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Optics in Parallel Shared Memory Computing

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Final Technical Report, 7/1/93-10/31/97

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13. ABSTRACT (*Maximum 200 words*)

A summary of accomplishments on the grant, "Optics in Parallel Shared Memory Computing", over the period 7/1/93-10/31/97, is given. Accomplishments include the design of a parallel shared memory optical/electronic computer, and a centralized control algorithm for its processor-to-memory interconnection network. The grantee has also designed a volume-holographic shared memory system that can implement a set of parallel-access memory modules in a system comprising a single photorefractive crystal and 2 arrays of self-coherent but mutually incoherent sources. A proof-of-concept experimental demonstration has been successfully conducted. A closer-to-optimal multiplexing technique, which incorporates space, angle, and wavelength multiplexing, has also been developed. A technique for "blind copying" of a multiplexed volume hologram has been analyzed and applied to various combinations of photorefractive and photopolymer media. The grantee has also developed and analyzed a multiple-access protocol based on wavelength, space, and time multiplexing, for use in distributed-memory parallel processors that use optical symmetric cellular hypercube interconnections. A hybrid optoelectronic CMOS-SEED chip, designed by the grantee and fabricated under the DARPA CO-OP program, provides conversion from electrical to parallel-optical formats with programmable number representation. This report also describes objectives of, personnel supported by, publications resulting from, and interactions/transitions of, the effort supported by this grant.

14. SUBJECT TERMS Parallel computing, shared memory, optical memory, volume holography, hologram copying, volume hologram multiplexing, optoelectronic spatial light modulator, CMOS-SEED	15. NUMBER OF PAGES 13
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1. Objectives

The objectives of this effort are to:

(1) Develop techniques for 2-D parallel access to 2-D and 3-D memories;

(2) Develop or identify parallel computer architectures that are compatible with these memory access techniques;

(3) Incorporate the capability for a large number of memory input/output channels that are, at the same time, efficiently utilized; and

(4) Do this by incorporating optics where appropriate.

These objectives have not changed since the inception of the effort.

2. Technical Summary of Accomplishments

We have developed a **parallel computer architecture, the shared memory optical/electronic computer (SMOEC)**, which is based on the shared memory computing paradigm and uses optics and electronics, each where appropriate for high computational performance. It is designed for implementation with relatively near-term components but is also extendible to implementation using longer-term components for higher performance. It uses optics to provide 2-D parallel optical access to 2-D electronic (or photonic) memory modules. In conjunction with this architecture, we have designed an optical multistage reconfigurable interconnection network that enables the set of electronic processing elements to controllably access the set of memory modules. We have also performed a detailed design and analysis of a centralized control algorithm for this interconnection network, and it provides routing control in approximately $O(\log N)$ time (empirical result), a significant improvement over other pertinent techniques. More information is available in publications [P1, P2, P5, T2].

We have designed a **3-D optical shared memory system** that can implement a set of parallel-access memory modules by using a single photorefractive crystal, two arrays of self-coherent but mutually incoherent sources, and two spatial light modulators. It is compatible with the SMOEC architecture described above, or can be used in other shared-memory systems. It can implement a complete memory-instruction set. The operation of each memory module within the photorefractive crystal can proceed essentially independently of, and in parallel with, the operation of the other memory modules. This independence of simultaneous operations on different memory modules allows much more efficient use of the memory input/output channels than do other techniques for optical access to volume holographic memory. We have also completed an experimental demonstration of this 3-D optical shared memory system concept. More information is available in publications [P3, T1].

We have developed a **closer-to-optimal multiplexing technique for such a volume holographic memory**, which incorporates space, angle, and wavelength multiplexing together to provide a better combination of storage capacity, accessibility, and crosstalk than previous approaches. This technique uses incoherent/coherent recording and recall, partially overlapping subholograms, partial angular multiplexing, and enough sufficiently different wavelengths to substantially reduce both grating-degeneracy and beam-degeneracy crosstalk as compared with other multiplexing techniques for flexible-access memory systems. Design principles have been developed and numerical simulations indicate reduced crosstalk and improved interconnection density. More information is available in publication [T1].

We have also developed a **technique for "blind copying" of information between one volume holographic memory and another volume holographic medium**, wherein the two holographic media may be different materials, and the information content of the first (master) memory isn't known a priori except for the nature of the reference beams used to read out the holographic memory data. We have analyzed copying of this multiplexed volume information from a photorefractive material to a photopolymer material and vice versa, as well as between two photorefractive media and between two photopolymer media. Information on gain from the master to the copy and on signal-to-noise in the copy comes out of our analysis, as well as insight into how to control these parameters experimentally. More information is available in publications [P7, T3].

We have also considered the case of a **distributed-memory parallel processing** system that uses optical symmetric cellular hypercube interconnections for communication. Cellular hypercube interconnections have been studied for optical implementation by a number of research groups, and offer a useful compromise between aggregate useful communication bandwidth and number of interconnection channels. An example of an optoelectronic architecture for such a system is described in publication [P6]. We have developed a protocol for communication among the processing/memory elements, based on a combination of wavelength, space, and time multiplexing. Analytic models based on semi-Markov processes were employed to analyze this protocol and compare it with two other techniques. The two key measures evaluated, network throughput and data packet delay, compared favorably with the other two approaches. More information is available in publications [P4, T1].

We have designed an **optoelectronic hybrid CMOS-SEED spatial light modulator for conversion between 1-D parallel (edge fed) electronic data and 2-D parallel (surface readout) optical data**. The chip has an array of 10 or 20 shift registers (depending on mode of operation), and can operate with any of 4 different optical number representations. It has an array of 10 x 10 or 10 x 20 optical outputs, depending on number representation (single rail or a variety of dual rail techniques). It has been fabricated by AT&T/Lucent under the DARPA-sponsored CO-OP program. We have experimentally verified the electrical function of the chip. The optical function will be tested under a different program. Chips having this function are particularly efficient at providing input of 2-D parallel optical information to systems that operate on scrolled information. The underlying technology is also useful for inputting 2-D parallel optical data to the chip, and for 2-D optical input and 2-D optical output with processing in between. Chips based on this underlying technology can enable many of the functions that are useful in interfacing between electronic computation and optical parallel-access memory (as for the 3-D optical shared memory system described above), as well as between optical interconnection networks and electronic memory (as for the shared memory optical/electronic computer, with 2-D electronic/photonic memory, described above). More information on this particular electronic-to-parallel-optical chip is available in publication [A1].

Under separate sponsorship, we have also investigated the use of **holographic photopolymer materials for storage of holograms and analog data**. The time dynamics of (single or multiple mutually incoherent) grating formation, effects of diffusion processes, and effects of self diffraction in a volume hologram that is modulating the beam as it is being written, have been investigated experimentally and theoretically. It is mentioned here because it clearly relates to volume holographic memory systems. More information is available in publications [P7, T3].

Relevance. This work of this grant relates directly to the incorporation of parallel-access memories in computers in order to realize substantial improvements in computational performance. It considered architecture of a parallel computer that incorporates highly parallel memory access; control; architecture and implementation of volume-holographic optical memory; and interface to electronic memory. It also addressed the problem of transferring data between volume holographic memories, including loading data from an optical read-only memory to an optical read-write memory, or recording information that exists in an optical read-write memory into a permanent optical storage medium, which are crucial issues for the practical use of optical volume memories.

3. Personnel Supported

The following personnel were supported at least in part by this grant.

Faculty

B. Keith Jenkins, as principal investigator.

Armand R. Tanguay, Jr.

Administrative staff

Gloria Halfacre

Linda Varilla

Post-doctoral research staff

Clare Waterson

Ph.D. graduate students

Adam Goldstein

Chingchu Huang

Kuang-Yu Li

Sabino Piazzolla

Clare Waterson

4. Publications

Listed below are peer-reviewed publications that resulted in whole or in part from this grant.

P1. C. Waterson and B. K. Jenkins, "Shared Memory Optical/Electronic Computer: Architecture and Control", *Applied Optics*, Vol. 33, 1559-1574 (1994).

P2. C. Waterson and B. K. Jenkins, "Passive Optical Interconnection Network Employing a Shuffle-Exchange Topology", *Applied Optics*, Vol. 33, 1575-1586 (1994).

P3. K.-Y. J. Li and B. K. Jenkins, "Optical parallel-access shared memory system: analysis and experimental demonstration," *Applied Optics*, Vol. 34, No. 2, pp. 358-369 (10 Jan. 1995).

P4. K.-Y. J. Li and B. K. Jenkins, "A collisionless wavelength-division multiple access protocol for free-space cellular hypercube parallel computer systems," in *Optical Computing*, 1995 OSA Technical Digest Series, Vol. 10, pp. 266-268 (Optical Society of America, Washington DC, 1995).

P5. C. Waterson and B. K. Jenkins, "Routing algorithm for a circuit-switched optical extended generalized shuffle network," in *Optical Computing*, 1995 OSA Technical Digest Series, Vol. 10, pp. 29-31 (Optical Society of America, Washington DC, 1995).

P6. K.-S. Huang, C. B. Kuznia, B. K. Jenkins, and A. A. Sawchuk, "Parallel architectures for digital optical cellular image processing," *Proc. IEEE*, Vol. 82, No. 11, pp. 1711-1723 (Nov. 1994).

P7. S. Piazzolla and B. K. Jenkins, "Holographic grating formation in photopolymers," *Optics Letters*, Vol. 21, No. 14, pp. 1075-1077 (15 July 1996).

Listed below are Ph.D. dissertations that resulted in whole or in part from this grant.

T1. Kuang-Yu Li, *Optical Shared Memory Computing and Multiple Access Protocols for Photonic Networks*, Ph. D. Thesis, USC-SIPI Report No. 291 (Signal and Image Processing Institute, University of Southern California, Los Angeles, California, 1995); available from USC-SIPI, contact Gloria Halfacre, phone (213) 740-4145, fax (213) 740-4651, email gloria@sipi.usc.edu.

T2. Clare Waterson, *Design for a Shared Memory Computer with a Combining Optical Interconnection Network using External Routing*, Ph. D. Thesis, USC-SIPI Report No. 284 (Signal and Image Processing Institute, University of Southern California, Los Angeles, California, 1995); available from USC-SIPI, contact Gloria Halfacre, phone (213) 740-4145, fax (213) 740-4651, email gloria@sipi.usc.edu.

T3. Sabino, Piazzolla, *Real Time Effects in Volume Holographic Materials for Optical Storage, Copying, and Optical Neural Networks*, Ph. D. Thesis, USC-SIPI Report No. 316 (Signal and Image Processing Institute, University of Southern California, Los Angeles, California, 1997); available from USC-SIPI, contact Gloria Halfacre, phone (213) 740-4145, fax (213) 740-4651, email gloria@sipi.usc.edu.

Listed below are other Ph.D. theses that provide relevant information.

A1. Goldstein, Adam, "Scalable Photonic Neural Networks for Real-Time Pattern Classification," Ph.D. Thesis, USC-SIPI Report No. 307 (Signal and Image Processing Institute, University of Southern California, Los Angeles, California, 1997); available from USC-SIPI, contact Gloria Halfacre, phone (213) 740-4145, fax (213) 740-4651, email gloria@sipi.usc.edu.

5. Interactions/Transitions

Three Ph. D. graduate students that worked on this effort have graduated and taken employment in industry, taking with them expertise gained from this effort:

- Clare Waterson, worked on this effort as both a Ph.D. graduate student and subsequently as a post-doctoral research associate. She is now employed at XonTech, Inc., Van Nuys, California, a company involved in DoD work.
- Adam Goldstein is now employed at Raytheon (formerly Hughes Aircraft Co.), El Segundo, California, and is working on DoD projects.
- Kuang-Yu Li is now employed at Hughes Space and Communications Co., El Segundo, California, working on commercial communication and satellite systems.

In addition, numerous conference and workshop presentations and interactions occurred to disseminate the knowledge and results generated from this grant.

6. New Discoveries, Inventions, or Patent Disclosures

No patents have been applied for, and no inventions have been disclosed, based on the work supported by this grant.

USC

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B. Keith Jenkins, Ph.D.
Associate Professor

April 27, 1998

Dr. Alan E. Craig
Program Officer AFOSR/NE
110 Duncan Ave., Suite B115
Bolling Air Force
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Dear Alan:

Enclosed please find one original and two copies of our final technical report on the grant, "Optics in Parallel Shared Memory Computing," grant No. F49620-1-93-0437, for the period 7/1/93- 10/31/97. Also enclosed is a PC formatted disk with the report in Microsoft Word '97 format.

Thank you for your support; it enabled what in our view was some exciting and significant research.

Sincerely,

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