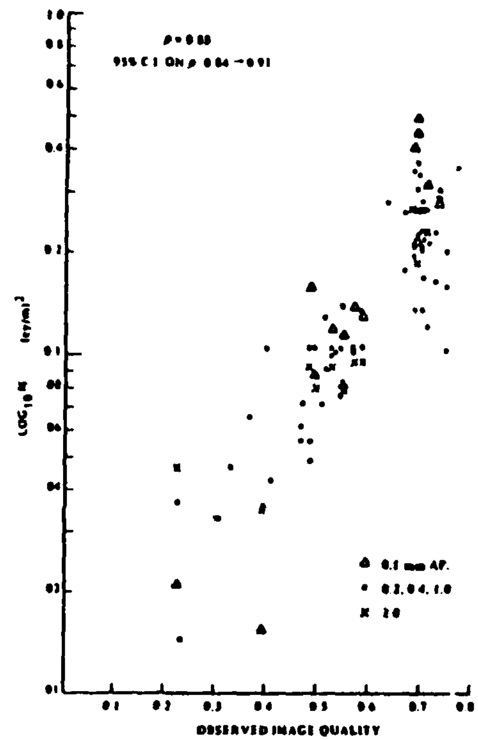
2.3.2 Image Quality Measurements: Optical and Digital Simulation Experiments

We propose to investigate through both experiment and analysis the effect on the moment function M, and similar algorithms, of introducing small degradations to scene content. We plan to show that the sensitivity of the moment function to small degradations decreases as the image quality lessens.

It is well known that the quality of an image is directly related to its high frequency content. A high quality image has much more high frequency content than a low quality image, thus the merit function M responds more favorably to a high quality



a)



b)

Fig. 1 a) Sensitivity Range: The solid curve corresponds to an image judged by experienced observers to be of higher quality than the image corresponding to the dashed line. Note the inversion of the lines outside of the sensitive range.

b) Merit function vs. observed quality: The image quality merit function M as calculated from 54 film images plotted against image quality as judged by trained photointerpreters.

Figures reprinted with author's permission; from N.B.Nill,"Scene Power Spectra: The Moment as a Image Quality Merit Function," Appl.Opt. 15,2846-2854(1976).

image. By degrading the image, i.e. modifying the high frequency content in a way that removes energy from the sensitive range of the power spectrum, the value of M is reduced. It is our contention that a given (small) level of degradation will cause a greater change in M for a high quality image than it will for a low quality image and that this change in M can itself be used as a criterion for image quality.

Figure 2(a) depicts an optical setup for such a study. Consider an original scene described by an intensity irradiance P(x). The recorded amplitude transmittance will be proportional to

$$g(x)=P(x)*T(x),$$

where T(x) is a degradation introduced by the system in the original recording. The power spectrum is given by the intensity distribution in the transform plane, i.e.,

$$\Phi(f_x)=\tilde{p}(f_x)\tilde{p}(f_x)^*\tilde{t}(f_x)\tilde{t}(f_x)^*$$

where ∿ denotes Fourier transform and superscript * denotes complex conjagation. The second order moment is then given by:

$$M = \frac{\int_{f_{xa}}^{f_{xb}} f_x{}^2\Phi(f_x)\, df_x}{\int_{f_{xa}}^{f_{xb}} \Phi(f_x)df_x} \qquad (1)$$

By introducing a slight degradation H(x) as depicted in Fig. 2(a) the moment function can be given by:

$$M = \frac{\int_{f_{xa}}^{f_{xb}} f_x{}^2\Phi(f_x)\tilde{h}(f_x)\tilde{h}(f_x)^*df_x}{\int_{f_{xa}}^{f_{xb}} \Phi(f_x)\tilde{h}(f_x)\tilde{h}(f_x)^*df_x} \qquad (2)$$

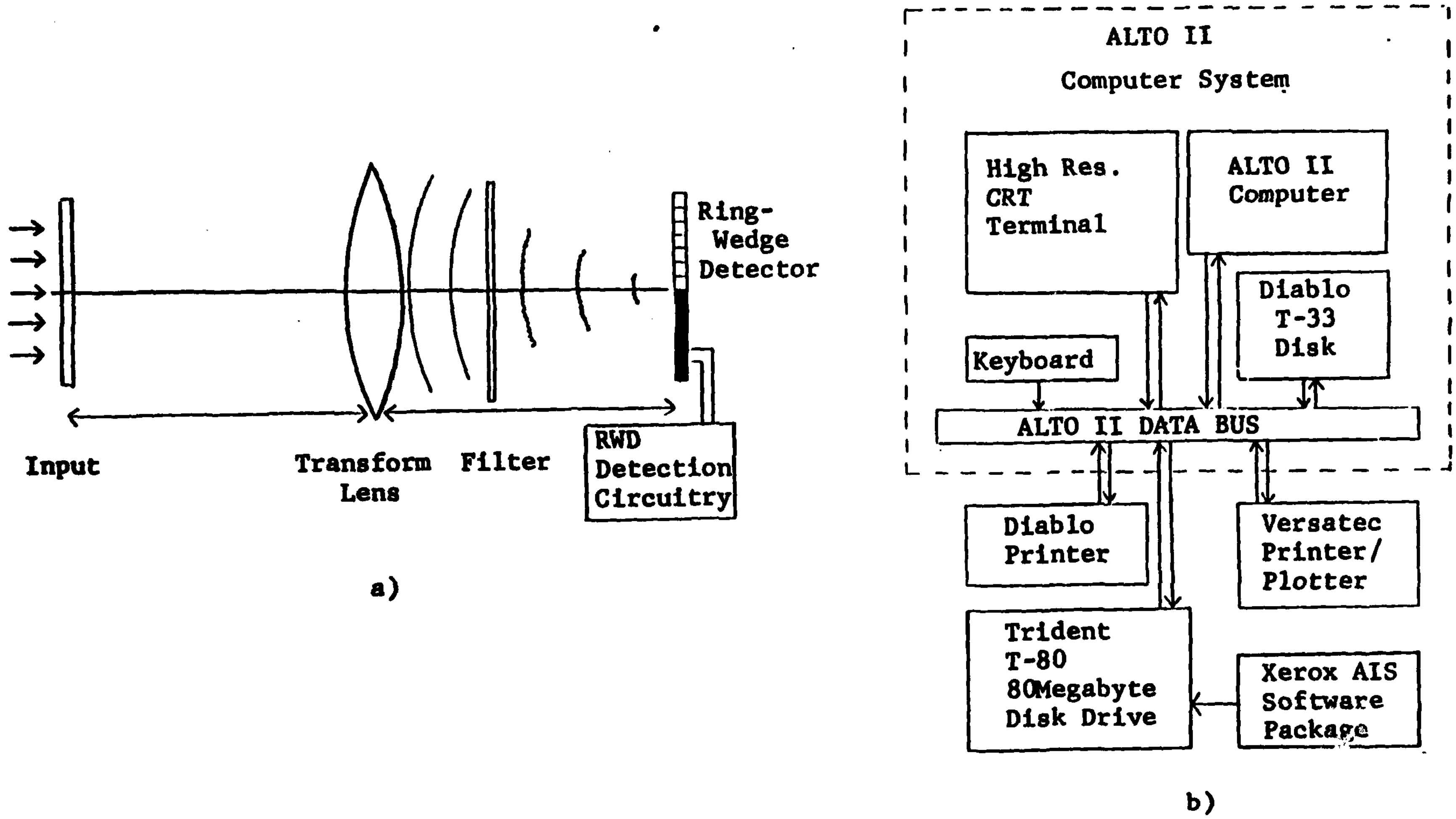


Fig. 2 IMAGE QUALITY MEASUREMENTS: Optical and Digital Simulation Experiments

a) Optical setup for experimentally measuring M and the change in M when the degrading filter is applied.

b) ALTO II Digital Image Processing facility for digital simulation of the degradation experiments.

or,
$$M = \frac{\int_{f_{xa}}^{f_{xb}} f_x^{\,2}\, [\tilde{P}(f_x)\tilde{t}(f_x)*\tilde{h}(f_x)]^2 df_x}{\int_{f_{xa}}^{f_{xb}} [\tilde{P}(f_x)\tilde{t}(f_x)*\tilde{h}(f_x)]^2 df_x} \qquad (3)$$

depending on whether the degradation filter is convolved or multiplied with image space.

We plan to examine how M varies as a function of H(x) and T(x) over a wide range of image classifications. In other terms we plan to study the difference in M, $\Delta M(H,T)$, as well as the normalized difference. Our thesis is that normalized differences in M will lead to an image quality criterion that is widely independent of scene content.

Aspects to be considered include what to choose for T and H. In many cases T will be of the form $\mathrm{sinc}^2(ax)$ or $\Lambda(x)$, i.e. impulse-like, such as degradations arising from high f-numbers or atmospheric turbulence.

It is well known that film grain noise can be the limiting factor in the image quality of some camera systems. Non-uniform distribution of the grains, processing errors, etc., can cause energy to be shifted outside the sensitivity range thus reducing the value of M. Armstrong and Thompson* have shown that film grain characteristics can be evaluated using optical power spectra techniques. We then propose to use film grain noise as the degradation filter H(x) in our experiments. The spectral characteristics of this filter can be controlled somewhat by its overall density and its distance from the optical transform plane.

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* S. A. Armstrong and B. J. Thompson, Comparison of Coherent and Incoherent Optical Spectrum Analysis in Image Evaluation, Optical Engineering, Vol. 17 No. 3, 1978.

S. A. Armstrong, Studies on the Importance of Photographic Grain in Optical Systems, Ph.D thesis, University of Rochester, 1978.

2.3.3 Progress Report

During the past year, we have greatly expanded our facility both for digital processing and for diffraction pattern sampling.

A new digital image processing facility has been assembled at The Institute of Optics. It was purchased with funds granted by Xerox Corporation and the Perkin Fund.

Secondly, a new high-speed system for diffraction-pattern sampling is just being assembled. It was purchased for $55,000 by Eastman-Kodak and is being installed in N. George's laboratory complex. It will be available for use on image quality research at no direct cost to the contract.

In this research both direct image processing via a digital computer and a diffraction pattern sampling method will be compared. Dennis Venable, a doctoral student now, is currently writing a formal thesis proposal on automatic quality assessment of continuous-tone and sampled images. For this year, we have no publications to report, but we will have some results during 1982 on this topic.

2.4 Roughness Measurement of Machined Surfaces

Statement of the Problem and Objectives

Many machine tool finishes are characteristically one dimensional, scratch-like patterns on a flat metal surface. When illuminated by a laser, the resulting speckle pattern differs considerably from that observed for two-dimensional roughness, e.g., sand-blasted or frosted glass surfaces. Our objective is to analyze this class of speckle pattern using statistical methods and computer simulation as well. We will consider remotely sensing such surfaces with roughness in the range from 0.05 μm to 500 μm. For roughness in the 0.05 μm to 0.8 μm range, a single tone laser is useful; and for the regime to 500 μm, we will use a tunable dye laser.

2.4.1 Status

During the past two years, we have found that essentially the same opto-electronic hybrid is very useful for remotely sensing the diameter of fine wires or optical fibers[1,2]; and it is useful for measuring roughened surfaces as well. This setup is shown in Fig. 1. It consists of a laser, converging optics (L), a rough surface, a linear photodiode array, and a floppy disc recorder. To position the photodiode array, we place a smooth reflector where we have indicated the rough surface; and then we locate the photodiode array so that its center is at the focal point of the laser beam. After this, the rough surface is located as shown; and the intensity of the speckle pattern can be recorded.

While a variety of rough surfaces can be used, we decided to use metallic surfaces that had been machined. From a theoretical standpoint, this gives us a class of surfaces that has not been analyzed in detail in the literature. Also the roughness function for heights is far from a Gaussian density. Moreover, in order to obtain results that can be easily verified later at other laboratories, we have used a precision set of standard-finishes manufactured by Fowler-Rubert. As shown in Fig. 2, these standard rough surfaces provide an excellent variety including lapping, grinding, horizontal and vertical milling, and turning.

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1 See last year's proposal for a review of this topic.
2 M.A.G. Abushagur and N. George, Appl. Opt. 19, 2031 (1980).

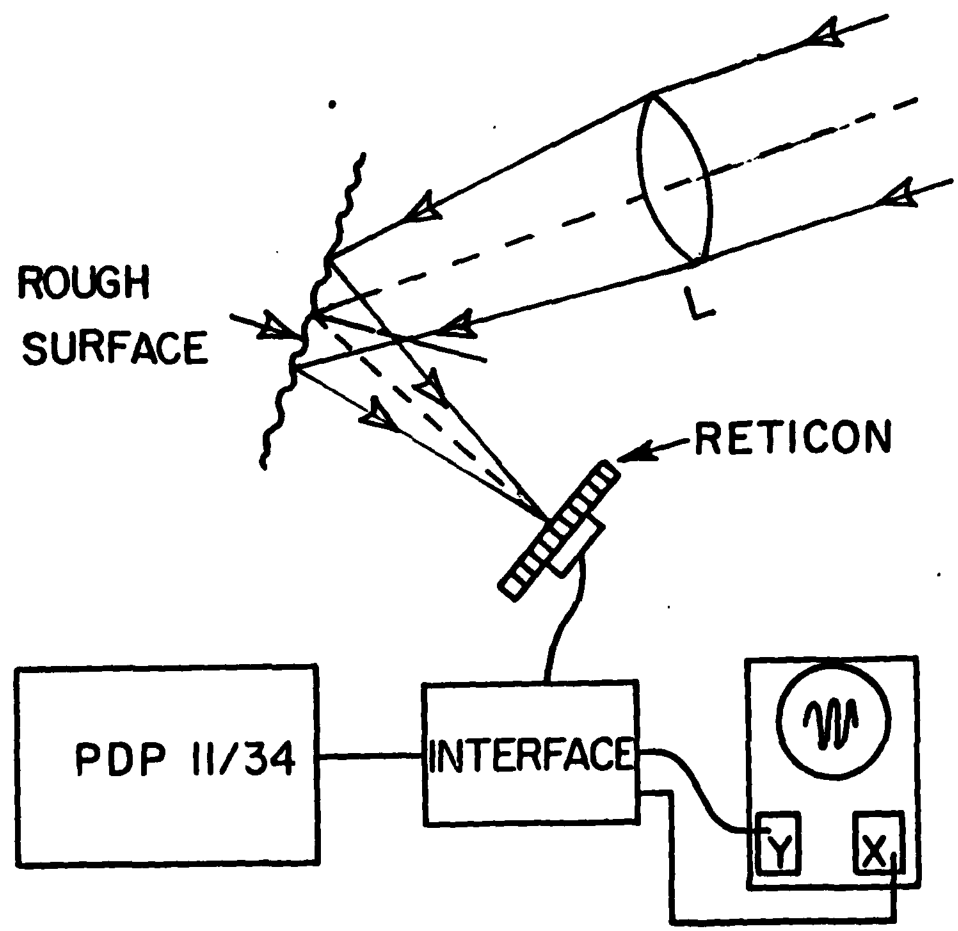


Fig.1. Experimental optical-hybrid for measuring rough surfaces. A plane wave of light is focused by lens(L) onto the Reticon photodiode array after reflection from the rough surface.

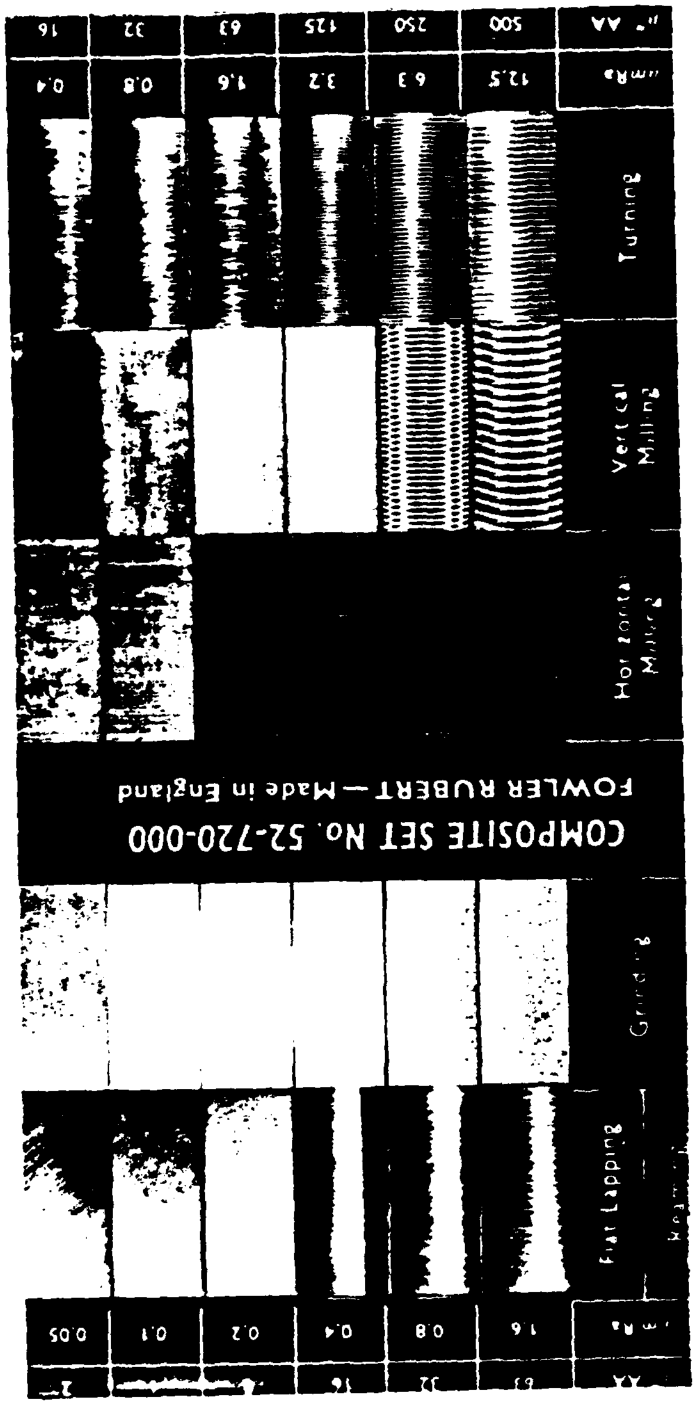
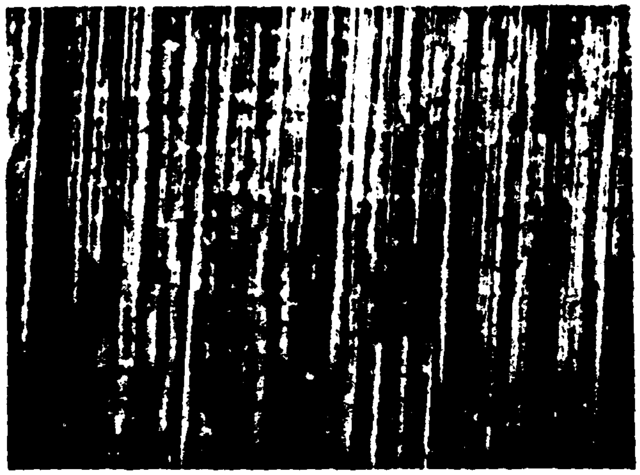
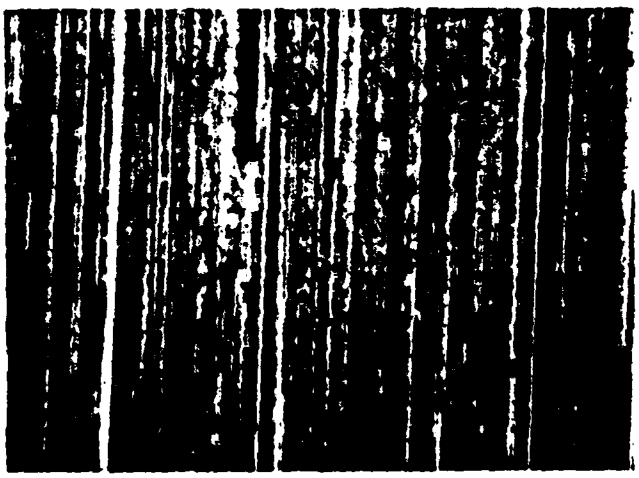


Fig.2. Standard rough surfaces used in the experiments.



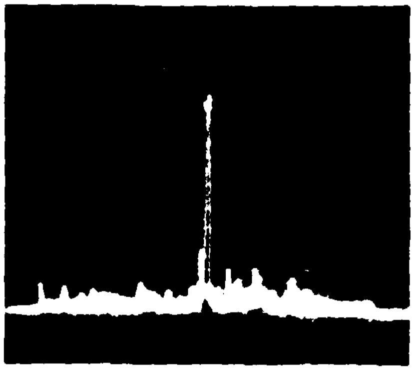
(a)

0 200 μm

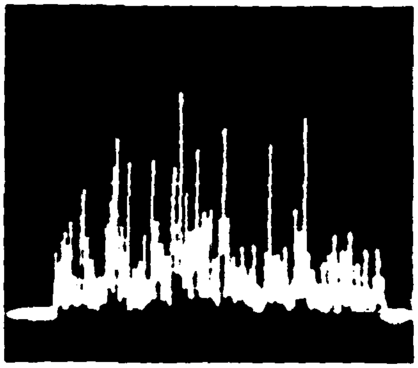


(b)

Fig.3. Micrographs for grinding surfaces for (a) 0.05 μm and (b) 1.6 μm.



(a)



(b)

Fig.4. Osciloscope pictures for the intensity pattern for a) 0.05 um and b) 1.6 um roughness.

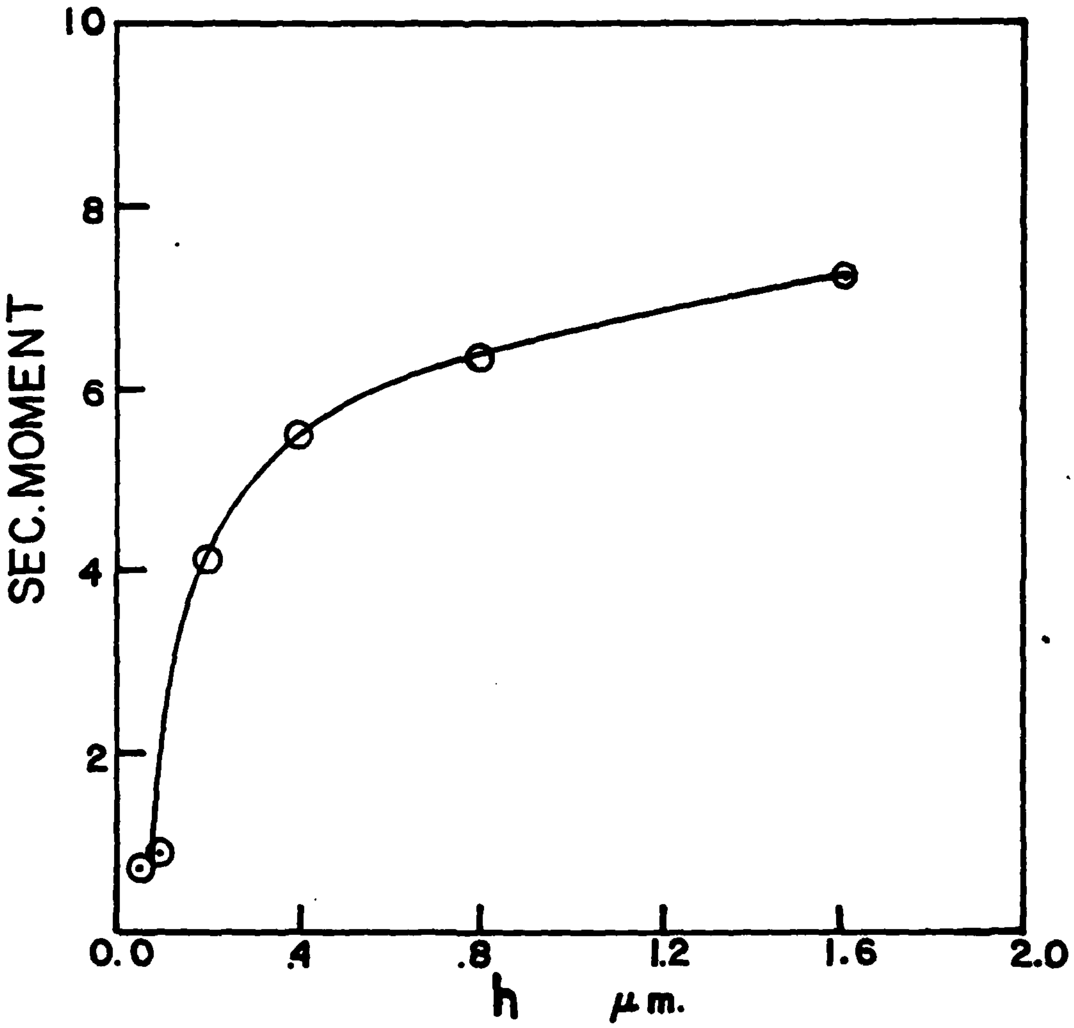


Fig. 5. Experimental data for the second moment vs. the roughness of the surface.

Photomicrographs of the grinding samples are shown in Fig. 3. See the scale to indicate the enlargement and notice that the surface has scratches in one direction. These surfaces are grating-like lines irregularly spaced and of varying heights. Their diffraction pattern in the optical transform plane consists of a bright spike extended in the direction perpendicular to that of the scratches, and a speckle pattern around it.

The d ffraction patterns of the 0.05 μm and 1.6 μm surfaces are shown in Fig. 4. The two intensity patterns are normalized to the same central spike. From a simple computation, one can show that the oscilloscope traces show range from -365 cycles/mm to +365 cycles/mm. It is certainly easy to distinguish the 0.05 μm surface (smoothest of the grinding samples) from the 1.6 μm one by their respective scattered intensities in Fig. 4.

During the contract period of this report, M. Abushagur has developed an algorithm base which permits one to measure remotely the surface roughness of the ground surfaces. This is illustrated in Fig. 5 using the second moment in frequency space. It should be emphasized that this monitoring method will work well as the metal surface rolls by. Thus, it has application in manufacturing plants that are producing sheet steel or aluminum. Many industrial visitors have expressed strong interest in this technique for remotely measuring the texture of an object.

M. Abushagur is currently writing a two-part doctoral thesis including this measurement of surfaces with scratches. Separately, he is analyzing subtle differences in the diffraction patterns for four similar objects: dielectric cylinders, absorbing cylinders, perfectly conducting cylinders, and an open gap. In the literature, typically the incident field is assumed to exist all around the object. This quasi-static approximation is appropriate at radio and microwave frequencies when a metallic cylinder of radius $a \ll \lambda$ is the scatterer. However, at optical wavelengths, when the scatterer has a size of 50 to 100 μm, this approximation is no longer valid. This research is continuing.

2.5 Automatic Color Recognition and Optical Subtraction

Three interim scientific reports have been prepared from three separate theses. The title page, DD1473 Abstract form, and introduction for each is reproduced here so that one can gain an understanding of the scope of the research*. The reports included are listed:

Automatic Hybrid Processor for the
Measurement and the Comparison of Colors
Francois Dufresne de Virel 159 pages

A Method of Image Subtraction for Process Control
Neil D. Hickey 162 pages

A Coding Method for Optical Image Subtraction
Dennis L. Venable 106 pages

* Complete copies are available upon written request to The Institute of Optics, Attn. Nicholas George.

EXTRACT FROM

AUTOMATIC HYBRID PROCESSOR FOR THE MEASUREMENT AND THE COMPARISON OF COLORS

by

François Dufresne de Virel

Submitted in Partial Fulfillment
of the
Requirements for the Degree

MASTER OF SCIENCE

Supervised by Professor Nicholas George
The Institute of Optics
University of Rochester
Rochester, New York

1981

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		6. PERFORMING ORG. REPORT NUMBER 5-29272
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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Color measurement
Color difference
Just Noticeable Difference
OSA Uniform Color Scales
CIE
Spectrograph
Diode array
Computer

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An opto-electronic hybrid processor for automatically sorting color samples is described. A grating spectrograph is interfaced to a 1024-element Reticon diode array and a PDP digital computer. Detailed design information on this system is provided. The processor was used to perform some standard color measurements of the Commission Internationale de l'Eclairage (CIE). A simple method for color-difference detection was also developed: it consists of using various algorithms to compare the spectra obtained with the system.

(over)

#20, Abstract, continued

A study of the sorting effectiveness of these algorithms is presented. The Uniform Color Scales of the Optical Society of America (OSA) were used in order to test the performance of the system. Also, special color samples were fabricated with color differences much less than the Just-Noticeable-Difference (JND) of an average human observer. These were used to establish the limitation in color resolution of the processor. The color-difference recognition of the hybrid system was found to be better than the recognition of the human eye.

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CHAPTER I

INTRODUCTION

Color, for its specification, evaluation and measurement has been a source of interest for years[1]. Its importance in everyday life is well known in many different areas: color paints, textile dyes, color photography, television, art, etc. Color Science has been established over the years[2]; the Commission Internationale de l'Eclairage (CIE) is now the organization in charge of the definition and establishment of universal standards for color evaluation and measurements. These standards are mainly constituted by the definitions of the standard illuminants, reflectance factors(whites), illuminating and viewing conditions, observers and computation procedures for color measurement[3,4]. Working standards and color-measuring instrumentation have been described and compared[5-12].

Different color scales have been developed to provide a direct visual evaluation of the colors[13]. Also, color difference formulae have been established for computing the size of the measured color-difference from the tristimulus values of the samples[14-17].

Today's spectrophotometric methods of color measurement use some apparatuses whose design is based on two different principles. The first one uses a spectrophotometer where the sampling of the spectra is performed with a timesequential analysis, wavelength by wavelength; the same detector is used for the complete spectrum analysis. Commercially available types of color-measuring instruments of this kind are, for example, the Match-mate of Diano Corporation[18] or the D54P-5 of Hunter Associates Laboratory[19].

The second method uses a spectrograph (no exit slit) and parallel analysis of the spectrum by a set of several detectors (generally between 15 and 33) without any optical scanning, each detector having a spectral window of 10-20 nm width. An available device of that kind would be, for example, the color measuring instrument MS-2000 of Macbeth Division of Kollmorgen Corporation[20,21].

The first design has the advantage of an adaptable geometry, e.g. possible modifications of the wavelengh increment of the spectrum range to be scanned while the second has the advantage of its rapidity but has a fixed geometry.

By the use of a diode array the size of whose elementary detector is small (typically 25 μm or less), it is possible to combine the two functions to perform an analysis of the spectrum wavelength by wavelength (spectrometer) by the electronic scanning of the array, and at the same time to do a general analysis of the spectrum (spectrograph). An adaptive geometry is possible with a pretreatment of the array outputs. One can think, for instance, of a partial sampling (readings taken every n^{th} diode), an average sampling (averaged readings of n consecutive diodes), or use of a portion of the diode array length.

A large size diode array has been used as detector in many applications in spectrometry because of its easy sampling of spectra[22-29].

The purpose of this study is to investigate color comparison and color measurement, using a hybrid opto-electronic system. This thesis also includes the design of the system and the evaluation of its performance in some standard tasks (measurement of the CIE tristimulus values) or others (Sorting of colors, detection of small color-differences).

The grouping of topics is briefly described as follows. In Chapter II, the design of the system is presented. For the dispersive element of the spectrograph, both a prism and a grating are considered. The grating design, Sec. 2.4.3, constitutes the final design, because of its overall superior performance features over the prism design, Sec. 2.4.2.

In Chapter III, the hybrid system is used to perform CIE color measurements. A study for the choice of the spectral sampling interval is also included in this chapter.

Chapter IV contains a description of a color-sorting experiment by use of simple algorithms to compare spectrum readings of color samples. An optimization of the number of sampling points is also studied in this experiment.

In Chapter V, the precision of the system is evaluated by comparison with the Just Noticeable Difference of the human eye, both with OSA/UCS samples and with special custom-made samples. It is shown that the system performs better than the average human eye for color-difference detection.

In Chapter VI, the color-sorting method, described in Chapter IV, is studied with the CIE computations method for their application to the problem of color-difference detection. Although the first method does not permit standard color-measurements, it can lead to efficient color-sorting in a fast and simple way.

Finally, in Chapter VII, the color-sorting algorithms and the mathematical features used to compute these algorithms are evaluated for their capacity to detect curve differences in the different experiments performed with the hybrid system. A ranking in sensitivity of these features will be given.

EXTRACT FROM

A METHOD OF IMAGE SUBTRACTION FOR PROCESS CONTROL

by

Neil D. Hickey

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of the

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Master of Science

Supervised by Dr. Nicholas George

Institute of Optics

College of Engineering and Applied Science

The University of Rochester

Rochester, New York

1980

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18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Image Subtraction	Differential Image
Photodiode Array	Image Processing
White Light	Quality Control

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A hybrid optical system which calculates the difference between two intensity images is described. The images are detected using self-scanned photodiode arrays and the difference is calculated prior to digitization and input to the computer. Descriptions of system hardware and software are included. The system response is analyzed and a number of digital correction techniques are discussed. The use of the system to detect faults in the printed circuit boards is described.

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CHAPTER 1 -- INTRODUCTION

1.1 General Introduction

Many control applications require the difference between two signals to be calculated. In a multi-stage system, the stage at which the difference is calculated can greatly affect the overall performance and usefulness of the system. This effect is particularly important when the two signals are nearly identical as, for example, when one is searching for slight differences between two supposedly identical signals. There are many methods to realize the difference when the signals in question are optical images. Unfortunately, most of these methods have limited application and present various degrees of difficulty in practice [Ref. 1].

In many systems the difference image is not the final result; it is converted to an electrical signal for storage, analysis, and/or feedback control. In this case the subtraction may be performed after conversion, either by subtracting two converted signals or by subtracting the converted signal from a stored reference.

The subject of this thesis is a hybrid optical and electronic system designed to calculate the difference between two optical images using either method. The system consists of two identical imaging systems, two photo-diode arrays, necessary support electronics, and a PDP-11/34 computer (Figure 1.1).

The general system design considerations are discussed in the following section and a summary of system parameters is given in table 1.1. Chapter 2 contains a detailed description of the system hardware. The control, calibration, and application software developed for the system is described in Chapter 3. Chapter 4 contains a discussion of the system response and Chapter 5 describes the use of the system for fault detection in printed circuit boards.

EXTRACT FROM

A CODING METHOD FOR OPTICAL IMAGE SUBTRACTION

by

Dennis L. Venable

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Supervised by Dr. Nicholas George
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College of Engineering and Applied Science

University of Rochester
Rochester, New York

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	6. PERFORMING ORG. REPORT NUMBER 5-29272
7. AUTHOR(s) Dennis L. Venable	8. CONTRACT OR GRANT NUMBER(s) AFOSR-77-3434
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18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Image Subtraction
Optical Image Subtraction
White Light
Image Processing
Grid Coding

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Optical image subtraction, a process in which differences between objects are distinguished, is a powerful technique for use in quality control, reconnaissance, and other pattern recognition applications. This thesis contains a description of a general 2-stage method of optical image subtraction using incoherent illumination and coherent optical processing. A general expression describing the transform plane distribution is derived in terms of object-reference alignment. modulation mechanism, and spatial

Block 20)

filter function. Periodic and random coding mechanisms are examined theoretically and experimentally. Periodic modulation is seen to provide greater output signal and higher signal-to-noise ratio. Subtraction resolution is shown to approach the theoretical limits set by sampling theory. The system is shown to exhibit a linear response to gray level differences when the difference in intensity reflectance is in the range $0.2 \leq R \leq 0.5$.

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PREFACE

This thesis is a report of an investigation to develop a technique of optical image subtraction for practical application. Many methods of determining the difference between two scenes have been studied. If a really practical method is developed, it will have applications in earth resource studies, surveillance and inspection, pattern recognition, bandwidth compression, etc.

Methods of optical image subtraction have been known for many years. Early in this century astronomers used a form of image subtraction to the detect motion of heavenly bodies. The instrument used would show two photographs of star fields, first one then the other, very rapidly. Differences between the photographs would be seen to flicker, thus giving the instrument the name "flickerscope."

In the late sixties and early seventies, many new techniques of optical image subtraction were developed. One group of methods uses coherent holographic and spatial filtering systems [1-4]. Another uses incoherent Fourier holography [5], and a third group uses modulation of the objects either by periodic [6,7] or random [8] coding methods. For a practical system, desirable characteristics would include the use of white light object illumination, subtraction at high resolution, attainment of high signal-to-noise ratio's, large tolerance values in object positioning, and the potential for real time capability. Of the three groups mentioned above, the first requires coherent illumination and the second requires interferometric tolerances. Only the third group, the "coding" method of optical image subtraction, demonstrates the characteristics desired. In this thesis a general coding method of optical image subtraction is developed. Both theory and experiments are reported in three Chapters.

Chapter 1 contains background information on the various existing techniques to effect optical image subtraction including a review of the literature.

Chapter 2 is a theoretical analysis of the coding method of optical image subtraction. Equations are derived that express amplitude distributions in both the optical transform plane and the image plane. A preferred form of modulator mechanism (coding device) is developed and the form of spatial filter discussed.

Chapter 3 is a report of a series of experiments of the subtraction technique developed in Chapter 2. Several demonstration experiments are reported that show the effectiveness of system under various conditions. Also, subtraction negatives containing the modulated images of the objects are examined.

Briefly, a description of one implementation of the coding method of optical image subtraction is double exposure on film of two objects, A and B. Both objects are modulated by a coding mechanism shifted a distance ε between exposures. Spatial filtering in the optical transform plane may result in an image of the object differences. A report on an investigation of the effect of ε on the subtracted image is found in Chapter 3. Similarly, an experiment investigating an object misalignment is discussed. Also, signal and noise characteristics of periodic and random coding techniques are compared.

Of particular interest are experiments to investigate the system's ability to distinguish gray levels and to determine the spatial frequency resolution of the output image. These may also be found reported in Chapter 3.

3.0 LIST OF PUBLICATIONS (1980)

3.1 Conference Report (Abstract Only)

N. George, G.M. Morris, T.W. Stone, and B.D. Guenther, "Achromatized Matched Filtering," J. Opt. Soc. Am. 70, 1613A (1980).

3.2 Publications

Nicholas George and G.M. Morris, "Diffraction by Serrated Apertures," J. Opt. Soc. Am. 70 6-17 (1980).

G.M. Morris and Nicholas George, "Matched Filtering Using Band-Limited Illumination," Opt. Lett. 5, 202-204 (1980).

M.A.G. Abushagur and Nicholas George, "Measurement of Optical Fiber Diameter Using the Fast Fourier Transform," Appl. Opt. 19, 2031-2033 (1980).

G.M. Morris and Nicholas George, "Frequency-Plane Filtering with an Achromatic Optical Transform," Opt. Lett. 5, 446-448 (1980).

G.M. Morris and Nicholas George, "Space and Wavelength Dependence of a Dispersion-Compensated Matched Filter," Appl. Opt. 19, 3843-3850 (1980).

N.D. Hickey, A Method of Image Subtraction for Process Control (M.S. thesis, University of Rochester, 1980 and Interim Scientific Report).

3.0 Continued

LIST OF PUBLICATIONS (1981)

3.1 Conference Reports (Abstract Only)

G.M. Morris, R.E. Hopkins, T.W. Stone, C. Brophy, and J. Oschmann, "Achromatic Fourier Transformation: Theory and Practice," J. Opt. Soc. Am. 71, 1600 (1981).

3.2 Publications

G.M. Morris, "Image Recognition Using Noncoherent Illumination," article in Image Analysis Techniques and Applications, edited by P.N. Slater and R.F. Wagner, SPSE Conf. Proc. (SPSE, Washington, D.C. 1981), p. 87-90.

F. Dufresne de Virel, Automatic Hybrid Processor for the Measurement and the Comparison of Colors (M.S. thesis, University of Rochester, 1981 and Interim Scientific Report).

G.M. Morris, "Diffraction Theory for an Achromatic Fourier Transformation," Appl. Opt. 20, 2017-2025 (1981).

Nicholas George and G.M. Morris, "Optical Matched Filtering in Noncoherent Illumination," article in Current Trends in Optics (Taylor and Francis, London, 1981, pp. 80-94.

G.M. Morris, "An Ideal Achromatic Fourier Processor," Opt. Commun. 39, 143-147 (1981).

D.L. Venable, "A Coding Method For Optical Image Subtraction," (M.S. thesis, University of Rochester, 1981 and Interim Scientific Report).

4.0 PERSONNEL AND RELATED SUPPORT

4.1 Faculty

The faculty investigators who have been actively engaged and partially supported on this research sponsored by the Air Force Office of Scientific Research are listed:

1.	Dr. Nicholas George Professor of Optics	Principal Investigator
2.	Dr. G. Michael Morris Scientist in Optics	Investigator

In addition valuable contributions to the research on the optical design of a Fourier transform achromat have been made by Dr. Robert E. Hopkins, Professor of Optics. He is also an active participant on the topic described in Section 2.1.2. His services have been available without direct cost to the contract.

4.2 Graduate Assistants

Several excellent students are active in the research described in other sections of this report and have been partially supported by funds from the subject contract. Their names and major topics of interest are listed alphabetically in the following table.

Student	Research Topic
M.A. Abushagur	Scattering by rough surfaces
	Scattering by large diameter cylinders and spheres
F. Dufresne de Virel	Automatic sorting by color
Neil D. Hickey	Optical subtraction
Paul Kane	Diffraction by tiny apertures
Thomas W. Stone	Holographic optical elements; Wavelength and Efficiency
Joseph C. Mazurowski	Computer generated holography
Jacobus M. Oschmann	Optoelectronic systems
Dennis L. Venable	Optical subtraction (M.S.) Image quality assessment (Ph.D.)
S. Wang	Diffraction pattern sampling using noncoherent illumination

Graduate students who have completed their thesis work and obtained a graduate degree are listed chronologically as follows:

G. Michael Morris	Ph.D. 1979
Neil D. Hickey	M.S. Degree 1981 Refer to Section 2.5

F. Dufresne de Virel	M.S. Degree 1982 Refer to Section 2.5
Dennis L. Venable	M.S. Degree 1982 Refer to Section 2.5

4.3 Related Research Activity

Additional funding was granted last year from ARO in order to support expanded activity in white light processing. The level of funding obtained is shown below. No further proposal to other agencies is planned for the program of research described herein.

Proposal Title	Dates	Funding Level	Agency
Image Correlation Using Noncoherent Illumination	8/1980-7/1981:	$98,480	Army Research Office
	8/1981-7/1982	$98,682	(Dr. B.D. Guenther, Physics)

Annual Report Submitted by

Nicholas George

Nicholas George
Principal Investigator

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