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Analytical and experimental investigations of 2-D space-variant optical processing techniques have been conducted. Coherent processing investigations have included 1) an experimental study of the characteristics of photoresist phase masks for multiplex holography, 2) the development of a facility for generating high quality computer-generated holograms by use of a laser plotter, & 3) analytical investigation of an idea for using 1-D techniques to perform 2-D space-variant operations. In the incoherent processing area we have proceeded with experiments to test the tristimulus-based technique for performing complex operations

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SPACE-VARIANT OPTICAL SYSTEMS

Annual Technical Report

on

AFOSR Grant [redacted] AFOSR-79-0076

(Sept. 30, 1980 - Sept. 30, 1981)

by

John F. Walkup and Thomas F. Krile

Principal Investigators

November 1981

Optical Systems Laboratory

Department of Electrical Engineering

Texas Tech University

Lubbock, Texas 79409

ABSTRACT

Analytical and experimental investigations of 2-D space-variant optical processing techniques have been conducted. Coherent processing investigations have included (1) an experimental study of the characteristics of photoresist phase masks for multiplex holography, (2) the development of a facility for generating high quality computer-generated holograms by use of a laser plotter and, (3) analytical investigation of an idea for using 1-D techniques to perform a 2-D space-variant operation. In the incoherent processing area we have proceeded with experiments to test the tristimulus based technique for performing complex operations using hue, saturation, and intensity parameters to represent complex numbers.

RESEARCH OBJECTIVES

During the funding period from September 30, 1980 to September 30, 1981, the major research objectives have been to analytically and experimentally investigate both coherent and incoherent optical processing techniques for performing two-dimensional (2-D) space-variant operations. In the coherent processing area, the major topics of investigation have been (1) the use of interferometric and correlation techniques to experimentally evaluate the quality of photoresist phase masks for use in multiplex holography, (2) completing the development of a facility for directly "writing" a computer-generated hologram on film using a computer-controlled laser plotter, and (3) an analytical study of a technique for using the well understood 1-D space-variant processor to perform the more difficult 2-D space-variant processing operations. In the coherent optical processing area, we have gotten well into our experiments designed to evaluate the tristimulus-based approach to the use of color as a parameter which enables us to perform the operations needed in 2-D space-variant processors. Details are provided in the following sections.

SUMMARY OF RESULTS

(1) Random Phase Masks for Multiplex Holography

Phase masks for reference beam encoding are an essential element of space-variant processors using multiplex holography[1]. During the past funding period, studies were carried out to determine how to construct and evaluate binary phase masks using photoresist as a recording medium. An argon-ion laser with UV mirrors was used as a source to provide controlled exposures of photoresist plates. A step function test pattern was used in an attempt to gather experimental data on exposure time and development techniques versus phase depth. It was determined experimentally that an ordinary Michelson interferometer does not have enough finesse to provide phase change readings with the required accuracy. Thus a multiple-beam interferometer was seen to be required. An order has been placed for a Varian A-scope, which is a multiple-beam interferometer utilizing a Fizeau plate. This instrument will have the required accuracy for the step function test patterns, and may even be usable for checking single-cell phase variations on diffuser masks because of built-in magnification.

Another method for checking the quality of random phase masks is to determine their auto- and cross-correlation functions, which ideally should be delta functions and zero, respectively. A two-step recording process was used to do this, where in the first step a Fourier transform was taken optically to produce a power spectrum on film. This film was then developed and Fourier transformed again to display an autocorrelation (if one diffuser mask was placed in the original input plane) or cross-correlation (if two different diffuser masks were placed in the original input plane). Tests were run using Gold-coded amplitude diffusers, Gold-coded phase diffusers (on photoresist), and ground glass. Computer simulations were also run on the Gold-code diffuser functions to see what the results should be. The ground glass results were excellent, but a problem of limited film dynamic range was encountered with both the amplitude and photoresist diffusers. Techniques for getting around the dynamic range problem and still extracting the desired correlation information are presently being researched. A solution to this problem, along with the computer simulations, should provide a good way to check and correct for large scale defects, such as non-uniform phase and/or amplitude variations over the mask.

(2) A Facility for Directly "Writing" Computer-Generated Holograms

The ability to produce high quality computer-generated holograms for multiplex holography applications such as space-variant processing has been needed on the grant [2,3]. During the past year we have constructed a system which presently has the capability of writing a 1024 by 1024 pixel "image" on a 1.7 cm square frame of 35 mm film, with 256 gray levels per pixel. The basic generator of the CGH is a VAX 11/780 minicomputer with 1.25 Mbytes of core memory, two 28 Mbyte disks, and a 1600 bpi tape drive. This computer permits us, for example, to perform FFT's on images or 2-D functions to be multiplexed. By adding up the holograms to be multiplexed on the computer, we can then renormalize the final CGH so as to optimally use the available dynamic range of the recording film. Once the CGH to be plotted is available on a hard disk, it is transmitted to our Compucolor II microcomputer and stored on floppy disks. The Compucolor II also has stored in its memory the film characteristic of the recording film to be exposed. The microcomputer controlls the process of shuttering the laser beam and controlling the galvanometer beam scanners which move the beam across the film plane.

Software for the laser plotter has been developed, and an M.S. thesis which will document the development of the laser plotter is presently being completed[4,5]. Test CGH's are still being generated, due to some hardware problems with the Compucolor II microcomputer. It is anticipated that the plotter will be used eventually to perform experiments with computer-multiplexed holograms for performing 2-D space-variant operations, along with other applications such as writing phase diffuser masks directly on photoresist.

(3) Performing 2-D Processing With 1-D Processors

The objective of this new project has been to make use of the advantages of our previously developed 1-D space-variant processors[6] in attempting to perform the more difficult task of 2-D space-variant processing. We recall that in performing a 2-D space-variant operation, the input is a 2-D function, and the kernal $h(x,y;\xi,\eta)$ is potentially a 4-D function. Clearly one difficulty in performing a 2-D superposition integral is making enough parameters available to handle a function such as $h(x,y;\xi,\eta)$. Our approach here is to assume that h( ) is separable in Cartesian coordinates: i.e. that $h(x,y;\xi,\eta) = h_1(x,\xi)h_2(y,\eta)$. We then plan to use an achromatic coherent processor (i.e. a white light coherent processor), so that the wavelength of the light provides us with an additional parameter. The processor makes use of the dispersive properties of prisms, as well as an achromatic Fourier transformer, as part of its operation. The basic theory of operation of the processor has been worked out at this time, and we are presently designing a proof-of-principle experiment to test the operation of the technique. It is anticipated that fully testing the concept may take some time, as the operations involved are somewhat complex. We hope to be able to report on the progress of the work at the 1982 meeting of the Optical Society of America in Tucson, Arizona.

(4) <u>Tristimulus Incoherent Processor</u>

A system has been designed which exploits tristimulus color properties for representation and manipulation of complex numbers to produce the integral of a product of complex functions[7]. This system uses color television monitors and cameras to represent and operate on complex numbers in the 3-dimensional space defined by the National Standards for Color Television transmissions (the NTSC standards). These 3-dimensions also correspond to the intensity, hue, and saturation model of human vision. In this system, multiplication of numbers represented in polar form is done by controlling hue and saturation separately from intensity. The phase angles of the numbers to be multiplied are displayed as the saturations of two complementary hues for positive and negative phase angles. These angles are then added optically in a constant intensity plane. Then, the intensities are manipulated separately in a subtractive system to represent the multiplication of two complex number magnitudes.

The results of the multiplication are detected by a color television camera. A polar-to-rectangular transformation is then done electronically on the output signals from the camera. The transformed output may then be fed to the chrominance (hue and saturation) inputs of a color television monitor, keeping the intensity constant. The output of this monitor, now in complex rectangular form, may then be summed by a collecting lens and the result may be detected by another color television camera. Thus, since both operations of complex multiplication and addition can be done, the space-variant superposition integral may be evaluated.

A system has been set up to conduct a proof-of-principle test of this approach. The white light sources, appropriate filters, and T.V. cameras for the first step in the process have been obtained and set up. A black-and-white camera is used to detect luminance information, while a color camera detects chrominance information. This two-camera approach was chosen because of the interactions between luminance and chrominance signals in a single color camera. Camera noise and nonlinearities were found to be a problem in the first run of calibration tests. A special synchronizing circuit and filters have greatly reduced the noise, and tests are now being run to characterize the system's transformations from color and intensity space to chrominance and luminance signals. A vector display and single-line-scan displays have been constructed to make the required luminance and chrominance signal measurements. Work is also progressing on construction of the polar-to-rectangular converter which interfaces the multiplication and summation portions of the tristimulus processor. To date, no major problems have been encountered in this tristimulus approach to incoherent processing.

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1. R. Kasturi, "Space-Variant Processing Using Phase Codes and Fourier-Plane Sampling Techniques," Scientific Report AFOSR-79-0076-1, Optical Systems Laboratoy, Dept. of Electrical Engineering, Texas Tech University, Lubbock, Texas, June 1, 1980.

2. C. A. Irby, "Computer-Generated Multiplex Holography," M.S. thesis, Dept. of Electrical Engineering, Texas Tech University, Dec. 1979.

3. C. A. Irby, M. O. Hagler, and T. F. Krile, "Multiplex Holograms: Digital Generation and Optical Retrieval," Appl. Optics, 21, (to appear January, 1982).

4. B. H. Jones, J. F. Walkup, and T. F. Krile, "Hybrid Laser Plotter for Optical Processing," Paper presented at 1981 Annual Meeting, Optical Society of America, Kissimmee, Florida, October, 1981.

5. B. H. Jones, "A Laser Plotter for Optical Processing," M.S. thesis, Dept. of Electrical Engineering, Texas Tech University, Lubbock, Texas (to be completed January, 1982).

6. R. J. Marks II, J. F. Walkup, M. O. Hagler, and T. F. Krile, "Space-Variant Processing of 1-D Signals," Appl. Optics, 16, 739-745 (1977)

7. R. F. Carson, J. F. Walkup, and T. F. Krile, "Tristimulus-Based Approach to Incoherent Optical Processing," Paper presented at 1981 Annual Meeting, Optical Society of America, Kissimmee, Florida, October, 1981.

RESEARCH PERSONNEL (1980-1981)

1. Faculty

   Dr. J. F. Walkup, Co-Principal Investigator, Professor

   Dr. T. F. Krile, Co-Principal Investigator. Associate Professor

   Dr. B. M. Khorana, Research Associate, (July 1 - Aug. 15, 1981) (Rose Hulman Institute of Technology)

   Dr. J. Shamir, Research Associate (Sept., 1981), Visiting Associate Professor, (Technion-Israel Institute of Technology)

2. Graduate Students

   D. S. Tavenner
   S. Chase
   B. H. Jones
   J. M. Adams
   R. F. Carson

3. Undergraduate Laboratory Assistants

   A. Barsallo
   F. Bermudez
   E. Kwan
   S. Whiteside
   S. Rankin

COMPLETED THESES AND DISSERTATIONS (1980-1981)

1. D. S. Tavenner, "Space-Variant Incoherent Optical Processing Using Color," M.S. thesis, Dept. of Electrical Engineering, Texas Tech University, May, 1981.

RECORD OF JOURNAL PUBLICATIONS ON AFOSR-75-2855 and 79-0076

Journal Articles Published

1. L. M. Deen, J. F. Walkup and M. O. Hagler, "Respresentations of Space-Variant Optical Systems Using Volume Holograms," Appl. Optics, 14, 2438-2446 (1975).

2. R. J. Marks II, J. F. Walkup and M. O. Hagler, "A Sampling Theorem for Space-Variant Systems," J. Opt. Soc. Am., 66, 918-921 (1976).

3. R. J. Marks II, J. F. Walkup and M. O. Hagler, "Line Spread Function Notation," Appl. Optics, 15, 2289-2290 (1976).

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5. R. J. Marks II, J. F. Walkup and T. F. Krile, "Ambiguity Function Display: An Improved Coherent Processor," Appl. Optics, 16, 746-750 (1977); addendum, 16, 1777 (1977).

6. T. F. Krile, R. J. Marks II, J. F. Walkup and M. O. Hagler, "Holographic Representations of Space-Variant Systems Using Phase-Coded Reference Beams," Appl. Optics, 16, 3131-3135 (1977).

7. R. J. Marks II, J. F. Walkup and M. O. Hagler, "Sampling Theorems for Linear, Shift-Variant Systems," IEEE Trans. on Circuits and Systems, CAS-25, 228-233 (1978).

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10. R. J. Marks II, J. F. Walkup, and M. O. Hagler, "Methods of Linear System Charactetication Through Response Cataloging," Appl. Optics, 18, 655-659 (1979).

11. R. J. Marks II, M. I. Jones, E. L. Kral, and J. F. Walkup, "One-Dimensional Linear Coherent Processing Using a Single Optical Element," Appl. Optics, 18, 2783-2786 (1979).

12. J. F. Walkup, "Novel Techniques for Optical Information Processing: An Introduction," 18, 2735-2736 (1979).

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14. M. O. Hagler, R. J. Marks II, E. L. Kral, J. F. Walkup, and T. F. Krile, "Scanning Technique for Coherent Processors," Appl. Optics, 19, 4253-4257 (1980).

15. R. Kasturi, T. F. Krile, J. F. Walkup, "Multiplex Holography for Space-Variant Processing: A Transfer Function Sampling Approach," Appl. Optics, 20, 881-886 (1981).

16. C. A. Irby, M. O. Hagler, and T. F. Krile, "Multiplex Holograms: Digital Generation and Optical Retrieval," Appl. Optics, 21 (to appear, January, 1982).

Journal Articles in Press

1. E. L. Kral, J. F. Walkup, and M. O. Hagler, "Correlation Properties of Random Phase Diffusers for Multiplex Holography," (in press, Appl. Optics).

2. M. I. Jones, J. F. Walkup, and M. O. Hagler, "Multiplex Hologram Representations of Space-Variant Optical Systems Using Ground-Glass Encoded Reference Beams," (submitted to Appl. Optics).

Scientific Reports

1. R. J. Marks II, "Space-Variant Coherent Optical Processing," Scientific Report AFOSR-75-2855-1, Optical Systems Laboratory, Department of Electrical Engineering, Texas Tech University, Lubbock, Texas 79409, December 1, 1977.

2. M. I. Jones and E. L. Kral, "Multiplex Holography for Space-Variant Optical Processing," Scientific Report AFOSR-75-2855-2, Optical Systems Laboratory, Department of Electrical Engineering, Texas Tech University, Lubbock, Texas, September 1, 1979.

3. R. Kasturi, "Space-Variant Processing Using Phase Codes and Fourier-Plane Sampling Techniques," Scientific Report AFOSR-79-0076-1, Optical Systems Laboratory, Department of Electrical Engineering, Texas Tech University, Lubbock, Texas, June 1, 1980.

INTERACTION ACTIVITIES (1980-81)

A. Conference Papers Presented

1. R. Kasturi, T. F. Krile, and J. F. Walkup, "Space-Variant Processing Techniques - A Comparison," J. Opt. Soc. Am., 70, 1590A (1980). Paper presented at the 1980 Annual Meeting, Optical Society of America, Chicago, IL, Oct. 1980.

2. J. F. Walkup, "Space-Variant Coherent Optical Processing," invited paper presented at the Second SPSE Symposium on Optical Data Display, Processing, and Storage, Las Vegas, NV, March, 1981.

B. Other Activities

1. Completed and distributed final report on the Workshop on Future Directions for Optical Information Processing (ARO-sponsored workshop, March 1, 1981, J. F. Walkup and T. F. Krile).

2. Attended ONR sponsored Symposium on Two-Dimensional Signal Processing Techniques and Applications held at Naval Research Laboratory, March, 1981 (J. F. Walkup).

3. Visited laboratory of Prof. J. W. Goodman at Stanford University, June, 1981 (J. F. Walkup).

4. Visited laboratory of Prof. R. J. Marks II at University of Washington, Seattle. Also presented a seminar on "Space-Variant Optical Processing," June, 1981 (J. F. Walkup).

5. Attended NASA Conference on Optical Information Processing for Aerospace Applications, Hampton, VA, August, 1981 (R. F. Carson).

6. Attended SPIE Technical Symposium, San Diego, CA, August, 1981 (J. F. Walkup).

7. Discussed results on AFOSR Grant with Mr. J. Trimble of ONR, Lubbock, TX, August, 1981 (J. F. Walkup and T. F. Krile).

8. Discussion of progress in interferometric study of phase encoding masks for multiplex holography, Terre Haute, IN, September, 1981 (T. F. Krile and Prof. B. Khorana).

9. Presented briefing on results obtained under AFOSR Grant 79-0076 to officials from ONR during review of the Texas Tech University Joint Services Electronics Program, September, 1981 (J. F. Walkup).

SUMMARY OF SIGNIFICANT ACCOMPLISHMENTS

1. Experimental studies relating to the quality of photoresist phase masks for use in multiplex holography.

2. Development of a facility for directly writing computer-generated holograms (CGH's) on film using a computer-controlled laser plotter.

3. Analytical derivation of a technique for performing 2-D space-variant operations using 1-D processors and white light coherent processing developments.

4. Design and development of experiments to test the tristimulus incoherent processor as one approach for using color to perform incoherent space-variant processing.