MillePede-II
short review

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MP - Introduction

- Millepede is a software package for linear least squares fits with a large number of parameters
- Developed and implemented in FORTAN77 by Volker Blobel (Univ. Hamburg)
- Used by several experiments for track based alignment and calibration

MP basics

$$\chi^2(\Delta\mathbf{p},\Delta\mathbf{q}) = \sum_{j}^{\text{tracks}} \sum_{i}^{\text{hits}} \frac{1}{\sigma_{ij}^2}\left(\mathbf{m}_{ij} - \mathbf{f}_{ij}(\mathbf{p}_0,\mathbf{q}_{j0}) - \frac{\partial \mathbf{f}_{ij}}{\partial \mathbf{p}}\Delta\mathbf{p} - \frac{\partial \mathbf{f}_{ij}}{\partial \mathbf{q}_j}\Delta\mathbf{q}_j\right)^2$$

- Track based alignment (and calibration)
  - Minimizing χ^2 sum
    - for large number of global (alignment) parameters $\Delta\mathbf{p}$
    - from large number of local fits (tracks $\Delta\mathbf{q}_j$)
    - with model **f** linearized at initial parameters $(\mathbf{p}_0,\mathbf{q}_0)$
  - Linear equation system with bordered band matrix
    - Border populated due to global derivatives $\partial\mathbf{f}/\partial\mathbf{p}$
    - Block diagonal by (independent) local derivatives $\partial\mathbf{f}/\partial\mathbf{q}_j$
  - Local fits ($\partial\chi^2/\partial\Delta\mathbf{q}_j$=0) done with $\mathbf{p}=\mathbf{p}_0$
    - Size of lin. eqn. system reduced to number of global par.
    - Correlations of global trough local parameters maintained

Millepede basics (II)

- Procedure
  - Local (track) fits
    - For all tracks 'j' solve linear equation system $\mathbf{A}_j \cdot \Delta \mathbf{q}_j = \mathbf{b}_j$
    - With solution and $\mathbf{A}_j^{-1}$ fill global matrix $\mathbf{A}_g$ and vector $\mathbf{b}_g$
  - Global fit
    - Optionally add constraints ($\mathbf{C} \cdot \Delta \mathbf{p} = \mathbf{c}$, e.g. implement hierarchy)
    - Solve linear equation system $\mathbf{A}_g \cdot \Delta \mathbf{p} = \mathbf{b}_g$
    - Update alignment parameters: $\mathbf{p} = \mathbf{p} + \Delta \mathbf{p}$
  - Iteration
    - For outlier rejection repeat previous steps
    - χ^2 cut for local fit changed from soft to hard

Millepede history (I)

- Millepede-I
  - Development started 1996
  - One set of (FORTRAN) subroutines
  - Since 1997 main user has been H1 for calibration and alignment of the central drift chambers
    - Online calibration: mean drift velocity, Lorentz angle vs t
    - Offline calibration: v_d, α_{lor} vs R, φ, B(Z,R), E, P, ..
  - Applicable for up to several thousand parameters
    - Matrix inversion as only solution method, CPU time ~ n_{par}^3

MillePede history (II)

- MillePede-II
  - Development started 2005 for LHC experiments
    - Allow for 100 000 parameters
  - Split into two parts
    - **Mille**: create binary files with measurements, errors and derivatives from user code (C/C++ or FORTRAN)
    - **Pede**: standalone FORTRAN executable, steering text file and binary files as input
  - Main user is CMS for alignment of the Si tracker
    - 25k (curved) Si sensors

MillePede history (III)

- New features with MillePede-II
  - Matrix storage
    - **Sparse**: only nonzero matrix elements M_{ij} stored
      - In alignment typically only 10-30% of M_{ij}<>0 (i,j connected by track(s))
  - Solution method
    - **MINRES**: stepwise minimize $|A_g \cdot \Delta \mathbf{p} - \mathbf{b}_g|$ to obtain $\Delta \mathbf{p}$
      - A_g^{-1} is not calculated ➜ no errors for results
      - CPU time dominated by product 'matrix times vector': $\sim n_{par}^2 \cdot n_{step}$

V. Blobel: Track based alignment,
Nuclear Instruments and Methods A, 566 (2006), pp. 5-13)

MillePede today

- MillePedeII@svnsrv.desy.de
  - Maintenance and development by Statistics Tools group of Analysis Center in Helmholtz Terascale Alliance
- Moved to FORTRAN90, 64bit (doxygen documentation)
- Optimization of (Pede) resource usage
  - Memory: matrix compression
  - CPU: parallelization with OpenMP™
  - Fit 200k parameters from 10^7 tracks in 32GB in 10h