A Streaming Sensor Challenge Problem for Ubiquitous High Performance Computing

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Ubiquitous High Performance Computing

- DARPA program to develop next generation of energy-efficient high throughput computers
  - Nominal goals: 1 petaflop, 50 gigaflops/watt Linpack, 1 cabinet, 57KW whole system
  - Modular and scalable: embedded to cabinet
  - Complete goals TBD based on Defense needs
Ubiquitous High Performance Computing: CHASM

OBJECTIVE
Drive the focus of UHPC architecture designs toward scalable capability on defense applications.

SUMMARY
The CHASM team is designing challenge problems that embody the computing needs of 2018 defense missions, and developing new execution models that can support million-way parallelism and maintain performance with frequent faults.

PARTNERS
• GT College of Computing
• GT Electrical and Computer Engineering
• Louisiana State University
• Lawrence Livermore National Laboratory
• Oak Ridge National Laboratory
“We are going to find ourselves in the not too distant future swimming in sensors and drowning in data.”

Large volumes of data must be distilled to manageable, actionable knowledge in order to benefit the warfighter.
Overview - SSCP

**Inputs:**
- Sensor collections
  - For each of many pulses:
    - Sensor position
    - Measured returns at many time instances
  - Grid of image point locations

**Outputs:**
- Location of each detection

**Front-end Processing**
- Digital Spotlight
  - Back Projection
  - Back Projection
  - Back Projection

**Back-end Processing**
- Coherent Change Detection
  - P Images $P=2+$

**Knowledge Generation**
- CFAR
Why Backprojection?

- **FFT-based reconstruction techniques exist**
  - Require either linear or circular collections
  - Only modest deviations can be compensated
  - Requires extra steps to get georeferenced imagery
  - Images only onto planar surface

- **Procedure**
  - Attempt to fly a perfectly straight line
  - Compensate for unwanted motion
  - Form image using Fourier-based method backpropagation
  - Register and interpolate image onto map coordinates

- **Flexibility**
  - Can image directly onto map coordinates without postprocessing

- **Expanded operating envelope**
  - Can image in adverse environmental conditions during maneuvers
Digital Spotlight

\[ e^{-2n\Delta f/K} \]

Flow diagram:
- \( P_1 \times S_1 \) (Spatial) FFT
- \( P_1 \times S_1 \) (Frequency) Range Shift
- Elwise Multiply: \( e^{-2n\Delta f/K} \)
- \( P_1 \times S_1 \) (Frequency) FFT
- \( P_1 \times S_2 \) (Spatial) Range Gate
- \( P_1 \times S_2 \) (Spatial) Cross-Range Downsample (Decimating FIR)
- \( P_2 \times S_2 \) (Spatial)
Image Formation

Back Projection

For $i = \{I_x\}$
  For $j = \{I_y\}$
    For $k = \{P_3\}$
      $R =$ range to $i,j$
      $S =$ sample at $(k,R)$
      $S * e^{aR}$
      $Out(i,j) += S$
Digital Spotlight Loading Impact

Compute Load vs. Tiling - Scenario 4

FLOPs

Tiling, T=

1 2 4 8 16 32 64 128 256 512

3.1E+14 1.6E+14 7.8E+13 4.1E+13 2.8E+13 4.3E+13 1.4E+14 5.3E+14 2.1E+15 8.4E+15

Total  Spotlight  Backprojection
CCD(1) - Affine Registration

2D Correlate x \( N_c \)
(\(2S_c - 1 \times 2S_c - 1\)) 2D FFT
Elwise mult
2D IFFT
\( R_c \times R_c \) Max Mag

Warp & Sample
\( C = AZ \)
Bilinear sample @ \( C \)

Find Global Affine Transform

\[ X_o = Z_1 + Z_2 X_i + Z_3 Y_i + Z_4 X_i^2 + Z_5 Y_i^2 + Z_6 X_i Y_i \]

Control Points: \( N_c \times 4 \) (Locations, Offsets)

Solve for \( Z \)

\( A: N_c \times 6 \)
\[ [1 \ x\ y \ x^2 \ y^2 \ xy] \]
\( (x, y = \text{Control point locations}) \)
\( b: N_c \times 2 \) (each row = final x, y position)

\( Z = \text{Warp Weights: 6x2} \)

\[ C = AZ \]
Bilinear sample @ \( C \)

\( C: \text{Warped loc} \)
\[ A(i,:) = [1 \ x \ y \ x^2 \ y^2 \ xy] \]
\( i = 1..M^2 \)
One row per pixel
\( Z: 6x2 \)

\( R_c = \sim 2^\% \times M \)
• Round up to NPOT
\( S_c = R_c \times r \)
\( S_{cf} = 16 \times r \)
\( r = 4^* \)
\( N_c = \text{ceil}(M/R_c)^2 \)
• Heuristics

M x M Complex Image
CCD(2) – Thin Spline Registration

2D Correlate x N_f
(2S_{cf} - 1 x 2S_{cf} - 1) 2D FFT
Elwise mult
2D IFFT
R_f x R_f Max Mag

2D Correlate x N_f
(2S_{cf} - 1 x 2S_{cf} - 1) 2D FFT
Elwise mult
2D IFFT
R_f x R_f Max Mag

Warp & Sample
\Delta X_{x,y} = W_{N_f} + W_{N_f-1}x + W_{N_f-2}y
\sum W_i U(|P_i - (x,y)|)

P_i: location of ith control point
Bilinear sample @ X_{x,y}

Find Weights
LW = Y
Each row of Y: control point + offset
Rows N_f+1 -> N_f+3 are zeroes
Solve for W

Form L
L = [K P; P' O]
K(l,j) = U(|X_l - X_j|)
U(n) = n^2 \ln(n)
P(i,:) = [1 x_i y_i]
O = 0
X_k: Ctrl Pt. Locs

L: (N_f+3)x(N_f+3)
W = Warp Weights: (N_f+3) x 2
X = pixel location

W = Warp Weights: (N_f+3) x 2
X = pixel location

\begin{align*}
W_f &= 2^{\text{ceil}(\log_2(R_c)/2)} \\
S_{cf} &= R_f x 4^* \\
N_f &= \text{ceil}(M/D_f)2 \\
D_f &= 200^* \text{(easy)} \\
&\sim1000^* \text{(hard)} \\
R_n &= 5^* \text{ (~1.5m)}
\end{align*}

*Heuristic

Control Points: N_f x 4
(Locations, Offsets)
**Coherence**

For each pixel: $N_{cor} \times N_{cor}$ 2D neighborhood correlation between current frame and reference frame

**Constant False Alarm Rate (CFAR):**

For each pixel, calculate whether this pixel’s value is lower than $T_{cfar}$% of pixels in $N_{cfar} \times N_{cfar}$ neighborhood. If so, emit detection
<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Area (square edge size, m)</td>
<td>609.6</td>
<td>1086</td>
<td>2438</td>
<td>8690</td>
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<tr>
<td>Image Size (edge size, pixels)</td>
<td>4000</td>
<td>7127</td>
<td>16000</td>
<td>57018</td>
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<tr>
<td>Pulses per Image</td>
<td>4800</td>
<td>12095</td>
<td>19200</td>
<td>96763</td>
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<tr>
<td>Samples per Pulse</td>
<td>4000</td>
<td>10079</td>
<td>16000</td>
<td>80636</td>
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<tr>
<td>Pulses per Second</td>
<td>1084</td>
<td>497</td>
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<td>2809</td>
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<td>Throughput (images per second)</td>
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<td>1</td>
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<td>Affine registration control points</td>
<td>3629</td>
<td>14,513</td>
<td>58050</td>
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<td>Thin-spline registration control points</td>
<td>100</td>
<td>100</td>
<td>200</td>
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<tr>
<td>CCD neighborhood size</td>
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<td>5x5</td>
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<tr>
<td>CFAR neighborhood size</td>
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<td></td>
<td></td>
<td>15x15</td>
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<tr>
<td>Scenario</td>
<td>1</td>
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<td>--------------------------------</td>
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<tr>
<td>Floating Point Operations</td>
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<tr>
<td>Image Formation</td>
<td>$23.2 \times 10^9$</td>
<td>$149 \times 10^9$</td>
<td>$942 \times 10^9$</td>
<td>$28.0 \times 10^{12}$</td>
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<tr>
<td>Affine Registration</td>
<td>$1.11 \times 10^9$</td>
<td>$4.45 \times 10^9$</td>
<td>$17.8 \times 10^9$</td>
<td>$160 \times 10^9$</td>
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<tr>
<td>Thin-spline registration</td>
<td>$25.8 \times 10^9$</td>
<td>$103 \times 10^9$</td>
<td>$819 \times 10^9$</td>
<td>$13.1 \times 10^{12}$</td>
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<td>Coherent Change Detection</td>
<td>$79.4 \times 10^9$</td>
<td>$317 \times 10^9$</td>
<td>$1.27 \times 10^{12}$</td>
<td>$20.3 \times 10^{12}$</td>
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<td>CFAR Detection</td>
<td>$715 \times 10^6$</td>
<td>$2.86 \times 10^9$</td>
<td>$11.4 \times 10^9$</td>
<td>$182 \times 10^9$</td>
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<tr>
<td>Total FLOPS</td>
<td>$130 \times 10^9$</td>
<td>$577 \times 10^9$</td>
<td>$3.06 \times 10^{12}$</td>
<td>$61.8 \times 10^{12}$</td>
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<tr>
<td>Input bandwidth (bps)</td>
<td>$80.0 \times 10^6$</td>
<td>$320 \times 10^6$</td>
<td>$1.7 \times 10^9$</td>
<td>$14.5 \times 10^9$</td>
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<tr>
<td>Input footprint (Bytes per Image)</td>
<td>$244 \times 10^6$</td>
<td>$975 \times 10^6$</td>
<td>$3.9 \times 10^9$</td>
<td>$62.4 \times 10^9$</td>
</tr>
</tbody>
</table>
SSCP Status

- Reference implementation completed & available to UHPC participants
  - Includes challenge problem & data generator
- Accelerated / Parallel implementations under development
- Investigating addition of EO/IR & Fusion
- Adjustments to registration process under investigation
- Adjustments to load-influencing parameters under consideration