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Fast pattern recognition with the ATLAS L1Track trigger for the HL-LHC

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A fast hardware based track trigger is being developed in ATLAS for the High Luminosity upgrade of the Large Hadron Collider. The goal is to achieve trigger levels in the high pile-up conditions of the High Luminosity Large Hadron Collider that are similar or better than those achieved at low pile-up conditions by adding tracking information to the ATLAS hardware trigger. A method for fast pattern recognition using the Hough transform is investigated. In this method, detector hits are mapped onto a 2D parameter space with one parameter related to the transverse momentum and one to the initial track direction. The performance of the Hough transform is studied at different pile-up values. It is also compared, using full event simulation of events with average pile-up of 200, with a method based on matching detector hits to pattern banks of simulated tracks stored in a custom made Associative Memory ASICs. The pattern recognition is followed by a track fitting step which calculates the track parameters. The speed and precision of the track fitting depends on the quality of the hits selected by the pattern recognition step. The figures of merit of the pattern recognition are measured by the efficiency for finding hits from high transverse momentum tracks and the power of rejecting hits from low transverse momentum tracks and fake tracks.

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1. Introduction

The ATLAS experiment studies interactions and properties of elementary particles produced in high-energy proton-proton collisions at the Large Hadron Collider (LHC). The experiment is aimed at probing the Standard Model of particle physics and to search for phenomena beyond. The ATLAS detector consists of three barrel shaped sub-detectors centred around the collision point. Closest to the interaction point is the tracker, followed by the electromagnetic and hadronic calorimeters, and finally the muon spectrometer [1].

The LHC delivers 1000 million proton-proton collisions every second to ATLAS. Saving every event for offline analysis is impossible due to the sheer volume of data. Instead, a few hundred events per second are selected using a two-stage trigger system consisting of a hardware trigger based on input from calorimeter and muon trigger chambers followed by the software-based High Level Trigger.

The High Luminosity upgrade of the LHC (HL-LHC), scheduled to start operating in 2024, is expected to increase the instantaneous proton-proton luminosity to $7.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and the number of interactions per proton bunch crossing, so called pile-up, from 40 to approximately 200. At the same time, the ATLAS Phase-II upgrade will take place, which will, amongst other things, replace the current tracker with new silicon pixel and strip detectors.

In the HL-LHC pile-up conditions, the current ATLAS trigger will not be able to maintain reasonable trigger rates with acceptably low energy and momentum trigger thresholds. The proposed solution in the Phase-II upgrade is to introduce a two-level hardware trigger. The first level, L0, will use the calorimeter and the muon spectrometer to define Regions of Interest (RoIs) covering maximum 10 % of the detector volume. In the second level, the Level-1 Track Trigger (L1Track), will read out the inner tracker in these RoIs and search for tracks of charged particles. L1Track will first perform a pattern recognition step to find hits consistent with high-momentum tracks, then pass these to a track fitting step that computes the track parameters using constants predetermined from simulation. The baseline approach for the pattern recognition is to use custom designed Associative Memory (AM) ASICs to perform *pattern matching* [2]. Track fitting would be performed in an FPGA. A track trigger of this kind has been shown to maintain reasonable trigger rates while still maintaining low energy and momentum thresholds [3].

2. Pattern recognition for L1Track using the Hough transform

An alternative approach to using AM ASICSs is to use the Hough transform for pattern recognition. This has the advantage of there being no need for custom made integrated circuits.

The Hough transform aims to detect a fixed type of feature in a binary image by parametrising that feature and mapping each point in an image to the set of all parameters compatible with that point. Then, votes are cast in a discrete parameter space, called an *accumulator*, for each point. If two points belong to the same feature, their votes in the accumulator will overlap at the specific parameter values describing that point [4]. For example: if the feature is a line, it would be parametrised by a slope and an offset. The accumulator would then be a two-dimensional histogram with the slope on one axis and the offset on the other. All combinations of slopes and offsets would then be calculated for each point and the corresponding bins in the accumulator incremented. Bins with contributions from several points would then be considered line candidates with slope and offset given by the bin coordinates. In a track trigger, the feature one would like to detect is high-momentum tracks.

The track of a charged particle in the transverse plane (x-y plane) of the ATLAS tracker has the shape of a circular arc which can be described by the transverse momentum p_T and its initial angular direction ϕ_0. For small angles, and if a vertex constraint is imposed, each detector hit will make a straight line in the accumulator described by

$$\frac{A}{qp_\mathrm{T}} = \frac{\phi_0 - \varphi}{r}, \tag{2.1}$$

where (r,φ) is the hit's polar coordinates, q is the charge of the particle, and $A \approx 3\times 10^{-4}\,\mathrm{GeV\,mm^{-1}}$ is the curvature constant for the 2 T magnetic field of the tracker. Figure 1 shows an illustration of the application of the Hough transform using Equation 2.1 to hits in the tracker.

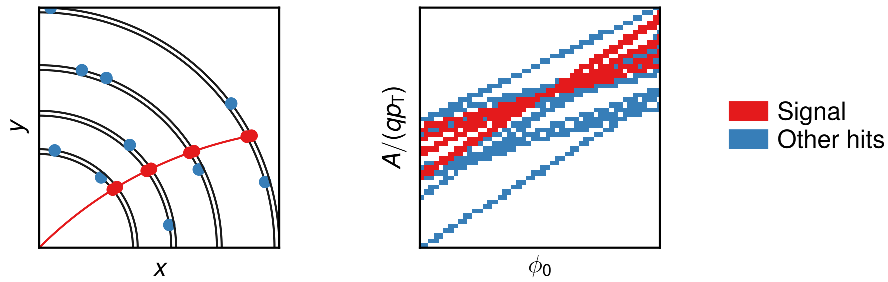

Figure 1: Illustration of the Hough transform. The left figure shows a slice of the transverse detector plane with hits in eight layers along a charged particle track and some unassociated hits. The right figure shows the corresponding Hough accumulator.

To simulate the Hough transform pattern recognition for L1Track, a single step of the Hough transform is applied to $\Delta\phi_0 = 0.2$ by $\Delta\eta = 0.2$ RoIs with $z_0 \in [-150, 150]$ mm. The large extension in z causes overlap of hits in the transverse plane which makes it hard for the Hough transform to separate signal from background. To help mitigate this, the RoI is split into several parts in z, as illustrated in Figure 2, with splitting boundaries given by

$$z_{\mathrm{min},n}(r) = z_0 + n\Delta z + r\sinh\eta_{\mathrm{min}}, \tag{2.2}$$

$$z_{\mathrm{max},n}(r) = z_0 + (n+1)\Delta z + r\sinh\eta_{\mathrm{max}}, \tag{2.3}$$

where $n = 0,1,\ldots,N$ is the split index, $[\eta_{\mathrm{min}}, \eta_{\mathrm{max}}]$ is the η range, $[z_0, z_0 + N\Delta z]$ is the z range, and r is the radial coordinate of the detector layer. Each of the split parts has its own accumulator. This splitting technique reduces the occupancy in the accumulators which improves the track finding efficiency and the rejection of unwanted hits. It is also suitable for a multi-threaded environment, such as an FPGA. It should be noted that nearby splits are overlapping and the same hit can show up in multiple accumulators.

After the accumulator has been filled for each split in z, using Equation 2.1, a threshold is applied on the minimum of number of unique layers hit. Hits from nearby bins in the accumulator that pass the threshold are merged into "hit groups" using a simple geometric cut. Finally, the number of hit groups are reduced by removing groups which are fully contained in other groups,

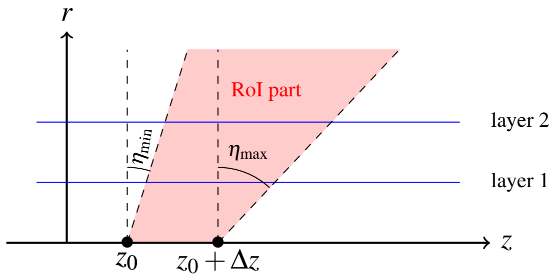

Figure 2: The RoI is split into several parts in z to reduce occupancy in the Hough accumulators. The boundaries are given by Equations 2.2 and 2.3.

i.e. groups where the list of hits is a subset of the list of hits in another group. The surviving hit groups would be passed on to the track fitting.

3. Performance of the Hough transform for L1Track

In this section, the performance of the Hough transform for finding single muons embedded in minimum bias events is studied for the RoI defined by $\phi_0 \in [0.3, 0.5]$ and $\eta \in [0.1, 0.3]$. First, the performance as a function of the number of hits per RoI is studied using an overlay of single minimum bias events, then the performance at pile-up 200 is compared with AM pattern matching using full event simulation. The muons which are embedded in pile-up have a flat $1/p_\mathrm{T}$ spectrum with $4\,\mathrm{GeV} < p_\mathrm{T} < 400\,\mathrm{GeV}$, $|z_0| < 150\,\mathrm{mm}$, flat angular distributions, and equal probability of having positive or negative charge. The detector studied is an eight layer silicon strip tracker. This particular detector layout was chosen for comparison to the existing results for the AM approach.

The z-range is split into 12 parts as described in Section 2. Using a finer splitting is found not to improve the result due to the limited z resolution of the silicon strip detector at this point in the read-out chain. The ϕ_0 range of the accumulator is limited by the RoI and the A/p_T range by the minimum accepted p_T. The optimum number of bins in the two dimensions of the accumulator depends on the geometry and resolution of the detector. For the particular detector geometry used here, it was found that using between 40 and 50 bins in A/p_T and between 1000 and 1200 bins in ϕ_0 for each split in z gives good rejection of minimum bias events whilst maintaining a high efficiency of finding muon tracks. The efficiency of finding muon tracks is computed relative to the offline reconstruction and a muon is considered to be found if at least 6 muon hits are found in unique layers.

The performance of the Hough transform for single muons embedded in minimum bias events has been investigated. The pile-up in minimum bias events was varied by overlaying single minimum bias events; 800 hits per RoI corresponds roughly to a pile-up of 200. The muon finding efficiency was kept between 98.5 % and 99.0 % by slight variations of the configuration of the Hough transform. The number of hit combinations, i.e. the number of fits that would have to be performed by the subsequent track fitting, is found to increase exponentially for a fixed configuration of the Hough transform. However, at high pile-up the muon finding efficiency for a certain configuration of the Hough transform increases enough that the configuration can be changed to lower the number of hit combinations while maintaining an efficiency of 98.5 %. The total number of fits that would have to be performed stays below 400 and the rejection of hits from minimum bias events above 85 % for up to 900 hits per RoI.

Table 1 compares the performance of the Hough transform with AM pattern matching. Here, the efficiency for single muons is studied without pile-up for the AM approach but with pile-up for the Hough transform. The number of hit combinations passing the pattern recognition stage for minimum bias events is studied using full event simulation at pile-up of 200. The number of hit combinations for the AM approach is determined by the number of fits performed by the track fitting. For the Hough transform, it is first calculated for each "hit group" by taking the product of the number of hits in each layer. The total number of hit combinations is then given by summing over the hit groups. The AM pattern matching has a higher efficiency and better rejection. It should also be noted that the muon finding efficiency for the Hough transform actually improves when adding adding minimum bias because this occasionally pushes the area of the accumulator where the muon is over the detection threshold.

	Efficiency		Number of fits	
Sample	Hough	AM	Hough	AM
Min. bias	-	-	344	170
Muon	98.3 %	99.2 %	2	11

Table 1: Performance of the Hough transform and the AM approach for a $\Delta\phi_0 = 0.2$ part of the central barrel region RoI of $0.1 < \eta < 0.3$. The efficiency of finding a muon track candidate is computed relative to the ATLAS offline reconstruction. The minimum bias sample has a pile-up of 200. For the Hough transform, the number of fits is computed by taking all combinations of hits passing the recognition step. For the AM approach, the number of fits is determined by performing the actual track fitting. The number of fits for muons is for samples containing only single muons.

4. Conclusions and outlook

The Hough transform, as implemented here, shows a track finding efficiency of above 98.5 % for single muons with $p_T > 4$ GeV in the central barrel RoI of $0.1 < \eta < 0.3$. At the same time, it is able to reject between 85 % and 95 % of the total number of hits for up to 900 hits per RoI.

Comparing pattern recognition using the Hough transform to AM pattern matching, it is clear that the AM approach requires fewer fits in high pile-up conditions and has a higher efficiency for finding single muons tracks. However, the Hough transform has the advantage that it can be implemented in a standard FPGA, even the same FPGA as the track fitting, rather than having the added complexity of additional AM ASICs. The Hough transform also has the possibility to include more layers to increase efficiency if needed, although this would increase the complexity of the track fitting and data readout.

Work is currently ongoing to implement the Hough transform in an FPGA in order to measure the execution time. In principle, the transform can be computed for each combination of hit, bin in ϕ_0, and split in z in parallel. This opens up the possibility of implementing a highly parallel algorithm.

References

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