Optical Computing: A Personal Perspective

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Abstract : The well-known advantages and dis-advantages of optics relative to electronics are re-viewed and found to contain useful insights but to be based largely on a false rivalry. The view is presented and defended that future computer design-ers will regard that rivalry with amusement be-cause optics and electronics both will have unique and valuable roles in all computers. The field is not "optical computing" but simply "computing."

1. Introduction

Optical computing is the use of light in making numerical calculations. Although analog optical computing has been discussed for many years,[1] it was only in the 1980s that numerous research effort were devoted to this effort. In this paper I will offer one person's perspective on optical com-puting, why it is important and where it is going. I will not attempt to either review the field or give specific credit to the large number of people who have made important contributions to the field in the last few years. Readers desiring that information may wish to look elsewhere for it.[2-4]

2. Why Use Optics ?

There are many reasons to consider using optics in computing. Some of these reasons are very persuasive. Some are not. Let us examine those reasons here.

First, optics allows massive parallelism. Since it is the number of operations per seconds (OPS) that counts, doing many operations in parallel increases the OPS. This argument is at least partially true but it is also misleading. Electron-ics, too, can achieve high parallelism. It is true that most electronic circuits are essentially planar, but so are many optical systems such as integrated optics and acousto-optic cells. Acousto-optic cells can be "stacked" into multicell arrangements but so can VLSI chips. If optics has an advan-tage here it must be one in current practicality. Two dimensional spatial light modulators can uti-lize their roughly 10^6 channels in parallel[5] or systolically.[6,7] This many channels would not be easy electronically but it could be achieved.

Second, optics offers easy and flexible intercon-nects through the air. A good lens can connect 10^8 channels to 10^8 channels without substantial cross talk. Furthermore, the connections need not be regular or even fixed. Deflectors and/or holograms can rearrange and/or combine patterns quite arbi-trarily and, if desired, quite rapidly. Free space and the ability of light rays to cross in space without degradation provide this real and continu-ing advantage.

Third, optics provides the fastest possible com-munication. Because of capacitive effects speed through closely-packed electrical interconnects may be roughly 100 times slower than the speed of light through air. This slow speed forces supercomputer designers to very short "wires." Furthermore those wires must be of substantially equal length to allow for synchronicity through the computer. With optics, the "wires" (light paths) can be substantially (the same factor of 100) longer and path matching requirements are greatly relaxed (again by the same factor). This offers much greater flexibility to the computer architect.

Fourth, optics offers electrical isolation for pre-vention of "ground loops" or even more destruc-tive effects due to electrical "shorting to ground."

Fifth, some operations are very easy in optics. The main two easy analog operations are multi-plication and addition. Multiplication is simply variable attenuation or, as it is usually called in optics, modulation. A detector can sum (or inte-grate) multiple optical signals in parallel (space integration) or in sequence (time integration) or both.

3. Some Advantages of Optics

Some of the widely known disadvantages of optics are real. Others are simply the result of misunderstandings. I will review some of these here.

First, optics is inherently analog. As we will show later, it is not clear that this is a disadvantage. Likewise most digital electronic operations are based on thresholding analog signals. Thus, whatever problem analog operation offers is a problem shared by electronics. Both can operate in a digital mode if utilized properly. Both work faster in analog mode.

Second, optics requires conversions (electronic-to-optical and optical-to-electronic) which consume power, space, and money and which can be avoided in electronic computers. One presumption in this argument is that electronics will be used for both input and output. There is no advantage in speed if the optical computer needs data at rates faster than it can be input or provides data faster than it can be used. This problem is quite real and has been called the "wall of silicon." On the other hand, in many cases the price has already been paid and the information is provided in the optical domain. This is true because optical communication (within and between computers) and optical electrical isolation are already in routine use. Furthermore, the necessary optics-to-electronics and electronics-to-optics transducers are improving immensely and, themselves, add many useful nonlinearities to optical computing.[8,9]

Third, light does not act on light. For all practical purposes this is true. Indeed this interference is part of the previously discussed interconnect advantage. Thus to control light we need something beyond light. Light controllers which use no external power are said to be passive. Light controllers which use external power are said to be active. Active controllers may be directed, triggered, or addressed either optically or electronically. Optically addressed controllers may slow down the system but they involve almost no sophisticated electronics. Much current research is aimed at speeding up these systems even letting the electric field vector of one light beam provide the electrical field to cause an electro-optic material to modulate another light beam. This may be as close as we ever come to light operating on light.

4. A Balanced View

With optics having real advantages and disadvantages relative to electronics, where does this competition stand? My answer is surprising to many but seems obvious to me. The answer is: that is the wrong question. Optics and electronics are partners not competitors. More precisely, optical computers can only achieve their promise of extremely high speed if electronic circuits for input, output, and transformation of optical signals become faster. Optics is not in a race with electronics. Rather, it is so tied to electronics that it is speed limited by it. Optical computers can never be merely passive, so they are and will always be "electro-optic." In my opinion "optical" computers may be a major application for electronic computers by the end of the century. The perceived rivalry between optics and electronics will come to be viewed as an illusion. An electronic computer expert will view optics as one of the required parts of a computer. An optical computer expert will view electronics in the same way. Both will be right.

5. Achieving Accuracy

Two approaches to high accuracy may be distinguished. First, we can "go digital." That is, we can use multiple analog channels in space or time to share the accuracy requirements among them. This is the primary thrust of current research. Second, we can use analog optics for fast, complicated, moderate accuracy calculations and seek iterative improvements. This is discussed in detail elsewhere.[10] It is noted here simply to remind the reader that analog computing combined with digital computing may achieve, imperfectly, the advantages of both.

6. Architecture Design

A delicate balance must be struck in the design of architectures for optical computers. Optics has unique components and unique strengths. These require unique architectures. Electronics has a vast array of proven architectures designed at great expense by teams of brilliant workers. Ignoring this rich store of ideas would be foolish and perilous. Optics must both invent and borrow (adapt). Doing this well requires a currently-rare

combination of backgrounds. Universities would do well to begin now preparing the needed "cross disciplinary" computer architects of the future.

7. The Future

Predictions are notoriously unsafe, but at least one prediction seems so obvious that it can be made with great confidence: "Optical computing" will soon cease to be a helpful term. Optics and electronics will be recognized as the required disciplines in computing. Computers will be forever hybrid and that fact will cease to seem remarkable.

References

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光コンピュータへの期待——画像処理分野からの声

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"Optical computing" と聞くとフーリエ変換やマッチドフィルタなど古めかしい言葉が連想されるが，「光コンピュータ」というと 21 世紀に向かう輝かしい未来技術の印象すら与える．こう感じるのは筆者だけであろうか？　たんに -ing が -er に変わっただけで先端技術の香りがするのは，未来は光コンピュータだ，バイオコンピュータだと騒ぐ過熱気味の技術マスコミの悪弊に毒されているためかもしれない．

しかしながら，「光コンピュータ」と呼ぶときには，暗黙のうちに「並列処理」や「ディジタル演算」の意味が含まれていて，現在のシリコンコンピュータにとって代わる限りない夢が託されている感がある．これはいわば温故知新，歴史のある光学技術から現在の情報処理技術のボトルネックを解消する何かが生まれることへの期待であろう．筆者は，情報処理分野での画像処理研究を生業としているが，まさにこの種の夢がまずディジタル画像処理の世界で実現できないかと考えている．

そもそもパターン認識・画像処理（以下，PRIP と略す）と光情報処理とはきわめて近い関係にあり，いわば親戚づきあいの間柄である．それをあえて光学側への期待と断わるのは，現在の画像処理はまったくディジタル処理の全盛であり，それも半導体技術の支配下にあるからである．"Optical computing" を古めかしく感じるのは，この分野で旧来の光学（アナログ）処理が実用的にはほとんど見るべき成果を示しえなかったからであろう．

いうまでもなくディジタル処理の優位性は，高精度・再現性・柔軟性等にある．とりわけ，PRIP 分野にとっては，古典的光学処理ではきわめて限られた演算しかできないのに対して，自由自在にプログラムで各種線形/非線形演算を組み立てられるディジタル処理の柔軟性は魅力である．また，試行錯誤を繰り返す PRIP にとっては，同じ実験を何度でもやり直せるコンピュータ処理というのは，大きな福音であった．いったん画像をディジタル化して計算機内に取りこんでしまえば，後はいつでも何度でも好き勝手な処理ができる．端末が与えられ，プログラミング能力さえ有れば，（筆者のように）物理的な現象に精通していなくても研究ができるわけである．かくして，洋の東西を問わずディジタル処理が主流となり，膨大な量の論文の山とともにある種の技術体系が築かれるところとなった．

長い間，ディジタル処理の欠点は価格と速度の問題で