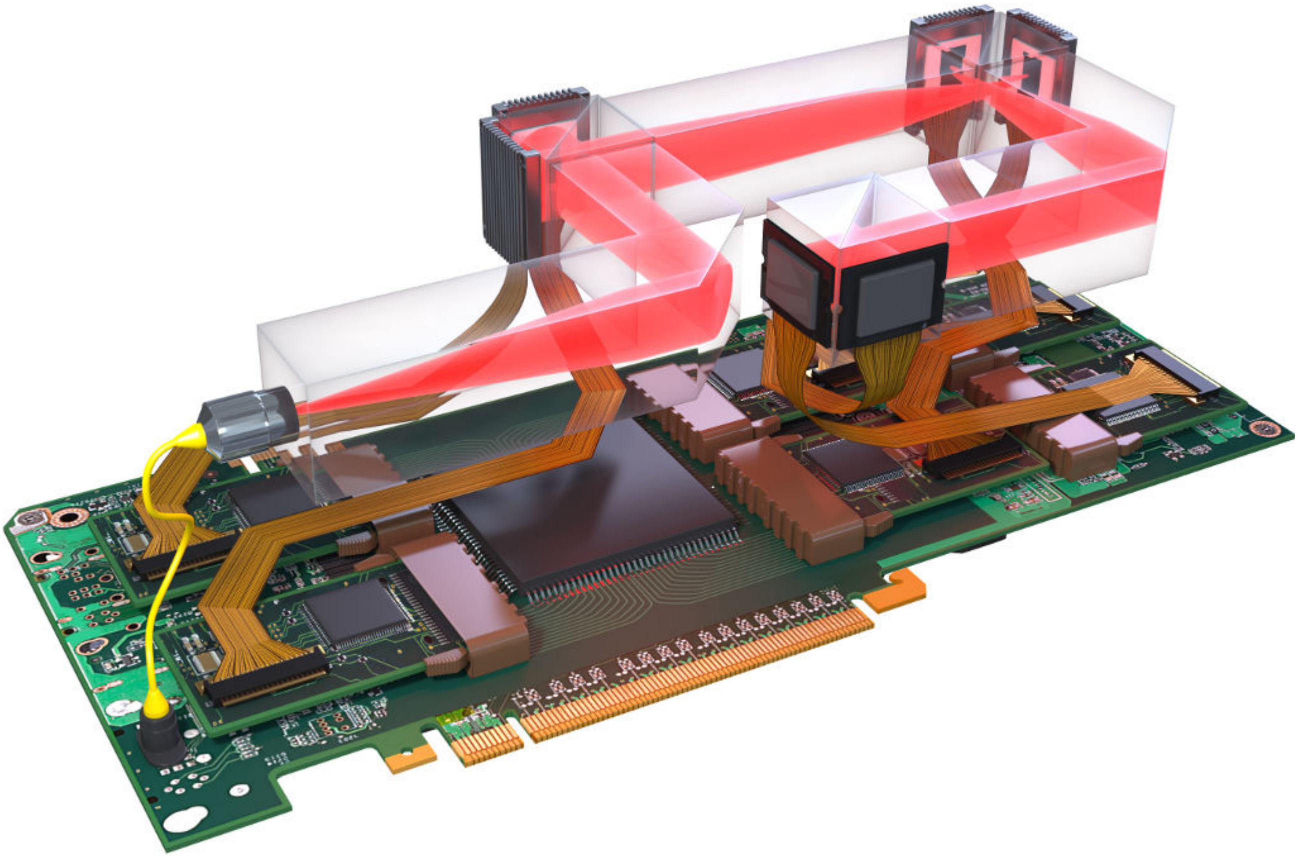
Optalysys Optical Processing System

Technical Overview



July 2017

Revision History

Version	Date	Authors	Approved by	Comments
1.0	19/07/2017	AJM		First version
1.1		AJM		Minor changes to content and structure

Summary

Optalysys are releasing a high-performance optical processing system, designed for tight integration with traditional computing architectures. A wide variety of computational and pattern recognition problems may be recognised, formulated, and processed as two-dimensional correlations. Many of those can benefit from the Optalysys system, which offers extreme and inherent parallelism and processing at literally the speed of light.

This optical processing system exploits the power of the optical Fourier transform and is ideally suited to search and pattern recognition applications. In addition to a number of targeted pre-packaged applications and lower-level interaction modes, Optalysys are providing this system with an API to allow users to exploit this capability towards their own applications. Optalysys will assist partners and customers in interacting new applications to the abilities of the Optalysys system. Section 3 contains an example of converting a nominally 1D process to 2D, thus realising the benefits of our system.

This document is designed to enable users to understand how the system can be applied to accelerating their particular computational application. First, a general background on optical processing is given. Then, the design and capability of the Optalysys optical processor at performing extremely high speed, high resolution correlations is described. This is followed by a 'case study,' outlining a practical implementation of the technology in a bioinformatics application.

Finally, the physical hardware and software interfaces provided are described at a high-level. This allows potential users to understand how this optical processor can interface with and accelerate their existing applications.

1. Optical processing

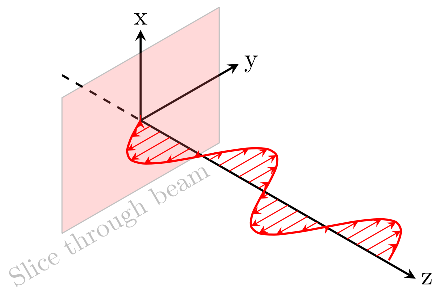
As a technology, optical processing has a rich pedigree. It is arguably one of the oldest and most successful non-electronic computing platforms. This section provides a background to the field of optical processing to explain the underlying operation of the Optalysys processor for the interested reader. To simply start exploiting the formidable processing power of the Optalysys system, head to the next section.

The Optical Fourier Transform

Coherent optical information processing exploits the serendipitous fact that a simple lens renders a Fourier transform.

Carrying information in a light beam

Consider a propagating laser beam. It is coherent; it has one wavelength and the waves rise and fall in a predictable sinusoidal pattern. We can consider a slice perpendicular to this beam. Light propagates in a deterministic manner. If we can fully specify the beam in one slice, we can define the beam along its entire path.

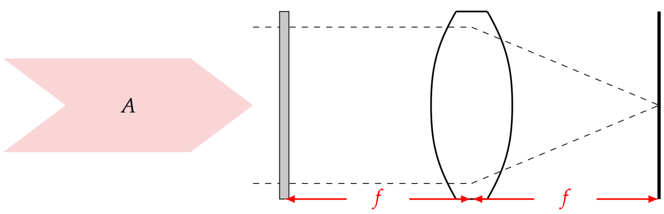


In order to define the beam across this slice, we need to specify how bright the beam is, and the phase of the sinusoid (at what point in the cycle we are at). This can be done using a simple complex number: the magnitude corresponds to the brightness, and the phase corresponds to the point in the oscillatory cycle the beam is at (neglecting the time dependance).

Hence, a propagating coherent optical beam can be defined at one point in the beam by a complex function $A(x,y)$. We can modify this beam to encode information.

A lens performs a Fourier transform

What happens when a light beam encounters a lens? If we had a completely flat beam, we know it would get focussed to a single point. However, what if our beam was carrying information? What does the focal plane look like then?



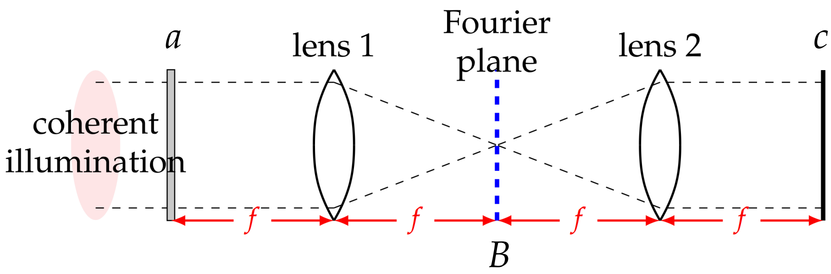
The focal plane contains precisely the Fourier transform – both amplitude and phase – of the complex field found at the back focal plane. This is consistent with the fact that for a perfectly flat beam, we get a single spot (the 'DC' term in Fourier theory).

Information can be input into the optical system at the back focal plane. For example, if a beam of complex amplitude $A(x,y)$ passes through a transparency with a spatially-varying transmission function $t(x,y)$, the resulting beam has an amplitude $A(x,y) \cdot t(x,y)$.

This optical Fourier transform is exploited in many applications. It forms the basis of many holographic techniques and underpins coherent optical processing. This powerful phenomenon is the driving force behind the Optalysys optical processor.

The Optical Correlator

The Optalysys processor is a high-performance optical correlator. The optical correlator is the classic application of coherent optical processing. It consists of two lenses performing sequential optical Fourier transforms ($\mathcal{F}$), with a multiplicative filter situated at the intermediate focal – or Fourier – plane.



The filter effectively multiplies the optical field by a 2D function B. Input data a are placed at the front of the system, and a camera sensor images the output beam c.[1] The system performs the mathematical operation

$$c = \mathcal{F}^{-1}\{ \mathcal{F}\{a\} \cdot B \}$$

where C is a complex amplitude function. (The lens in reality performs a forward, rather than inverse Fourier transform, but the net effect is a coordinate inversion compensated for by the camera sensor orientation.) The camera sensor measures the intensity of this field,

$$I = |c|^2.$$

The convolution theorem uses the Fourier transform to effect the convolution ($*$) of two functions, f and g, by simple multiplication:

$$\mathcal{F}\{ f * g \} = \mathcal{F}\{f\} \cdot \mathcal{F}\{g\}.$$

By inspection, it can be seen that the effect of the optical system is to evaluate the convolution

$$a * \mathcal{F}^{-1}\{B\} = a * b.$$

One of the inputs to the correlation, a, is directly input into the optical system. The other input to the correlation, b, is derived digitally. This is the slow part of the process, and done off-line, producing B using a digital discrete Fourier transform. (This fact indicates appropriate use of an optical correlator; there is some overhead in generating the filter B from the target b). Optalysys excel in this filter design process and can provide appropriate assistance.

[1] Although at the correlation plane it's technically an 'imager,' not a 'camera,' in this overview we'll use the looser term 'camera' for its familiarity

The optical Fourier transform and all of the functions are inherently two dimensional. The propagating light beam can be thought of as a 2D function propagating and transforming along a third direction. The system is most naturally applied to 2D datasets, and many problems can be mapped to an appropriate representation.

Correlation

While it is the convolution theorem that fundamentally underpins the *4f* system, they are referred to as optical correlators. Correlation is tightly related to the convolution process, simply corresponding to reversing coordinates in the function being convolved with. Note that in 2D images, a reversal in each coordinate is a rotation of the image. As is customary in the literature of the discipline, we will define these functions in 1D for clarity, though they naturally extend to 2D.

Convolution ($*$) of two functions $f(x)$ and $g(x)$ is defined, in both discrete and continuous representations, as:

$$f * g\,(x) = \boldsymbol{\Sigma}_i\, f(i)\, g(x-i),$$

$$f * g\,(x) = \int f(\chi)\, g(x-\chi)\, d\chi.$$

Correlation ($\circ$) of the same two functions $f(x)$ and $g(x)$ is defined as:

$$f \circ g\,(x) = \boldsymbol{\Sigma}_i\, f(i)\, g(x+i),$$

$$f \circ g\,(x) = \int f(\chi)\, g(x+\chi)\, d\chi.$$

From these definitions, it is clear that the operations are interchangeable under coordinate reversal of one of the functions. This reversal is done in the optical correlator simply by rotating the filter. For symmetric functions, correlations and convolutions are equivalent.

The optical Fourier transform is a true continuous Fourier transform. Consequently, the convolutions and correlation operations are, in principle, continuous. However, the optical system inputs and outputs are pixilated, meaning the data is discretised. While the operations can be considered to be discrete, the camera sensor pixels at the output do not sample at a single location (Dirac-function sampling), but integrate over a finite region.

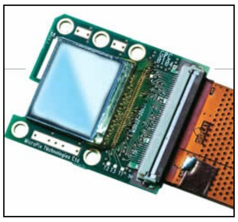
(a) **(b)** **(c)**

An example of correlation of two functions. A test image (a) is correlated with a target (b). A peak in the output (c) shows where there is a match (highlighted).

Correlation is, amongst other things, very useful for pattern matching applications. The process is essentially dragging one function over another, and taking the dot-product between them at the set of all displacements. Two functions will have a large dot-product, and produce a 'correlation spot' optically, corresponding to locations where their displaced versions match.

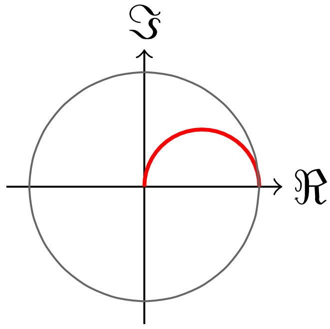
In an optical correlator, the first input a contains a representation of one function, while B is the Fourier transform of the other function. This transform is evaluated digitally, producing an appropriate filter (a frequency-domain representation of b). As will be discussed, this frequency-domain representation is not simply the Fourier transform of b, due to the characteristics of the devices used to encode information optically.

Encoding information in a light beam



Information is encoded into the optical beam by using spatial light modulators (SLMs). These are essentially very small displays (indeed, some of the devices used in the Optalysys processor system originate in display projectors). These devices use liquid crystal technology – combined with linear polarisers – to modulate the light beam. In general, the magnitude and relative phase of the light beams can be modulated.

Each pixel of the SLM is addressable with an 8-bit value (256 levels). The SLM is not capable of independently modulating the magnitude and phase of the optical field. In the Optalysys processing system, the SLMs are configured to modulate both the amplitude and phase in a coupled manner, such that optimal correlation performance is achieved. A representation of a typical operating curve is shown in the adjacent Argand diagram.



An Argand diagram of the complex plane showing a curve where the 256 modulating levels offered by the SLM typically lie.

Accommodating SLM operating curves

A key barrier to effectively ustilising optical correlators is accommodating the fact that only a restricted region of the complex plane can be accessed. Optalysys provides a number of different methods to facilitate this, depending on the application and whether the user wishes to interact with the fundamental operation of the correlator, or simply exploit its performance.

For example, if the user wishes to simply exploit the high-performance correlation performance, in-built Optalysys functions are offered which optimally convert the input and filter data into SLM drive values and return the correlation plane via peak-detection. Among the technical aspects that Optalysys address is analytical optimization of performance under an SLM's restricted modulation range. This is implemented at input and filter planes, designed synergistically in concert with detection algorithms at the correlation plane.

If the user wants to develop more specific applications, a flexible addressing scheme, where the SLMs are driven directly is offered. In order to facilitate this operating mode, representative operating curves for the SLMs are supplied. These two interaction paradigms are discussed in Section 3.

Precision

Fundamentally, our system is a analogue computation process wrapped within digital I/O. As is intrinsic with analogue processing systems, it cannot compete with digital systems in terms of precision. However, it can compete in terms of offering a significant performance increase in certain applications due to its colossal throughput and ability to tackle highly-interconnected problems by exploiting the serendipitous occurrence of the Fourier transform optically.

As such, users are encouraged to consider what precision they actually need for a particular task, and whether the few-bits offered by the optical process are sufficient. The optical correlator is best suited for tasks which involve high-data throughput, with low precision in terms of the output peak intensity, but high sensitivity to features which span large regions of the input data.

Other resources

The field of optical correlators is a venerable one, and there is much extant literature on exploiting this technology. The Optalysys optical processing system provides the highest-performance platform to date on which to exploit this significant body of knowledge. Select recommended resources for this include:

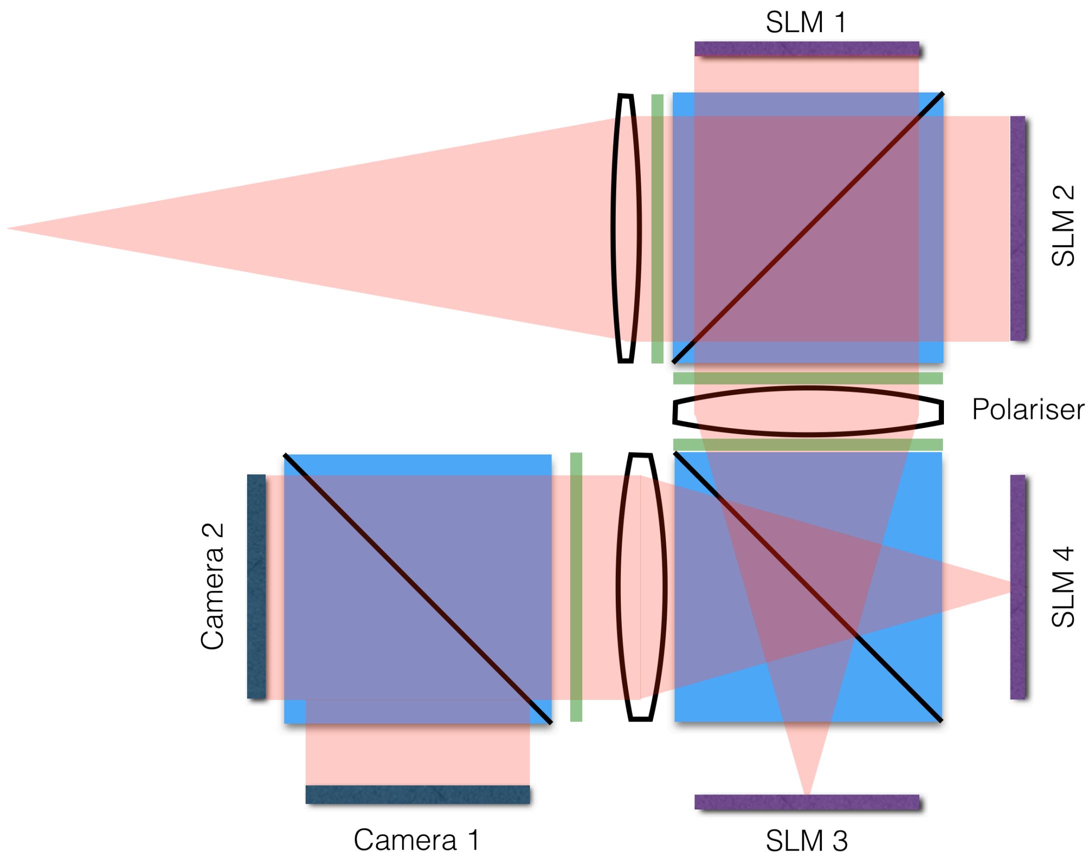
- **Goodman, Joseph W. *Introduction to Fourier optics.* Roberts and Company Publishers, 2005.** An excellent introduction to the field of Fourier optics.
- **Kumar, BVK Vijaya, Abhijit Mahalanobis, and Richard D. Juday. *Correlation pattern recognition.* Cambridge University Press, 2005.** A good background book on the application of the optical correlator to pattern recognition.

2. The Optalysys Optical Processing System

The Optalysys optical processing system combines a number of high-performance electro-optic elements, utilising the optical Fourier transform to enable a convolutions at rates far beyond those offered by conventional processors. In this section, we describe the hardware configuration and outline the capability of this system.

Optical hardware configuration

The Optalysys system combines a robust optical design with a high-performance electronics backplane.



Shown in schematic form, the Optalysys system combines several of the *4f* correlators described in the previous section.

This system has 2 input SLMs, 2 filter SLMs, and 2 camera sensors; i.e. the I/O hardware for 2 separate optical correlators. Through the use of the beamsplitters, there are 4 separate possible optical paths through the system: from each of the 2 input SLMs, to each of the 2 filter SLMs. This is one of the multiplexing approaches to increase the performance of the system.

The two input SLMs (1 & 2) are staggered along the optical path; one is closer to the beamsplitter than the other. The corresponding correlation planes of these SLMs are staggered and concordant with the two staggered camera sensors offset about a beamsplitter.

Polarisers are used throughout the system to set the operating curves of the SLMs. These are configured during manufacture to maximise correlation performance.

Electro-optic interface components

The system makes use of 4 spatial light modulators and 2 camera sensors. Two different types of spatial light modulators are used. The performance of these components is summarised in the following table.

Component	SLMs 1 & 2	SLMs 3 & 4	Camera sensors 1 & 2
Description	Fast binary input SLM	Multi-level (256) filter SLM	Greyscale camera sensor
Resolution	2048×1536	1920×1080	4096×3072
Framerate	2400 Hz	120 Hz	120 Hz

These hardware are all tightly synchronised through the electronics system. The input SLM runs faster than the output camera sensor, thus facilitating further multiplexing.

Multiplexing

By multiplexing, we mean methods which efficiently exploit certain redundancies in the system to increase capacity. The ultimate goal is to exploit every input and output pixel as efficiently as possible. Different applications will be able to exploit the multiplexing capability to different extents. In applications as an optical correlator, this depends on the sparsity of the hits, where these hits might occur, and the digital post-processing overhead.

As well as offering two input SLMs, each with an associated output camera sensor, the Optalysys optical processing system utilises two different multiplexing techniques.

- **Filter multiplexing** is possible because the light from each input SLM is focussed through a beamsplitter onto separate filter SLMs. Two filter functions can be used with each input, leading to correlation spots on a corresponding camera sensors relative to the input t. In order to find out which sub-frame is responsible for the correlation peak, either brute-force inspection (digitally or optically) of the candidates can be undertaken, or the filter can be designed to include a 'tilt,' which displaces correlation spots by a filter-dependent amount. By this method, with an appropriately structured input representation, the responsible filter can be directly conveyed to the output.

- **Temporal multiplexing** is possible because of the high speed of the input SLMs relative to the filter SLMs and camera sensors. This means that a number (2400÷120=20) of input sub-frames can be searched against a given filter during a specified camera sensor exposure. The camera sensor will integrate across the exposure. Provided they are bright enough, correlation peaks will appear against the integrated background noise. To determine which sub-frame is responsible for the correlation peak, again either brute-force inspection of the candidates can be undertaken, or the input can be displayed such that it is known that correlation peaks due to certain sub-frames will only fall on certain camera sensor pixels.

Depending on the application, it may or may not be possible to take advantage of all of these different methods for multiplexing. In particular, the temporal multiplexing assumes that the correlation signal due to one of the correlation planes is bright enough to out-shine the other planes. If it is not, sub-frames will have to be grouped together. Optalysys will work with customers on a per-application basis to maximise exploitation of the multiplexing capability.

The case study of the bioinformatics application presented in the next section is a good illustration of how to exploit these different multiplexing methods.

Capability

The Optalysys optical processing system offers a computational capability digitally unmatched at its power and size requirements. The table below shows the effective wall-clock time and rate for Fourier transforms at the resolution of the input. While the Fourier transform happens 'at the speed of light,' the limiting factor is the refresh period of the input SLM. For simplicity, we quote the 'time' for the Optalysys system as this refresh period.

However, the rate of transforms for the Optalysys system is more than simply the reciprocal of the time to perform an individual transform, due to both the inherent system parallelism and multiplexing. Each correlation operation consists of 2 sequential Fourier transforms, and there are multiple light-paths. While these Fourier transforms cannot be accessed directly, they do represent the equivalent transform capability required of a digital solution in order perform the same computations.

As a comparison, we show some equivalent times for evaluating the same transform on state-of-the art electronic platforms. In the times shown, only the execution time is considered.

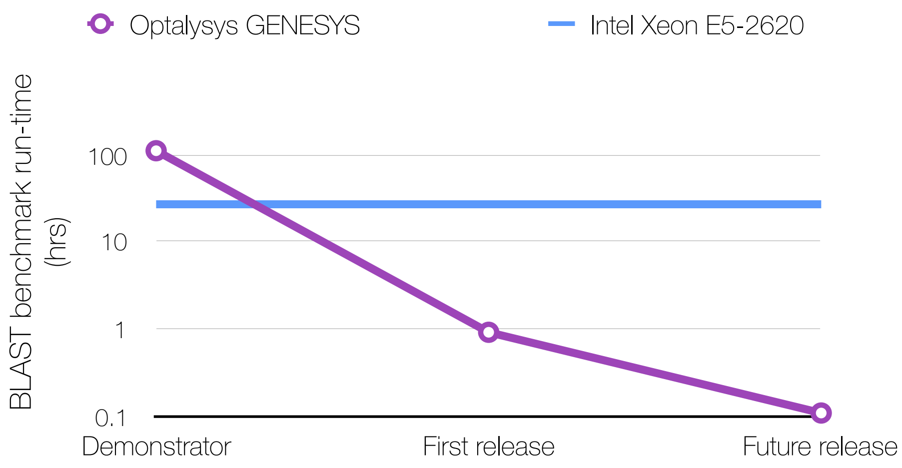
2048×1536 resolution Fourier transform	Optalysys system	NVIDIA Quadro P6000	Intel i9-7900X
Time	0.4 ms [1]	0.36 ms [3]	1.04 ms [5]
Rate	14.4 kHz [2]	2.7 kHz [4]	0.96 kHz [6]

Digital benchmarks evaluated using gearshifft v0.2.0 (https://github.com/mpicbg-scicomp/gearshifft). In all cases, the average time for the best exemplar of the problem is taken (in/out place, precision, real/complex). Only execution time is considered: planning, upload and allocation times are neglected.

1: The 'time' is taken as the refresh time of the SLM, although in reality more equivalent operations are being conducted in this time.
2: This rate includes all of the parallelism; long the 4 different optical paths, two forward and one 'inverse' transform are evaluated.
3: Average of 10 outplace, real, float transforms
4: Reciprocal of [3]
5: Average of 10 inplace, real, float transforms (outliers removed)
6: Reciprocal of [5]

Future hardware performance

Our technical roadmap envisages a significant increase in performance with subsequent releases, which any applications developed for this system will be well-placed to capitalise on. The inherent parallelism of the optical process, and the fact that the computation substrate for the Fourier transforms is 'free' space, means that bandwidth can be increased at the same execution-time by increasing the input capacity. This can be achieved either by using faster devices, higher-resolution devices, or tiling devices.



An example of the anticipated performance increase is shown in the adjacent graph. The benchmark shown is for the application we are initially targeting: genetic alignment. Specifically, implementing a BLAST-like process to sensitively find short genetic sequences in a large database. We ultimately project a potential ×2000 improvement relative to an high-performance computing node.

While the competing digital technology will not stand still, and there are significant engineering challenges to overcome in unlocking the capability of the optical processor, this plot shows a tantalising hint of the performance we could unlock in an optical processor.

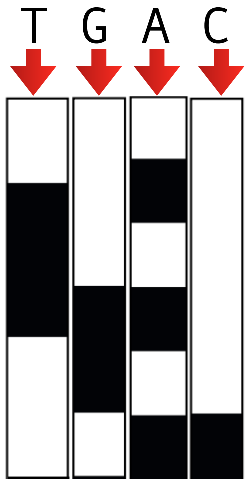
3. Applications

In this section, we present a case-study of an application of the Optalysys processing system: genetic alignment. This illustrates a potential way in which the system can be used. We also discuss other application ideas, and what properties of certain problems make them appropriate for the Optalysys system.

Case study: Genetic alignment

Genetic alignment is a problem in bioinformatics which attempts to locate DNA sequences relative to each other. The specific application we demonstrate here is short-read alignment. That is, locating short strings of DNA (length ~100 bases from a sequencing machine) within a reference genome (human genome ~3 billion bases).

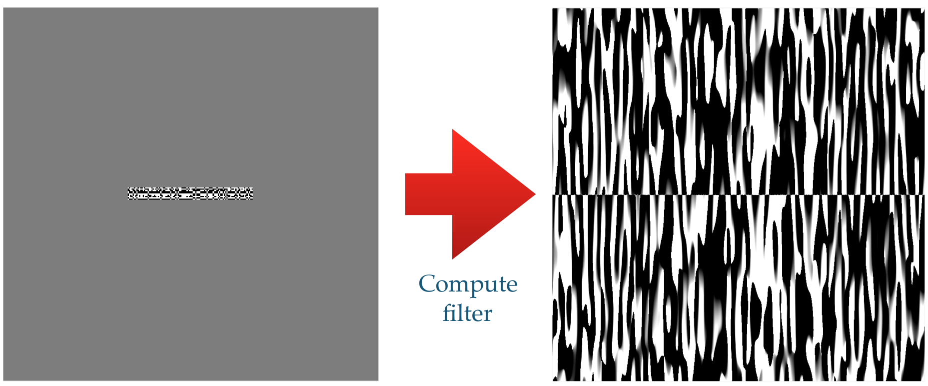
The optical method is appropriate for this task because of its high sensitivity. It is able to convolve the entire genome, comparing sequences across their entire length instantaneously. This is in contrast to the software method BLAST, which builds alignments up by matching highly similar sub-sequences.



In order to use the optical correlator to align the genetic data, an appropriate representation must be used. The first obstacle is the fact that DNA is a 1 dimensional dataset, whereas the correlator performs 2D operations. Hence, we represent the data using binary 'tiles' for each character (TGAC) of the DNA. These tiles are 1D, and concatenated along the short direction. In this way, the dimensionality of the data is increased. The subsequent representation of a given sequence has an area equal to the length of sequence multiplied by the tile height.

For the application of aligning a short read to a reference database, the reference database is represented on the input SLMs (1 & 2). The sequence segments are written across the SLM, row by row. (There is some overlap between rows so that the target sequence does not align to a sequence that straddles rows.)

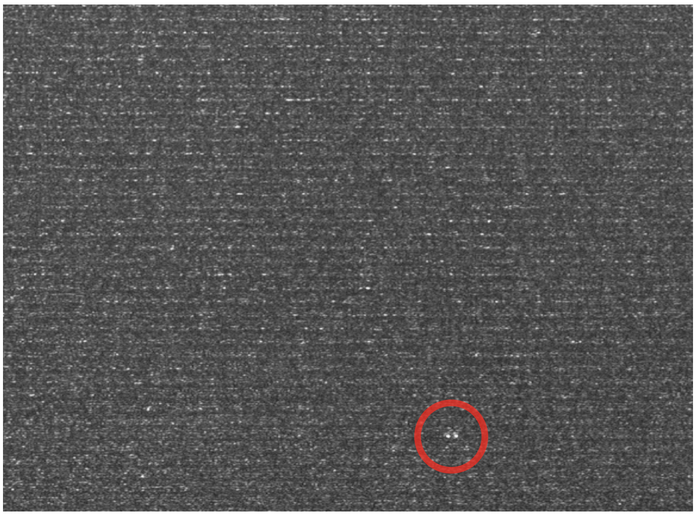
The short search sequences are displayed on the filter SLM. The sequence is transformed into the appropriate representation and then situated in a matrix padded to an appropriate size. The discrete Fourier transform of this representation is computed. Optalysys proprietary software, solidly founded in optical and statistical pattern recognition theories and practical details of our hardware, determines the drive signals sent to the filter SLM:



A target sequence, for which we wish to compute the correct filter to display on the SLM.

SLM drive values, obtained by taking the DFT of the target and then assigning SLM drive values.

When these data are passed through the system, any matches between the reference database and the short sequence are indicated by a bright 'correlation spot.' Peak detection algorithms are used to detect these spots, and return the coordinates with respect to the data displayed on the input SLM. This location is passed back to software for further analysis.



Bright spots in the output plane show aligned sequences.

Exploiting multiplexing

This application is a good platform to demonstrate the multiplexing ability of the correlator system. We rely on the fact that a correlation spot will appear in correspondence of a filter's matching set of points. For an appropriately designed filter, the spots will appear only along the line through the middle of the symbols. Different filter designs can be used to move this line up and down.

The red line shows the region where spots corresponding to the alignment might appear in the correlation plane.

It is this fact which permits the multiplexing approach. The different filters can be aligned so that they deflect the points by different amounts. The different time-sequenced inputs on the fast input SLM can be translated pixel-by-pixel down the screen, translating the corresponding output peaks down. Thus, which row of the output camera sensor the correlation plane lies on can be traced back to certain input and filter combinations.

Depending on the parameters chosen, there may not be enough footprint to fully constrain the filter-input pair, and a subsequent digital investigation may be required. However, the correlator will have fulfilled its purpose of finding the 'needle-in-the-haystack.'

Other application ideas

The Optalysys system is fundamentally appropriate for any case where fast, high resolution 2D convolutions are required. As the genomics examples illustrates, Optalysys have shown that given the right data representation, other dimensionality data can also be effectively processed.

Features of a promising application

There are a number of different features which may imply a certain application is a promising candidate for acceleration on the Optalysys system:

- **Processing large amounts of data.**
- **High sensitivity search** (i.e. not just looking for exact matches), but with **low computational precision requirements.**
- **A highly interconnected problem,** that benefits from a system where every output point depends on every input point (through the Fourier transform).

An example of an idea which matches these criteria is evaluating the convolutional layers in a ConvNet.

4. Interacting with the Optalysys processor

The Optalysys system is designed for seamless integration with existing computer platforms. This section outlines the conceptual design of both the hardware and software interaction. *Both the hardware and software are still under active development, but this document gives an indication of what early users can expect, and how the Optalysys system can be integrated within existing workflows.* Optalysys actively solicit inquiries as to how your problem can be formulated and solved optically.

A number of different levels of interaction will be available. As discussed, the first application being promoted by Optalysys is genetic alignment. Hence, a high-level command line interface (CLI) will be offered which emulates the interaction with the BLAST tool it is emulating. However, this section focuses on what will be available to partners wishing to develop their own applications.

Engaging with the correlator

The most low-level way of engaging with the optical correlator is supplying it with images for both the input and filter SLMs, and receiving as an output the image at the camera sensor. However, a number of features are offered for higher-level interaction:

In-situ system calibration

The Optalysys system is, fundamentally, an analogue processor. In-situ calibration of the system can be performed to compensate for any system variability. For example, temperature and environmental changes can subtly affect performance.

As such, the software interface incorporates functionality that can compensate for these changes. It optimises optical alignment of the SLMs and camera sensor so that appropriate shifts can be incorporated in software, and collects information to allow for optimal filter calculation.

Filter computation

One of the main challenges when using an optical correlator is calculating an appropriate filter image for the problem being considered. It is the Fourier transform of this filter image which is represented on the filter SLM. This is one of the functions that the Optalysys software can perform on behalf of the user. This functionality will be supplied as a prototype in case the user wants to develop their own filter computation.

Peak detection

Often in correlation applications, it is the location of any correlation peaks – indicating a match between the input and the filter – which is important. The Optalysys system incorporates robust peak-detection algorithms, functioning synergistically with the filter generation algorithms and implemented in hardware on the FPGA for very high performance. When operating in this mode, the system returns simply the location of the peak values relative to the input dataset.

Hardware interface

The Optalysys optical processor makes use of a PCIe interface to provide a high-bandwidth interconnect. It can be connected directly to an appropriate motherboard, or used with a PCIe extender. It makes use of direct memory access (DMA) to allow it to access the system RAM directly without having to go via the CPU.

Hardware

The hardware itself comprises a high-performance FPGA system, from the Xilinx Kintex Ultrascale family. This system performs the task of interfacing with the conventional CPU, managing the jobs, and directly driving the SLMs and camera sensor.

The FPGA alone represents a significant amount of computational power. As such, excess FPGA capacity can be configured for application-specific processes, once the application has reached sufficient maturity. The bioinformatics application is a good example of this – the final stage of genetic alignment can be performed on the FPGA.

Software interface

A number of different software interfaces will be provided, appropriate for different applications and levels of engagement with the underlying hardware. These include:

- **Command line interface (CLI)**, for straightforward interaction. This will process input data and return either images of located peaks.
- **MATLAB / Octave plug-in**, for easy application prototyping and development by integrating with native variables types.
- ***C* API**, for high-performance interaction with the Optalysys system.

These Optalysys-supplied interfaces interact with a common low-level UNIX driver.

Job scheduling

It is important to specify how the multiplexing capabilities of the correlator are to be exploited – if at all – when specifying jobs. For example: which light paths are being used; and how is the fast binary input SLM being used with respect to the slower filter SLMs and cameras. To this end, jobs need to essentially be ‘scheduled’ across the system resources. The Optalysys software will take care of this by asynchronously scheduling the SLMs and cameras to seamlessly – from the user’s perspective – take full advantage of the device.