Randomized Computer Vision Approaches for Pattern Recognition in Timepix and Timepix3

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Aim of the talk

- Give brief overview of Timepix pixel detectors.
- Describe previous analysis works.

- Introduce *new* analysis work:
  - Extend current approaches to utilize new information,
  - CV-inspired overlap detection and separation,
  - Randomized regression of spatial trajectories in 2D and 3D,
  - ML: particle species classification.
Introduction
Timepix detectors

- Active pixel detector developed by Medipix collaboration, CERN
- 256 x 256 pixels with 55 µm pitch (1.98 cm² sensitive area)
- Hybrid design:
  - Sensor – thin layer of semiconductive material (Si, GaAs, CdTe),
  - ASIC – signal pre-amplifiers and counting circuitry (CMOS-based).
Working principle

Bias voltage source

Ionizing particle

Common electrode

Bump bonds

Pixel-site electrodes

Wire bonds

Pixel registers

Readout pads

Sensor

ASIC

PCB
Operation modes

**Time over Threshold (ToT)**
- Pixel intensity encodes amount of deposited energy.

**Time of Arrival (ToA)**
- Pixel intensity encodes incidence time since acquisition start.
Detector networks at LHC

- **ATLAS**
  - Medipix (run 1),
  - Timepix (run 2),
  - Timepix3 (run 2)

- **MoEDAL, LHCb**
  - Timepix (run 2),
  - Timepix3 (run 2)
Notable applications at LHC

Determination of absolute luminosity and induced radioactivity


Characterization of mixed radiation fields at different positions


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Notable applications in space

- **Proba-V satellite (2013)**
  - LEO, altitude: 820 km
  - SATRAM = Timepix-based spacecraft radiation monitoring platform

- **VZLUSAT-1 nanosatellite (2017)**
  - LEO, altitude: 450 km
  - Timepix-based X-ray telescope on board
Data examples
Morphological clustering

- **Idea:** separate pixels into tracks by their spatial adjacency

- **Possible failures:**
  - Broken up tracks
  - Overlaps

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Morphological classification

- Various thresholds on linearity, roundness, convex hull, etc.
- Powerful & simple discrimination between track types.
- Often combined with *a priori* info (about beam, converters, etc.)

- **Dots**
  photons and electrons (10 keV)
- **Small Blobs**
  photons and electrons
- **Curly Tracks**
  electrons (MeV range)
- **Heavy Blobs**
  heavy ionizing particles with low range
- **Heavy Tracks**
  heavy ionizing particles (photons)
- **Straight Tracks**
  energetic light charged particles (MIP)

Extension points

- Both techniques originally developed for Medipix2 (binary pixels)
  - ToT information not utilized
  - Susceptible to pile-up \(\rightarrow\) acquisition time tuning

- 6 classes have proven insufficient for more complex tracks, e.g.:
  - \(\delta\)-ray emissions,
  - collisions, fragmentation events,
  - exotic particles
2D Analysis
CV-inspired ideas

- Re-formulate task as an object detection problem
  - Treat ToT as “intensity” and frame as “image”

Photography: Timepix:

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CV-inspired ideas

- Re-formulate task as an **object detection problem**
  - Treat ToT as “intensity” and frame as “image”

- Combine data with *a priori* known information in order to achieve 3D results.

**Photography:**

**Timepix:**
Object class: heavy ions

- Desirable properties:
  - Large momentum $\rightarrow$ assumption of linear trajectory
  - Hidden parameters can be approximated with a line segment.
  - Charge sharing produces continuous pattern $\rightarrow$ suitable for LO.
Heavy ion tracks

Cross-section:

Observed track:

- Argon, 75 GeV/c
- Halo
- Core
- δ-rays
- Charge carrier motion
- Charge carrier diffusion (h⁺)
The Algorithm

Timepix Frame

Hough Transform

Event count, overlap separation

RANSAC

Local Optimizer

Angular Analysis

Angular Analysis

dE/dx Analysis

dE/dx Analysis

Preliminary trajectory

More precise trajectory

... for each detected line
The Algorithm

- **Timepix Frame**
- **Hough Transform**
  - Event count, overlap separation
  - Preliminary trajectory
- **RANSAC**
- **Local Optimizer**
  - More precise trajectory
- **Angular Analysis**
- **dE/dx Analysis**

Detector frame:

MoEDAL, detector #4
2015-09-12
The Algorithm

Timepix Frame → Hough Transform → RANSAC → Local Optimizer → Angular Analysis, dE/dx Analysis → More precise trajectory

Event count, overlap separation

Preliminary trajectory

Hough accumulator:

Angular Analysis, dE/dx Analysis → More precise trajectory
The Algorithm

1. **Timepix Frame**
2. **Hough Transform**
   - Event count, overlap separation
3. **RANSAC**
4. **Local Optimizer**
   - Angular Analysis
   - dE/dx Analysis
5. **RANSAC**
6. **Local Optimizer**
7. More precise trajectory
   - Angular Analysis
   - dE/dx Analysis

Segmented track + fit:
- ... Entry point
- ... Exit point
- \( \theta \) ... Incidence angle
- \( \varphi \) ... Azimuth
The Algorithm

Segmented track + fit:

- Entry point
- Exit point

θ ... Incidence angle
φ ... Azimuth

Difference:
Utility weighted by pixel intensity.

Angular Analysis, dE/dx Analysis, Angular Analysis, dE/dx Analysis
The Algorithm

1. **Timepix Frame**
2. **Hough Transform**
   - Event count, overlap separation
   - Preliminary trajectory
3. **RANSAC**
   - Local Optimizer
     - Angular Analysis
     - dE/dx Analysis
   - More precise trajectory
4. **RANSAC**
   - Local Optimizer
     - Angular Analysis
     - dE/dx Analysis

Histogram:
- Significant direction

Angular Analysis
- dE/dx Analysis
The Algorithm

1. Timepix Frame
2. Hough Transform
   - Event count, overlap separation

3. RANSAC
4. RANSAC
5. Local Optimizer
6. Local Optimizer
7. Angular Analysis
8. Angular Analysis
9. dE/dx Analysis
10. dE/dx Analysis

Histogram:
- Significant particle class

Angular Analysis

\[
\frac{dE}{dx} \approx \frac{\sum_i E_i}{\text{trajectory length}}
\]
Hough Transform: 
Overlap separation example

- Question: with Hough, are RANSAC & LO really necessary?
- Benchmarked performance, spatial and angular accuracy.
- Generated random frames from manually curated dataset of over 1K experimentally observed tracks.
Question: with Hough, are RANSAC & LO really necessary?
- Benchmarked performance, spatial and angular accuracy.
- Generated random frames from manually curated dataset of over 1K experimentally observed tracks.

<table>
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<th>Algorithm</th>
<th>n</th>
<th>\langle FR \rangle</th>
<th>\langle E(x_{far,1}) \rangle</th>
<th>\langle E(x_{far,2}) \rangle</th>
<th>\langle E(\varphi) \rangle</th>
<th>\langle E(\theta) \rangle</th>
<th>\langle t \rangle [ms]</th>
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Application at LHCb

- 5 Timepix detectors at MoEDAL (LHCb, CERN)
- Known locations, orientations of source and detectors.
- Unknown field composition, secondaries.
Angular Analysis

Fill #6024
3.5M tracks

TPX04
TPX02
117cm
98

Beam

VELO

104.5 cm
66 cm

TPX03
TPX05
dE/dx Analysis

Fill #6024
3.5M tracks

Beam

TPX01

TPX03

TPX05

PX04

TPX02

17 cm

104 cm

66 cm

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Particle Identification
Motivation

- $dE/dx$ includes information about particle species and momentum

**Theory:**

![Graph showing mass stopping power vs. beta gamma (\(\beta\gamma\)) for different particle types and momenta.](image)

- Observed $dE/dx$
- Mass stopping power [MeV cm$^2$ g$^{-1}$]
  - $\mu^+$ on Cu
  - Bethe
  - Radiative
  - Radiative losses
  - Without $\delta$

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Motivation

- dE/dx includes information about particle species and momentum.

Measurement:

- Oxygen (430 MeV)
  - θ = 0°
- Helium (221 MeV)
  - θ = 0°
  - θ = 60°
  - θ = 90°
Results (5 classes)

Configuration:
- k-NN classifier (k=7)
- 32 uniform dE/dx bins

Results:
- Accuracy = 0.89
Results (5 classes + rejection)

Configuration:
- k-NN classifier (k=7)
- 32 uniform dE/dx bins
- Confidence $\geq 0.95$

Results:
- Accuracy = 0.94
- Rejection Ratio = 0.25
WIP: 3D Analysis
Timepix3 vs. Timepix

- Simultaneous ToT and ToA operation mode

- Data-driven readout
  - Hits are reported during acquisition \(\rightarrow\) need to work with incomplete information in online scheme
  - Temporal consistency: hits may be out of order
  - Large data throughput (theoretically up to 80 MHz)

- Increased time resolution
  - Fast ToA clock at 640 MHz \(\rightarrow\) resolution: 1.56 ns
  - TDC synchronization \(\rightarrow\) coincidence analysis
Online morphological clustering

- Conventional morphological clustering cannot be used in Timepix3 → The algorithm needs to be extended.

- Data-driven mode: no frames, pixels are reported continuously
- Out-of-order timestamps: hit buffering in a priority queue
- Geometric DS: efficient adjacency test

→ Advertisement: L. Meduna et al. Real-time Timepix3 data clustering, visualization and classification with a new Clusterer framework
3D event reconstruction

- Estimation of relative depth from fToA $\rightarrow$ 3D point clouds

**Ref:** Bergmann B. *et al*, "3D track reconstruction capability of a silicon hybrid active pixel detector" *The European Physical Journal C* 77.6 (2017): 421.

- RANSAC and Hough methods easily generalize to 3D.

**Results:**

$$\frac{dE}{dx} = 3.39 \ \text{MeVcm}^2 / \text{g}$$

- RANSAC Fit
- Hough Fit
Conclusion

- Previously developed pattern recognition methods updated for new detectors (Timepix, Timepix3):
  - Utilized ToT, fToA (increased precision, online clustering alg., 3D reconstruction)
  - Updated clustering for data-driven readout mode → online algorithm

- New methods for HETE analysis developed and evaluated:
  - Randomized → accurate results, good performance
  - Trans-dimensionality → well-suited for overlap separation (simulated up to 20)
  - ML → basic feature model has shown accuracy up to 93.5%

- New methods tested in various applications:
  - Angular, dE/dx analysis (MoEDAL)
  - Particle identification (Heidelberg Ion-Beam Therapy Center)

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Further work

- Analysis of non-linear trajectories (under assumption of continuity)
  - Polynomial / spline interpolation
  - Principal curves

- Detection of interactions between events within detector.
  - Branch detection
  - Prong detection

- Application of deep learning (2D CNNs).

- Bus saturation $\rightarrow$ offload to readout hardware (FPGA).
Thank you for your attention. Questions?

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Literature: