Performance of a Real-time Multipurpose 2-Dimensional Clustering Algorithm Developed for the ATLAS Experiment

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Abstract—In this paper the performance of the 2D pixel clustering algorithm developed for the Input Mezzanine card of the ATLAS Fast Tracker system is presented. Fast Tracker is an approved ATLAS upgrade that has the goal to provide a complete list of tracks to the ATLAS High Level Trigger for each level-1 accepted event, at up to 100 kHz event rate with a very small latency, in the order of 100 μ s. The Input Mezzanine card is the input stage of the Fast Tracker system. Its role is to receive data from the silicon detector and perform real time clustering, thus to reduce the amount of data propagated to the subsequent processing levels with minimal information loss. We focus on the most challenging component on the Input Mezzanine card, the 2D clustering algorithm executed on the pixel data. We compare two different implementations of the algorithm. The first is one called the ideal one which searches clusters of pixels in the whole silicon module at once and calculates the cluster centroids exploiting the whole available information, included the precise sharing of charge produced by the particle between contiguous pixels of the cluster. The second one uses a sliding window technique to identify clusters of contiguous pixels, one at a time. In addition, a simplified centre of mass is calculated as the center of a bounding box which contains the cluster. The size of the window sets a limit to the maximum cluster that can be found, so clusters can be split if their sizes exceeds the window one. We show that the simplified implementation saves a large amount of hardware resources and has the equivalent performance for the use in the Fast Tracker processor. Finally, we describe an event display that is a powerful diagnostic/monitoring tool used to understand in detail the performance of the algorithm, also used during the data taking.

Index Terms—Clustering, Image processing, Parallel processing, Trigger circuits, Field programmable gate arrays, Pixel detectors.

I. INTRODUCTION

The algorithm implementations presented in this paper were developed for the Fast Tracker (FTK) [1], which is an approved ATLAS trigger upgrade [2]. The Fast Tracker will provide reconstructed tracks as input to the High Level Trigger (HLT) [3], in addition to the raw detector hits. Track

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reconstruction will cover the entire Silicon Detector with high quality events. In order to achieve these goals the first step of the Fast Tracker processing needs to perform clustering of the Pixel detector [4] data. We focus on the most challenging component on the IM card, the 2D clustering algorithm, which will be executed on all pixel modules [5] data.

The main challenge is to process the 160 Gbit/s input data. Data is received over 132 S-Link fibers each running at 1.2 Gbits/s. The data format consist of 32 bit words at a rate of 40 MHz and each word corresponds to one detector hit, with its coordinates (row and column within the module) and its Time over Threshold (ToT) information encoded [5]. The ability to process hits at a 40 MHz rate is required. The clustering algorithm must provide high quality resolution, in order to match the high quality required by the HLT.

In order to achieve sufficient speed combined with the required level of quality, the algorithm is split in three functional modules. The first module reorders the hits, which initially arrive randomly, into an order appropriate for their fast processing from the following modules. The second module groups together hits belonging to the same cluster. This is the most time-consuming part of the algorithm where we will exploit a dedicated logic in order to achieve linear processing time. The final module analyzes the hits of the cluster in order to calculate the cluster properties of interest, such as the center of mass of the cluster.

Powerful FPGAs with their logic distributed in a 2D structure are perfectly suitable for mapping the 2D array of a pixel module. The 2D grid of clustering cells implemented with FPGA logic array can work in parallel to speed-up substantially the first step of the algorithm. In addition the FPGA offers the needed flexibility to provide results as precise as needed for the second step.

II. THE ALGORITHM IMPLEMENTATIONS

Two different strategies have been used for the 2D clustering inside FTK. These strategies use different approaches in order to form the clusters of hits on the pixel module, consisting of 328×144 cells. Both strategies aim to group hits on the pixel detector modules which are connected either side-to-side or diagonally, thus to create a cluster, and then calculate the center of mass of the produced cluster. The centroid is then sent to the subsequent subsystems of the FTK and used for the track fitting.

83 A. The "ideal" implementation

84 The first implementation [6] used a 2D grid of logical
 85 cells representing a whole pixel module. On the first step,
 86 the cluster identification algorithm groups all connected hits,
 87 forming the cluster. On the second step, the center of mass
 88 of the cluster is calculated as a ToT weighted average of the
 89 positions of its hits. The second step is completely decoupled
 90 from the first one. It can be modified to calculate any cluster
 91 property of interest depending on the specific application. The
 92 ToT information is stored in the RAM while hits are being
 93 loaded on the grid. During the grid readout and cluster building
 94 procedure, the ToT is expected to be easily retrieved and sent
 95 to the second step logic.

96 The study of the hardware size and the clock speed of this
 97 implementation [4] demonstrated that the whole grid needs
 98 a lot of resources to meet the required timing performance.
 99 The implementation done in 2008 showed that 60% of the
 100 logic in the xv5vlx330 Xilinx FPGA [6], the largest of the
 101 xv5vlx group, was necessary to process data from one input
 102 S-Link. More capacious and expensive FPGAs would have
 103 been required.

104 B. The "simplified" implementation

105 The second implementation [7] uses a small sliding grid,
 106 a window moving on the pixel module, in order to reduce
 107 the hardware needs. The window is moving in the sense that
 108 during the several passes of the cluster identification process it
 109 is virtually placed on different positions on the pixel module
 110 and it is filled with the hits whose coordinates fall inside
 111 the dimensions of the window. This implementation reduces
 112 the required logic by a factor of approximately 64 compared
 113 with the ideal implementation [8], for the selected moving
 114 window size. The size of the window sets a limit to the
 115 maximum cluster that can be found, so a cluster can be split if
 116 either of its dimensions exceed the dimensions of the window.
 117 In addition, a simplified center of mass is calculated as the
 118 center of a bounding box which contains the cluster. This
 119 implementation does not use the ToT information associated
 120 with the hits of the cluster. These simplifications are expected
 121 to have a small impact on the tracking resolution since most
 122 clusters are up to two pixels wide along the ϕ direction and
 123 the z direction¹. Figure 1 shows the size of bounding boxes
 124 containing the identified clusters created by a top quark sample
 125 with a high pile-up. The window size is a free parameter in
 126 the implementation and it is chosen to have a height of 21
 127 rows and a length of 8 columns. This is a very large window
 128 for clean single particle clusters in the Pixel detector, which
 129 are at maximum 3×5 large [4].

130 III. THE ALGORITHM SIMULATION AND COMPARISON

131 A. The bit-accurate 2D clustering simulation

132 As any complex architecture, the 2D clustering algorithm
 133 requires a careful simulation. The simulation was developed
 134 as a module for FTKSim [9], which is a complete simulation,

Fig. 1. Cluster dimensions for a top quark sample.

135 of the FTK system. FTKSim processes complete ATLAS
 136 events and creates exactly the same list of tracks that will be
 137 produced by the FTK hardware. The program serves a number
 138 of purposes, such as:

- 139 • validation of the hardware,
- 140 • detailed and reliable evaluation of FTK physics performance by processing complete events produced by the full ATLAS detector simulation,
- 141 • evaluation of crucial parameters needed for the hardware design and optimization,
- 142 • determination of the large set of constants needed for programming FTK, and
- 143 • determination of tracking performance parameters for use in fast parametric detector simulation for high statistics studies of physics performance.

144 In the case of the clustering algorithm FTKsim is bit-accurate and is able to reproduce perfectly both the ideal and simplified implementation. The simplified hardware conditions were added:

- 145 1) the hits are ordered in the same way as the hardware to avoid any potential innaccuracy in the next steps.
- 146 2) the sliding window mechanism was added in FTKsim, to search for one cluster at time. This became an option to replace the direct search of many clusters on the whole module.
- 147 3) the use of the ToT became optional and the center of mass calculation as the center of the bounding box encircling the cluster became available.

148 The methods used for the cluster identification and for the centroid calculation can be switched by a flag inside the simulation, the Pixel Clustering Mode (PCM). The flag currently has three different values for the three different combinations of the available methods: (1) PCM1 selecting the ideal method for both cluster identification and centroid calculation; (2) PCM100 selecting the simplified clustering but the ideal centroid calculation; (3) PCM101 using both simplified methods.

171 B. Simulation results

172 In this section, the effect of the selected methods on the resolution of the output tracks of the FTK is examined. For

¹ ϕ and z coordinates refer to the cylindrical geometry of pixel modules in the barrel detector.

the comparison only one of the track parameters is shown, the pseudorapidity η .

Two types of simulated event samples were used to compare the three options. The first is a very clean sample consisting of single muons without any superposition of soft collisions (pile-up) which was simulated with a flat distribution in the particle helix parameters. The second is an extremely complex sample of top quark events with an overlay of an average of 60 pile-up events and a center of mass energy $\sqrt{s} = 14$ TeV.

Figure 2 and Figure 3 show the resolution of the track parameter η for the single muon and the top quark sample respectively. In both figures, the shaded area corresponds to PCM1, the red line to PCM100 and the blue line to PCM101. The switching between PCM1 and PCM100, by introducing only the realistic clustering algorithm, creates a minor deviation from the ideal implementation. As it can be seen in the legend of Figure 1, the percentage of clusters reaching the end of the window is 1.6% for the top quark sample, which is very complex, meaning that the percentage of split clusters will be smaller than that. However, the simplified centroid calculation has a bigger effect on the resolution, with the effect being more noticeable on the tails of the distribution although this is partially obscured the statistics is low.

Fig. 2. Resolution of track parameter η for the single muon sample.

Since the simplified implementation could potentially split a cluster, and thus create a fake hit in the detector, it is important to examine the impact of these extra clusters on the quality of the final FTK tracks. The quality of the track fitting should provide a valid indication on this effect. The FTK examines the χ^2 of the fit by performing a linear calculation [9]. The calculation is a set of scalar products of the hit coordinates and pre-calculated constants that take into account the detector geometry and alignment. First, FTK examines the tracks and keeps the ones that pass a χ^2/ndof cut. In case that there are hits on all the detector layers but the χ^2 fails the cut, the track is re-fitted with one hit dropped each time. This allows the system to recover from a random hit, which can be either a random hit, or a split cluster. Also, FTK examines possible

Fig. 3. Resolution of track parameter η for the top quark sample.

duplicate tracks. In case two tracks are considered duplicated, FTK keeps the one with the best χ^2 fit.

Figure 4 and Figure 5 show the χ^2 distribution for the single muon and the top quark sample respectively. The green line represents PCM1, the red line PCM100, while the blue line represents PCM101. The ideal implementation and the implementation using the simplified centroid match exactly. However, PCM101 leads to a loss of events, as seen on the ratio plot.

Fig. 4. χ^2 distribution for single muon sample.

IV. DEMONSTRATOR

In order to gain a better understanding of the operating principle, an event display able to portray the hardware operation has been developed in C++11 using the Qt toolkit. The

Fig. 5. χ^2 distribution for top quark sample.

Fig. 6. Region of a pixel module created with the demonstrator.

original implementation of the event display demonstrator was designed as a standalone program but the design is flexible in order to allow integration with the FTKSim. Furthermore, the modular design allows the user to choose freely any combination of clustering implementations and centroid calculation modes. Therefore, it can provide valuable insight for the future development of the firmware, allowing a visualization of the centroid location.

The display can accept the same input as the hardware and then perform an accurate simulation of the hardware. The results are presented on a 2D grid which represents a pixel or an Insertable B-Layer (IBL) module. Alternatively, the display is able to receive data from the hardware via spy buffers. Figure 6 shows a small active region of a pixel module taken from the event display. Each cell is color-coded based on the charge deposited on the pixel, with blue representing the lowest ToT and red the highest. The centroid is represented by a magenta circle. The moving window is represented by the yellow region. The window on the demonstrator follows the same movement as the window on the hardware. In this example, it can be seen that the largest cluster has been split (two magenta centroids appear on it) since it exceeded the width of the window (8 columns $\times$ 21 rows). Consequently, modifications of the algorithms can be evaluated and understood directly.

V. CONCLUSIONS

Two different implementations of a 2D clustering algorithm for pixel detector data have been compared to evaluate their relative performance. The simplified implementation, which reduces the required logic by a factor of approximately 64 for the selected window size, has the equivalent performance as the ideal implementation when they are compared using two event samples simulated with the FTK system.

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