TRACK IDENTIFICATION IN HIGH ENERGY PHYSICS

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ABSTRACT

The new particle accelerators and detectors create a challenging processing environment, characterized by huge mass of recorded data of which only small part is of scientific interest. This paper addresses the problem of muon track identification in a cathode strip chamber (CSC), which is a part of the ATLAS detector.
We suggest a new “detect-before-estimate” approach, which first detect the particle and then estimate its hit locations. In a presence of high background noise, this approach can significantly save computing time. We use a modification of the Hough transform and we show that using the appropriate transform parameters, the line detection performance is sufficiently close to the theoretical detection performance, based on a statistical model specially developed for this problem.

1. INTRODUCTION

The LHC, the largest hadron collider accelerator ever built, presents new challenges for physicists and engineers. With the anticipated luminosity of the LHC, we expect as many as one billion total collisions per second, of which at most 10 to 100 per second might be of potential scientific interest. The track reconstruction algorithms applied at the LHC will therefore have to reliably reconstruct tracks of interest in the presence of background hits.
One of the two major, general-purpose experiments at LHC is called ATLAS. Since muons are among the most important particles to be detected as a sign of new phenomena, a stand-alone muon detector system is being built for ATLAS. This system is also called the muon spectrometer [1]. The ATLAS muon spectrometer is located in a large background environment which makes the muon tracking a very challenging task.
Certain areas of the muon detection system are expected to receive a high flux of particles. In these areas, devices known as Cathode Strip Chambers (CSC) will be employed. Though many particle tracking algorithms were developed during the years by the High Energy Physics community [2], the requirement of high accuracy in an environment with such a high noisy background is a new challenge. The commonly used technique [1], which first estimates all particles hit location and then identifies the tracks, is very complex in a high noisy background environment. This paper will discuss the potential benefit of the detect-before-estimate approach which uses the physical measurements as the input for the track detection process without prior estimating the hit locations.

The identification of a relatively short track segment within a particle detector can be translated to a line identification problem in a noisy image [2].
The detection of straight line-segments in images is a problem that often occurs in image analysis. One method for detection of collinear points is related to the Hough transform (HT) [3,4,5]. Points in the image are transformed into lines in a line parameter space. Lines in the parameter space corresponding to collinear points will cross each other at one point. This point defines the spatial parameters of the line through the collinear points. Quantizing the number of lines crossing each cell reduces searching for collinear points in the image to looking for cells in the parameter space which are local maximum.

The performance of the HT-based detector has been analyzed and compared to other detection methods in a presence of additive noise [6,7]. It was shown that in the presence of Gaussian, uniform and Laplacian noise, both Hough transforms and Gaussian-based optimal processor have good detection performance [8]. While the Gaussian-based optimal processor has superior location estimation performance, it is computationally more intensive. However, due to the presence of interferences, the Gaussian noise assumption cannot be applied for the particle track detector, and robust detection method is needed. Moreover, the particle interaction rate requires a fast and efficient detection. The subspace-based line detection (SLIDE) is based on an analogy made between a straight line in an image and a planar propagating wave front impinging on an array of sensors [9]. A comparison made between SLIDE and the Hough transform [10] demonstrate that SLIDE is significantly less robust than the Hough transform.

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The CSC [1, 11] consists of four-layer chambers that give a position measurement based on a charge-interpolation. When an energetic particle, presumably a muon, passes through the chamber, it ionizes a local region of the gas that fills the chamber. The ionized cluster of electrons drifts towards a nearby anode wire and a charge avalanche is established. The charge avalanche induces charge on two sets of cathode strips that are mutually perpendicular. The induced charge is spread out over adjacent strips; each strip receiving a fraction of the total induced charge. The spread of strips that receive charge is called a hit-cluster. The concept is that with the knowledge of the interpolated total charge passing through a layer, calculating the relative magnitudes of both the charge on each strip and the position of the strip in the hit-cluster will give enough information to find a centroid of the charge. The centroid is the point in the chamber where the ionization cluster originated, thus, the position of the energetic particle's track. The cathode strips for the precision measurement are oriented orthogonal to the anode wires. A measurement of the transverse coordinate is obtained from orthogonal strips, i.e. oriented parallel to the anode wires, which form the second cathode of the chamber. Figure 1 describes the charge induction over the precision strips.

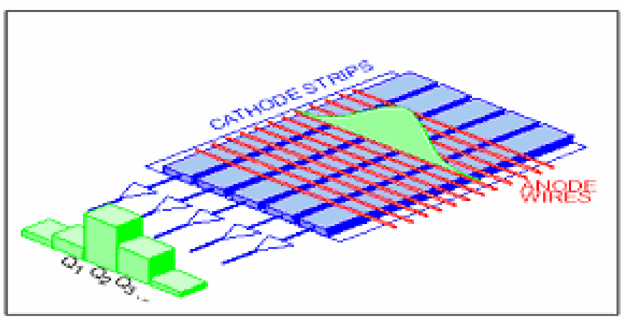

Figure 1- charge distribution over the precision strips

The CSC is located in a high radiation area, where the fluxes of photons and neutrons can reach 800Hz/cm². This can lead to situation where uninteresting particle hits are close to the muon track. In many cases, several hits would occur at the detector layers. Moreover, the interaction of the muons with the detector material that may cause the creation of secondary particles, the inefficiency of strip channels, and other electronic phenomena such as overflow and crosstalk, can produce false track candidates and reduce the detection performance of the real muon track. Figure 2 illustrates the hits clusters induced over the four layers CSC detector. Only those which are on the straight arrow belong to the muon track:

It can be seen in figure 2 that the detector physical quantized measurements, which are used as the input to the detect-before-estimate process, make the line segment wider. These segments become even wider with the presence of background particles. Therefore, the line detection procedure should be robust enough in order to detect the wide lines in one hand, without creating too many false tracks on the other hand.

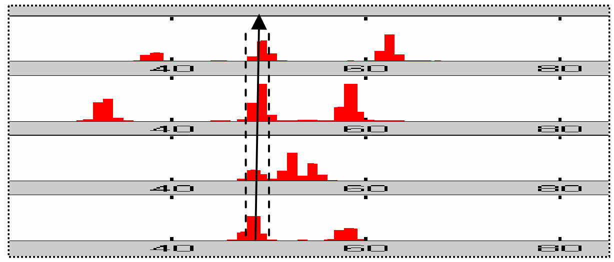

Figure 2- the hit clusters over the four layers of the CSC detector. The axes are the strip number and the CSC layers. Only the hit clusters on the upright arrow belong to the muon track. The other hit clusters are probably due to other particles. Taking the strip measurements as data for the detection process (instead of taking the estimated hit position), will make the line segment wider (the area between the two doted lines).

We suggest a revised version of Hough transform as a robust track identification technique in the muon spectrometer, which uses the known detector geometry for reducing the complexity.

The rest of the paper is organized as follows: In section 2 we describe the detect-before-estimate proposed approach. In section 3 we describe the theoretical detection problem and we calculate the detection performance for the model suggested. In section 5 we compare the algorithm results from the test beam with the analytical calculation, and we conclude in section 6.

2. THE PROPOSED APPROACH

In the presence of a noisy background, the number of recorded hits is much larger than the number of the muon hits. In order to reduce complexity, we suggest the detect-before-estimate approach, i.e. to identify the hits belong to a relevant track, and then to estimate the hits location. The revised version of Hough transform is shown to be a robust track detection technique which follows the detector requirement for a very low probability of miss detect.

In the following we describe a version of the HT adapted to the specific problem of detection of collinear tracks in Atlas. The algorithms consist of building the test statistics (based on the HT) and comparing it to a threshold. Because of the special characteristic of the additive noise in our problem, the theoretical tools used in image processing for setting up the threshold in a HT-based detector cannot be applied directly. As such, we have derived the appropriate theoretical tools and used them to set up the threshold and to evaluate the performance of the proposed detector.

2.1. Two-phase process

The muon gas ionization in each chamber results in different signal amplitude in each layer. This amplitude follows the Landau distribution [12,13]. The signal amplitude influences the hit detection in the layer, since higher amplitude causes higher signal to noise ratio (SNR) which improves the detection performance. However, for the line detection problem it is enough to get a binary result which indicate the existence of a hit in the layer. Hence, the line detection process has two phases: a preprocessing phase in which the multi valued image Y is converted to a binary image using a threshold, and a line detection phase using the modified Hough transform.

2.2. The modified Hough transform

The standard Hough transform can be applied to various applications [3]. Using the specific characteristics of the Cathode Strip Chamber (CSC) muon detector enables to make some modification to the standard Hough transform. These modifications reduce the complexity and improve the detection performance. The fact that we should look for straight lines within the detector layers that starting at the first layer and ending in the last (forth) layer can simplify the calculation. Instead of using the parametric form $y = kx + d$ or the polar form $\rho = x\cos\theta + y\sin\theta$ we suggest to use the two point form

$$y - y_1 = \frac{y_2 - y_1}{x_2 - x_1}(x - x_1) \qquad (1)$$

which represents a line connecting points (x_1, y_1) and (x_2, y_2). For the CSC detector, y_1, y_2 are both known (the layers location), so it is possible to implement a transform from any point (x, y) in the track to a straight line in the parameter space using (x_1, x_2) as the only two unknown parameters. This formulation allows using constrains on the tracks: (i.e. only lines that go through the first and the forth layer are valid). More reduction can be made by applying an angle constrains, i.e. the transform will be applied only for lines roughly projected to the interaction point.

2.3. Discretization errors in the Hough transform

The influence on the Hough transform of the quantization of the parameter space, the quantization of the image and the width of the line-segment was investigated in [14].
In our problem the quantization of the image is done by the detector, and the line width is relative to the position difference between the strips and the muon track. Thus, the free parameters are only those of the parameter space.

Since the strip charges are actually the samples of interpolated charge, the position error of the strip with the maximum charge is uniformly distributed: $\varepsilon \sim U(-w/2, w/2)$ where ε is the difference of the maximum charged strip to the track position in the same layer and w is the width of the strip. The position error can be even bigger in the presence of the detector noise and the background particles. Since two closed muon tracks is a very rare event, the Hough cell size should be big enough in order to contain all the potential track hits (i.e. the peak is not spread over several cells).

3. DETECTION ANALYSIS

In order to analyze the detection performance of the Hough transform, we first calculate the theoretical detection performance and then compare it to the Hough transform results. The analytical calculation is optimistic in a sense that we assume that there is no degradation in detection performance due to the quantization of the image and the parameter space. Therefore, the Hough transform detection performance is bounded by the theoretical one.

3.1. The signal statistical model

It can be shown that the muon straight line track can be modeled as:

$$y_i(n,m) = A_i S_x(n; x_p + i\Delta) S_t(m - t_p) + r_i(n,m) \qquad (2)$$

where i indicates the detector layer number, n is the spatial sample, and m is the temporal snapshot. $S_x(;)$ is the spatial signal shape over the detector strips and $S_t(\cdot)$ is the time dependent signal for each strip. $r_i(n,m)$ is a general expression for noise plus interferences. A_i, x_p, Δ, t_p are the amplitude, the hit position, the line slope and the hit timing, respectively, which are the parameters to be estimated.
We assume that the time of arrival is known (or estimated before). Substituting $m = \hat{t}_p$ in (2) we get:

$$\begin{aligned} y_i(n) &= A_i S_x(n; x_p + i\Delta) S_t(m = \hat{t}_p) + r_i(n, m = \hat{t}_p) \\ &= \widetilde{A}_i S_x(n; x_p + i\Delta) + \widetilde{r}_i(n) \end{aligned} \qquad (3)$$

The conversion of the model described in (3) to an image can done in several ways.
We choose to use the strip charges as the image pixels:

$$Y(i, j) = y_i(j), j = 1..M, i = 0..3 \qquad (4)$$

We define $S(i,j) = \widetilde{A}_i S_x(j; x_p + i\Delta)$ as the muon track image, and $N(i,j) = \widetilde{r}_i(j)$ as a two dimensional image of the noise and interferences.
Using (4) and omitting the indexes i,j we can state the muon detection problem as deciding between the two hypotheses:

$$\begin{aligned} H_0 &: Y = N \\ H_1 &: Y = S + N \end{aligned} \qquad (5)$$

3.2. Detection analysis in the preprocessing phase

The conversion of the multi valued image Y to a binary image requires detection for each strip in the detector. Practically, a threshold γ is used, and strips with maximum charge (in the appropriate time window) above the threshold are marked as active pixels.
The probability of detection of a muon hit in a layer i and strip j is given by:

$$p_{Di,j}(\gamma, p_{\bar{a}}) = p_m(Y_{ij} > \gamma \mid H_1, \bar{a}) \cdot p_{\bar{a}} \qquad (6)$$

where γ is the threshold, Y_{ij} is the maximum charge, and H_1 is the hypothesis that the strip was hit by a muon.
$p_m(Y_{ij} > \gamma \mid H_1, \bar{a})$ is the probability that the strip maximum amplitude is above the threshold γ given that the strip was hit by a muon and there was no photon that mask the muon signal. $p_{\bar{a}}$ is the probability that no photon will mask the muon signal. We assume that the maximum charge distribution follows the Landau distribution which approximated by [15]:

$$P_{Aij}(\delta) = \sqrt{\frac{1}{2\pi}\exp\left(-\frac{1}{2}(\delta + e^{-\delta})\right)} \qquad (7)$$

Since the photon usually has amplitude higher then the muon, we assume that every photon hit before the right time window could potentially mask a muon. It can be shown and verified using the real data that the photon background will reduce the probability of detection by 1% ($p_{\bar{a}} = 99\%$). Non-linear effects as cross talk have very low probability to mask the muon hit and therefore are ignored.

There are three elements that can cause false alarm; the additive electronic noise, the photon background and delta electrons. The probability of false alarm is the probability that one or more events happened (or one minus the probability that none of them happened).The false alarm probability for layer i and strip j is:

$$p_{Fi,j}(\gamma, p_{\bar{b}}, p_{\bar{c}}) = 1 - p_m(Y_{ij} < \gamma \mid H_0, \bar{b}, \bar{c}) \cdot p_{\bar{b}} \cdot p_{\bar{c}} \qquad (8)$$

where $p_m(Y_{ij} < \gamma \mid H_0, \bar{b}, \bar{c})$ is the probability that the strip maximum amplitude is under the threshold known there was no muon and there was no muon like caused by either photon or delta electron. $p_{\bar{b}}$ is the probability that there will be no muon-like hit caused by a photon. $p_{\bar{c}}$ is the probability that there will be no muon-like hit caused by a delta electron. These two events are statistically independent.
The probability that the electronic noise is bellow threshold is given by:

$$p_m(Y_{ij} < \gamma \mid H_0, \bar{b}, \bar{c}) = 1 - Q\left(\frac{\gamma}{\sigma}\right) \qquad (9)$$

Analyzing the data from the test beam we get:

$p_{\bar{b}} = 99\%, p_{\bar{c}} = 99.95\%$

Figure 3 shows the probabilities of detection and of false alarm for a single strip:

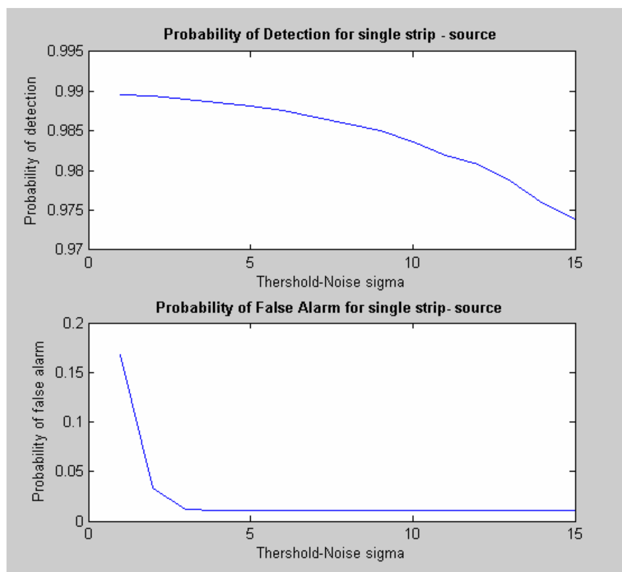

Figure 3- The probability of detection (bottom) and of false alarm (top) for a single strip vs. the threshold of the activity detection, γ. The noise sigma was calculated from the test beam data. The values of the background particle probabilities were taken from the test beam data as well.

3.3. Detection analysis in the line detection phase

The line detection phase includes executing the modified Hough transform on the binary image. A second threshold N is used in each cell of the accumulator space in order to detect a line. The probability of the line detection depends on the probability of detecting the hits in the previous phase, and on the threshold N .

Since the maximum charge distribution for each layer follows the Landau distribution and the noise in the different layers is uncorrelated, it is reasonable to assume that the probability of muon detection in each layer is independent. Therefore the probability of detection of a line is the probability of detecting at least N collinear points:

$$p_{Dl}(\gamma, p_{\bar{a}}, \mathrm{N}) = p(A_c > \mathrm{N} | H_1) = \sum_{i=\mathrm{N}}^{4} \binom{i}{4} \cdot p_D{}^{i}(\gamma, p_{\bar{a}})(1 - p_D(\gamma, p_{\bar{a}}))^{4-i} \qquad (10)$$

where A_c is the accumulator output for the parameter space cell, $p_D(\gamma, p_{\bar{a}})$ is the detection probability for a given strip with threshold γ and probability of no mask photon $p_{\bar{a}}$, given in (6).

Figure 4 shows the probability of detection as a function of the strip threshold γ.

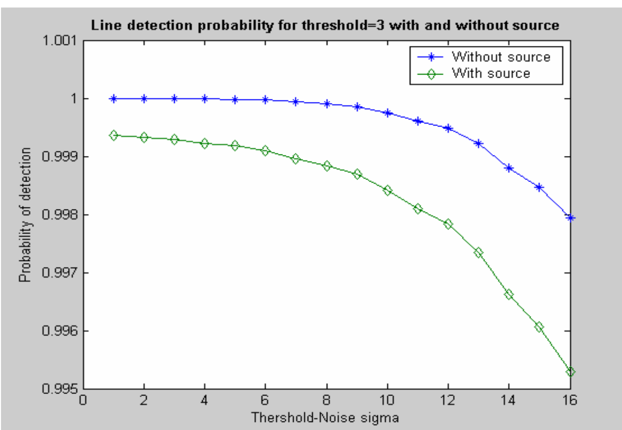

Figure 4- The theoretical probability of detection vs. the threshold of the activity detection, γ, for two cases: (a) there is no photon source and the cell threshold is set to 3. (b) With photon source and the cell threshold is set to 2.

There are four physical sources for false alarm; the white electronic noise, the photon background, the delta electrons and other non linear effects such as cross talk and overflow.

We assume that the muon hits contribute to false alarm tracks only when a closed delta electron exists. Though the electronic white noise is layer independent, there is a dependency between the layers for a delta electron hit and photon hit. A delta electron can cause more than one hit per layer and might be seen like a muon. We assume that a delta electron with two or more hits (together with one real muon hit) causes a line false alarm.

We model the cross talk and the other non-linear effects within the detector as an additional independent noise source of normal distribution with a zero mean and standard deviation σ_d. This noise source is only activated in the cases where a photon hit accrued, and it is located in the collinear strips in the next layer.

Figure 5 describes the probability of false lines detection for $\mathrm{N} = 3$:

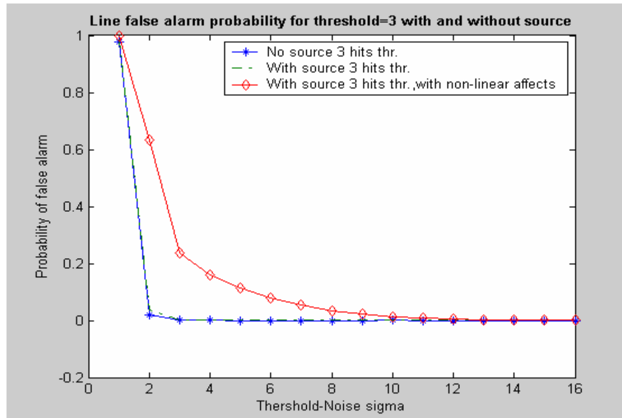

Figure 5- The theoretical probability of false line detection vs. the threshold of the activity detection, γ, for three cases: (a) there is no photon source. (b) With photon source. (c) With photon source and modeling the non-linear effects. In all cases, the cell threshold is set to 3.

We can see from figure 4 that a detection probability higher than 99.5% can be achieved for all cases with $\gamma < 12$. The photon source decreases the detection probability by about 0.3%. The non-linear effects increase the probability of false line significantly for $\gamma < 8$.

4. RESULT

The proposed algorithm was tested with a real data from a test beam (X5 data).

Two cases were analyzed:

a. A muon beam without an interfering photon source.
b. Muon beams with an interfering photon source.

For each strip channel, the noise level was estimated and the average value (pedestal) was subtracted from the strips signal output.

Figure 6 describes the probability of line detection and probability of false line detection.

It can be seen that a very high probability of line detection is achieved using the Hough transform algorithm, which is very close to the theoretical performance. The probability of false line is very close to the theoretical result for the case where the non-linear effects were added to the noise model and for $\gamma > 6$. For $\gamma < 6$ the theoretical results are less close to the experimental results, maybe due to the fact that the Hough space quantization was optimized for high probability of line detection, but – as expected – the theoretical, optimistic false detection performance lower bound the actual performance.

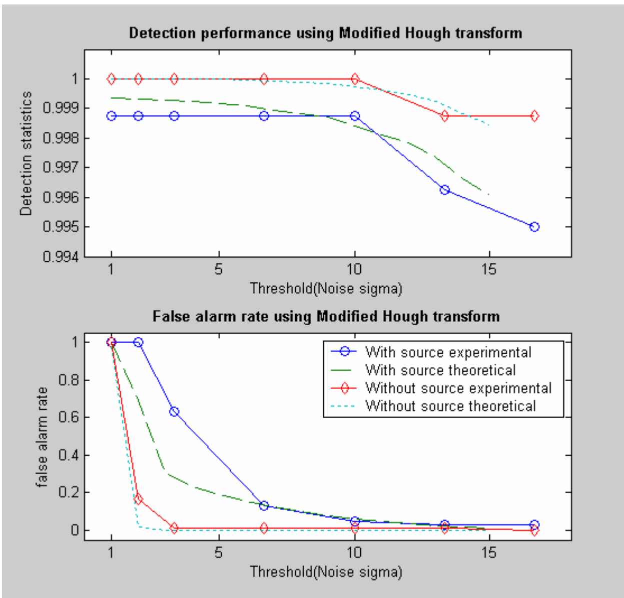

Figure 6: Experimental and theoretical detection results vs. the threshold of the activity detection, γ, for two cases: (a). There is no photon source (b). There is a photon source. For both cases we set the Hough cell threshold to 3. The upper graph describes the statistics of the line detection success and the theoretical probability of line detection. The lower graph describes the statistics of the false line detection and the theoretical probability for false lines.

5. DISCUSSION

The local track identification is one of many new challenges in HEP. We showed that the detect-before-estimate approach results in a very good detection performance. Moreover, it reduces the total algorithm complexity significantly since the hit position estimation can be applied only to the hit clusters which belong to the track candidates. The probability of line detection can be improved even more (in about 0.2%) if we use an additional information such as the existence of particles that could potentially mask the muon, and we add appropriate weights to the modified Hough transform. Unfortunately, for the CSC detector, the existence of the non-linear effects makes the probability of having those potential mask hits very high. Thus, using mask information increases the probability of false line even more. We expect that the use of such additional physical information will improve significantly the performance of other detector, in which non-linear effects are negligible.

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