Track finding in silicon trackers with a small number of layers

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February 14th, 2013
The experiments we are working for

- **ILD** - a validated detector concept for planned International Linear Collider (ILC)
  - ILC - a linear $e^-/e^+$-collider with collision energy of about 500 GeV-1 TeV
  - Purpose: precision machine for measuring Higgs and BSM

- **Belle 2** - the successor of Belle for the upcoming SuperKEKB collider
  - SuperKEKB - an asymmetric $e^-/e^+$-collider with collision energy at the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonance at $\sim 10$ GeV
  - Purpose: 2$^{nd}$ generation b-factory with planned integrated luminosity of 40 – 50 ab$^{-1}$ for precision measurements in the b-meson-system and BSM

- Both detectors use silicon trackers as the innermost tracking detectors
The task
The solution
The difficulties

- Bad signal to noise-ratio due to machine background, ghost hits and detector noise
- The combinatorial problem is a bottle neck for reconstruction time
- Detector layout
  - In our cases a small number of layers and therefore small number of hits available for reconstruction
  - Tracking software has to consider detector specific geometry (slanted or overlapping parts, blind spots, ...)
- Detector efficiencies below 100% (missing hits) because of blind sensors, radiation damage, ...
Tracking approaches

- Global
  - All hits are treated equally
  - No bias from seeding
  - Difficult for complex track models
  - E.g. Hough transformation (histogramming)

- Local
  - Use local seeds to find tracks
  - Extrapolation via track model
  - Consecutive adding of hits to the track candidate
  - Not so robust against missing hits
  - E.g. combinatorial Kalman filter
CA in general

- Semi-global approach: all hits can be processed at the same time but CA is not so robust for missing hits
- Consists of discretized cells
- Evolves at discrete time steps
- Properties of these cells
  - Neighbourhood - each cell has got neighbours which affect each other
  - State - a value (e.g. integer, boolean etc.) that can change with each iteration
  - Rules - are applied in each discrete time step and change the states
Adapting CA principle to track finding

- Cells in track finding are segments connecting 2 hits
Adapting CA principle to track finding II

- Cells evolve depending on rules and neighbourhood
- Neighbourhood defined as: attached *inner* cells, which pass certain tests:
  - These tests:
    - Have to be able to set apart genuine tracks from background
    - Should be fast
    - E.g. angles, distances, extrapolations
- States: unsigned integers starting at 0
- Rule: If *inner* neighbour has same state, cell can raise its own state by 1 at end of time step
- Steps are iterated until no cell evolves any more
- Result: state equals length of chain of compatible segments on the inside, i.e. high states indicate long chains $\rightarrow$ probable tracks
Adapting CA principle to track finding III

<table>
<thead>
<tr>
<th>Cell</th>
<th>State</th>
<th>Neighbours</th>
<th>Rules</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>state 0</td>
<td>nb nb nb</td>
<td>stays alive, when there are nbs with same state</td>
</tr>
<tr>
<td></td>
<td>state 1</td>
<td>nb nb</td>
<td></td>
</tr>
</tbody>
</table>

state number: number of time-steps current cell has survived so far

Initial situation

Result

- simultaneous update of all cells
- repeat steps until no cell evolves anymore

Final situation: innermost cells stay at state 0, outermost cells have got highest states
Adapting CA principle to track finding IV

Cells of different states:
0 (black), 1 (red), 2 (orange), 3 (green), 4 (cyan)
Adapting CA principle to track finding IV

Cells of different states:
0 (black), 1 (red), 2 (orange), 3 (green), 4 (cyan)
The International Large Detector

- Consists of tracking + ECal / HCal + muon system
- Aims for high transverse momentum and jet energy resolutions
ILD tracking system

- Main tracking done by large Time Projection Chamber (TPC)
- Forward region is covered by Forward Tracking Detector (FTD) (where the Cellular Automaton is used)
  - Covers area between TPC and beam pipe
  - Grants high hermeticity
  - Two arms of 7 disk-shaped silicon detectors
  - 2 pixel disks and 5 back-to-back silicon strip detectors
Large backgrounds on the inner disks (pixels), depending on used technology (integrated bunch crossings)

Ghost hits on the outer disks (strip), especially from jets

Cellular Automaton chosen for good background handling capability

Concept of cells with variable lengths grants high flexibility and additional removal of fake tracks

After CA further processing with:

- Kalman filter (estimation of track parameters)
- Hopfield neural network (solving of incompatibilities)
Status and results

- status
  - Successfully implemented in the ILD reconstruction framework
  - Used in upcoming Detailed Baseline Design report

- results
  - Superior results in comparison to other reconstruction algorithm (based on local seeding + Kalman filter procedure), but a close race: both algorithms well suited
  - Highest gain by combination of both algorithms
Results

- New CA based software in green
- Efficiency with no additional background
- With background the results are quite similar (of course efficiency is less)
- Forward region is a difficult place for reconstruction (compare efficiencies well above 99% in the TPC for example)
Nano beam option: 1 cm radius of beam pipe

- 2 layer Si pixel detector (DEPFET technology) 
  \( R = 1.3, 2.2 \) cm 
  monolithic sensor thickness 50 \( \mu \)m (!), pixel size \( \sim 50 \times 50 \) \( \mu \text{m}^2 \)

- 4 layer Si strip detector (DSSD) 
  \( R = 3.8, 8.0, 11.5, 14.0 \) cm 

"PXD"

"SVD"

Muons, neutrals scintillator strips 
(endcaps)

Em. calorimeter wave form sampling 
pure CsI (endcaps)

Drift chamber 
smaller cell size

Particle ID 
ring imaging Cherenkov devices 
(TOP in the barrel, ARICH in the forward)
Important for Track Finding

- New Si detector (windmill, slanted for small $\theta$) for Si-only track finding
  - SVD: 4 layers (double sided strips $\rightarrow$ fast (in range of ns/ROF) but ghost hits)
  - PXD: 2 layers pixel $\rightarrow$ slow (in range of $\mu$s/ROF) but no ghosts, higher resolution
- Reconstruct low momenta ($p_T \geq 50$ MeV/c) using 3-4 layers
- Higher luminosity, $5 \times 10^8$ bunch-crossings/s
- Therefore higher background (Touschek, Bhabha scattering)
- 30k events/s, 10 tracks on average
Approach for reducing combinatorics

Schematic view of the low momentum track finder in Belle II

- Unssorted hits from tracks, background, ghost coming from an event
- **Sector setup** - 1-hit filter, filters by set of compatible sectors, allows momentum dependent setups
- **Segment finder** - 2-hit filter, filters by distance, min\&max, including virtual Segment
- **Neighbour finder** - 3-hit filter, filters by angle and Δ-distance min\&max, pT
- **Cellular Automaton** evolving states, includes TC-collector
- **Post 4-hit filter** filters by zigZag, ΔpT, ...
- **Kalman filter** Calculates QI's
- **Circle fit** High occupancy bypass
- **Hopfield Network** uses QI's to find best subset among overlapping TC's
- **Clean TC's**

Black arrows represent a schematic interpretation of the possible number of combinations of hits at that point
Red arrows represent high occupancy bypass strategies
Filters marked with an O use external information generated by simulation
Steps marked with an L cycle through several passes

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HEPHY Wien & BELLE Collaboration
Motivation using sectors:

- Windmill structure and slanted sensors forbid simple layer-wise tests → at least sensor-specific tests needed
- Better: subdividing sensors in sectors and storing friend-lists
  → Allows customized filters to reduce combinatorics
  → Allows multi-pass optimizing for different momenta and curling tracks
Adapting CA to 3-4 layers, virtual segment and sectors

basic concept of cells, without sectorization restricted to sensor-wise combinations

extended concept using virtual segments attached to the IP and sectorMaps for segments in overlapping parts
3-pass-efficiency under evtGen depending on momentum range

- evtGen, wBG
- evtGen, noBG

Efficiencies with evtGen
Conclusions

- CA is versatile and compatible with practically any geometry, not restricted to silicon detectors (initially developed for DCs, implementations for TPCs also known)
- Highly parallelizable since rule checks are independent from choices of neighbouring cells and updates are simultaneous
- Using lookup-tables the CA can be made more robust versus missing hits

Outlook

- ILD - project completed and fully working in the ILD-Framework
- Belle2 - further optimizations regarding curling tracks and performance are planned
that’s all, folks!

Any suggestions, ideas or requests?
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