Hybrid Digital/Optical Computer Systems

Institution of Electrical Engineers - Seminar - Arundel
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Dr Young, Dr Budgett, Dr Birch, Mr Claret-Tournier, Dr Sharp

School of Engineering & Information Technology
University of Sussex
Filter Recording and Playback

Path difference must be within coherence length of laser

Plane phase reference beam

Spectrum of $g(x,y)$ recorded holographically by placing on carrier of spatial frequency $\alpha = \frac{\sin \theta}{\lambda}$

CORRELATION WITH INPUT SCENE

Input scene (Reference + Background)

Matched spatial filter MSF

$F^*(u,v)$

width of $g(x,y) = W_g$

width of $f(x,y) = W_f$

When $f(x,y) = g(x,y)$

Autocorrelation — Reference beam is reconstructed by MSF, focused by $L_2$ to an on-axis spot.

Correlation $g \otimes f$

TOTAL OUTPUT PLANE

width of $g(x,y) = W_g + W_f$

width of $f(x,y) = W_f$

$\alpha \lambda f > \frac{3W_g}{2} + W_f$

implies high carrier frequency required if moderate focal length lenses to be used.
Joint Transform Correlator
Conventional Optical Correlation

Source

object

Optical system-1
(Fourier Transform)

Optical filter

Optical system-2
(Inverse Fourier Transform)

Detect

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Hybrid Digital Optical Correlator

**Optical:**
- **object** → Optical system-1 (Fourier Transform) → Optical filter → Optical system-2 (Inverse Fourier Transform) → Detect

**Hybrid:**
- **object** → Camera → 2D-FFT → E-OR → SLM (Template) → Optical sub-system (Fourier Transform and laser source for SLM) → CCD-Detector
- PC
Hybrid System Aims

- Correlators offer high resolution image recognition but...
- Difficult to get data in and out at speed
- Input SLMs have low dynamic range
- Mechanical and thermal stability can be poor
- Large physical size
- Difficult to align
- f/# matching problems

Solution:
- Replace first Fourier transform with a digital FFT
- The data is mixed with template filters and placed on to an SLM which is then optically Fourier transformed
- We can search many filters in a video frame time
Summary

- Two systems will be described:
  - One with an optical template memory addressed by an acousto optic scanner
  - One with a digital template memory, which is far more compact

- Both these systems have been built by the Laser and Photonic Systems Research Group: Dr Young, Dr Budgett, Dr Birch, Mr Claret-Tournier, Dr Sharp
Schematic of Hybrid Optical/Digital Correlator Experimental Layout

- 512x512 FFT of input scene in < 40ms
- Phase image is displayed on the phase modulating SLM
- Acousto-optic deflector random access time < 15 microseconds
- X and Y position of any peak detected; Size of peak along X and Y axes; Density of correlation peak
- Correlation of reconstructed “image” and SLM “image” produced by final lens
- Phase image is displayed on the phase modulating SLM
High Speed Hybrid Correlator System: Image Acquisition
Volume Hologram Recording System
Seiko-Epson VPJ700 LCTV
Phase Lag and Normalised Transmittance Versus Grey Level (green LCTV)
Volume Hologram Recording System
Volume Hologram Recording System
Schematic of Hybrid Optical/Digital Correlator Experimental Layout in Read Mode
Optical Design

3 Lens Design

Symmetrical 2 Lens Design
TeO$_2$ Acousto-Optic Scanner

LS1100 from Isomet
Optimised to run at 488 nm with anti reflection coatings
Active aperture is 9 mm
Scan Angle 2.4 deg, random access time of 15 microseconds
Maximum playback speed 24,000 images/s
Acousto-Optic Cell Diffraction Efficiency

Variation of Diffracted Intensity from A/O Cell and Look-up Table Correction
Angular Calibration of Acousto Optic Device

Bragg Matching Alignment

Angular Position

64 x 1 Linear array Detector

Photo Diodes

To MicroProcessor
Major Digital Sub-systems

- Fast Fourier Transform Board based on the Sharp LH9124 chip set

- High Frame Rate FPGA Based Image Processing Board, the Imaging board incorporates 4 XiLinx FPGA devices and is used for fast correlation plane processing
Video Rate FFT board using Sharp LH9124 DSP

Data buses are 48 bits wide, allowing a wide dynamic range.

Sharp LH9124 - Butterfly digital signal processor, with built in radix 2, 4 and 16 butterfly structures.

Pythagoras chip to convert real and imaginary output data values to phase values.

4 address generator chips.

Multiple high speed memory buffers with 15ns access time.

The board is capable of computing a 512x512 FFT in 39.9 ms.
The input data is real, and the output data is symmetrical; exploiting these data features we were able to reduce the FFT computation time to 31 ms.
Video Rate 2D FFT Board
High Frame Rate FPGA Based Image Processing Board

The Imaging Board performs the following tasks using a common hardware design:

- SLM driver for PC including real time correction of aspect ratio
- SLM driver for FFT subsystem to display phase images
- Correlation processing board to calculate correlation peak parameters

Imaging boards incorporate 4 XiLinx FPGA devices

Provides an extremely flexible internal architecture
High Frame Rate FPGA Correlation Plane Processing

- Correlation plane output produced for every correlation between input and reference template
- Location of the correlation peak identifies the position of the object in the input scene
- The task is to discriminate between good and poor correlations
- Task is completed at a rate of 2900 decisions per second (DALSA camera frame rate)
# Correlation Plane Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>xMin, xMax</td>
<td>Minimum/maximum coordinates of target bounding box</td>
</tr>
<tr>
<td>yMin, yMax</td>
<td></td>
</tr>
<tr>
<td>xSum, ySum</td>
<td>Summation of X/Y coordinate of all target pixels</td>
</tr>
<tr>
<td>nSize</td>
<td>Number of pixels set to 1 in target</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>xGravity</td>
<td>Mean X/Y of the target</td>
<td>$xGravity = \frac{xSum}{n}$</td>
</tr>
<tr>
<td>yGravity</td>
<td></td>
<td>$yGravity = \frac{ySum}{n}$</td>
</tr>
<tr>
<td>nDensity</td>
<td>Concentration index of all pixels set to “1” in target</td>
<td>$nDensity = \frac{nSize}{((xMax-xMin)x(yMax-yMin))}$</td>
</tr>
</tbody>
</table>
High Frame Rate FPGA Based Image Processing Board

Frame Grabber 64x64 at 2900 fps Image Analysis

The PGA’s tackle tasks performed on every pixel in the image: summation, counting, comparisons and logic operations
Determine a threshold level for the image

Threshold must be adaptable to compensate for variations in the correlations image, essential for filtering out the noise floor

Output from this process is a binary image all pixels > threshold are mapped to “1” and all others to “0”

Algorithm implemented in phase two derives multiple correlation peak parameters

A peak density parameter, nDensity, is used to quantify the quality of the correlation peak

Peak density is a function of the number and extent of “1” pixels

Functions such as division, not required for each pixel, are executed by the host central processing unit
System Operation

- FFT trigger: 40 ms
- Individually select 72 database images, compute correlation: 40 ms
- AOD control: D/A, AOD settling, steady image: 688 us
- Rapid CCD: transfer, Frame integration: 688 us
Typical Correlation Outputs

- Autocorrelation of Test Component
- Cross correlations with rotated components
- Cross correlation with Synthetic Discriminant Function Multiplexed Filter
Orientation Determination Using an SDF Filter
Research Tasks

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PCI Bus Hybrid Digital/Optical Computer using an Analogue Ferroelectric Liquid Crystal Spatial Light Modulator
Motivations

• Correlators offer a powerful image recognition solution
• Example applications are target identification and tracking, high speed character recognition (Post Office sorting, number plate reading, banknote authentication) and many others
• Problems with them are designing filters, robustness, physical size.
• A Digital/Optical hybrid correlator is used with a full complex filter (amplitude and phase control) on a spatial light modulator (SLM).
Filter Design

• Optical filters for correlators are often approximations, e.g.
  • Phase only
  • Binary phase only
  • Nearest distance (TNSLM)
  • A fully complex modulation method would improve this.
• We use a phase detour technique using two pixels of an analogue ferroelectric liquid crystal SLM.
Real time recognition of: car number plates, banknotes and packet mail postcodes

Fourier Transform lens system

Laser Diode $\lambda = 600$ to $700$ nm

Input / 2D-FFT

Reference Template data (binary)

SLM/Template

Beam splitter

2D-FFT

FG

CCD

Video Rate

To DSP

OUTPUT

HS/LR

Peak Detection
Boulder Non-linear Systems 128x128 SLM

- Liquid Crystal Type Smectic A*
- Total Array Size 5.12mm x 5.12mm
- Pixel Pitch 40 μm
- Fill Factor 60%
- Frame Load Time 100 μs
- Resolution 8-bit (256 levels)
- Real axis modulation or binary phase modulation
Methods to Produce Complex Modulation

\[ +R -I +R -I \]

\[ +R -I -R +I \]

\[ a b c \]

\[ \pm R \pm I \pm R \pm I \]
Complex Modulation Method with AFLC

SLM gives 8 bit resolution, ie 256 level, hence the component of the polarisation vector that is horizontal can be made +ve or -ve.
Electronic Systems Layout

- **512x512**
- **DALSA**
- **SLM**
- **SHARC array**
- **FPGA**

**Processors and Control:***
- 40ms FFT on 8 processors
- SLM control (~1kHz)
- Camera control
- Peak detection

**Technology Hub**
Flow Diagram

1. Capture input
2. Compute FFT
3. Multiply with next template
4. Inverse FT
5. Detect correlation
6. Last template?
7. Report result

New input image every 40 ms
New template every 667 μs
DSP Technical Specifications

ADSP 21060 - 21062

- 32-bit floating point computation unit
- 40MHz clock cycle
- 25ns instruction rate, 40MIPS
- 80 MFLOPS
- Dual ported SRAM (4Mbit or 2Mbit)
- DMA Controller - 10 channels
- C++ compiler
Parallel Pipeline Configuration for 2D FFT

Frame N

input

DSP1
DSP2
DSP3
DSP4

2D-FFT (N)

Frame N+1

DMA

output

2D-FFT (N+1)

Alternatively

Alternatively
Timing Diagram of 2D FFT

- 2nd group
- 1st group
- Camera
- FPGA
- SHARC

Time (ms)
0 40 80 120 160 200

Pipeline delay 100ms

FFT rate = Input video Rate
40 ms

FFT rate = Input video Rate
40 ms
Digital FFT system

Timing Performance of 2D FFT (ms) for 1 group of 4 DSP

<table>
<thead>
<tr>
<th>Stages</th>
<th>Transpose and float</th>
<th>1st-pass FFT</th>
<th>Data re-ordering</th>
<th>DSP Communication</th>
<th>Re-order &amp; group</th>
<th>2nd-pass FFT</th>
<th>Packing</th>
<th>Total elapsed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (ms)</td>
<td>3.45</td>
<td>26.40</td>
<td>3.30</td>
<td>14.20</td>
<td>3.52</td>
<td>17.10</td>
<td>7.40</td>
<td>75.37</td>
</tr>
</tbody>
</table>
Custom Hybrid Optical/Digital PC Card Layout

- ADSP 21062
- Altera FPGA
- APAC 509 #1
- ADSP 21062
- Altera FPGA
- APAC 509 #2

- 32 bit bus
- CCDFiber optic image bundle
- SLM
- Laser diode system
- L1
- L2
- L3
- L4

- ISA control circuit
- Clock Generator
- SRAM memory
- 64 bit bus
- To CCD detector
Optical Layout

Beam profiler's CCD Camera
FT lens
SLM
Laser diode system
Fibre bundle link
Relay lens
Beam expander

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Hybrid digital optical correlator system
PCI Bus Hybrid System
Image Processing & Photonics

Miniatuirised Optical Computer, plugs into PC bus

Output Correlation
Complex Modulation Method with AFLC: Results
Example Correlation Result for Real Only Filter
Example Correlation Results for Fully Complex Filter
Hybrid Correlation Result
Fully Complex Hybrid Correlation

Matched filter

Phase only filter
Wiener Filter Example
Litton Hybrid Correlator

Litton Data Systems MROC™ Optical Correlator System
Conclusions

- Complex modulation technique demonstrated using two pixels of an SLM
- All optical demonstration
- Hybrid digital/optical system overcomes some problems with all optical correlators
- Future in DSP: ADSP 21160
  - 100 MHz, 700 Mbytes/s, 600 MFLOPS
  - 1024 pts CFFT in 90us (540us for 21060)
References

1. RKK Wang, L Shang, CR Chatwin, “Modified fringe-adjusted joint transform correlation to accommodate noise in the input scene,” Applied optics 35 (2), 286-296, 1996
References

15. RK Wang, CR Chatwin, RCD Young, Assessment of a Wiener filter synthetic discriminant function for optical correlation, Optics and lasers in engineering 22 (1), 33-51, 1995