# 1

# How optical computers, architectures, and algorithms impact system design

DAVID CASASENT
Carnegie Mellon University, Department of Electrical and Computer Engineering

## 1.1 Introduction

When a scientist or engineer is provided with a given processing problem and asked whether optical processing techniques can solve it, how does he answer the question and approach the problem? To address this, he first considers the basic operations possible. They are often not a direct match to a new problem. Hence new algorithms arise to allow new operations to be performed (often on a new optical architecture). The final system is thus the result of an interaction between optical components, operations, architectures, and algorithms. This chapter describes these issues for the case of image processing. By limiting attention to this general application area, specific examples can be provided and the role for optical processing in most levels of computer vision can be presented. (Other chapters address other specific optical processing applications.)

Section 1.2 presents some general and personal philosophical remarks. These provide guidelines to be used when faced with a given data processing problem and to determine if optical processing has a role in all or part of a viable solution. Section 1.3 describes optical feature extractors. These are the simplest optical systems. This provides the reader with an introduction and summary of some of the many different operations possible on optical systems and how they are of use in image processing. A major application for these simple systems, product inspection, is described to allow a comparison of these optical systems and electronic systems to be made.

Section 1.4 addresses the optical correlator architecture, since it is one of the most powerful and most researched architectures. The key issues in such a system used for pattern recognition are noted. These include: how do you achieve distortion-invariant recognition, which spatial light modulator (SLM) do you use and how do you alter the architecture to allow use of available devices, and what do you do if the SLM is binary and the data is analog? Optical correlator hardware has significantly matured and thus this architecture merits considerable attention.

However, if a correlator is to see use in a full image processing system, many operations beyond distortion-invariant object recognition are necessary. Section 1.5 notes these other required operations (the levels of computer vision) and how new algorithms allow each to be addressed. These operations are all possible on the same basic architecture, an optical correlator. Thus, a multifunctional general purpose optical system results. Such general purpose optical processors are felt to be essential if optical processors are to see practical use.

I conclude (Section 1.6) with brief remarks on optical neural nets and their role in image processing. A summary and conclusions are then advanced in Section 1.7.

## 1.2 Philosophy

When faced with a given processing problem and the question of whether optics has a role in its solution, one should ask at least three basic questions.

*You should look at the operations that optics can perform*. It is not enough that it can do the operations needed for the problem (Fore, 1991). Optics should offer a speed advantage over electronic approaches. The advantage would probably have to be at least a factor of ten before one could sell it. Cost is another major factor, but this is beyond the scope of these brief pages. Size, weight, and power consumption are other factors in some (but not all) applications. Several studies (Fore, 1991) have shown that optical correlators offer size, volume, speed, and power dissipation advantages over comparable electronic systems. Thus, our focus on them seems valid. In the area of image-processing optical components, architectures and algorithms are sufficiently developed, and thus this area is considered. For optical logic and numeric processors, these answers are not yet clear.

One must look at the application and consider *how the operations can be performed optically*. One generally develops an algorithm that does not require operations that an optical system cannot easily achieve. Specifically, an algorithm that requires many conversions between optical and electronic processing is not attractive. However, one need not become obsessed with performing all operations optically.

An arrangement of optical components is thus made that can perform the necessary operations. However, *the devices postulated must exist*. If they don't, they must be easily developed. New optical architectures and systems generally evolve by modifying devices developed for other purposes: displays, disks, fiber optic communications, printers, etc. Optical processing is generally not yet able to support the design of elaborate devices specifically needed only for it.

Other remarks that I personally advocate are now advanced. One should not copy an electronic processor or algorithm, since its design was inevitably based on electronic not optical components and functions. I feel that optical processors should be analog, since therein lies the power and uniqueness of optics. The accuracy possible on analog optical systems must be sufficient for the problem, or the algorithm must be chosen to be robust to analog accuracy components. Images are analog data; and image processing, pattern recognition, and neural net applications and algorithms generally satisfy these requirements.

Optical processing researchers must thus, by definition, be innovative in the algorithms and architectures they develop. As we shall see, this has been very true.

## 1.3 Optical feature extractors

Nearly everyone is familiar with the fact that a coherent optical system can form the 2-D (two-dimensional) Fourier transform (FT) of input data on an optical transparency. This section briefly notes a number of other useful descriptions of an input object that can be optically produced. This is intended to show the versatility of optical systems, the growing repertoire of operations they can perform, and how they are of use in image processing.

Figure 1.1 depicts the general problem and approach. A single object is input. Different features describing it are calculated and these are fed to a classifier. The output can be answers and information such as: is the input a good or bad product; if it is bad, what type of defect is it; what is the identity of the object; what is its orientation; etc.? The major computational load is calculation of the features, thus this is a viable portion of the system for which to consider the use of optics. Feature calculation requires global operations with many operations per input pixel, analog accuracy suffices for most cases, and the same

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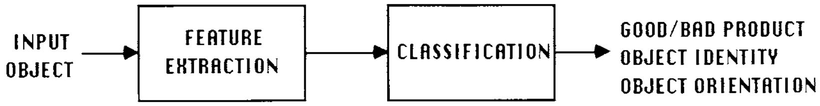

Figure 1.1 Block diagram of an optical product inspection system.

set of features can be useful in a wide range of different problems. Thus, this operation seems appropriate for a rigid non-flexible optical architecture. The classifier must be different for each application and thus classifiers are more suitable for electronic implementation. Thus, a viable hybrid optical/digital system seems realistic. In product inspection, lighting and illumination are controlled and thus no preprocessing is generally required and hence a simple system should suffice.

Figure 1.2 shows the well-known optical FT system with a wedge-ring detector (WRD) placed in the output plane. This WRD device consists of wedge and annular (half ring) shaped detector elements (Lendaris & Stanley, 1979), or the equivalent may be synthesized with a spinning disk with properly designed apertures (Clark & Casasent, 1988). A key point not generally acknowledged in the optics community is that digital hardware can also perform the 2-D FT at TV frame rates (30 objects/s). However, the cost of the digital system exceeds that of the optical system, if an inexpensive input SLM exists. This is now the case with liquid crystal TV devices (Liu, Davis & Lilly, 1985) as the SLM (if they are suitably modified to be optically flat and to have no residual images; i.e. active erasure, not decay, is needed). Producing an FT alone is not sufficient. Specifically, there are as many FT samples as there are input samples, and it is not easy to analyze all of them in real time. Thus, the WRD provides another vital property, data compression. With 32 wedge and 32 ring detectors, only 64 outputs need be analyzed for each input object. These features have other well-known properties that are vital for product inspection: the

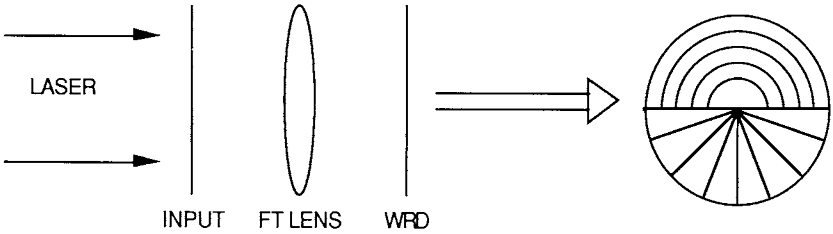

Figure 1.2 Optical WRD system (Casasent, 1991).

feature space is shift-invariant (since the intensity of the FT is detected, the wedge features are scale-invariant and their pattern shifts with image rotations, and the ring outputs are rotation-invariant and their pattern shifts with image scales).

A simple lens forms the optical FT. To produce other optically generated feature spaces, computer generated hologram (CGH) elements (Lee, 1992) can be used. With them, the resultant optical system remains simple (and hence inexpensive). Such architectures thus resemble Figure 1.3. If the CGH has a transmittance pattern that is a set of $N$ cylindrical lenses each at a different rotation, then the output pattern is the Hough transform (HT) of the input (Richards, Vermeulen, Barnard & Casasent, 1988). This feature space consists of peaks of light. The location of each peak denotes the orientation and position of each line in the input and the height (amplitude) of each peak denotes the length of each line. Extensions to curves, etc. are also possible with generalized HTs. This example is included because it demonstrates how CGHs (using integrated circuit lithographic techniques) allow new optical functions to be implemented very cost effectively. Another very vital and generally not appreciated property of an optical system is that it automatically performs interpolation. This has been used in the optical HT system and comparison of the calculated HT with digitally calculated results shows that *the optical system is actually more accurate* due to digital sampling problems (Richards & Casasent, 1989).

The WRD FT and HT feature spaces have proven very useful in product inspection and object identification. Other optically generated feature spaces include chord distributions, arc angle/length features of a contour, Mellin transforms, polar-log transforms, and moments (Casasent, 1985).

An optical system that computes the moments of an input object is shown in Figure 1.4. It is not competitive with digital chips that

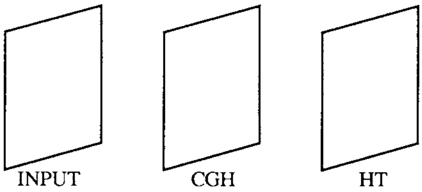

Figure 1.3 Optical Hough transform (HT) system using a CGH to implement multiple lens functions in a simple and cost-effective architecture.

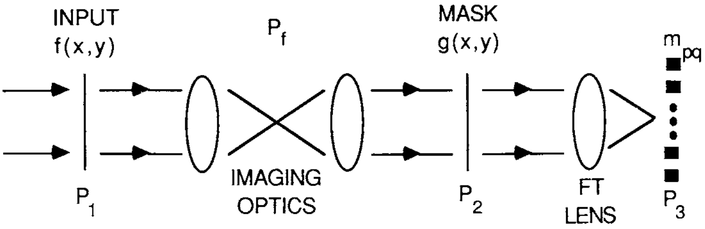

Figure 1.4 Optical system using frequency-multiplexed multiple filters or transfer functions achieving parallel multiplication and addition with multiple filters (Casasent, 1985).

calculate moments, but it is useful to demonstrate other unique functions and operations possible on optical systems. The input $P_1$ is imaged onto a mask at $P_2$ that contains $N$ different 2-D functions $g_n(x, y)$ each on a different spatial frequency carrier. The light leaving $P_2$ is the point-by-point product of $f$ and $g_n$ (optical systems can perform parallel multiplications). The output FT lens sums each of these $N$ 2-D products onto a different detector at $P_3$. Detector $n$ has an output $\iint f(x, y) g_n(x, y)\, \mathrm{d}x\mathrm{d}y$. With the $g_n$ being different monomial functions, the $P_3$ outputs are the moments $m_{pq}$ of $f(x, y)$. Our present concern is the fact that an optical system (Figure 1.4) can use frequency-multiplexing (of $N$ patterns at $P_2$). Thus, different paths through the system see different transfer functions and the processor can perform $N$ different 2-D functions on the 2-D input data.

Well-engineered optical hardware versions of the WRD FT and HT systems have been fabricated and their use has been demonstrated. Thus, they are viable simple optical systems. The fact that no one currently widely markets them is the major reason why they have not seen wide use. The HT is particularly attractive, since from it one can produce the WRD FT, the 2-D FT, moments, etc. (Gindi & Gmitro, 1984).

## 1.4 Optical correlators for pattern recognition

The optical correlator architecture (Vander Lugt, 1964) is a very important one. A simplified version is shown in Figure 1.5. The 2-D input scene $f(x, y)$ is placed at $P_1$ on an SLM, its 2-D FT $F(u, v)$ is incident on $P_2$ where a matched spatial filter (MSF) $G^*(u, v)$ is recorded. The light leaving $P_2$ is the product $FG^*$ and its FT formed at $P_3$ is the 2-D correlation $f \circledast g$. This operation is equivalent to shifting

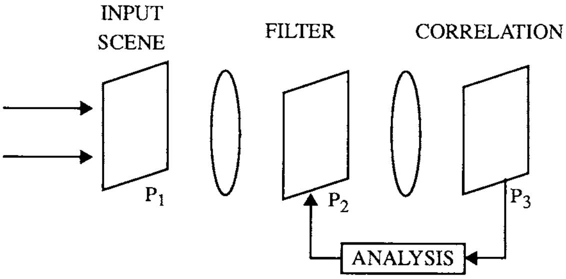

Figure 1.5 2-D optical correlator architecture (Casasent, 1992b).

the 2-D reference function *g* over all pixels in *f*. For each shift, the product of *g* and the corresponding region of *f* is formed and summed. The $P_3$ output contains a peak at locations in *f* where *g* is present. Thus, the architecture performs pattern recognition by template matching. The advantages of a correlator (optical or electronic) for locating objects are well known: it handles multiple objects in parallel and it provides the best detection in white Gaussian noise (due to the processing gain it provides). Figure 1.5 shows different filters fed to $P_2$ depending upon prior $P_3$ correlation results.

### *1.4.1 Fabrication*

A major practical issue has always been whether one could fabricate a well-engineered and rugged optical correlator. Recent results have provided several such processors. Figure 1.6 shows a solid optics correlator that has been fabricated and tested (Lindberg & Hester,

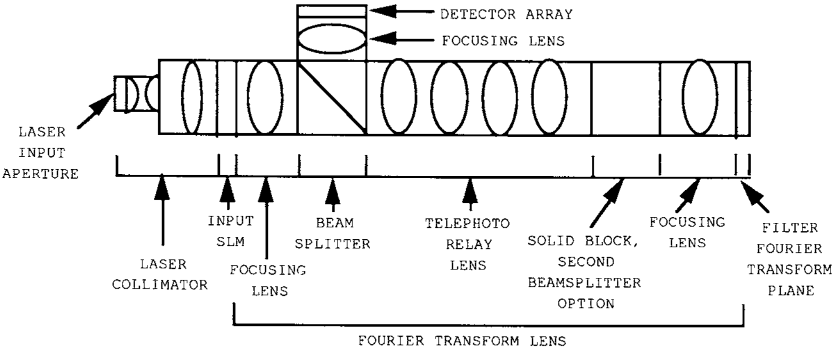

Figure 1.6 Solid optics correlator (Lindberg & Hester, 1990).

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1990). It uses modular graded index solid optics to perform the FT and for magnification. The optics collimates a laser diode source at the left. This illuminates the input SLM, whose FT is incident on a reflective filter. The light then travels right to left through the same optics and from a beam-splitter onto an output detector array. Figure 1.7 shows another compact correlator presently being fabricated (Ross & Lambeth, 1991). It has all its components mounted around the perimeter of a circle. Light enters from the left, reflects off of the different elements (magneto-optic light-mod SLMs are used) with the correlation appearing on the charge-coupled device (CCD) detector. Chapter 5 discusses another compact correlator design in detail.

The present versions of the systems in Figures 1.5–1.7 are limited by the SLMs (at $P_1$ and $P_2$). Electrically-addressed SLMs in which the input image data are fed electrically from the sensor to $P_1$ (or data are fed electrically to $P_2$) are the most attractive approaches. Presently, the most available and reliable 2-D SLMs are binary devices. This significantly limits the use of these architectures. Promising gray-scale electrically-addressed devices may mature and make such architectures viable. As a result, much research attention has been given to techniques to design filters that can be recorded on SLMs with binary phase (± 1 transmittance values) and ternary (0, ± 1 transmittance) values (Casasent & Chao, 1992). This work has yet to provide advanced distortion-invariant filters. However, considerable progress has been made. A binary device in the input plane is a more significant problem, since imagery is gray scale. Preprocessing methods to reduce

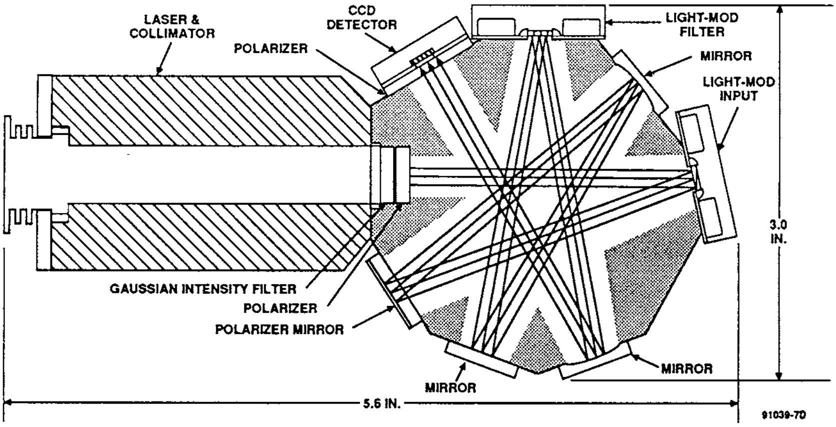

Figure 1.7 Hockey puck optical correlator (Ross & Lambeth, 1991).

a gray scale input to a binary pattern are conceptually possible, but are digital. It is unclear if one would analog-to-digital (A/D) convert the input, digitally preprocess it, reduce it to a binary pattern, and then perform optical correlations. By restricting the correlator to operate on binary inputs and binary filters, one would probably perform the correlation in digital hardware.

Section 1.5.1 details a viable preprocessing optical processor using binary devices. This algorithm and architecture are especially attractive, since the present optical SLMs can operate at 5000 frames/s data rates. In general, our remark (Section 1.2) that optical processors must employ analog data (to realize their full potential) is clearly true. We now address how a new algorithm and optical architecture emerged to address this issue (Psaltis, 1984). It avoids the need for 2-D SLMs by using other concepts and optical components, specifically acousto-optic (AO), that are analog and presently available. This is an excellent example of the need for and use of new algorithms and architectures with available operations and components to solve a major problem in optical processing.

### *1.4.2 2-D acousto-optic correlators*

To describe the architecture, we first consider the 1-D optical processor in Figure 1.8. This is the time integrating (TI) AO correlator (Cohen, 1983). It consists of a light emitting diode (LED) or laser diode point source at $P_1$ fed with a 1-D signal $g(t)$. Lens $L_0$ collimates this source and uniformly illuminates $P_2$ with a signal $g(t)$ *with no spatial variation*. A 1-D AO device at $P_2$ is fed with a second signal $h(t)$, which travels down the AO cell producing a transmittance function $h(t - x/v_s)$ for $P_2$ that varies with time and space (distance $x$ along $P_2$), where $v_s$ is the velocity of sound in the AO cell. The light leaving $P_2$ is the product $g(t)h(t - x/v_s)$. This light distribution is

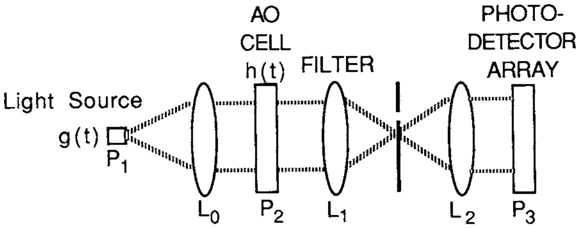

Figure 1.8 1-D TI AO correlator.

imaged (by $L_1$ and $L_2$) onto $P_3$. TI linear detector array at $P_3$ integrates this light distribution in time yielding an output

$$\int g(t)h(t - x/v_s)\,\mathrm{d}t = g \circledast t$$

that is the 1-D correlation of the 1-D signals $g$ and $t$. We now consider the final system in Figure 1.9. This is a multichannel version of Figure 1.8 with $N$ input point modulators (LEDs or laser diodes) and $N$ TI linear 1-D detector arrays at $P_3$. The $N$ 1-D outputs on $N$ 1-D linear detector arrays at $P_3$ are the correlations of $s(t)$ with the $N$ reference functions $r_n(t)$ fed to $P_1$. In the optical system, lenses $L_1$–$L_3$ image $P_1$ onto $P_2$ vertically and expand each $P_1$ output horizontally to illuminate $P_2$ uniformly at a different angle of incidence. Plane $P_2$ is imaged horizontally onto $P_3$ by lenses $L_4$ and $L_6$ and the $N$ inputs at $P_1$ are imaged vertically onto $N$ rows at $P_3$.

To consider how Figure 1.9 implements a 2-D correlation, we feed the 2-D reference function $r(x, y)$ to be recognized to the $N$ inputs $r_n(t)$ at $P_1$ (we assume an $N \times M$ reference function, with the $M$ samples for each row $r_n(t)$ of $r(x, y)$ fed time sequentially to the $N$ (number of image rows) inputs at $P_1$). This uses a 1-D input at $P_1$ ($N$ laser diodes or LEDs) and the space and time variables available to input a 2-D function to the system. The first line of the input scene $s(x, y)$ is fed to $P_2$ as $s(t)$. The 1-D correlations of it and the $N$ 1-D inputs $r_n(t)$ are formed on $N$ rows on the 2-D TI detector at $P_3$. The contents of $P_3$ are then shifted up by one row. The second line of the input scene is fed to $P_2$ and the reference is repeated at $P_1$. The $N$ 1-D correlations of the $N$ lines of the reference object and the second line of the input scene are formed at $P_3$ and added to the prior (shifted) $N$ 1-D correlations. This process is repeated for all rows of the input scene. The data leaving the top of $P_3$ (one row at a time) is the 2-D correlation of the 2-D reference function $r(x, y)$ (fed in time and space

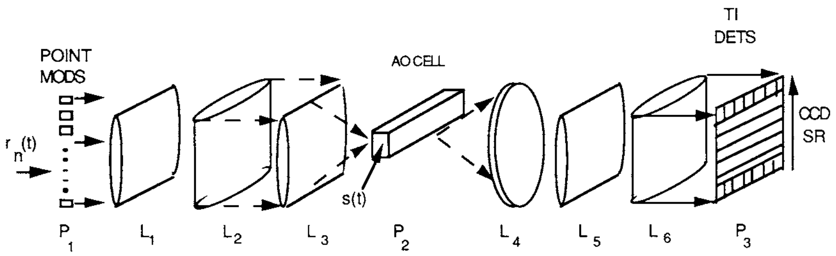

Figure 1.9 2-D TI AO correlator.