GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[x] ORIGINAL [ ] REVISION NO. _____

Project No. E-21-682 DATE 2/15/82

Project Director: T. K. Gaylord School/~~Lab~~ Elect.. Eng.

Sponsor: National Science Foundation, Washington, DC 20550

Type Agreement: Grant No. ECS-8106683

Award Period: From 2/1/82 To 7/31/85* (Performance) _____ (Reports)

Sponsor Amount: $100,000 Contracted through:

Cost Sharing: $ 12,500 (E-21-373) GTRI/~~GIT~~

Title: Two-Dimensional Optical Parallel Digital Work/Signature Detector

ADMINISTRATIVE DATA OCA Contact William F. Brown x4820

1) Sponsor Technical Contact:

Elias Schutzman, Program Official
Electrical, Computer & Systems Engr.
Electrical and Optical Communications Program
Washington, DC 20550
(202) 357-9618

2) Sponsor Admin/Contractual Matters:

Lee A. DeHerrera, Grants Official
Division of Grants & Contracts
Directorate for Administration
National Science Foundation
Washington, DC 20550
(202) 357-9602

Defense Priority Rating: none Security Classification: none

RESTRICTIONS

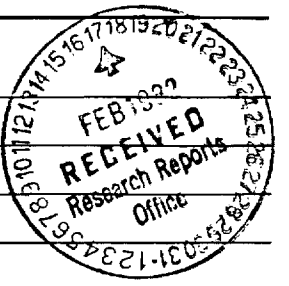
See Attached NSF Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT

COMMENTS:

*Includes the usual six-month unfunded flexibility period.



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FORM OCA 4:781

GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date April 14, 1986

Project No. E-21-682 (R5196-0A0) School/~~Lab~~ ee

Includes Subproject No.(s) N/A

Project Director(s) T. K. Gaylord and M. G. Moharam GTRC / ~~GTI~~

Sponsor National Science Foundation

Title ~~Industry - University Collaborative Research (IUCR):~~ Two-Dimensional Optical Parallel Digital Work/Signal Detector.

Effective Completion Date: 7/31/85 (Performance) 10/31/85 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [ ] Final Invoice or Final Fiscal Report
- [ ] Closing Documents
- [X] Final Report of Inventions (Patent Questionnaire)
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

Continues Project No. Continued by Project No.

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PROGRESS REPORT
July 1983

Two-Dimensional Optical Parallel Digital Word/Signature Detector

NSF

Industry/University Cooperative Program
Electrical, Computer, and Systems Engineering

Grant No. ECS 8106683

by

Thomas K. Gaylord
School of Electrical Engineering
Georgia Institute of Technology

Experimental Investigation of EXCLUSIVE OR Processing

A basic optical parallel processing system capable of performing the logical EXCLUSIVE OR and INCLUSIVE OR operations has been constructed. An argon ion laser is used in a holgraphic configuration with iron-doped lithium niobate as the recording material. For testing the parallel logic operations a series of data masks have been fabricated. Each contains a 32×32 array of binary data (an open aperture corresponds to a "0"). One binary data page is recorded holographically into the crystal. Another binary data page (to be EXCLUSIVE ORed bit by bit with the first data page) is then placed in the page composer and illuminated. A reference beam then reconstructs the stored data page. This image is coherently added to the image of the second data page. The EXCLUSIVE OR operation is then performed between the 1024 bits on one page with the 1024 bits on the other page when 1) the amplitudes of the two waves at the location of a "1" are adjusted to be equal and 2) the phases of one of the two waves is adjusted to be 180° shifted from its original phase during recording.

At the present time, a large number of EXCLUSIVE OR processing experiments have been performed. The EXCLUSIVE OR logical experiments have been outstandingly successful. The results that we are now achieving are very sharp and crisp. As viewed with the high resolution video monitoring system, the results look essentially perfect to the unaided eye.

However, this stage of development has come only after an extensive development effort to construct an automatic fringe stabilization system. Lack of phase stability made it impossible to perform operations repeatedly with any accuracy at the beginning of the experiments. After numerous unsuccessful attempts, a fringe stabilization system was finally developed that could accurately compensate any phase drift in the experiment. This system "dithers" the phase of the reference beam with a very small amplitude at 10Hz. A lock-in amplifier is then used to detect an error signal at this same frequency. The output error signal is then amplified and feedback to the high voltage op amp power supply that drives the phase modulator. Using this system, excellent phase stability is achieved.

The two-dimensional arrays of data from the EXCLUSIVE OR experiments have been digitized and written into computer files. These data will be analyzed in the next budget period to determine the probability of a false alarm and the probability of a miss for this type of processing.

Study of the Effects of Using "Fixed" Holograms

Making the holograms immune to erasure through ion-drift "fixing" is currently being investigated experimentally. Thermal fixing is achieved by heating the crystal to 100°C and thus allowing ions to drift and diffuse to compensate the electronic pattern. This produces charge neutrality on a local scale and the electric fields in the crystal are thus cancelled. the electrons, however, can be optically excited and redistributed uniformly with intense light. This leaves the permanent ionic pattern which causes the index of refraction to change through the linear electro-optic effect. Initial experiments have been performed on fixing the holograms and these will be continued and quantified in the next budget period.

Experimental Study of Optical Processing System

Marconi Avionics has designed and is developing the computer interfaces and software for handling the data that will be generated in the high data rate version of the EXCLUISVE OR word/signature detection system. This involves electronically transferring data rapidly to a two-dimensional spatial light modulator and receiving data at high rates from a video system. With these interfaces and software, a practical word/signature detection system will be constructed and demonstrated.

Georgia Institute of Technology
Atlanta, Georgia 30332

E 21-682

School of Electrical Engineering
Optics Laboratory
Telephone: (404) 894-2931

January 4, 1985

Dr. Elias Schutzman
Division of Electrical, Computer and
Systems Engineering
National Science Foundation
Washington, DC 20550

Subject: Progress Report on ECS8106683

Dear Dr. Schutzman:

Please accept the enclosed progress report on our Industry-University Collaborative Research grant entitled "Two-dimensional optical parallel digital word/signature detector."

Our progress in the previous report period was significantly delayed owing to phase stabilization of the optical holographic system used for recording the reference patterns. These problems, however, were overcome using 1) a constant-optical-path-length liquid gate (designed by me and described in this report), and 2) a real-time electronic active feedback fringe stabilization system (to be described in the final report). These previous improvements have led to excellent optical data processing results.

In the present report period, we are pleased to present significant results in several areas: 1) liquid gate design, 2) determination of optimum detector threshold setting, 3) experimental and theoretical bit error rates for optical digital parallel procesing, 4) residue number system moduli selection and logical minimization, 5) experimental results for EXCLUSIVE OR processing. Each of these results has now been published and two reprints of each are enclosed with the progress report.

Your help and support are very greatly appreciated. Thank you.

Sincerely,

Thomas K. Gaylord
Professor

Enclosures

PROGRESS REPORT
July 1984

Two-Dimensional Optical Parallel Digital Word/Signature Detector

NSF

Industry/University Cooperative Program
Electrical, Computer, and Systems Engineering

Grant No. ECS 8106683

by

Thomas K. Gaylord
School of Electrical Engineering
Georgia Institute of Technology

Liquid Gate Design, Fabrication, and Testing

A mechanical, three degree-of-freedom, index-matching, liquid-gate, photographic-glass-plate positioner that maintains a fixed optical path length (constant phase) over a 50 mm clear aperture has been designed, fabricated, and tested. Such a device is needed in critical interferometric applications such as laser holographic non-destructive testing and laser optical data processing. The device has proven to be essential in the experimental EXCLUSIVE OR data processing described below. The design of the liquid gate is described in the journal publication:

> T. K. Gaylord and C. C. Guest, "Optical interferometric liquid gate plate positioner," Review of Scientific Instruments, Vol. 55, pp. 866-868, June 1984.

Optimum Detector Threshold Setting and Probability of Error

The use of a holographic content-addressable memory system for parallel truth-table look-up digital data processing has been analyzed. For binary-coded residue numbers, the operations of 4-, 8-, 12-, and 16-bit addition and

multiplication have been treated. The minimum probability of error that can be achieved and the corresponding detector threshold settings are determined in each case allowing for the important effects of Gaussian distributions in the amplitude and the phase in the recording beams. Resultant probabilities of error for practical conditions (on the order of 10^{-6}) are found to be very competitive with those from state-of-the-art nonparallel technologies. These results are described in the journal publication:

> M. M. Mirsalehi, C. C. Guest, and T. K. Gaylord, "Residue number system truth-table look-up processing: Detector threshold setting and probability of error due to amplitude and phase variations," Applied Optics, Vol. 22, pp. 3583-3592, November 15, 1983.

Residue Number System Moduli Selection and Logical Minimization

Truth-table look-up processing using binary-coded residue numbers has been investigated for full-precision addition and multiplication for implementations using either electronic or optical technologies. The logically-minimized numbers of input combinations needed for each operation have been calculated for moduli 2 through 23. The moduli sets that require the minimum number of reference patterns have been determined for addition and multiplication of 4-, 8-, 12-, and 16-bit words. The total number of reference patterns (on the order of 500) has been found to be compatible with optical storage in electro-optic crystals. These results are described in the journal article:

> C. C. Guest, M. M. Mirsalehi, and T. K. Gaylord, "Residue number system truth-table look-up processing: Moduli selection and logical minimization," IEEE Transactions on Computers, Vol. C-33, pp. 927-931, October 1984.

Experimental EXCLUSIVE OR Optical Data Processing Results

Theoretical and experimental results have been presented for parallel EXCLUSIVE OR processing using thick Fourier holograms. The data pages used

contained 1024 bits in a 32 by 32 format. A holographically-stored data page is reconstructed together with an input data page that is imaged through the system. The amplitudes of the two wavefronts are adjusted to be equal and their relative phase is adjusted to be 180°, thus producing the bit-by-bit EXCLUSIVE OR operation between the pages. Using an expanded reference beam for the geometrical configuration treated, it has been calculated that the average dynamic range between a "0" and a "1" in the output power would be 17.4 dB. Experimentally, it is shown that excellent EXCLUSIVE OR results are obtainable. Photographs of these results have been presented. An average dynamic range of 7.7 dB was measured, the decrease from the calculated value being primarily due to noise in the video method of detection used in the measurements. The probabilities of miss and false alarm and the total probability of error were also measured. The use of a small diameter reference beam, necessary in some applications, causes a large mismatch in the shapes of the two wavefronts, thus degrading the EXCLUSIVE OR results. It has been shown theoretically and experimentally that using an aperture at the recording material produces partial compensation of the wavefronts, thus improving the EXLCUSIVE OR results. These results have been published in the paper:

C. C. Guest, M. M. Mirsalehi, and T. K. Gaylord, "EXCLUSIVE OR processing (binary image subtraction) using thick Fourier holograms," Applied Optics, Vol. 23, pp. 3444-3454, October 1, 1984.

APPENDIX VII

NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

FINAL PROJECT REPORT
NSF FORM 98A

PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING

PART I–PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. NSF Program	3. NSF Award Number
School of Electrical Engineering Georgia Institute of Technology Atlanta, GA 30332	Industry/Univers. Cooper.	ECS 8106683
	4. Award Period From 10-81 To 10-84	5. Cumulative Award Amount $100,000

6. Project Title

"Two-Dimensional Optical Parallel Digital Word/Signature Detector"

PART II–SUMMARY OF COMPLETED PROJECT *(FOR PUBLIC USE)*

The feasibility of an optical system for rapidly detecting matches between incoming data and prestored patterns was demonstrated. This system uses a laser both to store and to detect the patterns (or "signatures" or "words"). The reference patterns are represented as a string of binary digits (1's and 0's). Each reference pattern is holographically recorded in a photosensitive crystal of lithium niobate (a human made material that does not exist in nature). When the system is operated as a word/signature detector, the arriving data to be tested are also in binary form. Each new word is compared in parallel with all of the prestored words since the prestored words are holographically angularly multiplexed. The Boolean logical operation EXCLUSIVE OR is performed between the input data word and each prestored word. If a match occurs, the output word is all 0's and this is detected as a null in the optical power at the particular detector that corresponds to that prestored word. This type of system can be used in remote sensing, automatic inspection, air traffic control, and digital computing.

PART III–TECHNICAL INFORMATION *(FOR PROGRAM MANAGEMENT USES)*

1. ITEM *(Check appropriate blocks)*	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM	
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b. Publication Citations		✓			
c. Data on Scientific Collaborators		✓			
d. Information on Inventions	✓				
e. Technical Description of Project and Results		✓			
f. Other *(specify)*					

2. Principal Investigator/Project Director Name *(Typed)*	3. Principal Investigator/Project Director Signature	4. Date
Thomas K. Gaylord		Jan. 1, 86

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Form Approved OMB No. 3145-0058

FINAL REPORT

Two-Dimensional Optical Parallel Digital Word/Signature Detector

NSF

Industry/University Cooperative Program
Electrical, Computer, and Systems Engineering

Grant No. ECS 8106683

by

Thomas K. Gaylord
School of Electrical Engineering
Georgia Institute of Technology

November 1985

Introduction

A feasibility two-dimensional optical parallel digital word/signature detector demonstration system was theoretically analyzed and experimentally tested. Successful results indicate that large-scale operational word/signature detection systems capable of recognizing data patterns in high capacity data channels or in large data stores are possible.

The underlying scientific contributions that have allowed this type of system to be demonstrated are summarized in the following sections.

Phase Stabilization System for Optical Data Processing

Routine passive techniques such as temperature and air current control are frequently not adequate to provide interference fringe stabilization in holographic optical data processing experiments. A successful active phase stabilization system that can be adapted to a variety of experimental configurations was described. It utilizes a synchronous lock-in amplifier and an electrooptic phase modulator to provide real-time stabilization of the interference fringe pattern. Both a video detection method and a direct optical detection method were experimentally evaluated in conjunction with the phase stabilization system. Excellent stabilization results were obtained. These results were reported in the journal publication:

C. C. Guest, and T. K. Gaylord, "Phase stabilization system for holographic optical data processing," **Applied Optics**, vol. 24, pp. 2140-2144, July 15, 1985.

Liquid Gate Design, Fabrication, and Testing

A mechanical, three-degree-of-freedom, index-matching, liquid-gate, photographic-glass-plate positioner that maintains a fixed optical path length (constant phase) over a 50 mm clear aperture has been designed, fabricated, and tested. Such a device is needed in critical interferometric applications such as laser holographic non-destructive testing and laser optical data processing. The device has proven to be essential in the experimental EXCLUSIVE OR data processing described below. The design of the liquid gate is described in the journal publication:

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Complexity Analysis of Residue-Based Operations

The complexity of direct implementation of truth tables by associative logical processing has been analyzed. Analytic expressions for the lower bound for residue addition and multiplication were derived. Errors in the complexity that have previously appeared in the literature were corrected. These results will appear in the journal publication:

M. M. Mirsalehi and T. K. Gaylord, "Comments on direct implementation of discrete and residue-based functions via optimal

encoding: A programmable array logic approach," IEEE Transactions on Computers, vol. C-35, pp. xxx-xxx, 1986. (accepted)

Experimental EXCLUSIVE OR Optical Data Processing Results

Theoretical and experimental results have been presented for parallel EXCLUSIVE OR processing using thick Fourier holograms. The data pages used contained 1024 bits in a 32 by 32 format. A holographically stored data page is reconstructed together with an input data page that is imaged through the system. The amplitudes of the two wavefronts are adjusted to be equal and their relative phase is adjusted to be 180°, thus producing the bit-by-bit EXCLUSIVE OR operation between pages. Using an expanded reference beam for the geometrical configuration treated, it has been calculated that the average dynamic range between a "0" and "1" in the output power would be 17.4 dB. Experimentally, it is shown that excellent EXCLUSIVE OR results are obtainable. Photographs of these results have been presented. An average dynamic range of 7.7 dB was measured, the decrease from the calculated value being primarily due to noise in the video method of detection used in the measurements. The probabilities of miss or false alarm and the total probability of error were also measured. The use of a small diameter reference beam, necessary in some applications, causes a large mismatch in the shapes of the two wavefronts, thus degrading the EXCLUSIVE OR results. It has been shown theoretically and experimentally that using an aperture at the recording material produces partial compensation of the wavefronts, thus improving the EXCLUSIVE OR results. These results have been published in the paper:

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