Calibration and Evaluation of Kinematic Multi Sensor Systems

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I. Motivation

II. Calibration of scan-based MSS

III. Evaluation of scan-based MSS

IV. Test Field – Campus Klein-Altendorf

V. Conclusion & Outlook
Motivation

Mobile sensing everywhere

- available on the market
- operative in the field
- established in the community
Motivation

Challenges of mobile sensing

- **Object acquisition** (laser scanners, cameras etc.)
- **Georeferencing** (GNSS, IMU, odometer etc.)
- **Time synchronization**
- **Calibration**

**Kinematic 3D point cloud**

**Evaluation**

How good are kinematic 3D point clouds in terms of precision and accuracy?
Key issues of this thesis

Calibration

**Key issue 1:** What are suitable methods for the calibration of MSS and how can they be refined by a comprehensive configuration analysis of the calibration process?

Evaluation

**Key issue 2:** What are suitable methods and criteria for the comprehensive evaluation of MSS and how has an associated test field to be designed to allow for this?
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Calibration parameters

Different types of calibration parameters

- **intrinsic parameters** of individual sensors
  - GNSS
  - Odometer
  - IMU
  - Scanner

- **extrinsic parameters** boresight angles and lever arm between sensor frames
  - GNSS
  - Odometer
  - IMU
  - Scanner
Calibration of extrinsic parameters

Determination of lever arm $\Delta x$, $\Delta y$, $\Delta z$ and boresight angles $\alpha$, $\beta$, $\gamma$ between:

- 2D laser scanner
  laser scanning points
- GNSS/IMU unit
  platform trajectory

\[
\begin{bmatrix}
x_e \\
y_e \\
z_e
\end{bmatrix} = \begin{bmatrix}
t_x \\
t_y \\
t_z
\end{bmatrix} + \mathbf{R}_b^n (\phi, \theta, \psi) \cdot \begin{bmatrix}
\Delta x \\
\Delta y \\
\Delta z
\end{bmatrix} + \mathbf{R}_s^b (\alpha, \beta, \gamma) \cdot \begin{bmatrix}
0 \\
d \cdot \sin b \\
d \cdot \cos b
\end{bmatrix}
\]
Related work

Calibration methods for extrinsic calibration

**Special methods**

Very individual laboratory methods utilizing theodolite measurement systems, laser tracker, photogrammetric methods etc.

- Talaya et al. (2004)
- Gräfe (2007)
- Hesse (2007)
- Vennegeerts (2011)

**Entropy-based**

Optimization of an entropy-based target function calculated from the point cloud

- Sheehan et al. (2011)
- Maddern et al. (2012)
- Nüchter et al. (2015)

**Plane-based**

Least squares adjustment by constraining scan points to lie on reference planes

- Skaloud & Lichti (2006)
- Glennie (2012)
- Hartmann et al. (2017)
Related work

Wide-spread use of plane-based calibration

**Special focus:** comprehensive configuration analysis of the plane-based calibration (*accuracy + reliability*)

**On the ground, e.g.:**
- Rieger et al. (2010)
- Chan et al. (2013)
- Keller (2016)
- Heinz et al. (2017)

**In the air, e.g.:**
- Filin (2003)
- Skaloud & Lichti (2006)
- Lindenthal et al. (2011)

**On the water, e.g.:**
- Lu et al. (2017)
Plane-based calibration approach

General idea

• **Constraints:** ① Georeferenced planes ② MSS points

• **Discrepancies:** Imperfect MSS calibration parameters
Mathematical description

**Georeferenced TLS points** must fulfill the plane equations

\[
\begin{bmatrix}
  s_e \cdot \sin z_e \cdot \cos h_e \\
  s_e \cdot \sin z_e \cdot \sin h_e \\
  s_e \cdot \cos z_e
\end{bmatrix}^T
\begin{bmatrix}
  n_x \\
  n_y \\
  n_z
\end{bmatrix} - d_p \overset{!}{=} 0
\]

**Georeferenced MSS points** must fulfill the plane equations

\[
\begin{bmatrix}
  t_x \\
  t_y \\
  t_z
\end{bmatrix} + R^n_b (\phi, \theta, \psi) \cdot \left( \begin{bmatrix}
  \Delta x \\
  \Delta y \\
  \Delta z
\end{bmatrix} + R^b_s (\alpha, \beta, \gamma) \cdot \begin{bmatrix}
  0 \\
  d \cdot \sin b \\
  d \cdot \cos b
\end{bmatrix} \right)^T
\begin{bmatrix}
  n_x \\
  n_y \\
  n_z
\end{bmatrix} - d_p \overset{!}{=} 0
\]

**Solution:** Parameter estimation in a Gauß-Helmert model
Configuration analysis

Simulation environment

- V-REP for the simulation of reference planes and sensor observations
- MATLAB for configuration analysis based on geodetic quality criteria
  - parameter accuracies
  - parameter correlations
  - partial redundancies
  - minimal detectable errors
  - impact factors

\[ \sum x_x \]

\[ \sum v_v \]
Exemplaric simulation

- reference plane setup due to educated guess
- MSS with GNSS, IMU and laser scanner inclined by 45°
- scanning with opposite attitude (cf. red lines / blue lines)
Configuration analysis

Analysis of two different setups

• **Case A:** planes with 45° orientation
• **Case B:** planes with 0° orientation

Which setup is better?
Parameter accuracies

- accuracy of the calibration (~ mm, ~ mdeg) should be better than the accuracy of MSS georeferencing (~ cm, ~ cdeg)
- boresight angle $\beta$ almost 100 % worse in case B
- poorer calibration worsens the accuracy of the point cloud

<table>
<thead>
<tr>
<th>Accuracy</th>
<th>Case A</th>
<th>Case B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\Delta x}$</td>
<td>0.0053 m</td>
<td>0.0053 m</td>
</tr>
<tr>
<td>$\sigma_{\Delta y}$</td>
<td>0.0053 m</td>
<td>0.0053 m</td>
</tr>
<tr>
<td>$\sigma_{\Delta z}$</td>
<td>0.0053 m</td>
<td>0.0053 m</td>
</tr>
<tr>
<td>$\sigma_\alpha$</td>
<td>0.0071°</td>
<td>0.0071°</td>
</tr>
<tr>
<td>$\sigma_\beta$</td>
<td>0.0076°</td>
<td>0.0147°</td>
</tr>
<tr>
<td>$\sigma_\gamma$</td>
<td>0.0071°</td>
<td>0.0071°</td>
</tr>
</tbody>
</table>

Error propagation (Helmert point error)
Partial redundancies and impact factors

- case B: MSS pitch angles $\theta_j$ weakly controlled
- minimal detectable error increases $\rightarrow$ systematic impact on $\beta$
Configuration analysis

Findings of the simulation

- **plane configuration crucial** for the quality of MSS calibration
- application of **geodetic quality criteria** to the problem of MSS calibration is possible and **allows for a refinement**
Results of real calibration

Realization of the calibration field

• **calibration of a real MSS** in the calibration field
• 10 repetitions of the calibration → **10 parameter sets**
Results of real calibration

Calibration of MSS successful

- $\Sigma_{ll}$ according to variance component estimation (VCE)
- accuracy $\Sigma_{xx}$ of the parameters ($\rightarrow$ no correlations)
- sufficient reliability and controllability of the observations

Correlation matrix of $\Sigma^{10}_{xx}$

Partial redundancies of $\phi, \theta, \psi$
Results of real calibration

Comparison of the 10 parameter sets

- good repeatability: consensus between estimated parameter accuracies and variation of the 10 solutions

<table>
<thead>
<tr>
<th>Data set</th>
<th>$\Delta x$ [m]</th>
<th>$\Delta y$ [m]</th>
<th>$\Delta z$ [m]</th>
<th>$\alpha$ [deg]</th>
<th>$\beta$ [deg]</th>
<th>$\gamma$ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.7207</td>
<td>0.0393</td>
<td>-0.4308</td>
<td>0.1961</td>
<td>(0.1563)</td>
<td>-0.3513</td>
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<tr>
<td>2</td>
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<td>0.0391</td>
<td>-0.4314</td>
<td>0.1954</td>
<td>(0.1162)</td>
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<tr>
<td>3</td>
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<td>0.0395</td>
<td>-0.4318</td>
<td>0.1955</td>
<td>0.1103</td>
<td>-0.3517</td>
</tr>
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<td>4</td>
<td>-0.7212</td>
<td>0.0389</td>
<td>-0.4324</td>
<td>0.1953</td>
<td>0.1081</td>
<td>-0.3519</td>
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<td>5</td>
<td>-0.7208</td>
<td>0.0389</td>
<td>-0.4325</td>
<td>0.1950</td>
<td>0.1070</td>
<td>-0.3521</td>
</tr>
<tr>
<td>6</td>
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<td>0.0391</td>
<td>-0.4332</td>
<td>0.1952</td>
<td>0.1080</td>
<td>-0.3522</td>
</tr>
<tr>
<td>7</td>
<td>-0.7210</td>
<td>0.0390</td>
<td>-0.4308</td>
<td>0.1948</td>
<td>0.1076</td>
<td>-0.3523</td>
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<td>0.1950</td>
<td>0.1079</td>
<td>-0.3524</td>
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<td>-0.7209</td>
<td>0.0389</td>
<td>-0.4324</td>
<td>0.1952</td>
<td>0.1083</td>
<td>-0.3523</td>
</tr>
<tr>
<td>10</td>
<td>-0.7211</td>
<td>0.0385</td>
<td>-0.4316</td>
<td>0.1949</td>
<td>0.1082</td>
<td>-0.3526</td>
</tr>
<tr>
<td>$</td>
<td>\text{max} - \text{min}</td>
<td>$</td>
<td>0.0007</td>
<td>0.0011</td>
<td>0.0024</td>
<td>0.0013</td>
</tr>
<tr>
<td>$\sigma_{VCE}$</td>
<td>$\leq 0.0011$</td>
<td>$\leq 0.0011$</td>
<td>$\leq 0.0011$</td>
<td>$\leq 0.0045$</td>
<td>$\leq 0.0046$</td>
<td>$\leq 0.0045$</td>
</tr>
</tbody>
</table>
Outline

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Problems of MSS evaluation

What do we need to obtain $\Sigma_{pp}$?

- **functional model** $f$
  - complex and partially unknown ...
- **observations** $l$ and **calibration parameters** $c$
  - huge number ...
- **distribution functions** $\Sigma_{ll}$ and $\Sigma_{cc}$
  - mixture and in general not Gaussian ...

**Key issue 2:** What are suitable methods and criteria for the comprehensive evaluation of MSS and how has an associated test field to be designed to allow for this?
Current practice

Comparison with reference data

• detection of control points in point clouds and comparison to reference coordinates
• comparison of kinematic point clouds with TLS reference point clouds or 3D models

Kukko et al. (2012)
Schlichting et al. (2014)
Hauser et al. (2016)
Hofmann & Brenner (2016)

Heinz et al. (2017)
Haala et al. (2008)
Rieger et al. (2010)
Kartinen et al. (2012)
Current practice

Special reference structures

• **special driving maneuvers** past building facades or artificial reference structures (e.g. planes or cylinders)

• **promising approach**, but a reference trajectory and high accurate reference structures are needed

Rieger et al. (2010)
Keller & Sternberg (2013)
Sternberg et al. (2013)
Comprehensive evaluation

Requirements for a comprehensive evaluation

Analysis of individual system components:

(1) defined reference structure (e.g. planes, cylinders etc.)
(2) precise reference values (e.g. point clouds, 3D models etc.)
(3) reference trajectory for a defined object acquisition
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Structure and components

- **Reference trajectory** (railbound, rail vehicle)
- **Environment** (buildings, 3D model)
- **Reference point field** (fixed points, pillars)
- **Calibration objects** (planes, cylinders, cones)
- **Evaluation objects** (planes, cylinders, cones)

Test Field in Klein-Altendorf

MSS Test Field
**Reference Point Field**

**Instruments:** total station, leveling, GNSS

**Datum:** ETRS89/UTM, local level frame

**Accuracy:** mm to sub-mm
Reference Point Field

Purpose of reference point field

• fast and accurate stationing in a global reference frame (e.g. MSS, TLS, total station)

• measuring of infrastructure for calibration & evaluation

• setup of own master station as an alternative to SAPOS®

• ...

Google Earth
• variation in all 6 DoF
• length ~ 140 m
• rail vehicle for adaption of MSS
• pillars for MSS tracking

r = 2.0 m

roll ± 10°
pitch ± 10°

r = 6.8 m

pitch ± 20°
Reference Trajectory

Purpose of reference trajectory

- evaluation of estimated trajectory and object acquisition (platform tracking, repeated driving of a known trajectory)
- separation of individual system components
Evaluation Objects

Purpose of evaluation objects

- determination of position, orientation and geometry of buildings and artificial objects (→ TLS + reference point field)

- **kinematic point cloud vs. reference values**
Calibration Objects

Purpose of calibration objects

• determination of position and orientation of the reference plane setup (TLS + reference point field)

• alignment of MSS point clouds and TLS point clouds for the estimation of the MSS calibration parameters
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Conclusion & Outlook

Goals and current status

(1) **Plane-based calibration**: Configuration analysis for accurate and reliable system calibration

Almost Finished

(2) **Entropy-based calibration**: Use of reference trajectory and surrounding environment for system calibration

In Process

(3) **Evaluation**: Separation of individual system components by using reference trajectory and evaluation objects

To Do

(4) **Realization of test field** for MSS calibration and evaluation

In Process
**Peer-Reviewed**


**Non-Peer-Reviewed**


Thank you for your attention. Questions or comments?

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Entropy-based calibration

Calibration without reference information

• multiple scanning of an sufficiently structured environment with sufficient variation in all 6 DoF of the MSS
• optimization of an entropy-based target function calculated from the point cloud ("Quadratic Rényi Entropy")

• Result: (extrinsic) calibration parameters
Entropy-based calibration

Calibration without reference information

![Entropy-based calibration diagram](image)