Adaptive Extended Kalman Filter for Geo-Referencing of a TLS-based Multi-Sensor-System

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Why is a direct geo-referencing useful?

- No demand for control points (estimating control point coordinates is a generally time /computational consuming task)
- Efficient and effective work flow for acquiring geo-referenced 3D data
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1 Concept and strategy for the direct geo-referencing of static 3D laser scans
   - Observation concept for the transformation elements
   - TLS-based MSS @GIH
   - Present strategy for the direct geo-referencing procedure

2 Adaptive extended Kalman filter approach for direct geo-referencing purposes
   - Present filter setup: state vector and equation of motion
   - GNSS tracking results
   - Comparison of tracking approaches

3 Summary and future work
Methodology for direct geo-referencing of static 3D laser scans

Transformation rule

\[ \mathbf{X}_E = \mathbf{R}_S^E \cdot \mathbf{X}_S + \Delta \mathbf{X}_S^E \]

- Position vector of scan points in the local coordinate system
- Position vector of TLS center point in the global coordinate system
- Rotation of the local to the global coordinate system

Required elements to observe

- Spatial rotation about the Z-axis (orientation/azimuth)
- Position vector \( \Delta \mathbf{X}_S^E \) constant per station

Optional elements to observe

- Spatial rotation about the X- and Y-axis (leveling, optional residual divergence observable by inclinometer)
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Terrestrial laser scanner (TLS) with integrated geo-referencing

- Using only a minimum number of additional sensors with an adequate data rate
- Estimating the laser scanner position and orientation directly
- Undisturbed operation of the laser scanner
- Using the vertical axis rotation of the laser scanner as time reference
- Working without geo-referenced control points
Observation concept for the transformation elements

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Commercial products

Source: Leica Geosystems
Multi-Sensor-System (MSS) configuration

- Phase-based TLS *Z+F Imager 5006* (data rate: $\approx 10100$ Profiles@$364^\circ$, TTL-puls)
- *Javad* GNSS receiver Delta (data rate: $100$ Hz, GPS&Glonass, PPS, GPS event)
- *Schaevitz LSOC-1*° inclinometer
- Optional tracking sensor: *Trimble* 5700 (data rate: $10$ Hz, GPS) or tacheometry with $360^\circ$-prism (2 Hz)

Time synchronization aspects

Unique time scale for the different measurement types

(a) Use of the internal laser clock of a suitable device such as a TLS as temporary time reference
(b) Use of an external clock such as a GNSS receiver as absolute time reference
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Present strategy for the direct geo-referencing procedure

1. **Data acquisition**
   Individual data pre-processing for each sensor type of the MSS
   - 3D laser scan
   - Inclinometer measurements
   - GNSS data processing

2. **Data synchronization**
   Introduction of GPS time as unique time reference in the MSS

3. **Data fusion**
   Interpolation of measured data for each scan profile

4. **Adaptive extended Kalman filtering**
   Estimation of transformation parameters for the MSS

5. **Result visualization and applying the transformation parameters to the scan data**
   Next step in the ongoing work:
   Transformation of at least two different laser scanner stations from the same scene
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Main aim of a Kalman filter (KF)

- Optimal combination of a given physical information for a system and external observations of its state
- State estimation only optimal in case of linear state space systems

Modeling of trajectories of moving vehicle

Enhancement of the EKF with additional parameters
Main aim of a Kalman filter (KF)

Modeling of trajectories of moving vehicle

- Often leads to nonlinearities in the system equations of the KF
- Here: Functional relationship between the MSS coordinates and the other state parameters is nonlinear
- Solution: Extended Kalman filter (EKF) which is based on an approximation of the nonlinear functions by a Taylor series expansion (1\textsuperscript{st} order)

Enhancement of the EKF with additional parameters
Overview Kalman filter

Main aim of a Kalman filter (KF)

Modeling of trajectories of moving vehicle

Enhancement of the EKF with additional parameters

- Additional parameters are time invariant, system specific parameters with well known initial values
- Why?
  - Improvement of the filtering by adaption of the dynamic model
  - Brings the model closer to reality

⇒ EKF with adaptive parameters (AEKF); also well known as dual estimation
State vector and equation of motion

State vector: \( \mathbf{x}_k = \begin{bmatrix} \mathbf{x}^G_k & \alpha^L_{\text{Scan},k} & \beta^L_{\text{Scan},k} & \gamma^L_{\text{Scan},k} & r_k & \varphi_k & s_{\text{ltd},k} \end{bmatrix}^T \)

Equation of motion:

\[
\mathbf{x}^G_{k+1} = \mathbf{x}^G_k + R^G_{\alpha^G} (\lambda, \varphi) \cdot R^G_{\alpha} (\alpha^G) \cdot R^L_{\text{ScanN}} (\alpha^L_{\text{Scan},k}) \cdot \left[ \mathbf{x}^L_{k+1} - \mathbf{x}^G_{\text{GNSS ScanN},k} \right]
\]

- Disoriented local step between two epochs
- Local orientation by angle/motor increments of the TLS
- Global orientation of the MSS (a priori initial value computed by means of global positions)
- Transformation to the global coordinate system (geographic coordinates (\(\lambda, \varphi\)) computed by means of global positions)
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AEKF for Direct Geo-Referencing of a TLS-based MSS

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Concept and Strategy

AEKF

Filter setup

GNSS tracking results

Comparison of tracking approaches

Summary and future work

AEKF – results: trajectory
AEKF – GNSS tracking results: inclinations

\[ \beta - \text{inclusion in direction of motion} \]

\[ \gamma - \text{inclusion perpendicular to direction of motion} \]

- observed (median filtered(101)) \( \beta \)
- filtered \( \beta \)

- observed (median filtered(101)) \( \gamma \)
- filtered \( \gamma \)
Determination of the final global azimuth

- Calculation of geodetic azimuth ($\alpha_k^G$) for each epoch $k \in \{1 \ldots n\}$ between filtered trajectory and calculated center point $\implies \alpha^G = \frac{1}{n} \sum_{k=1}^{n} (\alpha_k^G)$
- Metric uncertainty of $\approx 1 \text{ cm}$ for the global azimuth calculation $\odot 35 \text{ m}$
Determination of the final global azimuth

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  \[ \alpha^G = \frac{1}{n} \sum_{k=1}^{n} \left( \alpha^G_k \right) \]
- Metric uncertainty of \( \approx 1 \, \text{cm} \) for the global azimuth calculation @35 m
Comparison of GNSS and tacheometer tracking

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Table: Coordinate differences between GNSS and tacheometer tracking for several control points

Facts for the comparison of the tracking approaches

- Distance between the TLS station and the targets is \( \approx 16 \, m \)
- Coordinate differences between GNSS and tacheometer tracking are less than one decimeter
- Comparisons to global reference control points shows significant larger differences (1.5 times)

3D scan of the Lower Saxony Steed (Lower Saxony’s landmark) and MMS with tracking sensors
## Comparison of GNSS and tacheometer tracking

### Facts for the comparison of the tracking approaches

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Summary

- Direct geo-referencing method for static terrestrial 3D laser scans
- Transformation parameters estimation by an AEKF approach

Future work

- Tailored data aggregation step to smooth high frequency trajectory positions to the TLS data rate
- Improvement of the prediction method for lower position data acquisition rates (collocation)
- Improvement of the stochastic model to gain better understanding of the process noise (⇒ variance component estimation)
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