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Track Pattern Recognition for the SHiP Spectrometer Tracker

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Abstract. SHiP is a new proposed fixed-target experiment at the CERN SPS accelerator. The goal of the experiment is to search for hidden particles predicted by models of Hidden Sectors. The purpose of the SHiP Spectrometer Tracker is to reconstruct tracks of charged particles from the decay of neutral New Physics objects with high efficiency. The goal is to develop a method of pattern recognition based on the SHiP Spectrometer Tracker design.

1. Introduction

Track pattern recognition is an early step of the reconstruction of data coming from a particle detector. It recognizes tracks among the subdetectors hits. Reconstructed track parameters allow to estimate the particle deviation in a magnetic field, and thus reconstruct its charge and momentum. This information is used for the reconstruction of the decay vertex, to identify the mother particle and for further particle identification.

There is wide variety of the track pattern recognition methods [1]. They differ in how they process the hits, what kind of tracks they are able to recognize and which requirements these tracks should satisfy. Therefore, specifics of an experiment and the detector geometry affect the tracking performance and track pattern recognition methods should be adapted to it accordingly.

The purpose of the SHiP experiment [2] is to search for very weakly interacting long lived particles including Heavy Neutral Leptons (HNL) - right-handed partners of the active neutrinos. In this study, a decay of HNL into a pion and a muon is considered. The goal is to recognize π , μ tracks and compare the performances of different track pattern recognition methods adapted to the SHiP Spectrometer Tracker geometry. The first method was presented by H. Dijkstra, etc. [3] in 2015. This solution is taken as the baseline.

2. SHiP Spectrometer Tracker Geometry

Figure 1a illustrates a HNL decaying into a muon and a pion in the decay vessel. The products pass through the spectrometer and hit straw tubes in corresponding stations. As presented in figure 1b, the spectrometer has two stations before the magnet and two ones after it. The width (in z) of each station is 40 cm. The distance between the 1&2 and 3&4 stations is 2 m, between 2nd and 3rd ones is 5 m [3]. Each station consist of 4 views: two Y-views with horizontal tubes and two stereo U, V views with tubes rotated by ± 5 degrees in every station. The distance



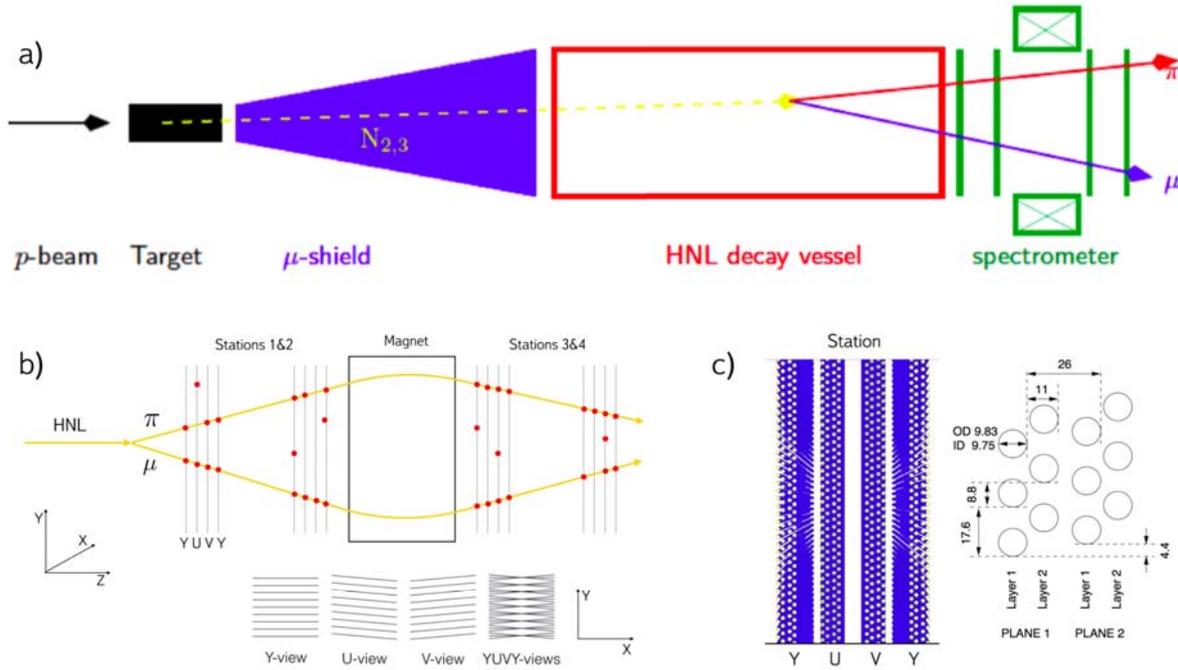


Figure 1. The SHiP Spectrometer Tracker geometry. a) The general scheme of the SHiP detector. b) The spectrometer schema. c) Geometry of straw tubes in one station of the spectrometer.

between two views is 10 cm. Each view has 4 layers of straw tubes. The geometry of one layer is shown in figure 1c.

3. Reconstructible Events

The track pattern recognition methods described in the following sections are tested on reconstructible events. For the decay of HNL into π and μ , reconstructible events in the MC truth are defined as follows [3]:

- Tracks (i.e. MC particles) must have their origin inside the decay volume.
- Tracks should not decay inside the tracking station area.
- Tracks must have a hit in the Timing Detector after the 4th station.
- Tracks must have at least one hit in each Tracking Station, inside the acceptance defined by $(\frac{x}{245})^2 + (\frac{y}{495})^2 \leq 1$.
- Tracks must be produced by an HNL decay products.
- An event must have one π -track and one μ -track.
- An event must have less than 500 hits.

4. General Scheme of Track Recognition

The general scheme used in this study was presented in [3] and contains four steps. First, linear tracks in the 16 layers with horizontal straw tubes (Y-views, y - z plane) are looked for. Then for each track found in the Y-view we look for intersection of the plane defined by this track and the x -axis with stereo (U,V) hits. This gives the coordinates of these intersections in x - z plane. Third, tracks in 16 layers of stereo-views in x - z plane are looked for using (z, x) coordinates

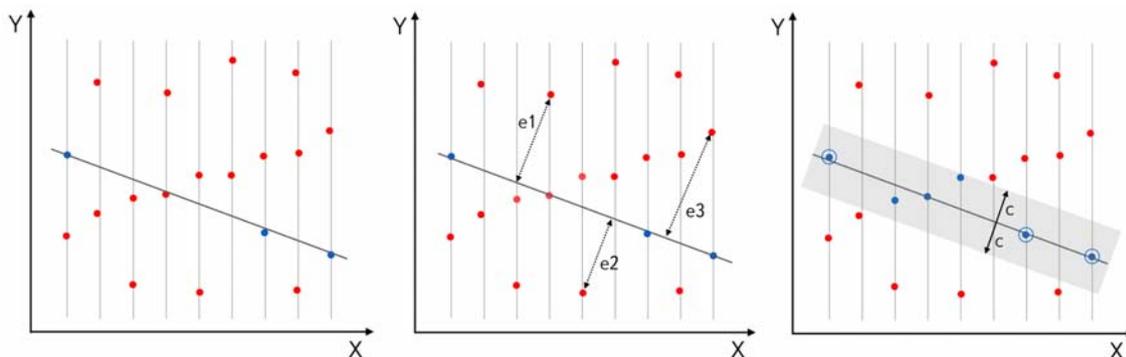


Figure 2. Demonstration of searching for one track by RANSAC.

of the intersections. These steps are performed for the stations before and after the magnet separately. Finally, tracks before and after the magnet are combined with each other and the particle momentum and charge are reconstructed.

5. Tracks Recognition Methods

In this study, the track recognition methods differ in how they are looking for tracks in Y and stereo views. These methods are divided into global [1] and local [1] ones. The global methods of the track recognition process all hits in a similar way. The result is independent of the starting hit or order in which hits are processed. The local methods reconstruct a track hit by hit starting from the track seed.

The local methods extrapolate a track to the next layer of a tracking station and add new hits to this track. These methods are sensitive to missing and noise hits. Moreover, the large distance between the layers decreases the precision of the track extrapolation and leads to the loss of hits. In this study, a track has in average 8 hits per station, so about 50% of hits are missing. The distance between two stations is 20 times larger than the distance between two views in one station and about 75 times larger than the distance between planes in one view. These reasons make local methods unsuitable for this study and are not considered further.

The global methods include three groups: template matching methods [1], transformation methods [1] and neural network techniques [1]. Template matching methods work well for a small number of tracks with simple shapes. These methods are indifferent to the distances between layers of tracking stations. This makes them good candidates for this study. Thus, two template matching methods are considered: baseline [3] and RANSAC [4].

Transformation methods work well in a large range of number of tracks and hits and are also indifferent to distances between layers. In this study, two transformation methods are considered: Hough Transform [5] and Artificial Retina [6].

Neural network techniques are used in cases of very high number of tracks and hits. In more simpler cases they are generally outperformed by other methods. Neural network techniques are hard to optimize and depend on the distance between the layers. Thus, these methods are not considered in this study.

6. RANSAC

RANSAC (RANdom SAMple Consensus) [4] is an iterative method for regression problems with samples contaminated by outliers. Figure 2 demonstrates the search procedure for one track by this method. Lets consider this procedure in more detail:

1. RANSAC selects a random subset of the hits.

2. The linear model is fitted to this subset.
3. The error of the data with respect to the fitted model is calculated.
4. The number of inlier candidates is calculated. An inlier is a hit with error smaller than predefined threshold value.
5. Steps 1-4 are repeated given number of iterations.
6. A model with the maximum number of inliers is returned.

In this study, the first track is searched in the sample of hits using RANSAC. Hits of the found track are excluded from the sample. Then, the procedure is repeated while the number of hits per track exceeds a threshold, or while the desired number of tracks are not found.

7. Hough Transform

Hough Transform [5] is a popular pattern recognition method. The key ideas of the method can be illustrated by considering the recognition of a straight line, that can be parameterized as follow:

$$y = kx + b \quad (1)$$

where:

x and y: are coordinates of a hit

k and b: are parameters of the line

The Hough Transform converts one hit in (x, y) space to the line in (k, b) space of the parameters by the following equation:

$$b = y - xk \quad (2)$$

Each point of the line in (k, b) space represents parameters of a line, that can go through the hit in (x, y) space. If several hits lie on one straight line, the Hough Transform lines will intersect in one point. This point corresponds to the parameters of a straight line in the coordinate space passing through these hits. Noise which smears the hit coordinates makes the Hough Transform lines to intersect not in a single point but in some region of the parameter space.

One of the widely used methods of the track recognition using the Hough Transform is histogramming. A demonstration of the method is shown in figure 3a. The bins in the figure with the highest values correspond to the track parameters.

In this study, the histogramming technique is modified. First, the bin with the largest value is found. Hits corresponding to this bin are marked as a track and removed from the sample. Then, the histogram is recalculated and the procedure is repeated while the number of hits per track exceeds a threshold, or while the desired number of tracks has not been found.

8. Artificial Retina

Consider the Artificial Retina [6] function which is defined as:

$$R(\theta) = \sum_i e^{-\frac{\rho^2(\theta, x_i)}{\sigma^2}} \quad (3)$$

where:

$\rho(\theta, x_i)$: is the distance between the i -th hit and a track with parameters θ

σ : is a smoothing parameter

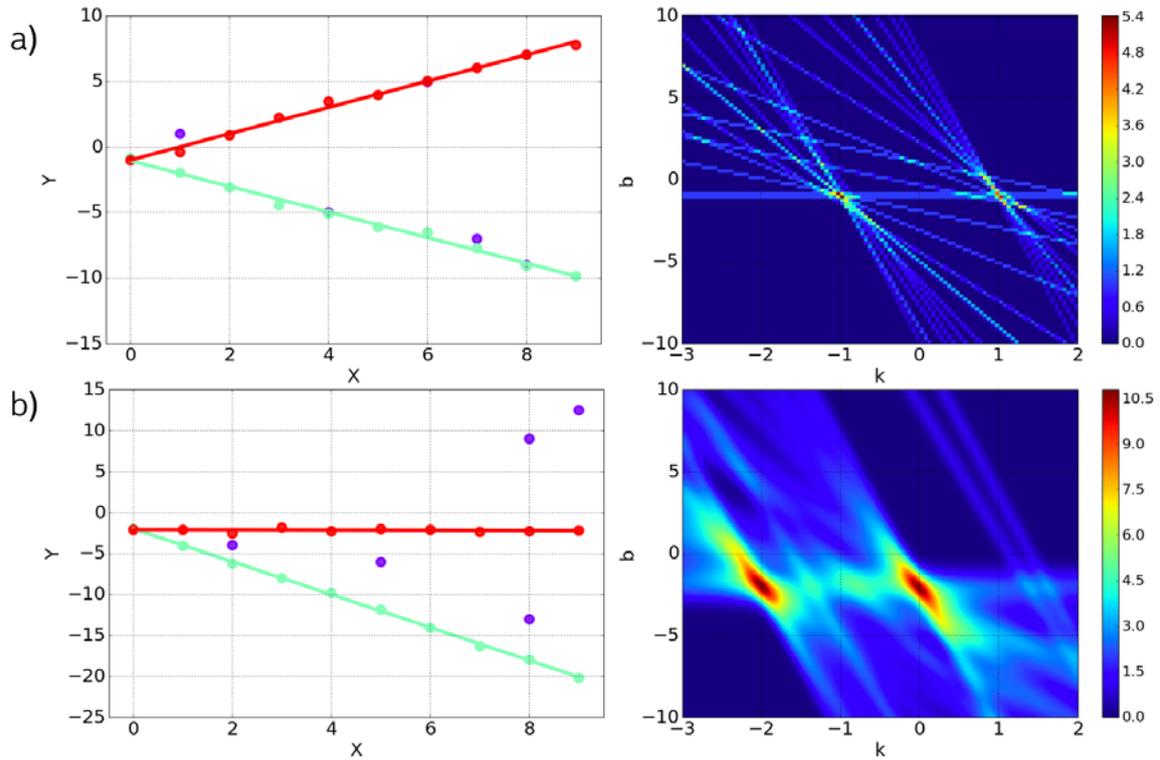


Figure 3. The Hough Transform (a) and the Artificial Retina (b) methods demonstration.

The sum is calculated over all hits in the event. In case of 2D tracks:

$$\rho^2(\theta, x_i) = (y_i - (kx_i + b))^2 \quad (4)$$

where:

k and b : are parameters of the track

The track recognition method is based on the fact that the track parameters correspond to the maximum values of the function. Figure 3b demonstrates this property.

The Artificial Retina function is differentiable and allows to compute its gradient and hessian. This means that the track pattern recognition can be considered as an optimization problem in the parameter space.

The optimization starts from an initial point. For that, parameters of lines constructed from each pair of hits are estimated. The parameters correspond to the higher Artificial Retina function value are selected as initial point of the optimization.

Starting from the initial point, the local maximum of the Artificial Retina function is searched using the BFGS [7] optimization algorithm. This maximum corresponds to the track parameters. The track hits are excluded from the sample and the optimization is repeated while the number of hits per track exceeds a threshold, or while the desired number of tracks has not been found.

9. Track Combination

Recognized tracks before and after the magnet are combined with each other. For this, they are extrapolated to the Z in the center of the magnet and the distances between them on x and y are calculated. Thus, each pair of tracks are described by their parameters and distances. This

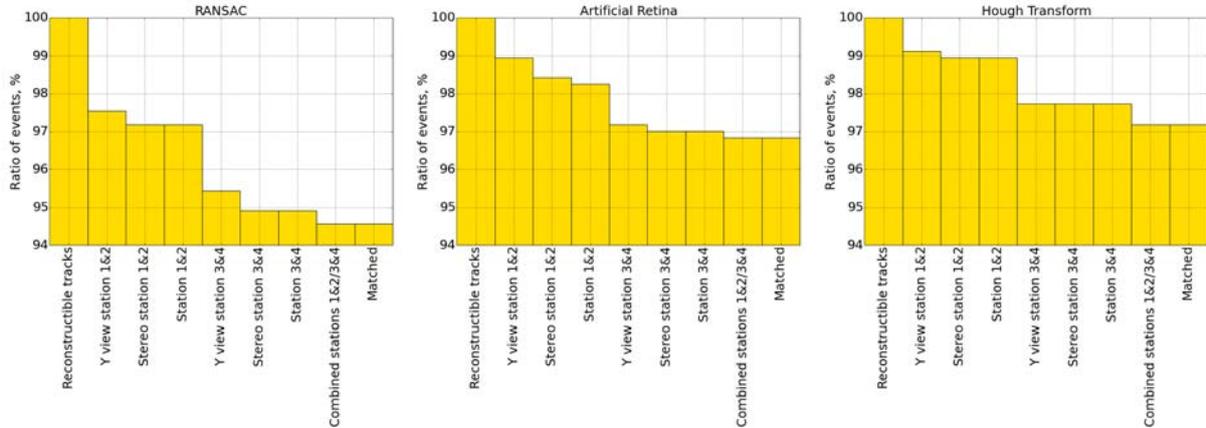


Figure 4. Total reconstruction efficiency.

information is used to train the Random Forest Classifier which predicts that a track before the magnet and a track after it correspond to one particle.

The combined tracks allows to estimate the particle deviation in the magnetic field thus reconstructing its momentum and charge.

10. Results

Figure 4 presents the fraction of reconstructible events which pass through different track finding steps. If two tracks (for muon and pion) in the event are not recognized, the event does not pass to the next step. The last column in the graphs shows the final reconstruction efficiency.

The dependence of the total reconstruction efficiency on the track efficiency threshold is shown in figure 5a. Track efficiency is a criterion which specifies whether a certain particle has been found by the algorithm or not. If the qualified majority of hits, for example at least 70% originates from the same true particle, the track is defined as matching this particle. The particle momenta reconstruction accuracy is demonstrated in figure 5b.

The comparison of these models with the baseline [3] is presented in Table 1. The table demonstrates that Artificial Retina and Hough Transform models have better total reconstruction efficiency and the particle momenta reconstruction accuracy.

Table 1. The tracks pattern recognition models comparison.

Model	Max RecoEff, %	Min RecoEff, %	P MeanErr., %	P Std.Err., %
Baseline [1]	94.1	-	3.2	-
RANSAC	94.6	81.2	2.8	12
Artificial Retina	96.8	83.7	2.2	14.9
Hough Transform	97.2	80.2	2.7	10.3

11. Conclusion

This study shows that the different track recognition methods can be successfully adapted to the SHiP Spectrometer Tracker geometry and physics of the experiment. These methods outperform

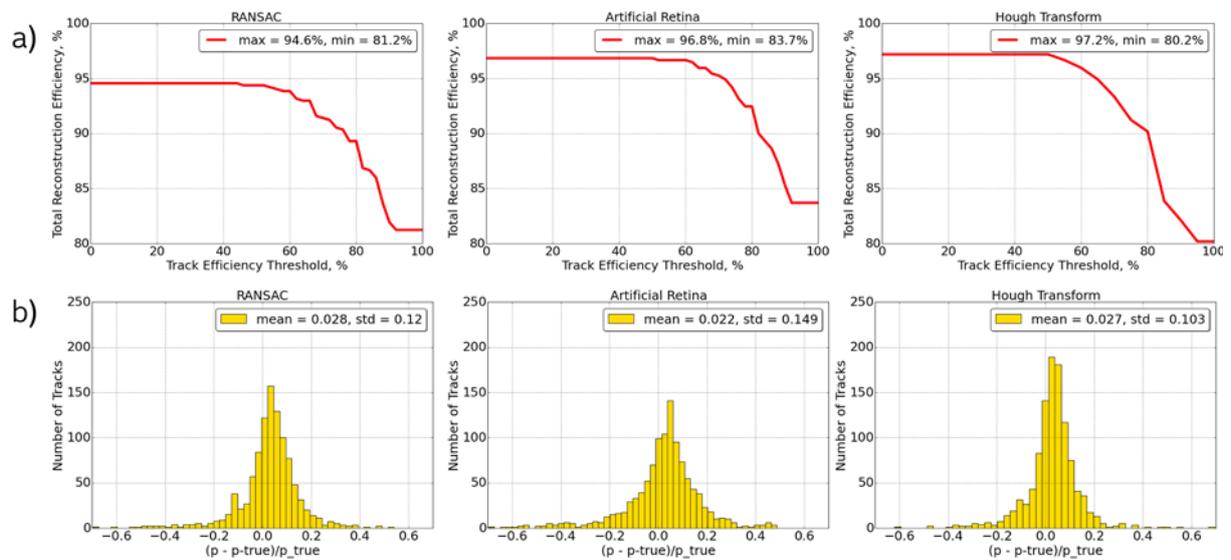


Figure 5. a) Dependence of total reconstruction efficiency on the track efficiency threshold. b) The particles momenta reconstruction accuracy.

the baseline solution and reconstruct tracks of charged particles from the decay of neutral New Physics objects with higher efficiency. Our current research is focusing on improving the speed of these algorithms so that it can be included in FairShip [8].

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