ACTS Track Fitter Status Update

ACTS Workshop 2024

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Overview

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3. Refitting
4. The Kalman Filter
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Concepts & terminology

- Track fitting in a nutshell:
  - Estimation of **track parameters** at a **reference surface** for a **track candidate**
  - Estimation of intermediate states (track state parameters, outlier flags, ...)
- ACTS track EDM in a nutshell:
  - **Track container**: Concept for interfacing to track & track state storage backends
    - Implementation with `std::vector` available in ACTS
    - Many predefined fields available (track parameters, reference surface, state flags, ...)
    - Custom fields possible!
  - **Track proxy**: Non-owning interface to a single track (reference semantics)

Pseudocode

- ACTS fitters are classes that steer and run a `Acts::Propagator`
  - You must provide the propagator yourself!
- For each call to the `.fit()` method, options must be provided
  - Most configurable components are exposed as `Acts::Delegate` (function-pointer like objects)
- Some details are ommitted, for a full example see the `ActsExamples::TrackFittingAlgorithm`.

```
Stepper myStepper(bfield);
Navigator myNavigator(trackingGeometry);
Propagator myPropagator(myStepper, myNavigator);
Fitter myFitter(myPropagator);

VectorTrackContainer trackStorage;
VectorMultiTrajectory trackStateStorage;
TrackContainer tracks(trackStorage, trackStateStorage);

Fitter::Options options;
Calibrator myCalibrator;
options.calibrator.connect<&Calibrator::calibrate>(
    myCalibrator);

auto trackProxy = fitter.fit(parameters, sourceLinks,
                             options, tracks);
```

Parameter estimation

- Usually done with conformal fit on three spacepoints (seed)
  - Tool in ACTS: `Acts::estimateTrackParamsSeed`
  - Some attempts to streamline interface (#3800, #3832)
- Estimation of initial covariance matrix
  - A bit tricky: $\text{var}(p) = f(\text{var}(\theta), \text{var}(p_T))$, $\text{var}(p_T) \propto p_T$
  - Only recently (#3638) available in ACTS Core: `Acts::estimateTrackParamCovariance`
  - **Note:** No off-diagonal terms are set currently
  - Initial variance inflation can help to control the error estimation if the initial parameters are very good.

Refitting

- Important applications of fitters: refine parameters of a already fitted track
  - E.g., refit electron tracks with GSF, refit CKF tracks with GX2F
- Currently, no special API for refitting in ACTS core
- It is possible to implement refitting using core tools, see `ActsExamples::RefittingAlgorithm` for an example

Potential action item

- Add a refitting API to the ACTS fitters, in the style of:

```
auto refittedTrack = fitter.refit(track, trackContainer);
```

Refitting

Ingrediants to implement refitting with current ACTS:

- Direct navigation:
  - Increase speed and stability by using surfaces sequence of the previouly fitted track
  - Fitters provide a `.fit()` overload, that accepts an additional surface sequence.
  - **Note**: The propagator must be equipped with a `Acts::DirectNavigator`.
    - Recently fixed & refactored (#3702)
  - **Note**: Its important to provide also material surfaces!
- Refitting source links & calibrator:
  - A special source link type and can be constructed to point to the track states of the fitted track instead of the raw measurement.
  - With a special calibrator, the calibrated measurement can be extracted from the previous track.

The Kalman Filter

- The Kalman Filter is:
  - Optimal estimation of parameters+uncertainties of a dynamic system based on a (time)series of measurements
    - Requirements: linear system, gaussian uncertainties
    - For tracking: linearized problem, assume gaussian uncertainties
  - With smoothing step: Equivalent to least square fit
- Implementation in ACTS: `Acts::KalmanFitter`

Implementation status

- Integrated within ACTS physmon, stable with only a few changes in recent years
- Validated within ATLAS software

Kalman Filter configuration: Smoothing

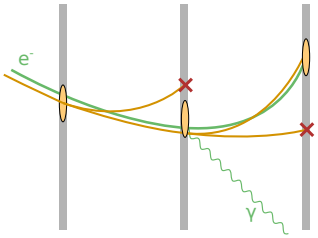
- Smoothing: Propagate information of measurements back to the initial ones
- Smoothing is handled within the `Acts::KalmanFitter::fit` function currently
- Two approaches to smoothing in ACTS:
  - Linearized transport: Use collected jacobians for reverse propagation
    - `Acts::GainMatrixSmoother`
    - **NEW** since #3420: `Acts::MbfSmoother` (computationally more performant)
  - Full reverse filtering:
    - In case non-linear effects are not negligible (e.g., low p_T tracks)
    - Computationally more expensive
- Behaviour can be controlled by `ReverseFilteringLogic` delegate

Potential action item

- Seperate smoothing (and extrapolation to reference surface) as done for CKF

The Gaussian Sum Filter

- The Gaussian Sum Filter (GSF) is an extension of Kalman Filter that can handle non-Gaussian uncertainties
  - Models track-state & material effects as Gaussian mixtures: $f(\vec{x}) = \sum_i^{N_{cmp}} w_i p_i(\vec{x})$
  - Used for electron (re)fitting (Brehmsstrahlung is highly non-Gaussian)
- Implementation in ACTS: `Acts::GaussianSumFitter`



Implementation status

- Integrated with ACTS physmon, some validation in ODD done
- Integration to ATLAS software ongoing, some issues are currently being investigated

GSF: Multi-Stepper

- In contrast to most other propagation-based algorithms, the GSF requires a special stepper, that can handle a multi-component track state
  - Currently only one stepper fulfills this concept: `Acts::MulitEigenStepperLoop`
  - In order to talk to the navigator, the multi-component state must be reduced to a single position and direction
  - **Recent change:** Dropped the previous default `Acts::WeightedComponentReducerLoop`, because it could lead to invalid navigation state (#3521, #3671)
    - New default is the `Acts::MaxWeightComponentReducerLoop`.
    - No significant changes in physmon have been observed.

GSF configuration: Basic options

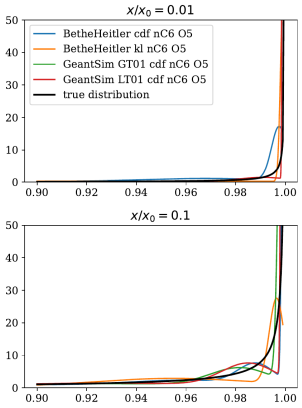
- Maximum Number of components
- Weight cutoff: When to neglect components
- Mixture reduction method: Reduce number of components to the configured maximum
  - Two implementations available: `Acts::reduceMixtureLargestWeights`, `Acts::reduceMixtureWithKLDistance`
- Store full multi-component state
  - If a custom column named `GsfConstants::kFinalMultiComponentStateColumn` is present in the track container, the full final multi component state is saved to the track container.

Potential action item

- Provide possibility to store full multi component states on the track states

GSF configuration: Energy loss approximation

- Approximation of Bremsstrahlung energy loss in material:
  - Parameterized as polynomial wrt X_0:
  - Currently rely on ATLAS parameterizations
    - Weights, means and variances of N_{cmp} components as a M-th order polynomial wrt. X_0.
    - Implementation: `Acts::AtlasBetheHeitlerApprox`
  - **Recently** introduced flag to silence a (very verbose) warning about encountering "to big" material slabs (#3739)



Potential action item

- Provide workflow & documentation on how to generate custom parameterization

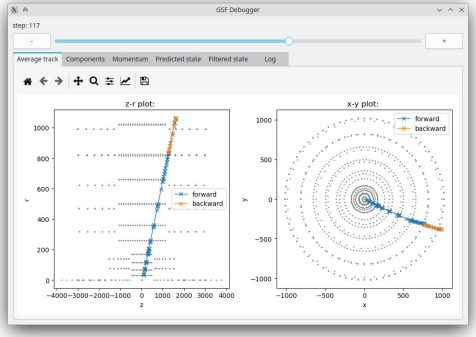
GSF configuration: Smoothing

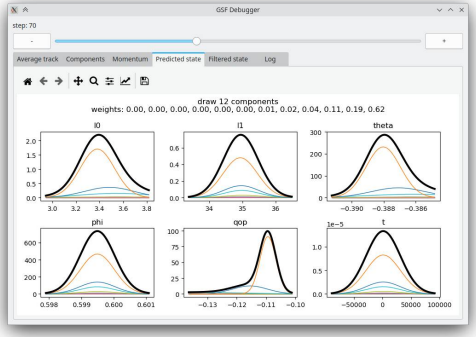
- Smoothing:
  - The GSF does only (and uncondionally) perform reverse filtering
  - **Note:** Measurement surfaces, that are not again found in reverse pass, are flagged as outliers
  - No special smoothing is done to improve the intermediate track states

Potential action item

- Implement smoothing algorithms from literature to improve intermediate track states

GSF: Debugger





- Since #2682 there is a GSF debugger in the repo (link to documentation)
- Based on `VERBOSE` log, should work with experiment integrations

The Global X^2 Fitter

- Covered by the presentation of Alexander Pfleger.

Outlook & Summary

- ACTS currently provides 3 different track fitters
  - KF: very stable & validated
  - GSF: less stable, less validated
  - GX2F: WIP (see Alex talk)
- Some track fitting concepts are not implemented yet in ACTS:
  - E.g, Deterministic annealing filter
  - Of course, maschine learning may change the way track fitting is done in the future...

Action items

- All: Refitting API in ACTS Core
- KF: Decouple smoothing & extrapolation to reference surface to increase flexibility
- GSF: Validate against ATLAS GSF, provide workflows to ease configuration.
- GX2F: Stabelize and optimize implementation

The End