Analysis of Different Reference Plane Setups for the Calibration of a Mobile Laser Scanning System

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Outline

I. Motivation

II. Plane-based calibration approach

III. Simulation and analysis of different plane setups

IV. Application to a mobile laser scanning system
Motivation

Paradigm change in engineering geodesy

The *surveying of the environment has changed*

- manual vs. **automatic**
- single points vs. **area-based**
- static vs. **kinematic**
- single sensor vs. **multi sensors**

3D surveying by using **kinematic multi sensor systems**
Motivation

Challenges of kinematic multi sensor systems

Georeferencing (GNSS, IMU, odometer etc.)
- data fusion for trajectory estimation in a filter algorithm
- integration of stochastic models

Object acquisition (laser scanners, cameras etc.)
- considering object characteristics, configuration, image processing, ...
- integration of stochastic models

Time synchronization
- time stamping of the observations within a common time reference

Calibration
- intrinsic calibration: calibration of individual sensor deviations
- extrinsic calibration: calibration of lever arms and boresight angles

3D point clouds
- How good are the 3D point clouds in terms of precision and accuracy?
- result of complex processing steps
Calibration of mobile laser scanning systems

Calibration of single sensors
- GNSS
- IMU
- 2D laser scanner

Installation position and orientation of sensors
- lever arms
- boresight angles

intrinsic calibration
extrinsic calibration
Mobile Laser Scanning System

GNSS/IMU unit

- iMAR iNAV-FJI-LSURV
- multi-frequency GNSS, fiber-optic gyroscopes and accelerometers

\[ \sigma_{\text{Position}} = \text{cm}, \quad \sigma_{\text{Attitude}} < 0.025^\circ \]

2D laser scanner

- Z+F Profiler 9012 A
- phase-based 2D laser scanner
- point accuracies of mm
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**Problem:** Determination of calibration parameters

- **lever arm** $\Delta x$, $\Delta y$, $\Delta z$ and **boresight angles** $\alpha$, $\beta$, $\gamma$ between GNSS/IMU unit and 2D laser scanner

- **range offset** $d_0$ of the 2D laser scanner

\[
\begin{bmatrix}
x_e \\
y_e \\
z_e
\end{bmatrix} = \begin{bmatrix}
t_x \\
t_y \\
t_z
\end{bmatrix} + R_b^n(\phi, \theta, \psi) \cdot \begin{bmatrix}
\Delta x \\
\Delta y \\
\Delta z
\end{bmatrix} + R_s^b(\alpha, \beta, \gamma) \cdot \begin{bmatrix}
0 \\
(d + d_0) \cdot \sin b \\
(d + d_0) \cdot \cos b
\end{bmatrix}
\]

- **georeferenced scan point**
- **position/attitude** (GNSS/IMU unit)
- **extrinsic calibration**
- **scan point (laser scanner)** + **intrinsic calibration**
Calibration Approach

**Approach:** Calibration field with reference planes

**Setup of reference planes**

1) georeferencing (e.g. TLS + GNSS control points)
2) static scanning with the MSS
Calibration Approach

Solution: Parameter estimation

• georeferenced TLS points must fulfill the plane equations

\[
g_1: \begin{bmatrix} s_e \cdot \sin z_e \cdot \cos h_e \\ s_e \cdot \sin z_e \cdot \sin h_e \\ s_e \cdot \cos z_e \end{bmatrix}^T \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} - d_P = 0
\]

• georeferenced MSS points must fulfill the plane equations

\[
g_2: \begin{bmatrix} tx \\ ty \\ tz \end{bmatrix} + R^n_b(\phi, \theta, \psi) \cdot \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + R^b_s(\alpha, \beta, \gamma) \cdot \begin{bmatrix} 0 \\ (d + d_0) \cdot \sin b \\ (d + d_0) \cdot \cos b \end{bmatrix} \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} - d_P = 0
\]

• adjustment of \(g_1\) and \(g_2\) in a Gauß-Helmert model
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Simulation of different configurations

What is a suitable configuration (setup of reference planes and how they are scanned with the mobile system) to obtain good calibration parameters (small variance, uncorrelated)?

Simulation and analysis of 4 configurations, each with:

– 8 reference planes
– 6 stations of the mobile laser scanning system
Simulation of configurations $F_{1a}$ and $F_{1b}$

**Configuration $F_{1a}$**: identical attitude of MSS, plane rotation of 45°

**Configuration $F_{1b}$**: diametrical attitude of MSS, plane rotation of 45°
Simulation of configurations $F_{2a}$ and $F_{2b}$

**Configuration $F_{2a}$**: identical attitude of MSS, plane rotation of $30^\circ$

**Configuration $F_{2b}$**: diametrical attitude of MSS, plane rotation of $30^\circ$
Covariance matrix $\Sigma_{ii}$ of the observations

- manufacturer information
- no correlations

<table>
<thead>
<tr>
<th>TLS + GCP</th>
<th>s (STD)</th>
<th>h (STD)</th>
<th>z (STD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1\sigma$</td>
<td>0.001 m</td>
<td>0.0025°</td>
<td>0.0025°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GNSS/IMU</th>
<th>$t_x$, $t_y$, $t_z$, $\Phi$, $\theta$, $\psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1\sigma$</td>
<td>0.01 m, 0.01°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2D scanner</th>
<th>d (STD)</th>
<th>b (STD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1\sigma$</td>
<td>0.0003 m</td>
<td>0.02°</td>
</tr>
</tbody>
</table>
Covariance matrix $\Sigma_{xx}$ of the parameters

- **Parameter accuracies** depend on the accuracy of the GNSS/IMU unit and the number of MSS stations.

- $\sigma_\beta$ and $\sigma_{d0}$ vary for different configurations.

\[
\sigma_{\Delta x, \Delta y, \Delta z} = \frac{0.01 \text{ m}}{\sqrt{6}} = 0.0041 \text{ m} \quad \sigma_{\alpha, \beta, \gamma} = \frac{0.01 \text{°}}{\sqrt{6}} = 0.0041 \text{°}
\]

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{\Delta x}$</th>
<th>$\sigma_{\Delta y}$</th>
<th>$\sigma_{\Delta z}$</th>
<th>$\sigma_\alpha$</th>
<th>$\sigma_\beta$</th>
<th>$\sigma_\gamma$</th>
<th>$\sigma_{d0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{1a}$ (I)</td>
<td>0.0041 m</td>
<td>0.0041 m</td>
<td>0.0041 m</td>
<td>0.0041°</td>
<td>0.0046°</td>
<td>0.0041°</td>
<td>0.02 mm</td>
</tr>
<tr>
<td>$F_{2a}$ (I)</td>
<td>0.0041 m</td>
<td>0.0041 m</td>
<td>0.0041 m</td>
<td>0.0041°</td>
<td>0.0070°</td>
<td>0.0041°</td>
<td>0.02 mm</td>
</tr>
<tr>
<td>$F_{1b}$ (I + II)</td>
<td>0.0041 m</td>
<td>0.0041 m</td>
<td>0.0041 m</td>
<td>0.0041°</td>
<td>0.0042°</td>
<td>0.0041°</td>
<td>0.01 mm</td>
</tr>
<tr>
<td>$F_{2b}$ (I + II)</td>
<td>0.0041 m</td>
<td>0.0041 m</td>
<td>0.0041 m</td>
<td>0.0041°</td>
<td>0.0058°</td>
<td>0.0041°</td>
<td>0.01 mm</td>
</tr>
</tbody>
</table>
Correlation matrix of the parameters

- **parameter correlations**: diametrical scanning  
  → decorrelation of β and d₀  
  → improving of σ_β and σ_d₀

**F₁ₐ**: not scanned diametrically  
**F₂ₐ**: scanned diametrically  
**F₁₉**:  
**F₂₉**:
Why is $\sigma_\beta$ generally better in $F_1$ than in $F_2$?

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{\Delta x}$</th>
<th>$\sigma_{\Delta y}$</th>
<th>$\sigma_{\Delta z}$</th>
<th>$\sigma_\alpha$</th>
<th>$\sigma_\beta$</th>
<th>$\sigma_\gamma$</th>
<th>$\sigma_{d0}$</th>
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<td>0.0041 m</td>
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<td>0.0041°</td>
<td>0.01 mm</td>
</tr>
<tr>
<td>$F_{2b}$ (I + II)</td>
<td>0.0041 m</td>
<td>0.0041 m</td>
<td>0.0041 m</td>
<td>0.0041°</td>
<td><strong>0.0058°</strong></td>
<td>0.0041°</td>
<td>0.01 mm</td>
</tr>
</tbody>
</table>

**Question:** How sensitive are the reference planes with respect to changes in the calibration parameters?

**Strategy:** Simulation of parameter deviations for the boresight angles in $F_1$ and $F_2$: $\nabla_\alpha = 0.03°$ / $\nabla_\beta = 0.03°$ / $\nabla_\gamma = 0.03°$
Sensitivity of the reference planes $F_1$ and $F_2$

Sensitivity in Field $F_1$

Sensitivity in Field $F_2$
Findings of the simulations

• **configuration in the calibration field is crucial** for the quality of the calibration results, which can worsen due to
  – parameter correlations
  – sensitivity of the reference planes

• **analysis allows for a refinement** of the network configuration
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Realization of configuration $F_{1b}$

- **TLS scan of reference planes**
  (size of $0.6 \times 0.9$ m)

- **georeferencing using 5 GCPs**
  (statically measured for $2.5 \text{ h}$, residuals $\leq 2 \text{ mm}$)

- **MSS scans of the planes**
  (30 diametrical stations)

- **static scanning**
  (about $60 \text{ s}$ per station: reduce noise, eliminate timing errors)
Calibration results confirm the simulation results

• $\Sigma_{\parallel}$ due to simulations ($\sigma_{\text{pos}} = 0.01 \text{ m}$, $\sigma_{\text{att}} = 0.01^\circ$)
• accuracy of the calibration parameters:

$$
\sigma_{\Delta x, \Delta y, \Delta z} = \frac{0.01 \text{ m}}{\sqrt{30}} = 0.0019 \text{ m}
$$

$$
\sigma_{\alpha, \beta, \gamma} = \frac{0.01^\circ}{\sqrt{30}} = 0.0019^\circ
$$

• no parameter correlations

<table>
<thead>
<tr>
<th></th>
<th>$\Delta x$</th>
<th>$\Delta y$</th>
<th>$\Delta z$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
<th>$d_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>-0.7957 m</td>
<td>0.0448 m</td>
<td>0.1731 m</td>
<td>0.2170°</td>
<td>0.1799°</td>
<td>-0.1817°</td>
<td>0.70 mm</td>
</tr>
<tr>
<td>STD (1(\sigma))</td>
<td>0.0019 m</td>
<td>0.0019 m</td>
<td>0.0019 m</td>
<td>0.0019°</td>
<td>0.0019°</td>
<td>0.0019°</td>
<td>0.01 mm</td>
</tr>
</tbody>
</table>
Repeatability of the calibration results

• subsampling of the observations into 5 blocks
• each block contains 6 stations from the original 30 stations

<table>
<thead>
<tr>
<th>Stations</th>
<th>Δx</th>
<th>Δy</th>
<th>Δz</th>
<th>α</th>
<th>β</th>
<th>γ</th>
<th>d₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>all</td>
<td>-0.7957 m</td>
<td>0.0448 m</td>
<td>0.1731 m</td>
<td>0.2170°</td>
<td>0.1799°</td>
<td>-0.1817°</td>
<td>0.70 mm</td>
</tr>
<tr>
<td>1-6</td>
<td>-0.7960 m</td>
<td>0.0451 m</td>
<td>0.1736 m</td>
<td>0.2143°</td>
<td>0.1894°</td>
<td>(-0.2036°)</td>
<td>0.60 mm</td>
</tr>
<tr>
<td>7-12</td>
<td>-0.7961 m</td>
<td>0.0451 m</td>
<td>0.1730 m</td>
<td>0.2190°</td>
<td>0.1636°</td>
<td>-0.1750°</td>
<td>0.74 mm</td>
</tr>
<tr>
<td>13-18</td>
<td>-0.7951 m</td>
<td>0.0447 m</td>
<td>0.1732 m</td>
<td>0.2170°</td>
<td>0.1782°</td>
<td>-0.1780°</td>
<td>0.57 mm</td>
</tr>
<tr>
<td>19-24</td>
<td>-0.7953 m</td>
<td>0.0444 m</td>
<td>0.1713 m</td>
<td>0.2189°</td>
<td>0.1761°</td>
<td>-0.1754°</td>
<td>0.76 mm</td>
</tr>
<tr>
<td>25-30</td>
<td>-0.7961 m</td>
<td>0.0448 m</td>
<td>0.1748 m</td>
<td>0.2152°</td>
<td>0.1885°</td>
<td>-0.1743°</td>
<td>0.65 mm</td>
</tr>
<tr>
<td>Max-Min</td>
<td>0.0010 m</td>
<td>0.0007 m</td>
<td>0.0035 m</td>
<td>0.0047°</td>
<td>0.0258°</td>
<td>0.0037°</td>
<td>0.19 mm</td>
</tr>
<tr>
<td>Simulation STD (1σ)</td>
<td>0.0041 m</td>
<td>0.0041 m</td>
<td>0.0041 m</td>
<td>0.0041°</td>
<td>0.0042°</td>
<td>0.0041°</td>
<td>0.01 mm</td>
</tr>
</tbody>
</table>
System Evaluation

Comparison of two kinematic scans

- two kinematic scans of the Poppelsdorfer Schloss
- opposite direction of movement
- mean distance of 15 – 20 m

Error propagation of:
- observations: $\Sigma_{ll}$
- calibration: $\Sigma_{xx}$

Expected accuracy of the point cloud: $\sigma_{3D} = 2 \text{ cm.}$
System Evaluation

Comparison of two kinematic scans

- two kinematic scans of the Poppelsdorfer Schloss
- M3C2-comparison in CloudCompare
  - deviations $\delta$ have an RMS of $2.75 \text{ cm}$ ($\approx 2 \text{ cm} \cdot \sqrt{2}$)
  - systematic effects at the facade (due to trajectory)
Conclusions

Scientific achievements

- analysis/refinement of the network configuration in a plane-based calibration field
- successful calibration of a mobile laser scanning system

Future activities

- permanent test field and repetition of the calibration (repeatability?)
- refinement of the calibration method and trajectory estimation algorithm
Thank you for your attention

Questions or comments?

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List of Figures

[7] https://t4.ftcdn.net/jpg/00/89/75/09/240_F_89750910_ybv8D9YfDmBQmYp5PadcC8JCYdyzzSZn.jpg (accessed: 24/04/17)