On-site self-calibration using planar features for terrestrial laser scanners

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Introduction

- Terrestrial laser scanners (TLSs) require calibration to determine their systematic error model coefficients.
- Most (but not all) previous research has focused on point-target-based methods.
- A plane-based, on-site calibration method has been developed primarily for the following two reasons:
  1. To remove the manual labour required by the point-based method. Though target measurement in the point clouds could be automated, target field set-up is laborious.
  2. Previous experiences with the Faro 880 scanner have identified long-term temporal instability in the calibration parameters, suggesting that (on-site) calibration is needed each time the instrument is used.
Outline

- Feature-based, on-site calibration concepts and equations
- TLS additional parameters
- Experiment descriptions and results
  - Simulated data
  - Real data and comparison with point-based results
- Conclusions
Calibration Methods

Point-based method

Plane-based method
Observation Modelling

- Spherical co-ordinate observation equations for point $i$ in scan $j$

\[
\rho_{ij} = \sqrt{x_{ij}^2 + y_{ij}^2 + z_{ij}^2} + \Delta \rho
\]

\[
\theta_{ij} = \arctan \left( \frac{y_{ij}}{x_{ij}} \right) + \Delta \theta
\]

\[
\alpha_{ij} = \arctan \left( \frac{z_{ij}}{\sqrt{x_{ij}^2 + y_{ij}^2}} \right) + \Delta \alpha
\]

\[
\begin{bmatrix}
    x_{ij} \\
    y_{ij} \\
    z_{ij}
\end{bmatrix} = R_3(\kappa_j)R_2(\phi_j)R_1(\omega_j) \begin{bmatrix}
    X_i \\
    Y_i \\
    Z_i
\end{bmatrix} - \begin{bmatrix}
    X_{sj} \\
    Y_{sj} \\
    Z_{sj}
\end{bmatrix}
\]
The rigid-body transformation equation can be rewritten more compactly in vector notation

\[ \vec{p}_{ij} = M_j \left( \vec{p}_i - \vec{p}_{s_j} \right) \]

and rearranged in terms of the object point vector \( P \)

\[ \vec{P}_i = M_j^T \vec{p}_{ij} + \vec{P}_{s_j} \]

where

\[ M_j = R_3(\kappa_j)R_2(\phi_j)R_1(\omega_j) \]

\[ \vec{p}_{ij} = \begin{bmatrix} (\rho_{ij} + \Delta \rho) \cos(\alpha_{ij} + \Delta \alpha) \cos(\theta_{ij} + \Delta \theta) \\ (\rho_{ij} + \Delta \rho) \cos(\alpha_{ij} + \Delta \alpha) \sin(\theta_{ij} + \Delta \theta) \\ (\rho_{ij} + \Delta \rho) \sin(\alpha_{ij} + \Delta \alpha) \end{bmatrix} \]
Condition Equation (2)

The point-on-plane condition for point i in scan j lying on plane k, \( f_{ijk} \), is thus given by

\[
f_{ijk} = \vec{n}_k^T \vec{P}_i - d_k = 0
\]

where the plane’s unit normal vector is given by

\[
\vec{n}_k = \begin{bmatrix} a_k & b_k & c_k \end{bmatrix}^T
\]

and \( d_k \) is the distance parameter.
Condition Equation (3)

- The unit length constraint for plane \( k \), \( g_k \),

\[
g_k = n_k^T n_k - 1 = 0
\]
\[
= a_k^2 + b_k^2 + c_k^2 - 1 = 0
\]

is implemented as a weighted constraint

- All model parameters are estimated simultaneously in a least-squares adjustment
## Additional Parameters

- AP set comprises physical and empirical terms
- Reduced AP set implemented at the time of writing

<table>
<thead>
<tr>
<th>AP(s)</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0$</td>
<td>Rangefinder additive constant</td>
</tr>
<tr>
<td>$B_1$</td>
<td>Collimation axis error</td>
</tr>
<tr>
<td>$B_2$</td>
<td>Trunnion axis error</td>
</tr>
<tr>
<td>$B_3$ and $B_4$</td>
<td>Non-orthogonality of the plane containing the horizontal angle encoder and vertical axis</td>
</tr>
<tr>
<td>$C_0$</td>
<td>The vertical circle index error</td>
</tr>
<tr>
<td>$C_2$</td>
<td>Vertical circle eccentricity</td>
</tr>
</tbody>
</table>

\[ \Rightarrow \Delta \rho \]
\[ \Rightarrow \Delta \theta \]
\[ \Rightarrow \Delta \alpha \]
Simulated Data Experiments

- For testing purposes a number of simulated datasets were generated.
- One important outcome was the resulting trends visible in the estimated residuals.
- These differ considerably from those of the point-based method, which generally resemble the functional form of the corresponding systematic error.
- Ramification: model identification may be difficult.
Simulated Experiment Results

Collimation Axis Error

Rangefinder Additive Constant
Experiments with Real Data (1)

- Two datasets captured with a FARO 880 scanner were used for plane-based calibrations in this study.
- Each comprised 8 point clouds captured from 2 nominal locations inside of a room.
- The scanner was manually rotated on the tripod by 90° after each of the set of four scans was captured.
- Some of the pertinent experiment data are given below:

<table>
<thead>
<tr>
<th></th>
<th>Dataset 1</th>
<th>Dataset 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room height (m)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Room width (m)</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Room length (m)</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Distance between scan locations (m)</td>
<td>4</td>
<td>6.7</td>
</tr>
<tr>
<td>Maximum range (m)</td>
<td>7.5</td>
<td>10</td>
</tr>
</tbody>
</table>
The Faro 880: Salient Properties

- **HFOV:** 180°
- **VFOV:** 320°
- Phase difference rangefinder
- Modulating wavelengths: 1.2 m, 9.6 m, 76.7 m
Experiments with Real Data (2)

- The planar patches for the on-site calibration were semi-automatically extracted from the wall, ceiling and floors of the original point clouds.
- The point-based calibration results were also derived using the 7 implemented APs for a fair comparison.

<table>
<thead>
<tr>
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<th>Dataset 1</th>
<th>Dataset 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Point-based calibration</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td># targets</td>
<td>134</td>
<td>131</td>
</tr>
<tr>
<td>Adjustment redundancy</td>
<td>2019</td>
<td>1738</td>
</tr>
<tr>
<td><strong>Plane-based calibration</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td># planes</td>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td>Adjustment redundancy</td>
<td>5538</td>
<td>8107</td>
</tr>
</tbody>
</table>
Residual Statistics Results (1)

- **Dataset 1—plane based**

<table>
<thead>
<tr>
<th></th>
<th>Without self-calibration</th>
<th>With calibration</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD $v_{\rho}$ (mm)</td>
<td>1.2</td>
<td>1.2</td>
<td>5.4</td>
</tr>
<tr>
<td>STD $v_{\theta}$ (&quot;')</td>
<td>67.9</td>
<td>18.6</td>
<td>72.6</td>
</tr>
<tr>
<td>STD $v_{\alpha}$ (&quot;')</td>
<td>24.3</td>
<td>19.9</td>
<td>18.4</td>
</tr>
</tbody>
</table>

All smaller than point-based results

- **Dataset 1—point based**

<table>
<thead>
<tr>
<th></th>
<th>Without self-calibration</th>
<th>With calibration</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD $v_{\rho}$ (mm)</td>
<td>2.4</td>
<td>1.9</td>
<td>21.0</td>
</tr>
<tr>
<td>STD $v_{\theta}$ (&quot;')</td>
<td>86.3</td>
<td>35.2</td>
<td>59.2</td>
</tr>
<tr>
<td>STD $v_{\alpha}$ (&quot;')</td>
<td>51.8</td>
<td>46.5</td>
<td>10.3</td>
</tr>
</tbody>
</table>
# Residual Statistics Results (2)

- **Dataset 2—plane based**

<table>
<thead>
<tr>
<th></th>
<th>Without self-calibration</th>
<th>With calibration</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD $v_\rho$ (mm)</td>
<td>1.0</td>
<td>0.8</td>
<td>21.4</td>
</tr>
<tr>
<td>STD $v_\theta$ (&quot;)</td>
<td>49.2</td>
<td>47.3</td>
<td>3.8</td>
</tr>
<tr>
<td>STD $v_\alpha$ (&quot;)</td>
<td>55.3</td>
<td>49.5</td>
<td>10.6</td>
</tr>
</tbody>
</table>

- **Dataset 2—point based**

<table>
<thead>
<tr>
<th></th>
<th>Without self-calibration</th>
<th>With calibration</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD $v_\rho$ (mm)</td>
<td>2.3</td>
<td>1.7</td>
<td>26.1</td>
</tr>
<tr>
<td>STD $v_\theta$ (&quot;)</td>
<td>109.8</td>
<td>36.7</td>
<td>66.6</td>
</tr>
<tr>
<td>STD $v_\alpha$ (&quot;)</td>
<td>65.88</td>
<td>20.9</td>
<td>68.3</td>
</tr>
</tbody>
</table>

Only range is smaller than point-based results.
Residual Plots (1)

- Horizontal direction residuals vs. horizontal direction for Dataset 1

Without Plane-Based Self-Calibration

With Plane-Based Self-Calibration
Residual Plots (2)

- Horizontal direction residuals vs. elevation angle for Dataset 1

Without Plane-Based Self-Calibration

\[
\begin{align*}
\Delta \theta &\quad \Delta \phi \\
\end{align*}
\]

With Plane-Based Self-Calibration

\[
\begin{align*}
\Delta \theta &\quad \Delta \phi \\
\end{align*}
\]
Conclusions and Future Work

- The plane-based calibration showed improvement in residual standard deviation by up to 73%
- In terms of residuals, the results are better in all 3 observables for Dataset 1, but only in range for Dataset 2
- Future work:
  - Implementation of the remaining APs and processing of the remaining 8 Faro datasets
  - Extension of the method to other features
Thank you for your attention!