**Downstream Pattern Recognition**

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**Abstract**

In this note the implementation of the downstream tracking for DC '06 is described, namely the package PatKShort v1r2. The principles of operation are described, together with the origin of the various algorithm parameters. Performance is given, in terms of efficiency, ghost rate and speed. Directions for improvement are also listed.

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1. Introduction

The downstream pattern recognition is the piece of code that tries to find tracks crossing TT and the T stations, starting from 'seed' obtained in the T-stations by the TSA algorithm [1]. This initial track will be called the 'T-Seed' in this document. This is mainly the search for the proper hit in the TT station to add to the T-Seed, more accurately measuring the momentum. The purpose of this algorithm is to find tracks useful for physics and not measured in the Velo, namely decay products of long lived particles, $K_0$ or $\Lambda$ decaying between the Velo and TT. Long tracks, that traverse the entire spectrometer from Velo to T stations, are supposed to be found by other algorithms.

2. Principle of operation

The basic principle is that TT and the T stations are on both sides of a magnetic field region, and thus the segment of track in TT and the T-Seed are crossing each other in the centre of the field. Reversing the argument, starting from a T-Seed, one can compute the point at the centre of the magnet, and search for a list of TT measurements making a straight line with this point.

The second point is that one search for tracks coming from not-too-far from the interaction region: The maximum transverse momentum of a pion, daughter of a $K_0$, is 209 MeV. For a momentum of 2 GeV for the decaying pion, the angle of this pion to the line of flight of the $K_0$ is less than 100 mrad. With a first TT planes at $z$ around 2.3 m, which gives the maximum flight distance for the $K_0$, the impact parameter at $z=0$ is at most $0.1 \times 2.3 \, \text{m} = 23 \, \text{cm}$. As the centre of the magnet is around $z=5.3 \, \text{m}$, this means that the window in the TT stations to look for measurements of a given track is around $23 \, \text{cm} / 5.3 \times 3.0 = 12 \, \text{cm}$. This is a wide range, compared to the strip pitch of TT, and $\pm 12 \, \text{cm}$ correspond to roughly 1200 strips! As the occupancy in TT [2] is at the 1% level,
this window will contain several candidates. Note that the size of this window scales with 1/p, and p is estimated for the T-Seed which is Kalman-fitted. The ghost rate is clearly the main challenge, and the size of the window is tuned to keep a good efficiency with a limited ghost rate, reducing the efficiency for decay products with maximum p_t and maximum decay length. As the maximum transverse momentum of daughter tracks is even lower for Λ, Σ, Ξ and Ω, the same constraint applies for all these particles.

2.1. Parameterisations

As the LHCb magnet has a trapezoidal aperture, the position of the centre of the magnet is known to not be a simple plane[3]. Using Monte-Carlo events, the average position of the intersection of the TT segment and the T-Seed for many tracks can be computed using a fit to the true MC hits. This position is parameterised as function of the variable we know in the reconstruction, namely the parameters of the T-Seed. This parameterisation is obtained by the package PatFitParams, also used to compute the parameters of the Forward tracking.

The parameterisation used is as follows: tx and ty are the slopes of the T-Seed at z=9450 mm, and xSeed is the coordinate of the T-Seed at this position

\[ z_{\text{Magnet}} = 5368.54 - 2155.88 \times ty^2 + 595.27 \times tx^2 - 0.00001455 \times x_{\text{Seed}}^2 \]  

(all in mm)

The values of the parameters are the result of the fit, obtained from the Pat/PatFitParam package. This formula means that the position of the centre of the magnet is shifted by -80 mm for tracks at ty=200 mrad, by +53 mm for tracks at tx= 300 mrad, and 57 mm for tracks at x=2 m on the side. These corrections are essentially a property of the field map, and don’t need to be measured with real data. However, it may be possible to check them with clean events.

There is another parameterisation, less important for the pattern recognition, the parameterisation of the momentum once the track has been found. It uses also tx, ty and the change in x-slope between TT and T-Seed dSlope.

\[ \text{momentum} = \frac{1190.86 + 605.67 \times tx^2 + 2656.55 \times ty^2}{d\text{Slope}} \]  

(in MeV)

This assumes the nominal field map. Note that this momentum value is only used as an initial value for the Kalman fit which produces the final momentum. The resolution is around 1%.

3. Algorithm

Each track is processed independently, one after the other. There is no special ordering of tracks, and no memory of measurements used on previously processed tracks.

3.1. Initial filtering

As first step, a local working track object, of type PatKsTrack is created. This object receives the parameterisation described in 2.1 to compute the centre of the magnet and the momentum. It computes in its constructor the position at centre of magnet, and transverse error on this position,
based on the T-Seed error matrix and on a parameter specifying the error on the z position of this centre of magnet.

\[ \text{errX} = \sqrt{\text{errX}_{\text{seed}}^2 + dz^2 \times \text{err Tx}_{\text{seed}}^2 + (errorZ \times \text{dSlope})^2} \]

where the first two terms are a simple extrapolation of the error on the T-Seed track, dz being the distance between the point the T-Seed state is defined and the centre of the magnet. The last term reflects the error on z, the first term is a job option value, 50 mm, and the second term is the change of slope between before and after the magnet. The slope before the magnet is computed by joining the origin (nominal crossing point) to the computed centre of magnet. Errors in x and y are different, as the T-Seed error matrix has no reason to be the same for x and y.

Once this object is initialised, the momentum can be computed using the parameterisation described in 2.1 and with the slope before the magnet computed as indicated just before. This is a sort of “Pt kick” computation. This momentum is compared to the value given in the T-Seed, and they should match for the track to be processed. This is to filter tracks found by the seeding algorithm which are not coming from the interaction region. The tolerance on \( \delta p/p \) is quite weak and controlled by a jobOption \( \text{deltaP} \) with a default value of 0.70.

### 3.2. Collection of interesting measurements

As discussed earlier, the window where interesting measurements can be found in TT is centred on the line centre-of-magnet to nominal interaction point, and has a width which is momentum dependent. The used value is

\[ \text{xPredTol} = \frac{m_{\text{xPredTol}}}{\text{abs}(p)} + 10 \times \text{mm}; \]

where \( m_{\text{xPredTol}} \) is settable by the job option ‘\( \text{xPredTol} \)’ and defaults to 100 mm x GeV. This is about twice smaller than discussed in section 2, because the gain in efficiency of widening this window is low compared to the increased ghost rate.

For each hit, which is at a different z, the y estimate of the track is computed, the hit’s position is updated to take into account this y value (stereo measurements), and this position is compared to the straight line extrapolation of the track, to see if this is inside the above computed tolerance. If so, the y coordinate of the track is also compared to the boundary of the strip in TT, with a tolerance of 15 mm, modifiable by the job option ‘\( \text{yTol} \)’. When both tests are met, the hit’s pointer is stored into one of the two containers of the tracks, one for x layers and one for stereo layers. The ‘projection’ of the hit is set to the distance between the hit and the straight line extrapolation of the track.

Once all measurements have been processed, the measurements assigned to the track candidate are sorted by projection. If there are less than three measurements in total, the track is immediately abandoned.

### 3.3. Search for the best group of measurements for this track

As TT has only 4 planes, and as a missing layer should be allowed, it is enough to find 3 TT measurements to form a track. But the position and slope of the track are measured from these measurements, leaving a very low number of degree of freedom. In fact, the only constraints is the centre of magnet point in x, and the straight line extrapolation in y. The other weak constraint to use is that one prefers a solution more compatible with coming from the origin than from a far distance, and that four planes is better than three.
The search for the best group is a loop on all X measurements, trying to find compatible measurements in the X layers, then adding stereo measurements and fitting with removal of the worst hit until the $\chi^2$ is good, or until there are less than 3 planes left. As there may be several solutions, a comparison with previously found solutions is performed, and only one combination is kept. One keeps track of the current best solution, and the X measurement in the loop should not be already part of the best candidate, to avoid finding again the same solution.

3.4. Matching X measurements

X measurements from the pre-selected list (section 3.2) are compared to the seed one, and added to a temporary vector if they are close enough. This tolerance depends if the measurements are in the same TT layer (0.1 mm) or in the other layer: In this case, the tolerance depends linearly on the (absolute value of the) vertical slope and varies form 2.5 mm to 3.5 mm for tracks at 200 mrad, the maximum vertical angle. For those large angle tracks, the occupancy is lower and the tolerance can be relaxed, increasing efficiency without significantly increasing the ghost rate.

3.5. Fitting the X projection

If two or more measurements are found, the track is fitted and the worst measurement identified. For the fit, one uses an extra constraint to pass at the centre of magnet point, with the tolerance $\text{errX}$ described in section 3.1. The measurement with largest distance is identified, and if this distance is higher than $\text{m\_maxDistance}$ (same as before) the measurement is rejected, and the fit iterated until the worst measurement is good enough, or until there is only one measurement left.

3.6. Adding stereo measurements

The measurement in the pre-selected list of stereo measurements (section 3.2) are compared to the predicted position (Y is known from the extrapolation of the T-Seed) and collected if their distance is smaller than $\text{m\_tolUV} = 3.0$ mm. If there are less than three measurements in total, X plus stereo, the track is abandoned. All measurements are sorted now by z coordinate; this is useful only for debugging.

3.7. Space track fit

A similar fit-and-remove-worst procedure is applied, in fact this is the same code than in section 3.5 but this code has if statements to handle stereo coordinates and fit the y projection only if there are some stereo measurements. At every iteration, the y coordinate of each stereo measurement is computed, taking the distance (in X) between the measurement and the track as a measure of the distance in y, multiplied by the tangent of the stereo angle, also known as dx/dy. With the limited number of stereo measurements, one fit only the average y displacement in TT.

To speed up the processing, and as the X projection was already fitted, Y hits are checked first for worst distance, with a tolerance three times $\text{m\_maxDistance}$, and removed if over this distance. If all are in this tolerance, the x projection is refitted, using also the x information from the stereo measurements, the hit with the worst distance identified and removed if the distance is larger than $\text{m\_maxDistance}$. The iteration stops if the distance is good enough, or if it remains less than 3 measurements. A final check is made that the vertical range (strip limits) of each measurement is
now compatible with the fitted track. If not, incompatible measurements are removed and the fit iterates again.

3.8. Final checks

A few checks are performed on the resulting candidate:

- At least 3 measurements
- At least 2 measurements with the High Threshold bit set. This is to remove combinations made with mainly/only spill-over measurements.
- The global $\chi^2$ per degree of freedom should be lower than 10. This value can be set by the job option “maxChisq”.
- The momentum computed from the change of slope should be compatible with the input momentum, this is the same test as described in section 3.1 but this time the slope before the magnet is the result of the fit.

3.9. Selecting the best candidate

The first criterion is the number of measurements. If the new candidate has fewer measurements than the “current value”, the new candidate is ignored. The “current value” is the number of measurement of the best candidate, limited to 4: If a candidate has more ghost hits, it should not be selected for that!

If the new candidate has at least that number of measurements, the candidate with the lowest $\chi^2$ per degree of freedom is kept.

3.10. Storing the track

Once all possible X measurements have been processed, one is left with zero or one candidate. This candidate is converted to a standard LHCb::Track object, and inserted in the output container. This track is a copy of the T-Seed, keeping its initial state and adding a new one in TT, with position, slope and momentum according to the best estimates. A diagonal covariance matrix is created, with fixed values (modifiable by job option) of the diagonal terms. The LHCbIDs of the TT measurements are added to the list of LHCbIDs of the track, and the flags are set properly to indicate that the track has not yet been fitted, and contains only LHCbIDs. The ancestor is set to the T-Seed track.

4. Performance

The efficiency and ghost rates are measured using PatChecker. This code counts how many MC Particles are reconstructed, for various subsets of MC Particles. For the downstream tracking, the MC Particles of interest are not reconstructable in the Velo, have a T-seed and TT hits. A sub-category is made of particles who are daughters of a strange particle ( $K_s$, $\Lambda$, $\Sigma$, $\Xi$ or $\Omega$ ) that was produced near the beam line (original vertex radius less than 8 mm). This covers all decay products of strange particles produced at the primary vertex or by the decay of a short lived
particles like B or D. Finally, a last subset corresponds to those daughters of strange particles having a momentum larger than 5 GeV. The efficiency table is given below, with hit purity (fraction of hits from the correct MC Particle) and hit efficiency (fraction of hits of this MC Particle in the T stations that are found on the track). This has been measured on about 2500 events \( B \rightarrow J/\psi (\rightarrow \mu^+\mu^-) K_s (\rightarrow \pi^+\pi^-) \) from the DC06 production.

<table>
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<tr>
<th>Efficiency Clone rate Hit purity Hit efficiency</th>
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<tbody>
<tr>
<td>Have T-Seed, no Velo, TT 48.6 % 0.7 % 98.12 % 89.16 %</td>
</tr>
<tr>
<td>+ daughter of strange particle 73.5 % 0.7 % 98.26 % 89.71 %</td>
</tr>
<tr>
<td>And &gt; 5 GeV 82.8 % 0.9 % 98.32 % 89.97 %</td>
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The event averaged ghost rate is 26.0 %, which is quite high, and the efficiency is far from 100%.

Since DC06, an improved version of the package has been released, with improved efficiency with similar ghost rate. More work is clearly needed to improve this downstream track reconstruction.

5. References

