Online Tracking

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Introduction

- Efficient online tracking algorithms are essential for triggering on physics events, such as those including states like J/ψ or D–mesons, those with interesting topologies, like displaced vertices, and as input to other trigger objects.
- We performed a survey of the algorithms used by other experiments as a starting point for STT online tracking.
- Our search concentrated on experiments
    - that ran in the past decade,
    - had cylindrically symmetric geometry (e.g. not LHCb)
    - had wire chamber-like main tracking system
- Caveat: Details were not always easy to find or compare between different experiments, and often changed during the course of the experiment. (Many people involved in their implementation have left physics, too!)

Tracking Algorithms

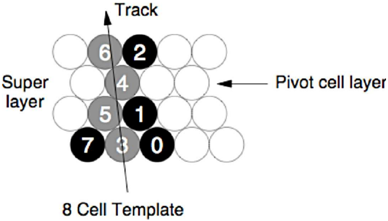
- Generally, there are two categories of track finding algorithms:
  - "local": track/road following, Kalman filter, etc.
  - "global": Hough transform, Histogramming, etc.
- The trigger systems investigated are generally divided into a series of well–defined levels, but for our purposes, it makes more sense to talk of a series of tasks, such as:

  track segment finding → track building → track fitting
- Improvements in processor and network speed have lead towards more comprehensive prompt reconstruction. Use of hardware–level parallelism is also crucial.

- N.B.: Algorithms are highly optimized for their specific detectors.

Template Matching

- Find track segments ("tracklets") in subset of detector ("superlayer") using large, fast associative memory banks in modern FPGAs
- Patterns based on realistic tracks, allowing for the possibility of missing hits. Can include patterns from tracks with displaced vertices.



- Example: BaBar matches eight–cell patterns that "pivot" around cell 4, with hits required in either four or three layers.

Track Following

- Start with initial track segment on inside or outside of detector
- Build track by extrapolating from initial segment, adding hits along predicted path
- Example: BaBar starts with track segments from inner superlayer, and builds outwards allowing one or two (in certain circumstances) superlayers to be missing.

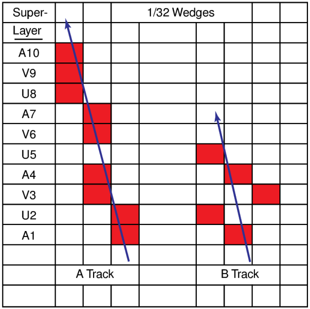


Figure 3: Track Linker Algorithm: two example tracks. The long track on the left side shows a segment hit pattern for an "A" track for which the segment hit corresponding to superlayer U5 is missing. The short track on the right side illustrates the stereo-wire rotation effect of a track with significant inclination, a track that is far from normal to the z-axis.

Experiment Parameters

	event rate	trigger rate (L1/(L2)/L3)	avg. track multi.	layers	cell size (mm)	trigger efficiency
e^+e^- Experiments						
CLEO III	250kHz	$<$ 1kHz/130Hz	~ 8 ($B\overline{B}$) 2 (e^+e^-)	47	7	$\sim$ 99%
BaBar	2kHz	970Hz/120Hz		40	$6-8$	$\sim$ 94%
Belle	5kHz	500Hz/500Hz		50	$8-10$	$>$ 90%
BES–III	$\sim$3kHz	$>$ 4kHz/1kHz	~ 4	43	$6-8$	$\sim$ 99%
ep Experiments						
ZEUS	$\sim$1MHz	600Hz/100Hz/20Hz	~ 10	72	~ 25	$\sim$ 70$-$90%
H1		1kHz/200Hz/50Hz/$\sim$5Hz		56	$23-43$	
$pp+p\bar{p}$ Experiments						
CDF	7.5MHz	30kHz/750Hz/75Hz	~ 35	96	8.8	96%
DØ		10kHz/1.5kHz/50Hz		32	0.4	$\sim$ 95%
CMS	$\leq$40MHz	100kHz/100Hz	> 100	~ 12	—	85–98%
ATLAS		100kHz/2kHz/200Hz		36	2	$>$ 90%
PANDA	$\sim$20MHz		$\sim 4-6$	24	5	

L1 Track Finding Algorithms

CLEO	templates for 16 axial layers, 8 stereo 4–layer superlayers stereo track "roads" matched, correlated to axial tracks
BaBar	$r-\phi$: tracklets found using templates for 8–cell groups in 4–layer superlayers, track following using 32 ϕ and 10 radial sectors z: Hough transform using 8 ϕ and 10 radial bins, followed by 2 χ^2 fits
Belle	$r-\phi$: tracklets found using templates for 5/6–layer superlayers track following using 64 wedges in ϕ and 6 radial sectors z: templates using 4 superlayers and 3 cathode layers in 8 ϕ sectors
BES-III	BaBar–style tracklet finding + track following in 4 superlayers (3 inner, 1 outer)

L1 Track Finding Algorithms

CDF	tracklet finding in 4 axial 12–layer superlayers, road finding in 288 $\phi-$ slices, both with templates
DØ	templates for 8 double layers in 80 $\phi-$ slices
ZEUS	templates for 3 axial 8–layer superlayers
H1	L1: tracklet finding in 4 3–layer superlayers, histogram track finder L2: finer histogram + χ^2 fit
CMS & ATLAS	Currently no hardware–based track finding, planned for upgrade in $\sim 2016 - 18$?

Later stages would either refine these results or fit tracks using simplified χ^2 fit or a variation of the offline reconstruction algorithms.

L1 Processing Hardware

CLEO	axial: 32 Xilinx 5202, 16 Altera 7084
	stereo: 60 Altera 8820, 60 Altera 7128
BaBar	Xilinx Virtex 2: 72 axial, 48 stereo
Belle	1024 track segment finder, 64 track finder (Xilinx?)
BES III	Xilinx Virtex 2
CDF	Altera Flex 10k: 336 Track Finder, 288 Track Linker
DØ	160 Xilinx Virtex 2

Challenges for PANDA

- The challenge for PANDA is to accurately reconstruct tracks in a high rate ($\sim$ 20 MHz) low average multiplicity ($\sim$ 4) environment.
- A simple order–of–magnitude calculation is informative:
    - The event rate expected at PANDA is most similar to other $p\bar{p}/pp$ colliders, roughly $2-3$ times that at the Tevatron.
    - However, the event multiplicity at PANDA is an order of magnitude smaller than at the Tevatron.
    - The STT has about the same number of channels as DØ's fiber tracker, and an order of magnitude fewer channels than CDF's central drift chamber.
    - Our online computing hardware will certainly be more powerful than previous experiments.
    - Therefore, effective online tracking at PANDA should be possible with a reasonable amount of resources.
- The required trigger performance is driven by the benchmark physics channels, so we are in the process of implementing several tracking algorithms for benchmarking.

Summary

- Online tracking at PANDA is of comparable difficulty to other recent experiments.
- We are implementing several algorithms for online tracking which will be benchmarked against key physics channels.
  - BaBar & ATLAS have similar geometries to PANDA STT, so they could be a good starting place.
    BaBar/BES–III's track finding algorithm are said to handle curling tracks well, but requires the use of z–information.
  - Displaced vertices are generally handled well, though dealing with decays inside the STT take more planning.
  - Tracking trigges are sensitive to beam–generated backgrounds.
- It is important to design algorithms to take advantage of hardware–level parallelism, and to take advantage of the specific properties of the STT.

Backup Slides

Online Algorithms

	detector	algorithm
CLEO	DR	L1: lookup table (full inner + four–layer outer) + road following
		L3: 2D χ^2 circle fit
BaBar	DR	L1: four–layer tracklet finding + road following
		L3: lookup table + fast Kalman fit
Belle	DR	L1: 5/6–layer tracklet lookup table + combinatorial wedge finder
		L3: conformal transform χ^2 fit
BES-III	DR	L1: 4–layer tracklet lookup + road following
		L3: Kalman fit
ZEUS	DR	L1: tracklet finding/matching in $r - \phi$ and $z - r$
		L2: Road following + $r - \phi$ χ^2 circle fit + z info
		L3: Kalman fit
H1	DR	L1: tracklet finding/matching in 4×3 axial layers
		L2: 2D χ^2 circle fit in $r - \phi$ and $r - z$
		L3: none
		L4: Kalman fit?

DR: Drift Chamber

Online Algorithms

CDF	DR	L1: 4 layer tracklet lookup + road finding in axial superlayers L2: add in stereo hits near axial tracks, simple χ^2 fit L3: Histogram & Kalman
DØ	Fiber	L1: lookup table (8 axial double–layers) L2: simple χ^2 fit, classification L3: road following (Kalman–like), silicon+fiber
CMS	Silicon	L1: none L3: Kalman + DAF (tracks/vertex) + GSF (electrons)
ATLAS	Straw tubes	L1: none – "Regions of Interest" are passed on L2: Kalman filter with seeding from silicon L3: Inside–out (road following + DAF), followed by outside–in (Hough trans. + Kalman)

In each of these four cases, the L3 algorithms were the same as the offline reconstruction.

- DAF: Deterministic Annealing Filter, sort of probabilistic Kalman filter, said to be good for high occupancies
- GSF: Gaussian Sum Filter, said to be good for particles with non–Gaussian energy loss