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Analysis of beam test data by global optimization methods

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ABSTRACT

Successful track reconstruction in a silicon tracking device depends on the quality of the alignment, on the knowledge of the sensor resolution, and on the knowledge of the amount of material traversed by the particles. We describe algorithms for the concurrent estimation of alignment parameters, sensor resolutions and material thickness in the context of a beam test setup. They are based on a global optimization approach and are designed to work both with and without prior information from a reference telescope. We present results from simulated and real beam test data.

1. Introduction

A track fitter requires an accurate model of the tracking hardware if it is to produce optimal estimates of the track parameters. This includes a precise alignment, a statistically satisfactory description of the hit position errors, and adequate knowledge of the amount of material traversed by the tracks, which determines the assumed amount of energy loss and multiple scattering a particle encounters.

There are many approaches to the computation of the alignment constants, for example the widely used Millepede program [1]. The resolution of detector elements can be estimated explicitly in simple cases [2]. In more complex detectors the resolutions are normally tuned manually such that various test statistics such as χ^2 probabilities or pull quantities have a distribution close to the theoretical one (uniform or standard normal, respectively). The amount and distribution of the material in a detector can be mapped by reconstruction of photon conversion vertices (see e.g. [3]) or hadronic interaction vertices (see e.g. [4]). Such a mapping can be used to detect discrepancies with respect to the detector description database, but to the best of our knowledge it has never been used to actually estimate the amount of material.

In a beam test setup it is convenient to have a simple standalone tool that is able to compute alignment, sensor resolutions and, if required, sensor material from a recorded sample of tracks immediately after or even during data taking. In this contribution we present two tools that employ global optimization algorithms to solve the task. They allow to use external information from a reference telescope, but are not dependent on such information.

2. The method

The track model in a beam test setup is usually a straight line. The track parameters can be estimated either by a Kalman filter (recursive least-squares) or by a global fit (regression by weighted least-squares). Besides the track parameters, the estimator can compute quality indicators such as local and global χ^2 statistics, standardized residuals (pulls), and standardized differences of state vectors. The standardized residuals or state differences must have mean 0 and rms 1, and the mean of all χ^2 statistics must be equal to the corresponding number of degrees of freedom. This also holds for non-Gaussian errors.

The principle of the approach presented here is to optimize an objective function based on the quality indicators as a function of a set of parameters. The parameters are alignment constants, hit resolutions, and material thicknesses, if appropriate. The objective function can be tailored to the problem at hand, as will be shown in the following examples. The minimization obviously requires multivariate optimization, preferably without the computation of gradients. The minimization algorithms must be able to find the *global* optimum. We have used two optimizers. The first one is the simplex algorithm according to Nelder and Mead [5], implementations of which are available in C++ and MATLAB. The other one is VXQR1, a recent development by Neumaier et al. [6], available in a MATLAB implementation. It turns out that in our problem the simplex algorithm is more prone to end up in a local minimum; this can be cured by restarting several times. VXQR1 on the other

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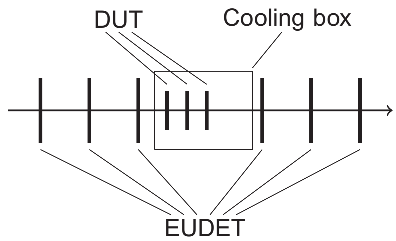

Fig. 1. The experimental setup, consisting of ATLAS pixel planes (DUT), and EUDET Mimosa26 planes (EUDET).

hand finds the region of the global optimum more reliably, but takes longer to converge to the actual optimum.

3. Examples

This section presents three examples of the global optimization approach.

3.1. Example 1: ATLAS pixel beam test

The first example is the one used in the papers that introduced the global optimization approach [7,8]. The setup consisted of the EUDET telescope [9] plus three devices under test (DUT), surrounded by a cooling box. The EUDET telescope consisted of six pixel sensors, with a pixel size of 18.5 μm × 18.5 μm and a spatial resolution $\sigma \approx 4$ μm. The DUTs were three pixel sensors, with a pixel size of 50 μm × 400 μm and a spatial resolution $\sigma \approx 15$ μm × 115 μm [10]. The total length of the beam test setup was about 1 m (see Fig. 1).

The aim of this study was to estimate as many resolutions and thicknesses as possible. The material was assumed to be concentrated in the sensor layers, and the hit position errors were assumed to be uncorrelated. The data were a set of about 40,000 tracks (π^+) with momentum $p = 120$ GeV/c. Several objective functions were formulated based on standardized hit residuals and state differences of a forward and a backward Kalman filter, such that their minimization forced the mean to 0 and the rms to 1. For details of the objective functions and the results, see [8]. The analysis program is written in C++ and is available on the web.[1] It uses the simplex algorithm for optimization.

Each call to the objective function requires a fit of the entire track sample, i.e. running the forward and the backward filter on all tracks, and computing hit residuals and state differences. The state difference equals the predicted state (forward) minus the updated state (backward) or vice versa. Its covariance matrix is the sum of the respective covariance matrices. $\Delta \vec{x}_k$ can be computed in all layers but the first and the last. In any case, the material thickness cannot be estimated in these layers.

A cross-check was done with simulated data, restricting the estimation to the DUTs. Fig. 2 shows the results for 40,000 simulated tracks and five different objective functions. A result from real data is shown in Fig. 3. The quality of the track fit and the resolution of the track prediction improve when the number of parameters estimated from the data increases.

3.2. Example 2: Belle II strip sensor beam test 2010

The setup consists of a stack of four double-sided sensors, where the n-side measures the horizontal position x, and the p-side measures the vertical coordinate y. The total length of the

[1] URL: https://github.com/hgjersdal/eigen2-track-fitter.

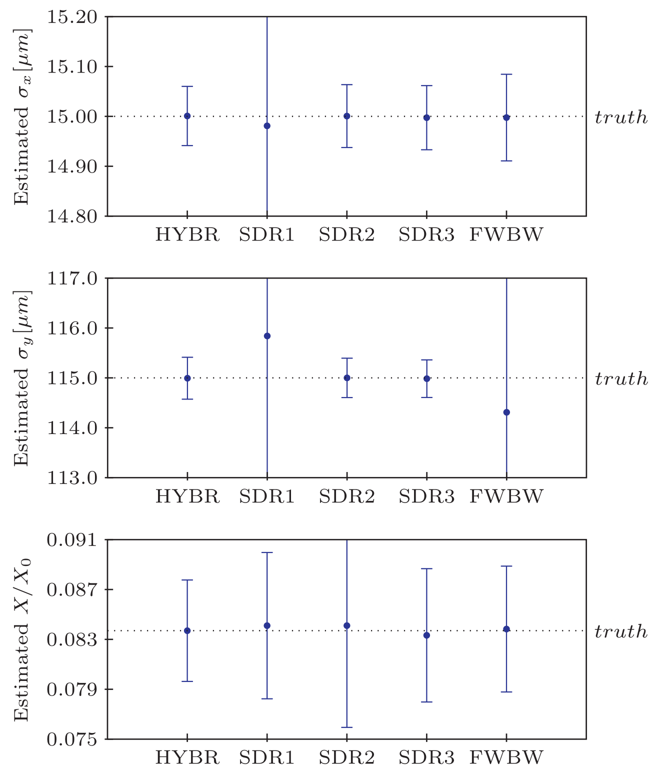

Fig. 2. Mean and standard deviation of resolution and thickness estimates from 500 simulation experiments, DUT 3, $p = 120$ GeV/c. From: Gjersdal, et al., Journal of Instrumentation 8 (2013) P01009. DOI: http://dx.doi.org/10.1088/1748-0221/8/01/P01009.

stack is about 27 cm. The outer two sensors are rectangular; the n-side has a 240 μm pitch, and the p-side has a 75 μm pitch. The two inner sensors are trapezoidal; the n-side has a 240 μm, and the p-side has a variable pitch of 50–75 μm. All sensors have intermediate strips on both sides. One of the trapezoidal sensors is shown in Fig. 4. The beam test was part of the R&D for the Belle II Silicon Vertex Detector [11].

The input data are about 58,000 tracks (π^+, p, K^+) with momentum $p = 120$ GeV/c. We estimate seven alignment parameters (four shifts and three rotation angles) and eight sensor resolutions (x and y). Because of the high beam momentum, the short lever arm and the very thin sensors there is not enough sensitivity to multiple scattering to estimate the thickness of the sensors. The objective function is based on the standardized hit residuals. Its minimization forces the mean to 0 and the rms to 1. Alternatively one can use the median and the MAD (median of absolute deviations from the median), thereby reducing influence of outliers. The algorithm is implemented in Matlab.

Each call to the objective function requires a fit of the entire track sample. A forward and a backward Kalman filter are run on all tracks, and the hit residuals are computed. For the sake of speed, all Kalman filter matrices are precomputed. The reconstruction of the entire sample takes about 400 ms on a 2.4 GHz Intel Core 2 processor. Convergence to the global minimum requires about 150 fits for the alignment, and about 500 fits for the resolution estimate. The total run time is therefore less than 5 min.

Using the simplex algorithm as minimizer, the estimated resolutions (in μm) are:

Side	L1	L2	L3	L4
x (n-side)	25	44	40	23
y (p-side)	13	11	9	12