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This report details the results of the first year of analytical and experimental investigations of programmable optical quadratic neural networks. The investigations have included: (1) computer simulations and theoretical characterizations of the performances of first and second order Hopfield associative memories in terms of a signal-to-noise ratio parameter C; (2) a hybrid electro-optical, polarization-encoding-based technique for implementing a quadratic neural processor and (3) use of photorefractive $BaTiO_3$ crystals to perform a vector-matrix-vector operation based on four-wave mixing. Details are summarized in this report and in the publications resulting from the research effort.

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PROGRAMMABLE OPTICAL QUADRATIC NEURAL NETWORKS

Annual Technical Report

on

AFOSR Grant 88-0064

December 1, 1987 - November 30, 1988

by

John F. Walkup and Thomas F. Krile
Co-Principal Investigators

December 1988

Optical Systems Laboratory
Department of Electrical Engineering
Texas Tech University
Lubbock, TX 79409

ABSTRACT

This report details the results of the first year of analytical and experimental investigations of programmable optical quadratic neural networks. The investigations have included: (1) computer simulations and theoretical characterizations of the performances of first and second order Hopfield associative memories in terms of a signal-to-noise ratio parameter C; (2) a hybrid electro-optical, polarization-encoding-based technique for implementing a quadratic neural processor and (3) the use of photorefractive $BaTiO_3$ crystals to perform a vector-matrix-vector operation based on four-wave mixing. The details are summarized in this report and in the publications resulting from the research effort.

RESEARCH OBJECTIVES

During the first year of the grant (December 1, 1987 - November 30, 1988), the major research objectives have been to perform both analytical and experimental investigations of optical quadratic neural networks. The major areas of investigation have been (1) theoretical analyses and computer simulations comparing the performances of linear versus quadratic neural networks; (2) a hybrid electro-optical implementation, based on liquid crystal television (LCTV) technology of a polarization-encoded neural processor and (3) a real-time quadratic neural processor utilizing the nonlinear properties of photorefractive $BaTiO_3$ crystals to perform vector-matrix-vector polynomial operations. Details of these first year investigations are presented in the following sections.

SUMMARY OF RESULTS

Since most of the results obtained under the grant are promptly submitted for publication, and are also presented at national and international scientific meetings, we will briefly summarize the major results obtained in this section, with references to the appropriate journal articles and conference proceedings.

1. Theoretical/Computer Analyses and Simulations of Linear and Quadratic Hopfield Associative Memories (HAMS).

Extensive computer simulations were conducted to explore the characteristics of both first and higher order Hopfield associative memories.[1] Based on the simulation results, a new statistical method, which we will call the C parameter approach, was developed and successfully applied to derive a series of equations capable of precisely estimating the memory capacity and the attraction radius of the HAMS.[2,3] The origins of this average SNR parameter come from the signal-to-noise ratio concept commonly seen in binary decision theory. We found that these two important performance characteristics of HAMS are closely related to the required convergence probability. More specifically, the required convergence probability of the HAM must be explicitly specified before the memory capacity can be quantified. We also showed, through our single parameter approach, that the memory capacity can be doubled by appropriately weakening the required convergence probability.

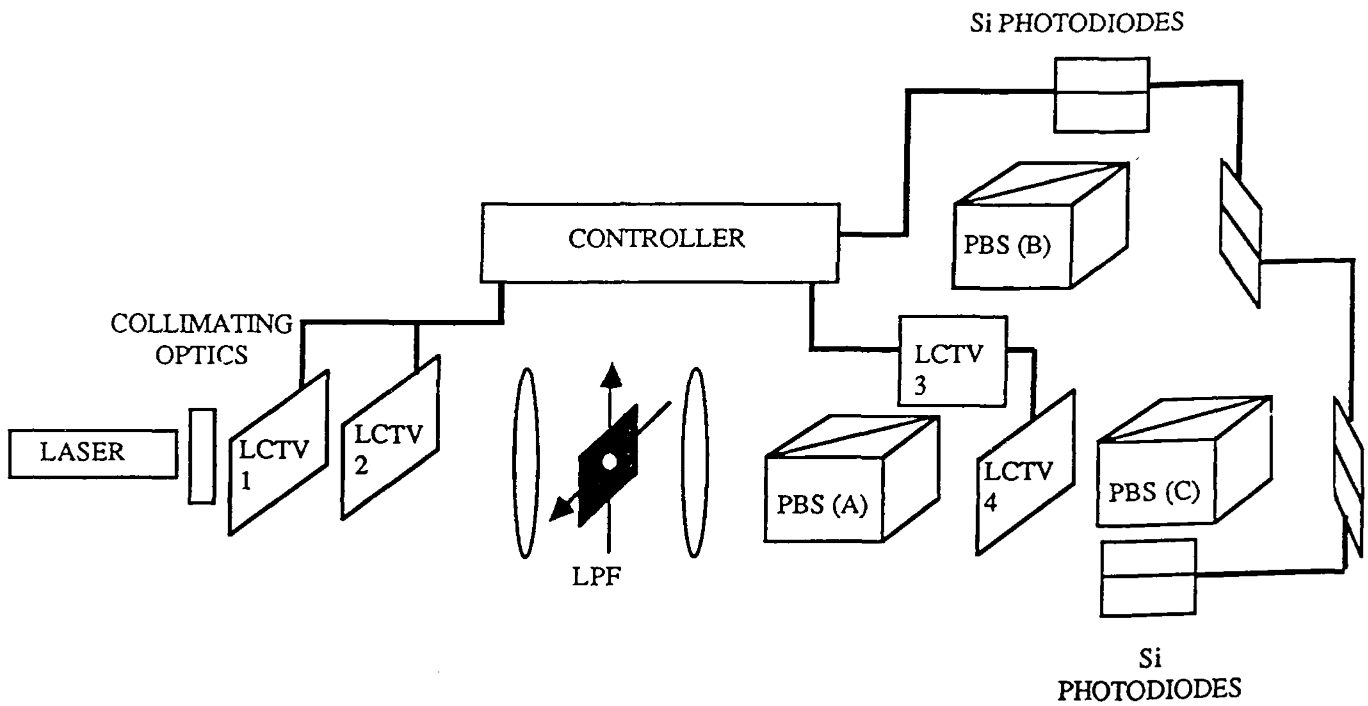
There are two significant advantages of the C parameter approach: (1) it is much simpler than any statistical approaches proposed by other researchers[4,5,6,7]; and (2) it is not only capable of characterizing the performance of the direct convergence HAM in which the network is required to converge precisely to the target vector in one iteration, but it is also capable of characterizing the indirect convergence HAM in which a small fraction ϵ of its N components are permitted to have errors even after multiple iterations (whether performed synchronously or asynchronously). An important result we found associated with the indirect convergence HAM is that there exists a one-to-one correspondence between P_{ic} (the required indirect convergence probability) and ϵ/η, where η is the probability that a particular neuron changes to an incorrect bit after one updating cycle. For example, when ϵ=0.06, η=0.000755 and ϵ/η=79, we have P_{ic}=0.994. If one tightens the allowance of input noise (i.e. smaller ϵ) to keep P_{ic} at 0.994, either the number of stored patterns allowed (i.e. M) or the maximum noise immunity (i.e. attraction radius) has to be decreased. Doing so is equivalent to reducing the value of η to the extent that we keep ϵ/η=79.[2,3] In fact, there also exists a similar relationship for the direct convergence HAM in which a constant value of N corresponds to a constant P_{dc} (the required direct convergence probability).

The concept of the memory capacity of the HAM can be best explained by the equation: $M' = (1 - 2\rho)^p M$,[3] where $\rho = 2b/n$, b is the number of noisy input bits; M' is the number of stored patterns for the noisy case $b \neq 0$, while M is the capacity for the case $b=0$. Finally p is the order of the HAM, i.e. p=1 is the first order HAM, p=2 is the quadratic HAM, etc. Therefore, one can think of the recall power of an arbitrary HAM being jointly characterized by the number of stored patterns M and the desired noise immunity of the HAM.

The power of the C parameter was further illustrated by its capability of providing satisfactory theoretical explanations for the performance differences between the (-1,1) and (0,1) binary-valued HAMS and similarly between the nonzero-autoconnection and zero-autoconnection HAMS. The trade-offs associated with the inclusion of the binary correlation matrix in the quadratic HAM was also investigated using this same technique.

2. Electro-Optical Implementation of a Quadratic Neural Network.

During the first year of funding, our approach was to build upon our previous designs with optical polynomial processors.[8] Using the approach outlined in the grant proposal, we have designed, built and tested a processor using polarization encoding. The processor implements a polynomial, which represents the discriminant function of perceptron-based neurons, as the outer product of a vector x and followed by a generalized inner product with a matrix of weights (coefficients of the polynomial) W. The result is obtained as the element-by-element multiplication between the outer product matrix and the weight matrix followed by spatial integration. The architecture is shown below.



Here the LCTV modulators 1 and 2 perform the outer product, while LCTVs 3 and 4 perform the weighting on the outer product matrix. By using the properties of the polarization-encoding technique, we have been able to reduce the space-bandwidth product to one-fourth of what would normally be required in systems for operating with bipolar numbers.

To date we have built and tested a system that implements a single neuron (only one polynomial can be evaluated at a time).[9] We are working to implement a multineuron system by using spatial multiplexing and utilizing a two-dimensional detector (i.e. a CCD camera) at the output. In addition, we have applied the processor to implement optical logic and perform binary and trinary valued transforms such as the Walsh and Haar.[10] The amount of memory required for storing the transform matrix has been drastically reduced by formulating the transform as an outer product.

We have simulated the improvement in performance of the quadratic neural network over the linear neural network in performing the EXOR operation. We are currently simulating the performance of the quadratic network in pattern recognition tasks, in particular the problem of character recognition. Depending on the results of these simulations, we will be investigating methods for reducing redundant terms in the outer product matrix.

3. Optical Implementation Using Photorefractive Crystals.

As part of our research on optical quadratic neural networks, we have developed an optical quadratic polynomial processor using four-wave mixing in photorefractive crystals. This processor can perform an all optical quadratic operation for use as a decision function for quadratic neural networks or as an optical polynomial processor. Given an N-dimensional input vector $\underline{x}$ and an N by N weight matrix $\underline{W}$, the processor performs the quadratic operation

$\underline{x}^T\underline{W}\underline{x}$ in parallel.[11] It extends earlier work on matrix-vector multiplication in photorefractive media by Yeh and Chiou.[12] There are a number of advantages of a photorefractive quadratic processor. First, the processor performs an all optical parallel multiplication and summing operation. Second, the multiplication in the processor is a coherent multiplication. Therefore, the system can perform quadratic operations on complex numbers and phase-encoded numbers. Third, with very low powers (10 uW on the input elements), the processor achieved a signal-to-noise power ratio of 20 at the output. With higher input powers, the signal-to-noise ratio will increase due to reduced ambient noise effects. Fourth, the efficiency of photorefractive processors is very high. Due to gain effects associated with four-wave mixing, the power in the output beam can be significantly higher than that in the signal beams. This helps eliminate a common fan-out problem encountered in many optical processors.

The processor has been implemented using a 4-watt argon ion laser as the light source, transparencies as the vector and matrix input modulators, and a $BaTiO_3$ crystal as the photorefractive processor. Problems associated with the reduced levels of power (approximately 300mW) currently available from our 4-watt argon laser will soon, we believe, be overcome with the planned purchase of a new laser.

References

1. J.J. Hopfield, "Neural Networks and Physical Systems With Emergent Collective Computational Abilities." Proceedings of the National Academy of Science of the United States of America, 79, 2445-2558 (1982).

2. J.H. Wang, T.F. Krile and J.F. Walkup, "Determination of Hopfield Associative Memory Characteristics Using a Single Parameter" (submitted to Neural Networks, Oct. 1988).

3. J.H. Wang, T.F. Krile and J.F. Walkup, "Determination of Quadratic and Higher Order Hopfield Associative Memory Characteristics Using A Single Parameter" (submitted to Neural Networks, Oct. 1988).

4. Y.S. Abu-Mostafa and J.S. Jacques, "Information Capacity of the Hopfield Model," IEEE, Transactions on Information Theory, IT-31, 461-464 (1985).

5. S. Amari and K. Maginu, "Statistical Neurodynamics of Associative Memory," Neural Networks, Vol. 1, No. 1, 63-73 (1988).

6. R.J. McEliece, E.C. Posner and S.S. Venkatesh, "The Capacity of the Hopfield Associative Memory," IEEE, Transactions on Information Theory, IT-33, 461-482 (1987).

7. D. Psaltis, C.H. Park and J. Hong, "Higher Order Associative Memories and Their Optical Implementations," Neural Networks, Vol. 1, No. 2, 149-163 (1988).

8. S.H. Lin, T.F. Krile, E.J. Bochove, and J.F. Walkup, "Electro-Optical Implementation of Programmable Quadratic Neural Networks," SPIE Proc. (presented at O-E/LASE '88, Los Angeles, January 1988).

9. A.P. Ittycheriah, J.F. Walkup, and T.F. Krile, "An Outer Product Processor Using Polarization Encoding" (submitted to Applied Optics, Dec. 1988).

10. A.P. Ittycheriah, J.F. Walkup, and T.F. Krile, "Applications of a Polarization-Based Optical Processor" (submitted for OSA Topical Meeting on Optical Computing, Salt Lake City, UT, Feb. 1989).

11. G. Henderson, J.F. Walkup, and E.J. Bochove, "An Optical Quadratic Processor Using Four-Wave Mixing in $BaTiO_3$" (in preparation for submission to Optics Letters).

12. P. Yeh and A. Chiou, "Optical Matrix-Vector Multiplication Through Four-Wave Mixing in Photorefractive Media," Optics Letters, 12, 138 (1987).

RECORD OF JOURNAL PUBLICATIONS ON AFOSR 88-0064*

Journal Articles in Press

1. J.H. Wang, T.F. Krile, and J.F. Walkup, "Determination of Hopfield Associative Memory Characteristics Using a Single Parameter," (submitted to Neural Networks, October, 1988).

2. J.H. Wang, T.F. Krile, and J.F.Walkup,"Determination of Quadratic and Higher Order Hopfield Associative Memory Characteristics Using a Single Parameter," (submitted to Neural Networks, October, 1988).

3. A.P. Ittycheriah, J.F. Walkup, and T.F. Krile, "An Outer Product Processor Using Polarization Encoding," (submitted to Applied Optics, December, 1988).

*Papers with published abstracts/proceedings presented at professional society meetings are listed under "Interaction Activities."

RESEARCH PERSONNEL (1987-1988)

(1) Faculty:
Dr. J.F.Walkup, Co-Principal Investigator, Horn Professor

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

Dr. E.J. Bochove, Research Associate, Visiting Associate Professor

(2) Graduate Students:
J.H. Wang
A.P. Ittycheriah
O.W. Spitz

(3) Undergraduate Laboratory Assistants
A. Lim
G. Henderson
D. Birkheimer

(4) Secretary
P. Burtis

COMPLETED THESES AND DISSERTATIONS (1987-1988)

1. J.H. Wang, "Characterization of First and Second Order Hopfield Neural Networks," M.S. thesis, Dept. of Electrical Engineering, Texas Tech University, Lubbock, TX, August 1988

INTERACTION ACTIVITIES (1987-1988)

Papers Presented at Major Professional Meetings

1. S.H. Lin, T.F. Krile, and J.F. Walkup, "Electro-optical Implementations of Programmable Quadratic Neural Networks, SPIE Vol. 882, (presented at O-E/LASE '88, Los Angeles, CA, Jan 1988).

2. J.F. Walkup, "Recruiting Students Into Optics," SPIE Vol. 978, (invited paper, First Interntl. Conf. on Education in Optics, San Diego, Aug. 1988).

3. A.P. Ittycheriah, J.F. Walkup, and T.F. Krile, "Optical Quadratic Neural Networks," (presented at 1988 Annual Mtg., Opt. Soc. Am., Santa Clara, CA, Oct. 1988).

4. A.P. Ittycheriah, J.F. Walkup, and T.F. Krile, "Applications of a Polarization-Based Optical Processor," (submitted for OSA Topical Meeting on Optical Computing, Salt Lake City, UT, Feb. 1989).

Other Interaction Activities

1. Served as Chairman of Education Council, Optical Society of America, 1987-88 (J.F. Walkup).

2. Lectured on "Optical Computing," at First International School and Workshop on Photonics, Oaxtepec, Mexico, July 4-8, 1988 (J.F. Walkup).

3. Faculty development leave research on optical neural networks and optical computing, Computer Engineering Dept., Wright State University, Dayton, OH (T.F. Krile, 15 July 1988-15 July 1989).

4. Interacted with Prof. Robert J. Marks II, University of Washington on optical neural networks as part of a joint U. of W./Texas Tech University SDI/ONR research project on accuracy limitations in optical computing (J.F. Walkup and T.F. Krile).

SIGNIFICANT ACCOMPLISHMENTS

1. Developed a signal-to-noise ratio parameter-based performance characterization of linear, quadratic and higher-order Hopfield associative memories (HAMS).

2. Investigated an electro-optical implementation of a polarization-based quadratic neural processor and its applications.

3. Achieved vector-matrix-vector real time processing operations in photorefractive $BaTiO_3$ crystals using 4-wave mixing. Also investigated other optical signal processing operations in $BaTiO_3$.