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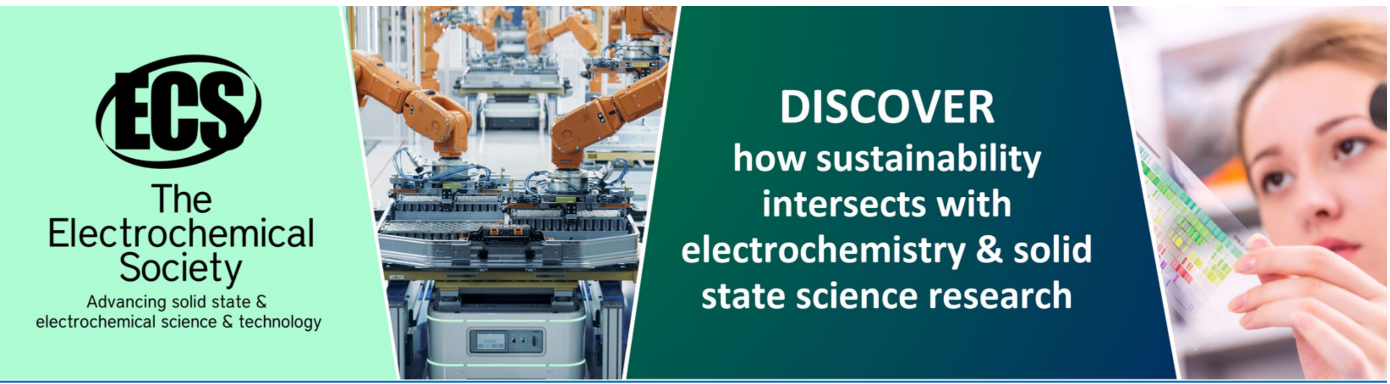

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Online track detection in triggerless mode for INO

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Abstract: The India based Neutrino Observatory (INO) is a proposed particle physics research project to study the atmospheric neutrinos. INO-Iron Calorimeter (ICAL) will consist of 28,800 detectors having 3.6 million electronic channels expected to activate with 100 Hz single rate, producing data at a rate of 3 GBps. Data collected contains a few real hits generated by muon tracks and the remaining noise-induced spurious hits. Estimated reduction factor after filtering out data of interest from generated data is of the order of 10^3. This makes trigger generation critical for efficient data collection and storage. Trigger is generated by detecting coincidence across multiple channels satisfying trigger criteria, within a small window of 200 ns in the trigger region. As the probability of neutrino interaction is very low, track detection algorithm has to be efficient and fast enough to process 5×10^6 events-candidates/s without introducing significant dead time, so that not even a single neutrino event is missed out.

A hardware based trigger system is presently proposed for on-line track detection considering stringent timing requirements. Though the trigger system can be designed with scalability, a lot of hardware devices and interconnections make it a complex and expensive solution with limited flexibility. A software based track detection approach working on the hit information offers an elegant solution with possibility of varying trigger criteria for selecting various potentially interesting physics events. An event selection approach for an alternative triggerless readout scheme has been developed. The algorithm is mathematically simple, robust and parallelizable. It has been validated by detecting simulated muon events for energies of the range of 1 GeV–10 GeV with 100% efficiency at a processing rate of 60 μs/event on a 16 core machine. The algorithm and result of a proof-of-concept for its faster implementation over multiple cores is presented. The paper

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also discusses about harnessing the computing capabilities of multi-core computing farm, thereby optimizing number of nodes required for the proposed system.

KEYWORDS: Trigger algorithms; Online farms and online filtering; Trigger concepts and systems (hardware and software)

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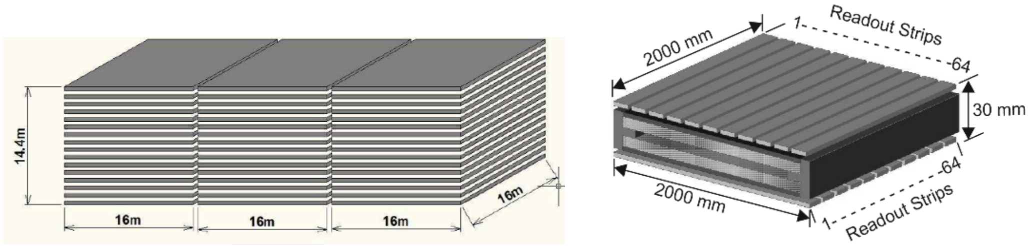
1 Introduction

INO is a proposed 50,000 tons magnetized Iron Calorimeter (ICAL) to study atmospheric neutrinos and to make precision measurements of neutrino oscillation parameters [1]. Charged-current interaction of neutrinos inside detector is identified by tracks of produced corresponding charged particles (such as muons). The detector will be housed inside a cavern with a rock cover of 1.3 km in order to reduce the cosmic muon background. The expected overall event rate is around 10 Hz [2].

1.1 Geometry of ICAL detector

The detector will consist of three identical modules each of dimension 16 m $\times$ 16 m $\times$ 14.5 m placed adjacent to each other as shown in figure 1(a). Each module is made up of 151 horizontal layers of 56 mm thick low carbon iron plates interleaved with 40 mm gaps to house the Resistive Plate Chamber (RPC) units [3].

It is designed using 28,800 RPCs, each with dimension 2000 mm $\times$ 2000 mm $\times$ 30 mm has 64 vertical and 64 horizontal readout strips of 30 mm width as described in figure 1(b).



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(a) (b)

Figure 1. (a) INO-ICAL Detector Assembly (b) RPC Detector.

2 Trigger system

2.1 Trigger criteria

According to the proposed trigger scheme for the ICAL detector [2], the trigger decision is based on the event topology and is defined as $M \times N/P$, where M is the minimum strip multiplicity per layer and N is the minimum number of layers out of a group of P consecutive layers having such M-fold multiplicity. There are a number of trigger criteria with different combinations of the trigger parameters M, N and P as described in table 1. The trigger system should ensure that if an event satisfies one or more user-specified trigger criteria in any part of the detector, a trigger signal is generated to initiate the data acquisition system to record the event.

Table 1. Trigger criteria.

Fold	$\boldsymbol{M \times N/P}$
1 - F	$1 \times 5/8$
2 - F	$2 \times 4/8$
3 - F	$3 \times 3/8$
4 - F	$4 \times 2/8$

2.2 Hardware trigger scheme

The proposed hardware trigger system detects correlated hits in a group within a coincidence time window. Individual trigger signal is generated from each of the RPC based on strip multiplicity. The detector volume is divided into non overlapping logical segments of $2 \times 2 \times 20$ RPC's. Considering all possible combinations within a segment for each of the trigger criteria, groups are formed and adder-based digital logic circuitry is employed for checking the validity. Individual trigger logic boards generate border trigger and full trigger signals from a segment. A global trigger logic board resolves border triggers from adjoining segments and also generates system level global trigger [2]. The hardware offers limited flexibility in selecting various potential trigger criteria for different types of interesting physics events. Also a lot of hardware and interconnections involved make it a complex and expensive solution. A software based track detection approach working on the hit information offers an elegant solution with possibility of varying trigger criteria.

2.3 Design challenges for triggerless readout

In triggerless readout scheme, the detectors will be continuously collecting all hits above a predefined threshold. This will increase raw data volume by 6 orders of magnitude as compared to hardware trigger system. The amount of data to be processed is 3 GBps with a significant reduction factor of the order of 10^3. The filtration has to be done in real time without introducing considerable dead time. Given an event rate of 10 Hz, the system should be efficient enough to not miss any real event. Given the possibility that an event can occur anywhere inside the assembly, the whole volume has to be inspected with unit stride in each dimension. This creates another design challenge, dictating the need to examine all possible groups in X, Y, Z dimensions, for each of the trigger criteria [2].

3 Scheme for triggerless event selection

Due to stacked layer geometry of ICAL, hits belonging to a neutrino event can be demonstrated as collinear points with various collinearity criterion. For instance, 5 collinear points within a span of 8 layers signify existence of 1-Fold event (described in table 1). Therefore the problem of validating trigger reduces to line grouping problem in a 3-D assembly under various criterion. The requirements of quickly recognizing collinear hits from large number of uniformly distributed hits in the coordinate system raises the need to have an algorithm which computes very few, computationally simple steps and should be suitable for parallel execution. There are three approaches to address the problem:

i A complete combinatorial approach examines all possible combinations of input data points, takes $O(n^2)$ time for n input points.

ii A local approach proceeds by interpolating or extrapolating an initial track candidate. Local methods like cellular automaton, takes $O(nlogn)$ time.

iii A global approach can be seen as transformation, which produces a list of tracks or a list of points, where tracks can be found easily. A global algorithm processes all the points in similar way irrespective of the order in which they enter in the algorithm. This characteristic makes global algorithms suitable for parallel execution. The processing complexity of a global method is $O(n)$ [4].

The Hough transform [5] is an effective and commonly used global algorithm to detect the collinear data points. The algorithm being computationally simple and global in nature; is faster and parallelizable. Also its robustness to missing data and noise makes it a good match for data processing requirements raised by physics experiments like INO.

3.1 Standard Hough transformation

Standard Hough transformation maps a data point in X-Y image space to a sinusoidal curve in Hough space. In the Hough space, coordinate axis are represented by line defining parameters ρ-θ, for the line equation $\rho = x\cos\ \theta + y\sin\theta$, where ρ is the length of a normal from the origin to this line and θ is the orientation of ρ with respect to the X-axis (figure 2). Each point and line in the image space is represented by a sinusoidal curve and a point (ρ, θ) in the Hough space, respectively.

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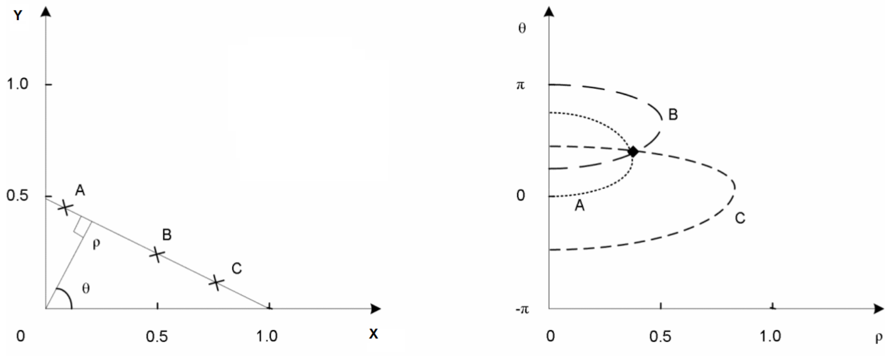
As each line consists of many points in image space, the mapped sinusoidal curves of these points will intersect at a point in Hough plane, which gives parameters of the line in image space [6].



(a) **(b)**

Figure 2. (a) Image space (b) Hough space.

It can detect collinearity in 2-D point clouds with time complexity of $O(pt)$ where p is number of points and t dictates collinearity tolerance. The algorithm takes $O(pt^4)$ [7] on application to 3-D space. Thus, an algorithm for neutrino event selection has been developed, which is an efficient extension of 2-D Hough transformation to 3-D space, preserving its mathematical simplicity, robustness and parallelizability and can detect collinear line segments oriented in any direction with time complexity of $O(kt^2)$, where k depends on the size of the detector.

The algorithm is based on the fact that a line segment in a 3-D space can be uniquely described by intersection of two planes. Hence, if a set of points is found collinear when projected on two mutually perpendicular planes, it's collinearity in 3-D space can be ensured. The approach consists of projecting the hit coordinates over two mutually perpendicular planes and then applying Hough transformation independently to both planes. Common set of data points from both planes is declared collinear in 3-D space. Subsequently, span of collinear points is examined against maximum distance given by trigger criteria.

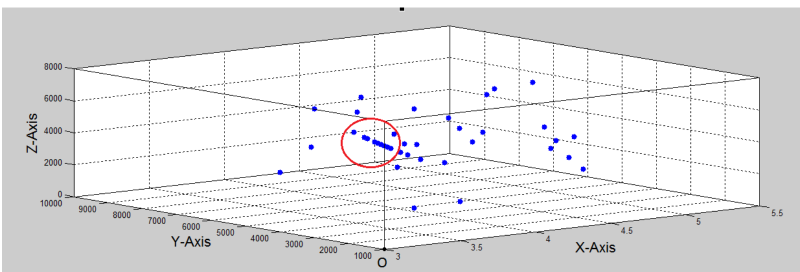


Figure 3. Neutrino event (encircled in red) along with random hits.

Geometrical distribution of data points is analyzed in a coordinate system with origin O (figure 3) to ensure positioning of these points on positive coordinates on all 3 fundamental axes. Limiting the region of interest to only positive coordinates, limits θ value to the range of $-90°$ to

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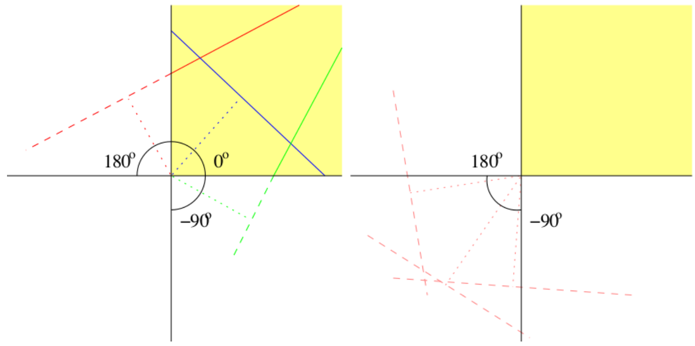

Figure 4. Range of θ values.

180° (figure 4) [4]. Certain algorithmic parameters are to be decided based on detector geometry and trigger criterion:

Two mutually perpendicular planes: to ensure the correctness of the algorithm it is necessary to maintain uniform accumulator bin size in both planes. Considering the geometry of the INO-ICAL detector the pitch in Z direction is 96 mm, while the pitch in X and Y direction is 30 mm. X-Z and Y-Z planes make the ideal choice offering uniform bin size, where each bin represents 96 mm × 30 mm area of coordinate space. Also, as given by trigger criteria there is no neutrino event, with all hits lying within single layer, hence X-Y plane can be omitted.

Collinearity tolerance ($\delta\theta$, $\delta\rho$): the resolution for Hough parameters ($\delta\theta$, $\delta\rho$) governs the precision of collinearity detection. $\delta\theta$ specifies spacing of the Hough transform bins along the θ-axis and $\delta\rho$ provides spacing of the Hough transform bins along the ρ-axis.

$\delta\theta$ signifies minimum angle difference necessary to conclude existence of two separate line segments. As per 1-Fold trigger criterion, minimum θ resolution is given by angle difference between strip ($X = 1$, $Y = 1$, $Z = 1$) and strip ($X = 2$, $Y = 1$, $Z = 8$) as shown in figure 5(a). Eq. (3.1) gives the relation between $\delta\theta$ and the pitch sizes in X (Δw) and Z (Δh) directions. For the geometry of ICAL detector, $\delta\theta = 2°$ as given by eq. (3.1).

$$\delta\theta = \tan^{-1}\frac{\Delta w}{\Delta h \times P} \tag{3.1}$$

$\delta\rho$ is the tolerance of deviation from collinearity. Points deviated by half of the layer pitch are considered collinear as shown in figure 5(b). For the geometry of ICAL detector, $\delta\rho = 48$ mm as given by eq. (3.2).

$$\rho = \frac{\Delta h}{2} \tag{3.2}$$

Maximum Span (ψ): ψ signifies maximum span covered by a valid neutrino event. In trigger criteria $M \times N/P$, P determines maximum span. For 1-Fold event maximum span is given by diagonal of a segment consisting of 8 layers with single RPC as shown in figure 5(c). It is given by eq. (3.3), where W and L represents width and length of an RPC.

$$\sqrt{(\Delta h \times P)^2 + W^2 + L^2} \tag{3.3}$$

Threshold (η): η signifies minimum number of collinear data points required to conclude existence of a valid neutrino event. For various trigger criterion $M \times N$ gives value of threshold. For instance for 1-Fold event $\eta = 5$.

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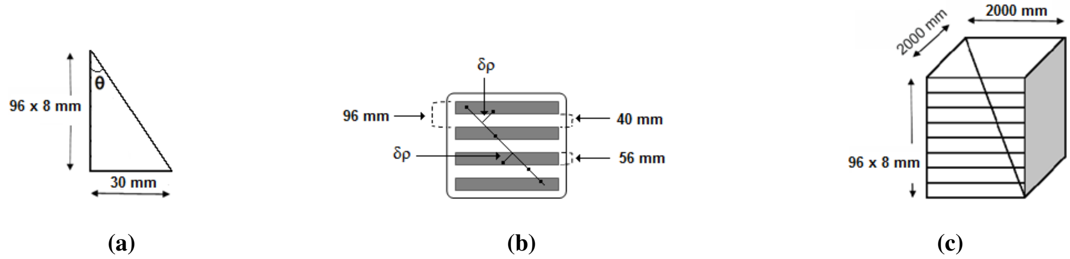

Figure 5. (a) θ resolution ($\delta\theta$) (b) ρ resolution ($\delta\rho$) (c) Maximum Span (ψ).

In worst case, all Y-Z HS elements are to be compared with each of the X-Z HS element, the operation takes $O(kt^2)$, where k depends on the size of the detector. After getting a collinear set of points, distance between 1 to η points is examined against ψ. If found valid, maximum span criterion is satisfied or else distance between 2 to $\eta + 1$ points is examined until the search is successful.

4 Parallel implementation

While employing coarse-grain parallelism, functional decomposition of tasks has been done such that synchronization requirements between the tasks is minimum. Data acquired during 1 s from the detector is partitioned into independent data sets belonging to one time coincidence window of 200 ns. Each set is considered as a task and independently deployed on a core. All 5×10^6 tasks are completely independent and share only some of the static data, which are read only. This ensures minimum data sharing and least usage of communication and synchronization mechanisms. A cache effective and spatially efficient Hough transformation approach [6] has been adopted in order to address both data dependence and poor data locality. Usage of bit array data structure reduces computational efforts required for finding common set of data points between both planes. It can be done efficiently by performing bitwise AND of two bit arrays in $O(1)$ time instead of comparing each data point in every HS element from both planes in $O(n^2)$ time. Algorithm also provides scope for exploiting medium-grain parallelism (by processing input data points on both planes in parallel) and fine-grain parallelism (by applying Hough transformation to all data points in parallel), which can be adopted depending on data processing requirements.

5 Validation

Event data generated by simulation framework has been used to evaluate the performance of the trigger scheme as a function of different trigger parameters and over the range of all desired events. Algorithm has been tested with simulated events generated from Monte Carlo runs for muons in the energy range 1 GeV–10 GeV and 500 MeV using Geant4[1] [8]. This is augmented with some randomly generated data points. Efficiency of the event recognition algorithm refers to the number of valid events identified over number of valid events produced. With muon energy level as 1 GeV to 10 GeV, efficiency obtained is nearly 100%, while for 500 MeV muon, it is about 96% with

[1]Geant4.10.00.p01, Physics list QGSP_BERT.

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algorithm parameters $\delta\theta = 2°$, $\delta\rho = 48$ mm, $\eta = 5$ and $\psi = 2930.84$ mm. Physics interest of INO-ICAL is limited to muons with energy in the range of 1–10 GeV.

6 Performance

The performance has been benchmarked on a machine with Intel(R) Xeon(R) 3.40 GHz processor with 64 GB RAM and hyper threading enabled 16 core.

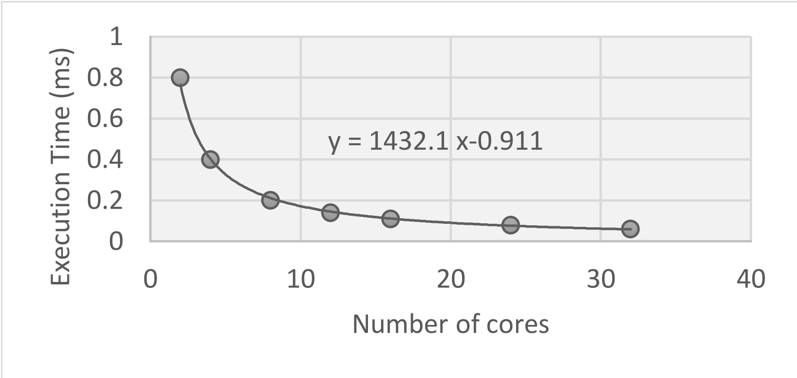

Figure 6. Execution time vs. number of cores.

CPU utilization for all configurations has been observed. With such heavy computational load 8, 4 and 2 cores are exploited with 100% CPU utilization. When number of cores increase beyond 8, some efforts are put for synchronization, which deteriorate speedup and brings down CPU utilization to 89% for 16 cores. Parallel algorithm enables identification of valid events for a single time coincidence window in 60 μs on 16 processing cores. With the results obtained, the performance on a 64 cores machine is expected to be 28 μs (figure 6). Above measurements demonstrate that a farm of 150 event processing nodes having 64 cores can cater to 200 ns time slices in a continuous time frame.

7 Conclusion

The possibility to perform fast and powerful computations at the software level is a key point for consideration of a trigger-less system. Results obtained are promising and prove feasibility of designing triggereless system for online event filtration in INO. Dead time of 60 μs introduced by the algorithm will be compensated by distributing input data belonging to various time frames over a farm of event processing nodes, working in parallel. Overlap of few nanoseconds across the nodes will take care of the events occurring at the boundary of these time frames. Use of GPU as multiple computing elements can be considered at later stages of implementations. A combination of multicore and GPU streams can be tried out to obtain optimum performance.

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