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A novel generic framework for track fitting in complex detector systems

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ABSTRACT

This paper presents a novel framework for track fitting which is usable in a wide range of experiments, independent of the specific event topology, detector setup, or magnetic field arrangement. This goal is achieved through a completely modular design. Fitting algorithms are implemented as interchangeable modules. At present, the framework contains a validated Kalman filter. Track parameterizations and the routines required to extrapolate the track parameters and their covariance matrices through the experiment are also implemented as interchangeable modules. Different track parameterizations and extrapolation routines can be used simultaneously for fitting of the same physical track. Representations of detector hits are the third modular ingredient to the framework. The hit dimensionality and orientation of planar tracking detectors are not restricted. Tracking information from detectors which do not measure the passage of particles in a fixed physical detector plane, e.g. drift chambers or TPCs, is used without any simplification. The concept is implemented in a light-weight C++ library called GENFIT, which is available as free software.

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1. Introduction

Spectrometers in nuclear and particle physics have the purpose of identifying the 4-momenta and vertices of particles stemming from high-energy collisions and decays of particles or nuclei. In addition to calorimetric and other particle identification measurements, the 3-momenta and positions of charged particles are measured by tracking them in magnetic fields with the use of position sensitive detectors. Cluster finding procedures can be applied in some detectors to combine the responses of individual electronic channels in order to improve the accuracy of the position measurements. The position measurements will be referred to as *hits* throughout this paper, regardless of whether they stem from a single detector channel or from a combination of several of them. Pattern recognition algorithms determine which hits contribute to the individual particle tracks. The hits identified at this stage to belong to one track then serve as the input for a fitting procedure, which determines the best estimates for the position and momentum of a particle at any point along its trajectory. A novel framework for this task of track fitting in complex detector systems is presented in this paper. It organizes the task of track fitting, i.e. the interplay between fitting algorithms, detector hits, and particles trajectories, with a minimal amount of interfaces. It is a toolkit which is independent of specific detector setups and magnetic field geometries and hence can be used for many particle physics experiments.

Tracking of particles is usually performed with a combination of different species of detectors. They can be categorized according to the different geometrical information they deliver:

(1) detectors which measure the particle passage along one axis in a detector plane, e.g. silicon strip detectors or multiwire proportional chambers;
(2) detectors which measure the two-dimensional penetration point of a particle through a plane, e.g. silicon pixel detectors;
(3) detectors which measure a drift time relative to a wire position, i.e. a surface of constant drift time around the wire through which the particle passed tangentially, e.g. drift chambers or "straw tubes";
(4) detectors which measure three-dimensional space points on particle trajectories, like time projection chambers (TPC).
But also higher-dimensional hits can occur:
(5) detector systems which measure two-dimensional position information in combination with two-dimensional direction information, including correlations between these parameters. Examples could be stations of several planes of detectors of categories 1 and 2, or electromagnetic calorimeters.

For detectors which do not deliver tracking information in physical detector planes, e.g. those of categories 3 and 4, the track fitting software of many experiments resorts to simplifications, which may be justified for a particular application but prevent the usage of the same program for different experimental environments. Examples are the projection of TPC data onto planes defined by pad rows or the projection of the surfaces of constant

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drift time in drift chambers onto predefined planes, just leaving two lines with left-right ambiguities. This approach is problematic if the drift cells are not arranged in a planar configuration and if there is no preferred direction in which the detector is passed by the particles. Another common simplification is the treatment of two-dimensional hits (e.g. from silicon pixel detectors) as two independent one-dimensional measurements.

In the framework presented here these problems have been overcome to make optimal use of the information from combinations of all types of tracking detector systems. All detector hits are defined in detector planes. For hits in detectors which do not have physical detector planes, so-called *virtual detector planes* are calculated dynamically for every extrapolation of a track to a hit. The dimensionality of detector hits is not restricted. One-dimensional hits constrain the track only along the coordinate axis in the detector plane which they measure. Two-dimensional hits are used in one fitting step to constrain the track in two dimensions in their detector planes. For hits in non-planar detectors (categories 3 and 4), the hit information (e.g. a surface of constant drift time) is converted into a position measurement in a plane perpendicular to the track, so that a fit is able to minimize the perpendicular distances between the track and the position measurements. The information from hits with higher dimensionality, like those of category 5, is used in four-dimensional hits, which contain all correlations between the parameters.

Tracks of charged particles in magnetic fields are (usually) described by five parameters and a corresponding covariance matrix. The ability to extrapolate a track described by these parameters and their covariances, taking into account the effects of materials and magnetic fields, to different positions in the spectrometer is mandatory for track fitting. The concept presented here provides a well defined interface for the invocation of external programs or libraries to perform these track extrapolations. It thus allows the straightforward use of established track following codes with their native geometry and magnetic field interfaces, such as GEANE [1], which is nowadays distributed as part of CERN's Virtual Monte Carlo (VMC) package [2]. This is the most significant difference to other projects (e.g. RecPack [3]), which offer more monolithic approaches to track fitting (e.g. defining their own geometry classes). The concept allows the simultaneous fitting of several representations of tracks to the same set of hits, i.e. to the same physical track. This flexibility is especially useful in the early phase of an experiment when different track parameterizations and extrapolation approaches can be compared with each other, in order to identify the ones with optimal performance. But also the flexible coverage of different phase space regions with different track models, or the fitting of different mass hypotheses with the same track model can be desirable. The implementation of the concept has been realized in a software toolkit called GENFIT. It is written in C++ and is designed in a fully object oriented way. It has been developed in the framework of the PANDA experiment [4], as part of the computing framework PANDAroot [5], but is now distributed as a stand-alone package [6].

GENFIT contains a validated Kalman filter. This algorithm is commonly used for track fitting in particle spectrometers [7], since it performs much better than global minimization approaches in the presence of materials and inhomogeneous magnetic fields. The concept is, however, not limited to the use of the Kalman filter. Other fitting algorithms, like Gaussian sum filters [8] or deterministic annealing filters [9], can be implemented easily.

Section 2 describes the concept of this new approach to track fitting in detail. Section 3 points out the key features of the implementation of GENFIT. Some examples of concrete track representations, on the dimensionalities of reconstruction hits and track representations, and the interplay between them follow in Section 4. Simulation studies which validate the Kalman filter implemented in GENFIT are presented in Section 5.

2. Concept

The basic functionalities which are required for any procedure of track fitting are the extrapolation of tracks to the positions of the hits in the detectors, and the calculation of the distances between hits and tracks, i.e. the residuals. The concept discussed here divides the problem of track fitting into three main entities which are separated from each other as much as possible and interact through well defined interfaces: (1) track fitting algorithms, (2) track representations, and (3) reconstruction hits. Fig. 1 presents this structure. The following sections explain these objects in detail.

2.1. Track fitting algorithms

"Progressive" fitting algorithms like the extended Kalman filter [7,10] are widely used for track fitting in high energy physics experiments. Although the track fitting concept discussed in this paper is not limited to the use of the Kalman filter, this algorithm shall serve as an example to illustrate which functionalities are generally required.

The extended Kalman filter is an efficient recursive algorithm that finds the optimum estimate $\vec{x}_k$ for the unknown true state vector $\hat{\vec{x}}_k$ of a system from a series of noisy measurements, together with the corresponding covariance matrix C_k of $\vec{x}_k$. The state vector contains the track parameters and the index k indicates that the state vector, and its covariance matrix are given at the detector plane of hit k.

Before a recursion step, the state vector $\vec{x}_{k-1}$ and covariance matrix C_{k-1} contain the information of all hits up to index $k-1$. In the *prediction* step the state vector and covariance matrix are extrapolated to the detector plane of hit k by the track following code. The predicted state vector is denoted by $\tilde{\vec{x}}_k$ and the predicted covariance matrix by $\tilde{C}_k$. This covariance matrix is the sum of the propagated track covariance matrix C_{k-1} (Gaussian error propagation by transformation with the Jacobian matrix of the propagation operation $\tilde{\vec{x}}_k = f(\vec{x}_{k-1})$), and a noise matrix which takes into account effects like multiple scattering and energy loss straggling. Then, the algorithm calculates the *update* for the state vector and the covariance matrix by taking into account the measurement $\vec{m}_k$:

$$\vec{x}_k = \tilde{\vec{x}}_k + K_k \tilde{\vec{r}}_k \tag{1}$$

$$C_k = (I - K_k H_k)\tilde{C}_k \tag{2}$$

with the residual

$$\tilde{\vec{r}}_k = \vec{m}_k - H_k \tilde{\vec{x}}_k \tag{3}$$

the weight of the residual (or Kalman gain)

$$K_k = \tilde{C}_k H_k^T (H_k \tilde{C}_k H_k^T + V_k)^{-1} \tag{4}$$

and the covariance matrix V_k of the measurement $\vec{m}_k$. I is the unit matrix of corresponding dimensionality. The projection matrix H_k is a linear transformation from the coordinate system of the state vector $\vec{x}_k$, to the coordinate system of the position measurement $\vec{m}_k$ of hit k, i.e. the detector plane of the hit. A discussion about dimensions of the vectors and matrices in the above equations can be found in Section 4.2 together with concrete examples for the matrix H_k. The elements of the covariance matrix C_k shrink with the inclusion of more hits, thus reducing the impact of a

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