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Program for reconstruction of charged particle tracks in the central part of the SPD experiment track system

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The paper describes a special algorithm for reconstructing the tracks of charged particles in the central part of the track system of the SPD experiment being built at the NICA collider. The program consists of a procedure for searching for track candidates in a two-dimensional space, followed by adding information about the longitudinal component of the track. The track parameters were estimated using a Kalman filter, which takes into account energy losses and multiple scattering during the passage of a charged particle through a substance. The program demonstrated high efficiency of track reconstruction and was added to the SPD experiment software.

Keywords: SPD experiment, Hough transform, track reconstruction, Kalman filter, Monte Carlo simulation.

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The main goal of SPD experiment (Spin Physics Detector) being constructed at NICA collider in Dubna is to study the spin-dependent structure functions of nucleons and other spin effects in proton-proton and deuteron-deuteron interactions with polarized and unpolarized particle beams [1]. In this paper, a dedicated algorithm for reconstructing tracks of charged particles is proposed, using measurements only in the central part of the tracking system of SPD experiment, and the outcomes of its use in events reconstruction by Monte Carlo (MC) method are outlined.

The tracking system of SPD-experiment described in detail in (TDR) detector data sheet [2], will include at the first stage only a vertex detector containing only one layer of a microstructure gas coordinate detector (MicroMegas), and a major track detector consisting of the thin-walled straw tubes. According to the latest proposals, the central tracking detector will be divided into six equal modules, symmetrically located around the beam collision axis, and the number of straw tubes layers in a module will be 70. Some of the straw tubes are located parallel to Z axis, directed along the collision axis of the particle beams, and the other part is located at a small angle of 2° to Z axis. The inner radius of the central part of the track detector is 27 cm, the outer radius is 86.7 cm, and the total length of the detector along Z axis is 236 cm. The Cartesian coordinate system used in SPD experiment is standard for most high-energy physics experiments: Z axis coincides with the direction of the colliding particle beams, Y axis is vertical, X axis is perpendicular to Z and Y axes and directed toward the center of the collider ring, and the center of the setup is considered the origin of the coordinate system. The magnetic field in SPD experiment will be solenoidal with a magnitude reaching 1.2 T, and the field non-uniformity in the central track detector does not exceed a few percent.

In general, the track reconstruction program consists of two successive parts: first, a search is conducted in the vertex and track detectors for measurements that may belong to a certain track candidate, and in the second step, the parameters of the found track candidates are determined using an approximation procedure. Since at the first stage of SPD experiment the vertex detector will consist of only one layer, it becomes impossible to use the standard track reconstruction procedure [3,4], in which track segments are first created from measurements in the vertex detector, and then measurements from the central track detector are added. Therefore, a sequential procedure was proposed for track reconstruction, in which tracks are reconstructed using measurements only in the central part of the track detector (Fig. 1).

According to the scheme proposed in Fig. 1, the track reconstruction procedure begins with finding the dimensions belonging to the track candidate in the two-dimensional XY space. At this stage, the measurement, or MC-hit, is the position of the central wire (x, y coordinate) of the triggered straw tube, which is parallel to Z axis. Here, we will use the fact that in a constant magnetic field, the trajectory of a charged particle in the transverse XY -plane is a circumference with radius $R \propto P_T/B_z$, where P_T — is the transverse momentum of the particle, B_z — is the component of the magnetic field along Z axis. Then for the dimensions (x_i, y_i) lying on the circumference passing through the reference point, the following expression is true:

$$r_i = 2R \sin(\varphi_i - \varphi), \quad (1)$$

where $r_i = \sqrt{x_i^2 + y_i^2}$ — radius-vector connecting the reference point (x_i, y_i) on the circumference, R — radius of the circumference, φ — particle solid angle (angle of tangent to the circumference) in the reference point,

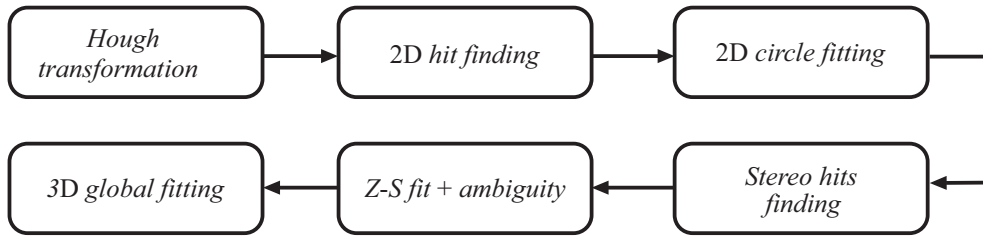


Figure 1. General scheme of the algorithm for reconstructing tracks of charged particles in the central part of SPD-experiment tracking detector.

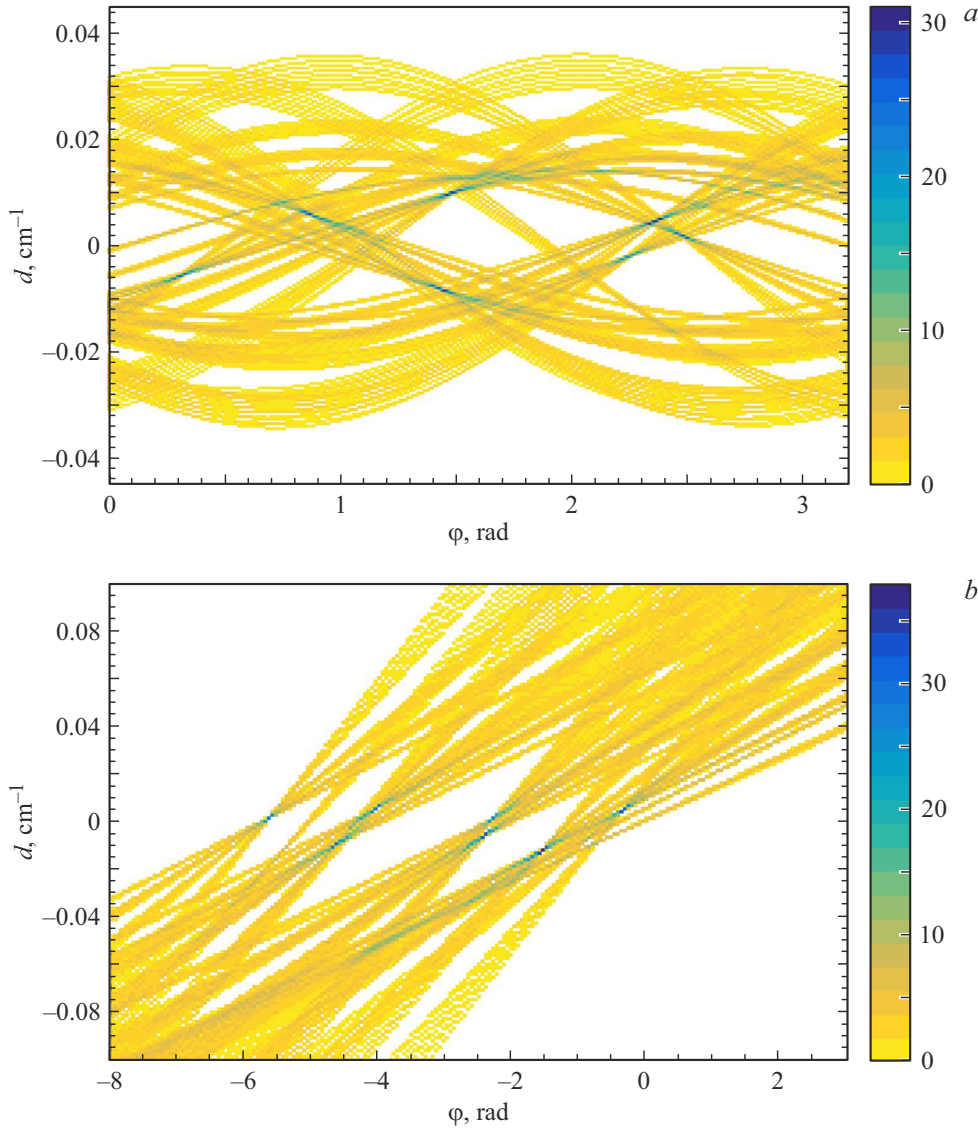


Figure 2. The 2D histograms in the space of d – φ -parameters, obtained using the expression (2) (a) and expression (3) (b).

$\varphi_i = \arctg(y_i/x_i)$ — radius-vector angle $\mathbf{r}_i$ relative to X axis. Expression (1) may be written as

$$d = \frac{1}{2R} = \frac{\sin(\varphi_i - \varphi)}{r_i}, \quad (2)$$

which is the Hough transform [5] for describing points (x_i, y_i) lying on a circumference in the space of

d – φ -parameters. In this Hough transform [5] each transform (x_i, y_i) or (r_i, φ_i) has its sinusoidal line in the space of d – φ -parameters. Thus, the set of measurements of (x_i, y_i) lying on the circumference is transformed into a set of sinusoidal lines in the space of d – φ parameters intersecting at a point corresponding to the parameters of the considered circumference. For tracks with a relatively large radius,

i. e., in the approximation of a small difference in $(\varphi_i - \varphi)$ angles, expression (2) is transformed to

$$d \approx \frac{\varphi_i - \varphi}{r_i}, \quad (3)$$

which is a straight line equation in the space of $d-\varphi$ -parameters. To find the intersection of sinusoidal or straight lines in the space of $d-\varphi$ parameters, a discrete two-dimensional distribution was used, where each dimension (x_i, y_i) contributes to a specific sequence of bins in a two-dimensional histogram. Such two-dimensional histograms for the expressions (2) and (3) is given in Fig. 2.

The problem of finding MC hits belonging to a track candidate implies finding the bins with the maximum number of entries on a two-dimensional histogram. This procedure is performed consecutively and consists of the following stages:

- the bin with a maximal number of entries is found;
- all measurements included in a given bin are assigned to a specific track candidate and removed from further consideration;
- the next bin with a maximal number of entries is found;
- the procedure continues until the number of inputs to the bin exceeds a certain threshold value;
- at the last step, the MC hits belonging to the track candidate are approximated by the circumference.

To improve the efficiency of finding MC hits, the above procedure was modified as follows:

- first, only hits from the first 52-th layers of the track detector were considered;
- then the found hits were approximated by the circumference;
- then the circumference was extrapolated to the outer layers of the track detector, and if MC hits were at some minimum distance from the circumference, they were added to the track candidate.

The bin size of the two-dimensional histogram was improved to achieve maximum efficiency in finding track candidates. Both considered variants of the Hough transform [5] (expressions (2) and (3)) were investigated and showed comparable results in the efficiency of finding tracks.

The next step of the reconstruction program is the procedure of adding information about the longitudinal component of the track, or finding stereo hits belonging to the track candidate. Stereo hits will be the measurements in the straw tubes located at a small angle to Z axis, and as a measurement we will consider not only x - and y -coordinates of the triggered tube, but also the drift radius, the projection of which onto XY -plane is an ellipse. Next, we will use the fact that in a constant magnetic field the trajectory of a charged particle can be represented as a straight line $z(S) = \text{ctg}\vartheta \cdot S + z_0$ in the space of $S-z$ variables. Here ϑ is the polar angle of particle escape or the angle relative to Z axis; S is the circumference arc length in XY plane; z_0 is the coordinate of track origin.

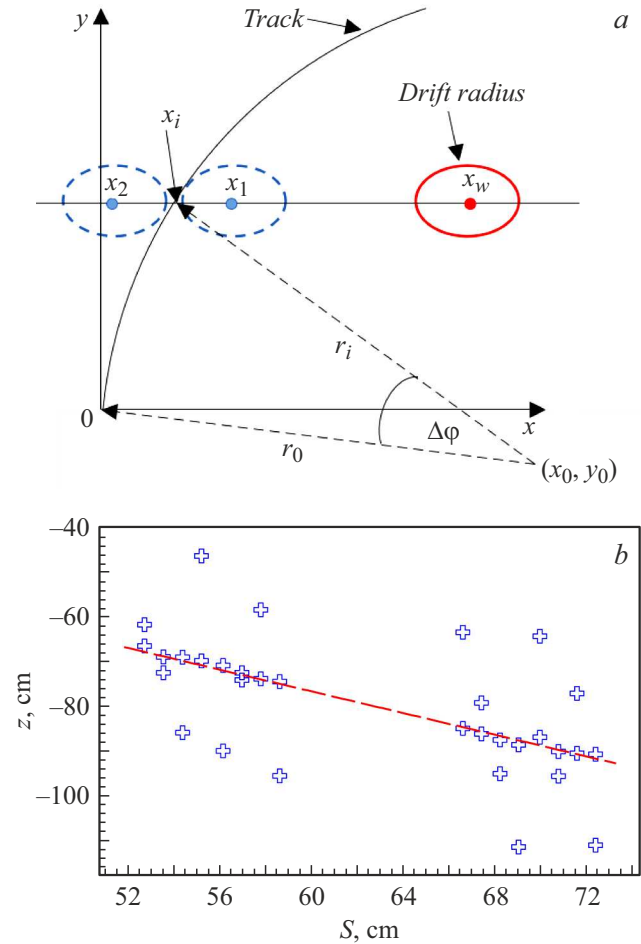


Figure 3. *a* — position of the triggered stereo tube (x_w) and the drift radius (solid circle), two possible ellipse positions x_1 and x_2 upon touching the track (dashed circles). *b* — the set of points in $S-z$ -space obtained using the procedure for determining z -coordinate.

Fig. 3, *a* (XY -plane, $z = 0$) illustrates the intersection of (x_i) track with one of the planes containing stereo tubes. Circumference arc length S equal to $S = R \cdot \Delta\varphi$, where R — radius of the track candidate circumference, $\Delta\varphi$ — azimuthal angle between the vectors r_0 and r_i . At that, r_0 vector is directed from the center of the circumference (x_0, y_0) towards the reference point, and r_i vector connects the center of the circumference (x_0, y_0) and the intersection point (x_i) . To find z -coordinate of MC-hit the expression $z = D / \text{tg} \alpha$ was used where D — distance at which it is needed to displace the ellipse along X axis until touching the track (Fig. 3, *a*), α — stereo tube inclination angle relative to Z axis. This can be explained as follows: if XY plane is moved along Z axis towards the MC hit, then the drift radius (ellipse) and the track will approach each other, and at z -coordinate equal to the position of the MC hit, the ellipse will touch the track. Since the trajectory of a charged particle can be either to the left or to the right of the central

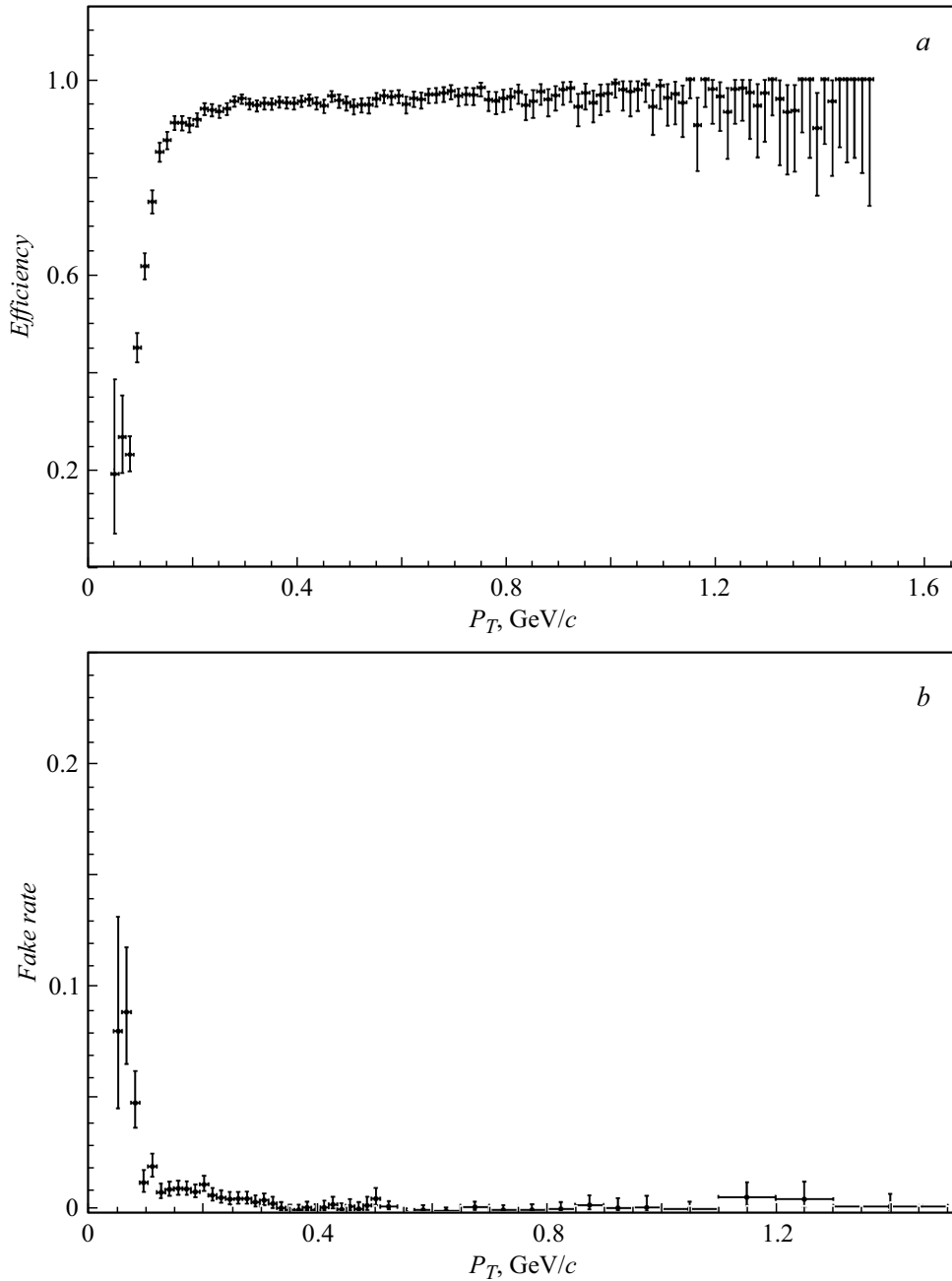


Figure 4. Reconstruction efficiency (a) and the number of falsely reconstructed tracks (b) as a function of the transverse momentum of P_T of track.

wire of the draw tube (left-right uncertainty), the procedure leads to two possible positions of the ellipse x_1 and x_2 on X axis and, consequently, to two values z_1 and z_2 of the MC hit coordinate. Fig. 3, b shows a set of points in the space of S – z -variables obtained using this procedure, in which each value of the length of the arc of the circumference S corresponds to two possible values of z coordinate of the MC hit.

To resolve the left-right ambiguity of z -coordinate, the recursive fit procedure was used:

— all points in S – z space are approximated by a straight line $z(S) = kS + z_0$;

— then the point with the maximum deviation from the obtained line is removed;

— the next straight line approximation is performed, and this procedure is repeated until for each S value (or stereo hit) only one z coordinate value remains.

As a result of the reconstruction procedure described above, we obtain a set of track candidates for which the sequence of MC-hits belonging to the track candidate, the initial estimate of the parameters of the charged particle and the position of the first point of the track are known.

The final stage of the track reconstruction program is the procedure for determining the parameters of track

candidates. For this purpose, many high-energy physics experiments use a Kalman filter, which is also included in the SPD package root [8], a software for modeling the response of various detectors in SPD-experiment.

To evaluate the performance of a reconstruction program, various characteristics are used, among which the efficiency of track reconstruction and the amount of falsely reconstructed tracks (fake track) are usually considered as the main performance criteria of the program. To determine these characteristics, 10,000 proton-proton interactions (Minimum Bias) were simulated, including diffraction and inelastic interactions, at a colliding proton energy of $\sqrt{s} = 10$ GeV. Minimum Bias events were generated using PYTHIA8 [9] program settings recommended for this class of events, and the response in the track detectors was modeled using SPDroot [8] package. The spatial resolution of the vertex and track detectors, equal to $\sim 150 \mu\text{m}$, was taken into account in the modeling, with the interaction vertex located at the origin. Additionally, a special set of MC tracks was formed, for which all hits belonging to the track were known, and the track parameters were determined using Kalman filter [7]. MC tracks shall also contain at least nine hits in the center portion of the track system, the track polar angle shall be in the range of $0.3 < \vartheta < 2.84$, and the track transverse momentum P_T shall exceed $0.05 \text{ GeV}/c$. These criteria allow the selection of MC tracks measurable in the central tracking system of SPD experiment, while events containing one or more selected MC tracks were used for analysis. Thus, this set of MC tracks represents the ideal characteristics of the reconstruction program and is used as a control set to study the properties of the program. The total number of selected MC-tracks was $\sim 43\,000$, which included both tracks formed at the primary interaction vertex and secondary tracks formed from the decays of short-lived particles. The average multiplicity of MC-tracks in an event was $\langle N^{\text{MC}} \rangle = 5.00 \pm 0.02$, and the multiplicity of reconstructed tracks under the given selection criteria was $\langle N^{\text{RC}} \rangle = 4.93 \pm 0.03$.

The efficiency of track reconstruction was defined as the ratio $\varepsilon = N_F / N_{\text{tot}}$, where N_{tot} is the total number of selected MC tracks, N_F is the number of MC tracks that have at least 50 % common hits with one of the reconstructed tracks. The number of falsely reconstructed tracks was determined similarly: $\varepsilon^{\text{fake}} = 1 - N_F^{\text{RC}} / N_{\text{tot}}^{\text{RC}}$, where $N_{\text{tot}}^{\text{RC}}$ is the total number of reconstructed tracks, and N_F^{RC} is the number of reconstructed tracks that have at least 50 % of common hits with one of the MC tracks. The condition of 50 % of total hits defines the maximum estimate of the effectiveness of the reconstruction program and can vary when studying different classes of physical events. The reconstruction efficiency and the magnitude of falsely reconstructed tracks as a function of the transverse momentum of P_T tracks are shown in Fig. 4. Upper and lower error bounds on the distributions were estimated based on the binomial distribution of events using Clopper–Pearson method in ROOT [10] software package and $\text{CL} = 0.6827$ confidence interval.

The obtained results demonstrate that the developed reconstruction program is featuring high efficiency of track reconstruction, reaching $\sim 95\%$ for tracks with a transverse momentum of $P_T > 200 \text{ MeV}/c$, while the contribution of falsely reconstructed tracks is less than 5% for reconstructed tracks with $P_T > 100 \text{ MeV}/c$. The use of this program not only expands the possibilities for studying physical events at the first stage of SPD experiment, but also allows for the optimization of the geometry of the central tracking system.

Conflict of interest

The author declares that he has no conflict of interest.

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