Is optical computing ready?

Is optical computing ready? Here my answer is only slightly less certain but much less dramatic. The answer is: "somewhat." There are aspects of optical computing which are already well developed (synthetic aperture radar processing, spectrum analyzers, some computer vision preprocessors, and so on). There are others which could be developed now to fill important, specialized niches. Still others seem to me strictly 21st Century.

Again, I dare not categorize my colleagues' various projects for you or for them. The point is very simple. Optical computing is not a well-defined goal. It is a direction. Directions are taken but never reached. As each year passes, more and more optical devices and systems will cross the hazy line from "vaporware" or, as I prefer, "chalkware" to hardware practicability. Our evolution seems likely to be smooth, with a large positive second derivative, but not discontinuous. The sheer number of independent approaches being taken seems to assure this.

Future generations are likely to look upon the 1980s and 1990s as the beginning of the optical computing revolution, but—not blessed with perfect foresight—we are left to muddle through these times as best our faith and enthusiasm allow. It should be exciting.

Optical Computing at Carnegie-Mellon University

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Optical computing is an area of research that has long intrigued many people. However, because of lack of knowledge and information on the topic and because of rapid advances in digital processing, industry has generally viewed this field as an area that has only produced cute ideas and much promise.

Many of the original architectures and concepts that were proposed required 2-D spatial light modulators (SLMs) that researchers kept promising would appear and would be inexpensive. Clever architectures using 1-D SLMs and inexpensive SLMs such as the Japanese liquid crystal television make such processors quite practical. Industry and aerospace companies often felt that one could not fabricate such processors without a granite table of large size and a large laser. Several recent demonstration systems have proven this thinking to be wrong, and several new optical architectures exist that do not require excessive accurate positioning requirements for components.

Another common objection and remark concerned the fact that each optical system was quite special-purpose and not general and programmable like a digital computer. Several of the newer optical processors are quite general in nature, and many of the inspection problems in industry are quite special-purpose in nature; thus, this objection is also rapidly disappearing. Much of the original research in optical systems involved materials and physics studies rather than processing and computing applications, and, in earlier years, the optics community generally did not interact with the digital processing and computer science areas. All this has also significantly changed in recent years. For these and similar reasons, there is an increased interest in optical computing.

The observation that funding for optical computing research is a minuscule fraction of 1% of the research funding given to digital, very large scale integration, and other processing research must be noted, together with the fact that there are: very few optical computing graduates; few researchers and companies in industry who understand this technology; a general lack of industry ability to fabricate such systems; and a desire within industry to purchase optical computing modules, rather than learning the fabrication techniques of the entire system.

This is now starting to change. The significant Japanese and Soviet attention to this research area should also be noted. Many in industry feel that the next generation of advances in computing will not arise from further advances in Si and GaAs technology, rather it will arise from a marriage of optical technology and these new advanced digital technologies.

Many components for use in such systems are now available, such as: laser diodes, computer-generated holograms (CGHs), fiber optics, acousto-optic devices, and advanced detectors. Today, optical and digital researchers intermix and interact at various conferences and in many joint research programs. This has created a most healthy atmosphere and direction for present optical computing research.

Optical processing researchers in pattern recognition now address and offer solutions for distortion-invariant multi-class pattern recognition, optical artificial intelligence and symbolic processors for advanced computers, and the ability for optical systems to perform floating-point accuracy operations on encoded data. For these reasons, optical computing is a most healthy and attractive present area of attention. It is also in the unique position of having components and architectures at a time when they are needed.

I will summarize several promising recent developments, highlight our Carnegie-Mellon University (CMU) research, and advance remarks on the future directions I see for this technology. At CMU, optical computing research is separated into four areas: optical signal processing (OSP), optical pattern recognition (OPR), optical array processing (OAP), and optical artificial intelligence (AI). I will briefly note the CMU research in each of these areas, with attention to recent practical results with which we have been associated.

Optical signal processing research involves the determination of various parameters for high-bandwidth signals. The techniques employed generally use acousto-optic devices in novel architectures. Company cooperation in this area is extensive as real-world problems requiring advanced optical algorithms and architectures are defined and university research in this area is properly directed. More attention to such work is needed to provide industry with the next generation of OSP systems, beyond spectrum analyzers and radar warning receivers. Universities can contribute significantly to new concepts in this area, and I note that our CMU program is quite active in such efforts.

CMU has been fortunate to be a major leader in recent optical pattern recognition achievements. Recent optical feature extraction research has advanced the repertoire of operations achievable on optical systems beyond the conventional Fourier coefficient feature space. The use of computer generated holograms (CGHs) has made many such architectures quite feasible. The generation of parallel optical feature spaces, their optical processing in parallel by CGHs, and advanced algorithms in this area are subjects of current research.

In recent correlator work at CMU and elsewhere, attention has been given to practical problems such as 3-D distortion-invariant recognition of multi-classes of objects. Extensive test results have been performed (rather than isolated tests on only several images), and this has shown the viability of these techniques and this technology. Attention to such practical and current problems and the results obtained have significantly advanced the viability of this technology.

Cooperative industry research with General Dynamics-Pomona and associated government support has provided major recent advances in this technology. More cooperative industry and university research is anticipated and is needed if transfer of such basic university research technology is to be properly effected. I foresee that much more basic research in these areas still remains; however, the major thrust of future university research will be in the application of optical techniques to artificial intelligence, symbolic processors, and neural processors. It is thus hoped that industry will pick up the detailed development of the recently established feature extraction and correlation optical techniques and their integration into systems.

I also anticipate that future OPR research will consider systems that do not require 2-D SLMs or SLMs of high optical quality. Such developments offer the promise of reducing system costs and making such techniques more viable and appropriate for inspection and robotics industry applications.

The area of optical array processing systems was recently one of the most active ones as algorithms, architectures, and papers abounded. The revelation to the digital processing community that optical systems could actually achieve floating-point accuracy and computational rates exceeding one GOP (giga operations per second) attracted considerable attention.

In general, most such research is generally conceptual. The CMU program is an exception in this area. By devoting attention to laboratory hardware, analog OAP systems, new number representations, data flow, and advanced algorithms, it is hoped that our

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program will make such systems more viable and will reduce the number of A/D conversions required per multiplication.

Such systems and architectures are also most appropriate for optical interconnections and the advanced artificial intelligence, symbolic, and neural optical processors that are the present major effort by this community. Increased attention by universities to laboratory hardware and demonstrations is needed to effect the necessary industry reaction to these concepts.

I foresee that optical computing will make a significant impact in the areas of: artificial intelligence, interconnections, pattern recognition, robotics, SDI, and other applications. This appears to be the proper technology that is available at an opportune time and with many components available and suitable for fabrication of systems. I see a bright future for this discipline, am pleased to be a part of its past, and look forward to being an active contributor to its future. Our CMU program is at the forefront of the major areas in which advances are foreseen.

Increased industry participation and increased government funding will be required to move this technology into practice in a timely manner. I hope that this will occur.

Optical Computing Research at the University of Dayton

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Optical computing and processing research at the University of Dayton Research Institute (UDRI) was significantly expanded and intensified in the past year. The major focus of this research (which was supported by the Innovative Science and Technology Office of the Strategic Defense Initiative Organization and managed through an Office of Naval Research contract by Keith Bromley of the Naval Ocean Systems Center in San Diego), was a broad and fundamental investigation of thresholding operations in optical computing.

The objective was to pursue research breakthroughs necessary to realize the now-widely-recognized potential of optical computing for multiple-order-of-magnitude increases in speed, power consumption, size, and reliability, compared to current and projected all-electronic computing technology.

In the six months since June 1985, the University of Dayton effort involved six senior researchers and five graduate students and resulted in ten papers published or prepared for publication. Some key features of this research are addressed here.

All-optical threshold elements and networks

Concerning all-optical threshold elements and networks, analysis was initiated of the potential of optics-based technology for performing the basic decision and interconnection operations required in any computing system.

Threshold logic designs for elementary operations were developed, including 2- and 8-bit multiply-add designs and designs for signed-digit arithmetic. An example is shown in Fig. 1. Threshold logic is a generalization of conventional Boolean logic in which each logic element multiplies binary inputs by analog weights, sums the results, and compares with a threshold so that the output is 1 if the threshold is equaled or exceeded and 0 otherwise.

Because threshold logic involves digital inputs and outputs but analog internal operations, it may be particularly appropriate for optical implementations. If the analog weights and thresholds have sufficient error tolerance, threshold logic is desirable because considerable reductions in the number of logic levels, elements, and interconnections are generally possible.

Circulating packet and lock-and-clock architectures suitable for current and projected bistable optical devices were identified. An example is shown in Fig. 2. Circulating packet architectures may take advantage of bistable or related optical devices with optical inputs and outputs that switch faster than the time required for light to transit the system optical loop. If