A MULTI-CORE FPGA-BASED 2D-CLUSTERING ALGORITHM FOR HIGH-THROUGHPUT DATA-INTENSIVE APPLICATIONS

Calliope-Louisa Sotiropoulou

Aristotle University of Thessaloniki

AUTH e-LAB

Aristotle University of Thessaloniki-Electronics Laboratory

**ATLAS
EXPERIMENT**

Clustering Modules – FTK IM Board

- Introduction – Motive
- ATLAS Application – FTK IM Board
- Clustering Problem
- Clustering Modules
- Parallelization

Introduction to 2D-Clustering

- High Resolution Pixel Detectors are used for a variety of applications:
 - High Energy Physics (Particle Tracking)
 - Medical Imaging and Biomedical Applications
 - Astrophysics Image Acquisition etc.
- 2D-Clustering is beneficial for all the above applications:
 - A preprocessing step for data reduction (N hits $\rightarrow$ 1 cluster)
 - Image segmentation process
 - Increasing resolution (e.g. spatial or other parameters)
 - Identifying patterns (e.g. object identification)
 - Performing cluster analysis

2D-Clustering for the ATLAS FastTracker Processor

- Main challenge: input rate 308Gbits
 - 256 S-link fibers from all pixel RODs
 - Running at 1.2 Gbits (total 308Gbits)
 - 32bit words at 40MHz, 1 hit/word

ATLAS Pixel Layer 2

FTK Input Mezzanine Board

2D-Clustering for the ATLAS FastTracker Processor

- Main challenge: input rate 308Gbits
 - 256 S-link fibers from all pixel RODs
 - Running at 1.2 Gbits (total 308Gbits)
 - 32bit words at 40MHz, 1 hit/word

Target:

- A system which clusters data on the fly

ATLAS Pixel Layer 2

FTK Input Mezzanine Board

The ATLAS Pixel Module

- 328x144 pixels readout by 16 Front End (FE) chips
- Each module is comprised of 2 rows of 8 FE
- Each FE reads out pixel hits by double column
- The hits in the double column are scrambled
- The pixels are 50 μm x 400 μm
- Pixels with larger occupancy (column 0 and 17 of each FE chip) are 600 μm wide

The ATLAS Pixel Modules

- Expected cluster sizes on the Pixel module from single particle simulation

η -Region					
	0.0–0.5	0.5–1.0	1.0–1.5	1.5–2.0	2.0–2.5
51.9	32.8	6.7	0.4	0.5
31.1	21.3	4.0	0.4	0.3
2.0	0.9	0.4	0.6	0.6
9.2	27.3	48.0	20.8	0.3
4.8	16.9	34.7	15.2	0.4
0.7	0.6	0.7	0.7	0.9
0.0	0.0	3.0	34.2	16.7
0.1	0.1	2.0	25.4	14.0
0.1	0.1	0.3	0.6	1.0
0.0	0.0	0.0	0.7	34.1
0.0	0.0	0.0	0.7	30.4
0.1	0.0	0.2	0.3	0.8

2D Occupancy Plot

- Small probability of large clusters with a size 10-30 pixels wide (Especially in the r-phi direction)

The Clustering Problem

	3	9	7						
	1					13	15		
	4	8	6	11					
							12		
2	5	10					14		

The Cluster Hits arrive scrambled →
Loop over the list of hits

1. Associate hits from same cluster
 - Loop over hit list
 - Time increases with occupancy & instantaneous luminosity
 - Non linear execution time
2. Calculate cluster properties
 - e.g. center, size, shape ...
- **Goal:**
Keep up with 40Mhz hit input rate

Clustering Modules

Clustering Modules

Grid Clustering – Generate Window

- Generate a **cluster window** (e.g. 4x5 pixels) around a reference hit
- The reference hit is located on the **middle row** of the window and
 - **Column 1** of the window if it belongs to an **odd** column

Grid Clustering – Generate Window

- Hits are read from the input until a hit which belongs to a column beyond the **cluster window** is identified
- The hits that belong to the same columns as the cluster window are stored in a separate **circular buffer**

- Generate a **cluster window** (e.g. 4x5 pixels) around a reference hit
- The reference hit is located on the **middle row** of the window and
 - **Column 1** of the window if it belongs to an **odd** column
 - **Column 0** of the window if it belongs to an **even** column

Grid Clustering – Select and Readout

- Two cells in the **cluster window** are selected as “seeds” (0, mid-row) and (1, mid-row)

Selected grid cells

Grid Clustering – Select and Readout

- Two cells in the **cluster window** are selected as “seeds” (0, mid-row) and (1, mid-row)
- The “selected” state is propagated to the neighboring hits

Grid Clustering – Select and Readout

- Two cells in the **cluster window** are selected as “seeds” (0, mid-row) and (1, mid-row)
- The “selected” state is propagated to the neighboring hits
- The previous hit is now readout

Grid Clustering – Select and Readout

- The hits are sent out in their **local coordinates** with regards to the **reference hit**
 - Less bits for calculation in the next processing element
- The **reference hit** is sent out in absolute coordinates in the **end cluster word**
- Two cells in the **cluster window** are selected as “seeds” (0, mid-row) and (1, mid-row)
- The “selected” state is propagated to the neighboring hits
- The previous hit is now readout
- Selecting and reading out the cluster is executed in parallel
- The hits that do not belong to the cluster are recovered and written to the circular buffer in their absolute coordinates
- 8 bits of the **end_event** word are used for **error flags**

Grid Clustering – Block Diagram

- The Grid Clustering Module's main components are:

- The Grid
- The ToT memory
- The Circular Buffer

- It is fundamentally a **control intensive data manipulation**

- Time Over Threshold (ToT) is the measurement of collected charge to be passed to the next processing step
- This information is necessary for the Centroid Calculation in the Clustering Implementation and also for the Track Fitting in the FTK

Grid Clustering – The Grid

- The Grid is based on a pre-existing algorithm, with some simplifications required because
 - it now has a smaller size than in its initially proposed implementation
 - a reference hit is defined
- The current Grid size chosen is 21x8 pixels
- Pixels exceeding this size will be split at the boundary (and recovered in the post-processing step)

Grid Clustering – ToT Memory

- The ToT Memory is a single port RAM of 256 words implemented on BRAM
(A BRAM is the configurable memory module on an FPGA device)
- In this memory the ToT (TimeOverThreshold) values of the hits loaded in the Grid are stored
- The stored values are addressed by their coordinates in a way that
 - allows the memory size to be generic
 - minimizes the imposed delay

Grid Clustering – Circular Buffer

- A circular buffer with extra functionality
- Hits are read and written simultaneously, which can cause data to be read multiple times in the same operational state →

- Done_read signal: Allows reading of hits up to a previously stored value of the write_pointer

Grid Clustering – Circular Buffer

- Everytime a hit is written to the circular buffer it is compared to the value of the **leftmost register**
- The **leftmost register** stores the value of the hit in the circular buffer with the leftmost column value
- This hit will become the **reference hit** when data are recovered from the circular buffer to be loaded to the Grid
- The process continues until an **end_event** or a **module_trailer** arrives and the circ_buff is empty

Grid Clustering – Current State

- The Grid Clustering module is **fully functional**
- Successfully passed **post-place&route simulation** with a **12ns clock** on a Spartan 6-LX150T FPGA

Slice Logic Utilization:

Number of Slice Registers:	816 out of 184,304	1%
Number of Slice LUTs:	2,021 out of 92,152	2%
Number of RAMB8BWERs:	2 out of 536	1%

- Typical algorithm execution will require on average $O(10)$ clock cycles for each input hit
- The number of clock cycles/hit will depend on module occupancy

Grid Clustering - Performance

- The Grid Clustering module has achieved an operational frequency of 80MHz
- For 80MHz / ~ 10 clock/hit $\rightarrow \sim 8$ MHz per hit
- By implementing 10 copies of the module:
10 parallel copies $\rightarrow \sim 80$ MHz hit processing rate $\rightarrow 20\%$ FPGA device area occupied
- An increase even to a parallelism of 15 to 20 modules can be achieved with even better performance results

The Clustering Implementation

- The current implementation is an evolution of a linear algorithm with a high cost in terms of FPGA resources
- In the previous algorithm grids of 168x4 or 328x8 pixels were used. For these grid sizes the extrapolated area and clock results (for the Spartan 6-LX150T) would be:

Grid Size	Slice Registers	Slice LUTs	Clock	Frequency
21x8 (current)	696 (1%)	1950 (2%)	12ns	83Mhz
168x4	2784 (1.5%)	7800 (8.2%)	68ns	14.8Mhz
328x8	10510 (5.7%)	30457 (33%)	265ns	3.8Mhz

- In the new version of the algorithm the logic of each grid cell is much reduced

Clustering Modules

Clustering Modules

Hit Decoder – Issues addressed

ATLAS Pixel Bytestream Format

Module header	001PtIbxxMMMMMMMSSSLLLLBBBBBBBB
[Module hit]	100xFFFFTTTTTTTTxxCCCCRRRRRRRR
[...]	100xFFFFTTTTTTTTxxCCCCRRRRRRRR
[Module errors]	...
Module trailer	010ZHVxxxxxxxxxxxxxxxxxxxxxxxx
[...]	001PtIbxxMMMMMMMLLLLLLLLLBBBBBBBB
[...]	100xFFFFTTTTTTTTxxCCCCRRRRRRRR
[...]	...
[...]	010ZHVxxxxxxxxxxxxxxxxxxxxxxxx

- Transform the input data to the format needed, dropping all unnecessary information (bits)
- Trace and fix errors of missing trailer words (end module, end event).
- Drop hits from unidentified events and modules

Hit Decoder – Issues addressed

- FE chip numbering is circular
- FE chips are readout in the order of their numbering →
- Incoming data is not in sequence:
 - Hits from FE < 8 come in the reverse column order
 - Hits from FE ≥ 8 come in the correct column order

Hit Decoder – Block Diagram

- Hits from $FE < 8$ are stored in a LIFO
- When a hit from $FE \geq 8$ arrives it is stored in a register
- The column value is compared with the last LIFO word
- The hit with the smallest column value is propagated to the output FIFO
- FIFOs are used to separate functions and simplify control logic
- Input and Output FIFOs could be used for possible Clock Domain crossing

Clustering Modules

Clustering Modules

Clustering Modules – Centroid Calculation

- The post-processing step in the Clustering system is the one that actually performs the data reduction:
It reduces the set of cluster coordinates to one
- **FTK cluster centroid** is calculated as linear interpolation of deposited charge
- The Centroid Calculation step will output the cluster centroid and also the cluster size in two coordinates
- A center of mass can also be used (will not be used for FTK) for different applications (e.g. image processing)

Clustering Modules – Centroid Calculation

0					
1					
2	30	70	80		
3	40	75	60		
4					
	0	1	2	3	4

$$qRatio = \frac{qColMax}{qColMin + qColMax} = \frac{80 + 60}{(30 + 40) + (80 + 60)} = \frac{140}{210} = \frac{2}{3}$$

$$x_average = \frac{ColMin + ColMax}{2} - a \cdot (qRatio - 0.5)$$

Centroid

Correction

- Constant a is a function of pixel position
- Calculate the charging balance between the two sides of the cluster (left-right for y, top-bottom for x)
- Apply a correction with respect to the centroid
- For the above 3x2 cluster the centroid coordinates would be (1.15, 2.5)

Clustering Modules - Parallelization

Clustering Modules - Parallelization

- The Grid Clustering and Center of Mass modules are working independently in different streams of data
- Each stream consists of data from the same module
- The data is tagged by its event and module number
- In the read out process data must be read in the proper event sequence
- The module number sequence in the read out process is irrelevant since the system will propagate each module data to a separate AM chip
- The full algorithm keeps up with the 40MHz input rate

Conclusions – Summary

- A **2D-Clustering** implementation was presented
- It targets the **ATLAS FastTrack** but it is generic enough to be used in general image processing applications
- The module achieves a **~80MHz** operational frequency with 1% FPGA slice Registers and 2% slice LUTs occupation
- An estimated **~10 cycles** per hit are necessary for cluster identification
(The numbers will be verified by FTK simulation in the near future)
- With x10 parallelization a **~80MHz** input rate will be covered (the specifications call for **40MHz**)

Acknowledgements

- The presented work was supported by Istituto Nazionale di Fisica Nucleare, and European community FP7 funds (Marie Curie IAPP Project 324318 FTK).

Thank you!

BackUp Slides – Data Format

BackUp Slides – Centroid Calculation

Calculation process

- Find the smallest and largest pixel index for column or row
- Sum the ToT (deposited charge estimator) for all pixels in the smallest and largest column or row
- Center is calculated as:
 - $qRatio_y = qRowMax / \text{float}(qRowMin + qRowMax);$
 - $qRatio_x = qColMax / \text{float}(qColMin + qColMax);$
 - $deltax = 30 * \text{micrometer} * (\text{sensorThickness} / (250 * \text{micrometer}));$
 - $deltay = \text{sensorThickness} * \text{fabs}(\text{pixelEstimateCotTheta});$
 - $y_average = (\text{rowMin} + \text{rowMax}) / 2. + deltax * (\text{etaRow} - 0.5) / \text{phiPitch};$
 - $x_average = (\text{colMin} + \text{colMax}) / 2. + deltay * (\text{etaCol} - 0.5) / \text{etaPitch};$
- where pixelEstimateCotTheta is an estimate of the CotTheta obtained from $(\text{colMin} + \text{colMax}) / 2.$