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Study of Track Reconstruction using Retina algorithm for charged particles in magnetic field

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ABSTRACT: Real-time track reconstruction in high energy physics experiments at colliders running at high luminosity is very challenging for trigger systems. When it is run on FPGAs, the Retina algorithm has been used in High Energy Physics experiments mainly in the case of parallel plane detection layer without magnetic field such as the LHCb VELO detector. However another interesting geometry is a tracking detector with a barrel shape made of multiple concentric cylindrical layers surrounded by a strong (several Tesla) magnetic field. In this paper we introduce our simulation work of reconstructing the charged particle trajectory in the strong magnetic field environment by using the Retina algorithm under the structure of this barrel shape detector. Based on simulations, preliminary results on the track reconstruction resolution are presented.

KEYWORDS: Track reconstruction; Pattern recognition; Retina algorithm;

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1. Introduction to the Retina Algorithm in particle track reconstruction

In High Energy Particle (HEP) physics experiments, the track reconstruction is always one of the important steps to identify the particles. Over the last decades, as the collider luminosity keeps increasing and therefore the rate of particles to be detected by the equipment, more rapid and efficiency triggering system have been required [1][2]. Therefore, new pattern recognition algorithms have been recently introduced in HEP. Retina is one of them.

The Retina algorithm is a recognition algorithm that finds the expected trajectory by scanning a discrete multi-dimension parameter space where each bin, also called cell, represents a pattern or a particle trajectory and by computing, for each cell, the “distance” between the detected hits and the corresponding pattern [3][4]. In our previous studies [5], the Retina algorithm has been applied to the reconstruction of linear particle trajectories in parallel-layer detector structures without magnetic fields. The initial position and direction of the straight line track are estimated by the Retina algorithm. Two firmware implementations have been developed on FPGA and tested with a Xilinx KC705 evaluation board [6].

In the present paper, we focus our study on the use of the Retina algorithm to reconstruct curved tracks from charged particles passing through a magnetic field. The goal of the track reconstruction in this case is to measure the transverse momentum, P_t, of the charged particles and their initial direction angle. While the ultimate goal is to perform the track reconstruction of bended trajectories with the Retina algorithm on FPGA devices, we present here our preliminary studies performed with simulations.

2. Track Simulation and reconstruction with Retina in magnetic field

The first part of this section presents the detector geometry and the simulation of charged particles inside. In the second part we describe the application of the Retina algorithm to reconstructed the curved particle tracks.

2.1 detector geometry setup & track generation

In order to investigate the feasibility and performance of the Retina trajectory reconstruction for a barrel-shape multi-layer tracker in a strong magnetic field, we first developed a simple simulation and then used a more complete simulation based on GEANT4 to better simulate the detector effects.

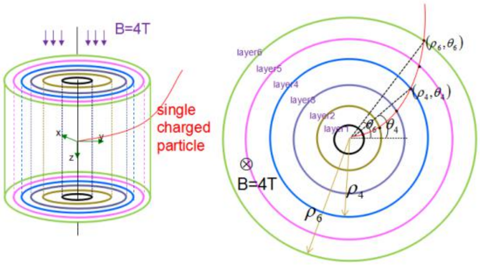


Figure 1. Detector geometry and track of charged particles in ideal case.

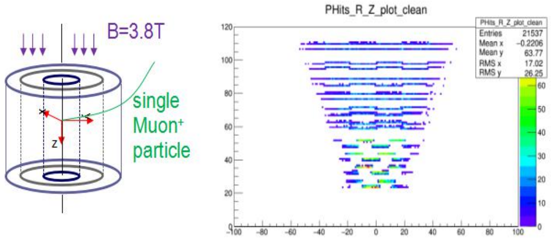


Figure 2. Detector geometry and track of charged particles generated by GEANT4.

Our simple simulation consists in an ideal detector model with a mathematical modeling of the charged particle trajectory. Figure 1 shows the detector geometry and the environmental configuration in this ideal case, with a six layer barrel tracking detector surrounded by a 4T magnetic field along the Z-axis. The concentric cylindrical layers are from 0.2 meters (innermost 1st layer) to 1.15 meters (outermost 6th layer) along the radius. One event consists in a single charged particle starting at the center (0,0,0) of these cylinder layers with a random initial angle, and crossing six barrel layers from inner to outer, providing the corresponding position information at each layer. This position information (coordinates) is used as the input of the Retina algorithm to reconstruct the Pt and initial flight direction of the particle. In presence of a magnetic field, the charged particle trajectories will bend. The trajectory changes from a straight line to a partial arc. We assume that the magnetic field strength (B) is equal to 4 Tesla and the particle is a muon of positive charge (Q). The relationship between the radius of the arc (r_0) and the particle transverse momentum (P_t) is given by eq.(1) while the relationship between the hit position at each layer and the particle P_t is given by eq.(2), where θ_0 represents the initial direction angle of the particles and θ_n ρ_n represent the particle coordinate in the nth layer.

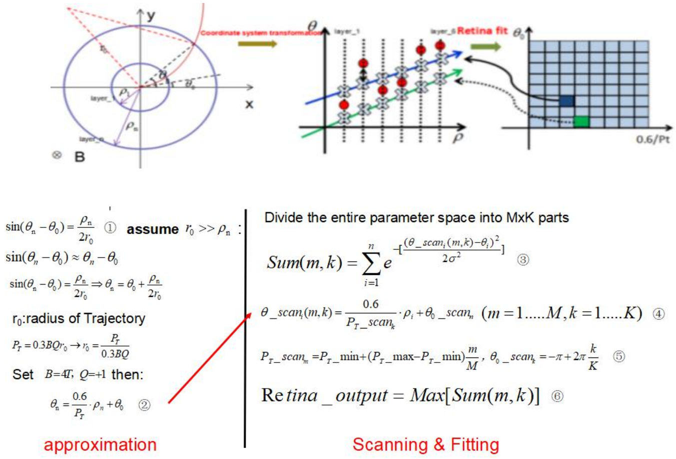
$$r_0 = \frac{P_t}{0.3BQ} = \frac{P_t}{1.2} \text{........} (1) \qquad \sin(\theta_n - \theta_0) = \frac{\rho_n}{2r_0} \text{.........} (2)$$

After this ideal detector simulation we have then implemented a more realistic simulation based on the GEANT4 software [7]. In this case, the detector geometry and environmental configuration are similar to the above ideal case (see Figure. 2). All muon particles will start at point (0,0,0) and go across 10 barrel-like layers. The right side of the Figure 2 shows the distribution of the hits accumulated on the 10 layers from 20000 tracks in the R-Z plane. From the graph, the detailed structure this more realistic barrel tracker is clearly visible.

By default, the effects of Multiple Scattering and detector resolution are included when we generate tracks with GEANT4. Therefore to compare the results between GEANT4 and our simple model, we have also added both detector effects in the track generation step of our ideal case. The position resolution of the detector we set in the ideal case amounts to 100um and the thickness of detector layer corresponds to 10% of the radiation length of the detector material.

2.2 Application of the Retina Algorithm for curved particle tracks

There are two main steps to apply Retina algorithm to reconstruct curved tracks in magnetic field (see figure 3): the first step is to linearize the patterns. For that we choose the polar coordinate system (ρ,θ) to represent the position information. We assume that the particles with high Pt will only slightly bend when they go through the magnetic field, so the change of direction θ_n-θ_0 is almost equal to 0 and $\sin(\theta_n$-$\theta_0)$ is almost equal to θ_n-θ_0.Consequently the exact equation ① (see Figure 3) simplifies and becomes the linear equation ②. Naturally, the Retina parameter space becomes the (ρ,θ) plane as the equivalent ($1/P_t$,θ_0).



$$\sin(\theta_n - \theta_0) = \frac{\rho_n}{2r_0} \quad ① \quad \textbf{assume } r_0 >> \rho_n :$$

$$\sin(\theta_n - \theta_0) \approx \theta_n - \theta_0$$

$$\sin(\theta_n - \theta_0) = \frac{\rho_n}{2r_0} \Rightarrow \theta_n = \theta_0 + \frac{\rho_n}{2r_0}$$

r_0:radius of Trajectory

$$P_T = 0.3BQr_0 \rightarrow r_0 = \frac{P_T}{0.3BQ}$$

Set B=4T, Q=+1 then:

$$\theta_n = \frac{0.6}{P_T} \cdot \rho_n + \theta_0 \quad ②$$

Divide the entire parameter space into MxK parts

$$Sum(m,k) = \sum_{i=1}^{n} e^{-[\frac{(\theta\_scan_i(m,k) - \theta_i)^2}{2\sigma^2}]} \quad ③$$

$$\theta\_scan_i(m,k) = \frac{0.6}{P_T\_scan_k} \cdot \rho_i + \theta_0\_scan_n \quad (m = 1.....M, k = 1.....K) \quad ④$$

$$P_T\_scan_m = P_T\_\min + (P_T\_\max - P_T\_\min)\frac{m}{M}, \ \theta_0\_scan_k = -\pi + 2\pi\frac{k}{K} \quad ⑤$$

$$Retina\_output = Max[Sum(m,k)] \quad ⑥$$

Figure 3. Steps to reconstruct curved tracks in a magnetic field with Retina algorithm

The second step is “Scanning & Fitting”. The full parameter space is divided into several cells: M bins for $1/P_t$ and K bins for the initial angle θ_0. Then, for each (m,k) cell, formula ③ in Figure 3 is used to accumulate the “relevance” between the expected hit position (ρ_i,θ_scan_i) and the measured hit position (ρ_i,θ_i). Equation ④ and ⑤ represent the position calculation of the expected hit for a certain (m,k) cell of the parameter space. At last, we scan the whole parameter space to find the maximum value of the Sum ③ and output the corresponding $P_{t}\_scan_m$ and $\theta_0\_scan_k$ as the reconstructed result of P_t and of the initial angle θ_0 of the particle (see formula ⑥ in Figure 3). At this point, the entire process of trajectory reconstruction using Retina algorithm is completed.

In our simulations, the range of P_t is from 1 GeV/c to 50 GeV/c and the range of θ_0 is from $-\pi$ to π. We tried two binning granularity: either 200 bins for P_t times 400 bins for θ_0 or 500 bins for P_t times 1000 bins for θ_0. Note that the parameter σ from formula ③ represents the weight adjustment parameter in the Retina algorithm. We assume all the positions have the same weight for the track reconstruction, so we fix σ to 1 in our simulation.

3. Performance and results

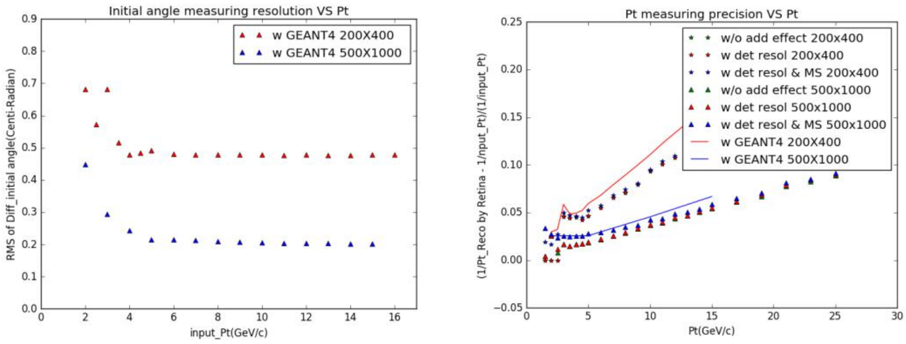


Figure 4. Pt and initial angle performance reconstructed by Retina algorithm.

The Figure 4 shows the performance of the reconstruction by Retina for tracks generated as described in chapter 2. The left side of Figure 4 shows the resolution on the initial angle θ_0 as a function of the generated particle P_t for the two GEANT4 parameter space granularities. The right side of Figure 4 shows the P_t resolution as a function of the generated particle P_t for both parameter space granularities and for the simple model as well as for the GEANT4 model. For the simple model, simulations with and without any detector effects are also shown.

From Figure 4 (right) we can see that the P_t resolution is quite close between the simple model and the GEANT4 model. Also, as expected, because of the bending, the P_t resolution degrades with high P_t. Note also that at very low P_t, less than 2.5 GeV/c, the resolution degrades because the linear approximation is not valid anymore. Finally we can also observe that the high Pt resolution improves by a factor ~2 when we increase the parameter space granularity.

Besides, from Figure 4 we can find that there is an abrupt jump at 3 GeV/c under the condition of the 200*400 space granularities. This is cased by two factors: One is the linear approximation we used began to become more different from the actual trajectory at 3 GeV/c, the distribution of the different between initial angle reconstruction by the Retina algorithm and generated by simulator are no longer Gauss shape. Another is the space granularities we set is not high enough, we can find from result (Figure 4) that the abrupt jump disappeared when we increasing the scanning bins from 200 times 400 to 500 times 1000.

4. Discussion and Conclusion

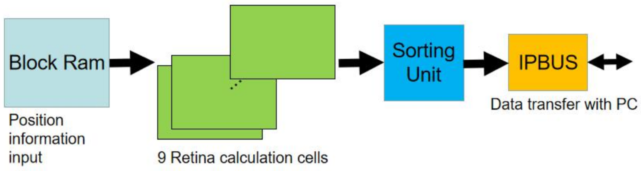


Figure 5. Structure of the Retina algorithm firmware design.

In this note, our research is targeted to adapt Retina algorithm to a tracker detector with cylindrical geometry and complex physical environment. Due to the magnetic field effects, charged particle trajectories are bent and treated as partial arc. A first Retina modelling of track reconstruction under the situation of particles in a magnetic field with barrel-like and multi-layer tracker has been built. We have shown the very preliminary results on track parameter resolution. In the further we will optimize this Retina simulation as well as start to convert it to FPGA firmware. Many generally functions have to be added to have a realistic detector simulations and we also have to check the resolution of the algorithm as measure of many tracks in the same time.

By the way, we are already working on the implementation of the Retina algorithm in FPGA. Figure 5 shows the current structure of the Retina algorithm firmware design. The position information of the hits for each track will be stored in BRAM and be read out by the Retina calculation cells. After calculation and fitting the results information will be send to PC via the Communication module IPBUS[8]. We plan to mainly use the DPS48 and BRAM resources in FPGA to implement Retina calculation cells. After the work is done,we will then compare the hardware performance of our design to our simulation results as well as other fast track trigger algorithm.

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