Tutorium Teil 1

UAV-basierte Luftbildauswertung - ein Update

Michael Cramer
• Is UAV-based mapping so much different to regular flight campaigns?

• “With a little help from my friends” – using GNSS/inertial-based georeferencing for UAV-imagery – case study

• Are there further updates in the georeferencing of UAV-based imagery?
  • Extended AT with relative position and attitude control
  • Fast AT
  • Hybrid LiDAR & images georeferencing
  • Tightly coupling of GNSS/inertial data & image observations in one adjustment
State-of-the-art in UAV-based mapping – an update

Is UAV-based mapping so much different to regular flight campaigns?
Use of UAV in Mapping / Photogrammetry

© Luhmann et al., 2006
Manned vs. unmanned photo flights
Platforms & cameras
Block configurations: Manned platform

Orthomapping flights LGL BW
Block configurations: UAS – fixed wing

fixed wing
No camera stabilization

Attitude variations within line
Block configurations: UAS – fixed wing

**fixed wing**
No camera stabilization

**Notice**: heavy wind gusts during flight. Flight conditions close to limit!
Block configurations: UAS – rotary wing

Multicopter / Rotary wing
Camera stabilization
Aerial Triangulation

Process chain

Initial Orientation / Set-up of Image Block

Orientation of image block

Transformation into object coordinate frame

camera calibration

Product generation DTM/DSM (Dense Matching) & Ortho
Aerial Triangulation (classical vs. UAV-based)

### Standard-AT
- Levelled camera
- High-precise GNSS/IMU
- "Few" tie points (FBM/LSM)
- GNSS supported AT (few) control points
- Pre-calibratedcams + self-calibration (math. models)

### UAV
- Larger off-nadir angles
- Less accurate attitudes > 0…20deg
- Many key points (SIFT)
- Control points (except RTK & GNSS/IMU)
- Full in-situ camera calibration (physical models)

### Process chain
- Initial Orientation / Set-up of Image Block
- Orientation of image block
- Transformation into object coordinate frame
- Camera calibration
- Product generation
  - DTM/DSM (Dense Matching) & Ortho

"few" tie points (FBM/LSM)
Tie point extraction

Sparse point cloud

SIFT-Points (SfM Bundler)  FBM/LSM points (inpho Match-AT)
**Manned vs. unmanned photo flights**

**Mapping Camera vs. Bridge Camera**

<table>
<thead>
<tr>
<th></th>
<th>Leica DMC III</th>
<th>Sony Alpha 7Rii</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Image format</strong></td>
<td>CMOS, 102 x 56 mm² 26112 x 15.000 pix 3.9 μm / 392 MPix</td>
<td>CMOS, 36 x 24 mm² 7952 x 5304 pix 4.5 μm / 42 MPix</td>
</tr>
<tr>
<td><strong>Lens</strong></td>
<td>Fixed lens, fix focus lens Multiple lens PAN&amp;MS</td>
<td>interchangeableable lens One lens only</td>
</tr>
<tr>
<td><strong>Shutter</strong></td>
<td>mechanical, <strong>global</strong></td>
<td>electronical, <strong>rolling</strong></td>
</tr>
<tr>
<td><strong>Motion comp.</strong></td>
<td>FMC (mechanical)</td>
<td>optical image stabilization</td>
</tr>
<tr>
<td><strong>Dimensions</strong></td>
<td>622 x 497 x 460 mm 60kg (plus 6kg memory)</td>
<td>127 x 96 x 60 mm 625g (plus lens)</td>
</tr>
</tbody>
</table>

*Universität Stuttgart*

*04.03.2020*

*Tutorium DGPF-Jahrestagung Stuttgart*
Rolling shutter – extreme sample
Rolling shutter

Global Shutter

Rolling Shutter

Arbitrarily motion of camera center & rotation over time

Source Pix4D
Ricoh-GXR Mount 12 & Zeiss Biogon 21mm lens Bridge Camera

Opening angle ~70deg Normal angle
Bridge Cam

dlGlcam 50 Mpix
8176 x 6132 pix, 50mm
Opening angle ~63deg
Normal angle
### Performance of camera – geometric resolution

Comparison Phase One iXM 100 & DJI Phantom 4 RTK

**Samples:** Siemens star in image center

<table>
<thead>
<tr>
<th></th>
<th>DJI Phantom 4 RTK</th>
<th>Phase One iXM-100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution MTF10</td>
<td>0.563 line/pix</td>
<td>0.769 line/pix</td>
</tr>
<tr>
<td>GSD (nom.)</td>
<td>6.9 mm</td>
<td>5.0 mm</td>
</tr>
<tr>
<td>tGSD or GRD</td>
<td>12.3 mm</td>
<td>6.5 mm</td>
</tr>
</tbody>
</table>

- DJI Phantom 4 RTK: 178%
- Phase One iXM-100: 130%
Performance of camera – geometric resolution

Comparison Phase One iXM 100 & DJI Phantom 4 RTK

**DJI Phantom 4 RTK**

- Sensor format: $13.2 \times 8.8 \text{mm}^2$
- Pixel count: $5472 \times 3648 \text{pix}$
- Pixel size: $2.41 \mu\text{m}$

**Phase One iXM-100 / 35mm lens**

- Sensor format: $43.9 \times 32.9 \text{mm}^2$
- Pixel count: $11664 \times 8750 \text{pix}$
- Pixel size: $3.76 \mu\text{m}$
Questions & Comments ?!
• Is UAV-based mapping so much different to regular flight campaigns?

• “With a little help from my friends” – using GNSS/inertial-based georeferencing for UAV-imagery – case study

• Are there further updates in the georeferencing of UAV-based imagery?
  • Extended AT with relative position and attitude control
  • Fast AT
  • Hybrid LiDAR & images georeferencing
  • Tightly coupling of GNSS/inertial data & image observations in one adjustment
State-of-the-art in UAV-based mapping – an update

“With a little help from my friends” – using GNSS/inertial-based georeferencing for UAV-imagery – case study
Indirect georeferencing

\[ \mathbf{X} + \mathbf{v}_X = \mathbf{X}_0 + \lambda \cdot \mathbf{R}_c^m (\omega, \varphi, \kappa) \cdot \mathbf{x}^c \]

- Collinearity equation

\[ x + v_x = x_0 - c \cdot \frac{r_{11}(X - X_0^m) + r_{12}(Y - Y_0^m) + r_{13}(Z - Z_0^m)}{r_{31}(X - X_0^m) + r_{32}(Y - Y_0^m) + r_{33}(Z - Z_0^m)} \]

\[ y + v_y = y_0 - c \cdot \frac{r_{21}(X - X_0^m) + r_{22}(Y - Y_0^m) + r_{23}(Z - Z_0^m)}{r_{31}(X - X_0^m) + r_{32}(Y - Y_0^m) + r_{33}(Z - Z_0^m)} \]
**GNSS-supported AT**

**adding GNSS position**

\[
\mathbf{X}^m + \mathbf{v}_X = \mathbf{X}_0^m + \mathbf{R}_c^m (\omega, \varphi, \kappa) \cdot \mathbf{A}^c + \mathbf{S}^m
\]

\[
\mathbf{X} + \mathbf{v}_X = \mathbf{X}_0^m + \lambda \cdot \mathbf{R}_c^m (\omega, \varphi, \kappa) \cdot \mathbf{x}^c
\]

- GNSS perspective centre coordinate observations significantly reduce requirements on geodetic measurements, i.e. ground control points
- Position observations are introduced as weighted observations
- System calibration (i.e. *lever arm vector*) is assumed to be known or determinable. Additional systematic GNSS shifts can be added to the model
**GNSS/inertial-supported AT / Direct georeferencing**

*adding* GNSS/inertial EO parameters

\[ \mathbf{X}^m + \mathbf{v}_X^m = \mathbf{X}_0^m + \mathbf{R}_c^m (\omega, \varphi, \kappa) \cdot \mathbf{A}_c^c + \mathbf{S}_m \]

\[ \mathbf{R}_b^m (\Phi + \nu_\Phi, \Theta + \nu_\Theta, \Psi + \nu_\Psi) = \]

\[ \mathbf{R}_c^m (\omega, \varphi, \kappa) \cdot \mathbf{R}_b^c (\Delta \omega, \Delta \varphi, \Delta \kappa) \]

\[ \mathbf{X} + \mathbf{v}_X = \mathbf{X}_0^m + \lambda \cdot \mathbf{R}_c^m (\omega, \varphi, \kappa) \cdot \mathbf{x}_c^c \]

- GNSS / inertial orientation parameters are beneficial - especially for non-standard block configurations, reducing requirements on control and tie points
- EO direct observations are introduced as weighted observations
- But: System calibration (i.e. Boresight parameter) is assumed to be known or determinable
Study: High-precision 3D monitoring for engineering applications

Research project with BfG Koblenz, Testsite Ship-lock Hessigheim

Quelle: BAW, 2016
Tests site Ship-lock Hessigheim

(netto) Site extensions: 570 m (EW) x 780 m (NS)
UAV – Systems: Photogrammetry and LiDAR

- **CopterSystems** with PhaseOne IXM 100, 35 mm lens (fix-focussed to 60m distance, lab-calibrated)
- Mean flying height: 40 m above ground, Mean nom. **GSD: 4.0 mm**
  - Image area coverage: ~50 x 35 m²
- Accuracy: scaleable (1 pix aspired)

- **Geografie Uni Innsbruck** RiCOPTER with VUX-1UAV
- Point density: 300-400 Pts/m² (per strip), 800 Pts/m² (multiple overlap)
  - 2 x Sony Alpha 6000 camera oblique
  - 1.2-2.0 cm GSD
- Accuracy: 10 mm, Precision: 5 mm
Testsite Ship-lock Hessigheim
Flightcampaign November 2018

- PhaseOne IXM 100 data
  - 12(+2) flights @ 2 days
  - Calibration flight (cross pattern) at first day (ship lock)
  - Quite poor sunlight / weather as flights were done Nov 14/15 2018 – no full coverage of test site possible

- Calibration block
  - 148 images, 2 different flight heights (40m & 50m)

- Block Western-Shore
  - 1037 (909) Images, one flight height (40m)
Calibration block: Performance of GNSS/inertial EO

UAV-application of Applanix APX-15 EI UAV

Residuals at camera positions (observed – adjusted)

RMS values for GNSS/inertial position

<table>
<thead>
<tr>
<th>X [m]</th>
<th>nom.</th>
<th>Y [m]</th>
<th>nom.</th>
<th>Z [m]</th>
<th>nom.</th>
<th>Total [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0114</td>
<td>0.03m</td>
<td>0.0164</td>
<td>0.03m</td>
<td>0.0121</td>
<td>0.03m</td>
<td>0.0234</td>
</tr>
</tbody>
</table>
Calibration block: Performance of GNSS/inertial EO

UAV-application of Applanix APX-15 EI UAV

Residuals at camera **attitude** (observed – adjusted)

RMS values for **GNSS/inertial attitude**

<table>
<thead>
<tr>
<th>Omega (X) [deg]</th>
<th>nom.</th>
<th>Phi (Y) [deg]</th>
<th>nom.</th>
<th>Kappa (Z) [deg]</th>
<th>nom.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.016330</td>
<td>0.025deg</td>
<td>0.017240</td>
<td>0.025deg</td>
<td>0.293340</td>
<td>0.08deg</td>
</tr>
</tbody>
</table>

Manufacturers specs
Calibration block: cross-pattern / ship-lock

Impact of GNSS- and GNSS/inertial-data in AT

Residuals from 20 Checkpoints (Checkerboards)

<table>
<thead>
<tr>
<th></th>
<th>AT with GCPs only</th>
<th>GNSS-supported AT</th>
<th>GNSS/inertial-supported AT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sigma0 [pix]</td>
<td>0.5815</td>
<td>0.5791</td>
<td>0.6691</td>
</tr>
<tr>
<td>RMS X [m]</td>
<td>0.0016</td>
<td>0.0014</td>
<td>0.0014</td>
</tr>
<tr>
<td>RMS Y [m]</td>
<td>0.0021</td>
<td>0.0023</td>
<td>0.0022</td>
</tr>
<tr>
<td>RMS Z [m]</td>
<td>0.0042</td>
<td>0.0019</td>
<td>0.0018</td>
</tr>
<tr>
<td>STD X [m]</td>
<td>0.0016</td>
<td>0.0014</td>
<td>0.0014</td>
</tr>
<tr>
<td>STD Y [m]</td>
<td>0.0021</td>
<td>0.0021</td>
<td>0.0022</td>
</tr>
<tr>
<td>STD Z [m]</td>
<td>0.0038</td>
<td>0.0019</td>
<td>0.0017</td>
</tr>
<tr>
<td>Max. X [m]</td>
<td>-0.0030</td>
<td>-0.0026</td>
<td>0.0033</td>
</tr>
<tr>
<td>Max. Y [m]</td>
<td>-0.0062</td>
<td>-0.0067</td>
<td>-0.0056</td>
</tr>
<tr>
<td>Max. Z [m]</td>
<td>0.0110</td>
<td>-0.0035</td>
<td>0.0034</td>
</tr>
</tbody>
</table>

3 GCPs (Pillars)
20 CHPs
**Calibration block: cross-pattern / ship-lock**

Impact of GNSS- and GNSS/inertial data in AT

AT with GCPs only

GNSS-supported AT

GNSS/inertial-supported AT

3 GCPs (Pillars)
20 CHPs
Block Western-Shore
Impact of GNSS- and GNSS/inertial data in AT

Comparison 3D object points $\Delta Z$ (sparse point cloud after AT)
**GCP only** based AT versus **GNSS-supported** AT
Block Western-Shore

Impact of GNSS- and GNSS/inertial data in AT

Comparison 3D object points $\Delta Z$ (sparse point cloud after AT)

**GNSS-supported** AT *versus* **GNSS/inertial-supported** AT
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Are there any further updates in georeferencening of UAV-based imagery?
Direct Georeferencing / Integr. sensor orientation orientation

- GNSS / inertial orientation parameters are **beneficial** - especially for such corridor flights, reducing requirements on link points (and points)
- **But**: System calibration (generally Boresight parameter) is assumed to be known or determinable
- **Problem**: corridor only provides poor geometry, in addition camera might not be really **stable** over time

\[
X^m + v^m_X = X^m_0 + R_c^m (\omega, \varphi, \kappa) \cdot A^c + S^m
\]

\[
R_b^m (\Phi + \nu_\Phi, \Theta + \nu_\Theta, \Psi + \nu_\Psi) = R_c^m (\omega, \varphi, \kappa) \cdot R_b^c (\Delta \omega, \Delta \varphi, \Delta \kappa)
\]
GNSS/inertial supported AT using **relative** GNSS/inertial EO parameters

Why using **relative** GNSS/inertial EO params / relative aerial control?

- elimination of system calibration parameters;
- stationary time dependent stochastic model for relative aerial control;
- new photogrammetric observation models for horizontal map-projected coordinates;
- new attitude aerial control observation models to avoid re-parameterisations steps

AT using relative aerial control

• **AT using relative** GNSS/inertial aerial control exterior orientation elements
  
  ▶ Boresight-Alignment \( \mathbf{R}_b^c(\Delta \omega, \Delta \varphi, \Delta \kappa) \) is eliminated

\[
\Delta \mathbf{X}^m(t_{ij}) + \mathbf{v}_{\Delta \mathbf{X}}^m = \left( \mathbf{X}_0^m(t_j) - \mathbf{X}_0^m(t_i) \right) + \left( \mathbf{R}_c^m(\omega_{t_j}, \varphi_{t_j}, \kappa_{t_j}) - \mathbf{R}_c^m(\omega_{t_i}, \varphi_{t_i}, \kappa_{t_i}) \right) \cdot \mathbf{A}^c
\]

\[
\Delta \mathbf{R}_b^m(\Phi_{t_{ij}} + v_{\Phi}, \Theta_{t_{ij}} + v_{\Theta}, \Psi_{t_{ij}} + v_{\Psi}) = \mathbf{R}_c^m(\omega_{t_j}, \varphi_{t_j}, \kappa_{t_j}) \cdot \mathbf{R}_m^c(\omega_{t_i}, \varphi_{t_i}, \kappa_{t_i})
\]

**absolut** GNSS/inertial EO elements

\[
\mathbf{X}^m + \mathbf{v}_{\mathbf{X}}^m = \mathbf{X}_0^m + \mathbf{R}_c^m(\omega, \varphi, \kappa) \cdot \mathbf{A}^c + \mathbf{S}^m
\]

\[
\mathbf{R}_b^m(\Phi + v_{\Phi}, \Theta + v_{\Theta}, \Psi + v_{\Psi}) = \mathbf{R}_c^m(\omega, \varphi, \kappa) \cdot \mathbf{R}_b^c(\Delta \omega, \Delta \varphi, \Delta \kappa)
\]
AT with relative GNSS/inertial aerial control

Position

Attitude

© Rehak, 2017

absolute

relative
AT with relative GNSS/inertial aerial control

Influence of GNSS receiver quality (positioning only)

Javad OEM TR-G3T
216 channels each of GPS L1/L2/L2C/L5, GLONASS L1/L2, Galileo E1/E5A
Costs: ~10000 $US

ublox NEO-8T
72-channel u-blox GPS/QZSS L1 C/A, GLONASS L10F, BeiDou B1
Costs: ~75 $US

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Fast AT

• particular case of Integrated Sensor Orientation (GNSS/inertial supported AT) characterized by the use of the following observations:
  ▪ (time) position and attitude (tPA) **aerial control observations**, either in the absolute or relative mode, for all images.
  ▪ Ground control point observations for a **limited number (in principle) of points** and images.
  ▪ Image coordinate observations **for the ground control points only**.


https://doi.org/10.1016/j.isprsjprs.2012.04.005
Fast AT Conceptual Layout (2/2)

Fast AT block

- image and tPA aerial control point
  - ground control point (GCP)

ISO block: 23 + 13 + 23 + 13 images, photo-measurements in all images.
Fast AT block: 18 + 13 + 20 + 12 images, photo-measurements in 2 + 3 + 3 + 2 images, 2 sub-blocks, no need for image/stripe overlap, image overlap recommended in areas with GCPs.
DiSO block: 17 + 12 + 18 + 11 images, no photo-measurements, no GCPs, no overlap requirements.

© Blázquez & Colomina, 2012
# Fast AT

## Observations of InSO, ISO, Fast AT and DiSO.

<table>
<thead>
<tr>
<th>Observations</th>
<th>InSO</th>
<th>ISO</th>
<th>Fast AT</th>
<th>DiSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>tPA/tPVA aerial control</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Ground control points</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td></td>
<td>many</td>
<td>few</td>
<td>few</td>
<td></td>
</tr>
<tr>
<td>Image coordinates</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td></td>
<td>many</td>
<td>many</td>
<td>few</td>
<td></td>
</tr>
</tbody>
</table>

## Properties of ISO, Fast AT and DiSO.

<table>
<thead>
<tr>
<th>Properties</th>
<th>ISO</th>
<th>Fast AT</th>
<th>DiSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision</td>
<td>+</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Accuracy</td>
<td>+</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Reliability</td>
<td>+</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>+</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>+</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

*: high. 0: average. -: low.

InSO – indirect sensor orientation
ISO – integrated sensor orientation
DiSO – direct sensor orientation
Fast AT
potential applications

• Fast AT is of interest in situations where ISO (integrated sensor orientation) is not feasible or required and where DiSO (direct sensor orientation) is not accurate or reliable enough. For instance, it may be used for ill-textured areas where image matching is difficult.

• for applications currently relying on DiSO, where accuracy and reliability matter, and that, for some reason, cannot afford the time and/or cost required by ISO and where the measurement or use of existing GCPs makes sense in the context of the application.

• can be used in combination with standard ISO procedures: One possibility is that a small ISO block be used for camera calibration and that Fast AT be applied for larger blocks. The data acquisition for the ISO block can take place at any time, before, in between or after the Fast AT blocks are acquired. Sensor calibration parameters can then be computed and, later on, used as constants or observations in the Fast AT blocks.

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Fast AT Mathematical Model

• Fast AT concept is independent from the particular functional models of the observation equations for image coordinate, ground control and aerial control observations

• Both possibilities
  ▪ Classical use of EOP observations: classical use of tPA aerial control observations in absolute mode, **absolute Fast AT**
  ▪ Relative use of EOP observations: use of tPA aerial control observations in relative mode, **relative Fast AT**
Influence of Aerial Control on Mapping Accuracy
Block Scenario

UAV test scenario
fixed-wing UAV with Sony NEX-5R, GSD 4.5cm, 7 + 7 flight lines, 207 images, 80% / 60% overlap 20 GCP / ChP (notice distribution!)

Test scenarios

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Indirect SO</td>
<td>-</td>
<td>-</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>ISO</td>
<td>Absolute</td>
<td>Absolute</td>
<td>Yes</td>
<td>Known</td>
</tr>
<tr>
<td>ISO</td>
<td>Absolute</td>
<td>Relative</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>ISO</td>
<td>Relative</td>
<td>Relative</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>Fast AT</td>
<td>Absolute</td>
<td>Absolute</td>
<td>No</td>
<td>Known</td>
</tr>
<tr>
<td>Fast AT</td>
<td>Absolute</td>
<td>Relative</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td>Fast AT</td>
<td>Relative</td>
<td>Relative</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td>DiSO</td>
<td>Absolute</td>
<td>Absolute</td>
<td>No</td>
<td>Known</td>
</tr>
</tbody>
</table>
Influence of Aerial Control on Mapping Accuracy
Block Scenario

Distribution of GCPs, ChPs, and tie-points
## UAV test using GNSS/inertial aerial control

<table>
<thead>
<tr>
<th>Test</th>
<th>Mean [cm]</th>
<th>RMS [cm] / [pix]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$X$</td>
<td>$Y$</td>
</tr>
<tr>
<td><strong>Indirect Georeferencing</strong></td>
<td>6.8</td>
<td>0.8</td>
</tr>
<tr>
<td>(5 GCP / 15 ChP) with CamCal</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Direct Georeferencing</strong></td>
<td>-0.5</td>
<td>-1.3</td>
</tr>
<tr>
<td>(0 GCP / 20 ChP) with Boresight, no CamCal</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Integrated SO + abs. Position + abs. Attitude</strong></td>
<td>0.6</td>
<td>1.6</td>
</tr>
<tr>
<td>(5 GCP / 15 ChP) with Boresight &amp; CamCal</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Integrated SO + abs. Position + rel. Attitude</strong></td>
<td>-0.5</td>
<td>1.6</td>
</tr>
<tr>
<td>(5 GCP / 15 ChP) no Boresight, with CamCal</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fast AT + abs. Position + rel. Attitude</strong></td>
<td>0.8</td>
<td>3.8</td>
</tr>
<tr>
<td>(5 GCP / 15 ChP) no Boresight, no CamCal</td>
<td></td>
<td></td>
</tr>
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GSD: 4.5 cm

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Hybrid LiDAR & image sensor orientation

Hybrid sensors

Standard georeferencing approach:

- each data stream processed / georeferenced independently, i.e.
  - LiDAR strip adjustment
  - Photogrammetric bundle
- Sensors moved on the same trajectory **not** considered!
Hybrid LiDAR & image sensor orientation

• simultaneously optimization of the relative orientation and absolute orientation (georeference) of the lidar and image data.

• sensor orientations are optimized by minimizing the discrepancies
  (1) within the overlap area of flight strips and/or images and
  (2) with respect to ground truth if available

• rigorous modelling using the original measurements of the sensors (i.e. scanner: polar measurements, camera: image coordinates) and the flight trajectory of the aircraft


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Hybrid LiDAR & image sensor orientation

Correspondence between two lidar strips (STR-to-STR)

Correspondence between CPC and lidar strip (CPC-to-STR)

Correspondence between images (tie point) (IMG-to-IMG)

Correspondence between tie point and GCP (IMG-to-GCP)

Correspondence between tie point and lidar strip (IMG-to-STR)

Minimization of point-to-plane distance in object space

Minimization of point-to-plane distance in object space

Minimization of reprojection error in image space

Minimization of point-to-point distance in object space

Minimization of point-to-plane distance in object space

strip adjustment of lidar point clouds

aerial triangulation

hybrid adjustment: lidar strip adjustment + aerial triangulation

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Hybrid LiDAR & image sensor orientation

(a) Lidar points colored by roughness $\sigma_p$

(b) Image tie points

(c) IMG-to-STR correspondences colored by weight $w_p$

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Hybrid LiDAR & image sensor orientation

**INPUT DATA**
- flight trajectory
- scanner measurements
- priors for mounting calibration of scanner(s)
- control point clouds (CPCs)
- coupled and loose images
- timestamps of coupled images

- priors for int.ori. of camera(s)
- priors for mounting calibration of camera(s)
- priors for ext. ori. of loose images
- ground control points (GCPs)
- IMG-to-GCP correspondences

**HYBRID ADJUSTMENT**
- for each strip: direct georeferencing with current parameters
  - for each strip pair: selection, matching, rejection of STR-to-STR correspondences
    - for each CPC: selection, matching, rejection of CPC-to-STR correspondences
      - for each image: selection, matching, rejection of IMG-to-STR correspondences

- aerial triangulation to estimate 3D coordinates of tie points (needed for subsequent matching of IMG-to-STR correspondences)

**OUTPUT DATA**
- corrected flight trajectory
- georeferenced lidar strips
- corrected scanner measurements
- mounting calibration of scanner(s)
- int. ori. of camera(s)
- mounting calibration of camera(s)
- ext. ori. of coupled images
- ext. ori. of loose images
Stand-alone LiDAR processing
Flight campaign November 2018

before strip-adjustment  
After strip-adjustment, **bias** correction  
After strip-adjustment, **spline model** correction
Stand-alone LiDAR processing

Absolute vertical accuracy from levelled (check-)planes

Bias model

Spline model
Stand-alone vs. hybrid LiDAR – image adjustment

**stand-alone** LiDAR – image adjustment

**hybrid** LiDAR – image adjustment
Bundle adjustment with raw inertial data

- typically GNSS/inertial data processing is done as pre-processing step before integrated sensor orientation
- this **approach fails in challenging scenarios**: short inertial/GNSS trajectories, weak photogrammetric block geometries, poor GNSS observations / signal quality
- **joint adjustment** of GNSS/inertial (raw) observations together with other sensors (camera / LiDAR) in **dynamic network / pose-graph optimization**


[https://doi.org/10.1016/j.isprsjprs.2017.05.008](https://doi.org/10.1016/j.isprsjprs.2017.05.008)

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Bundle adjustment with raw inertial data

Processing chains in sensor orientation

**Traditional workflow**

- Images
- feat. matching
- inertial obs.
- CP differential
- pos/vel obs.
- image times
- KALMAN FILTER
- INS/GNSS traj.
- Interpolation
- aerial control
- Bundle Adj.

**Modified workflow**

- Images
- feat. matching
- inertial obs.
- GNSS raw obs.
- CP differential
- pos/vel obs.
- image times
- Bundle Adj.

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Dynamic Networks – Integration of inertial raw data into sensor georeferencing

• determine the navigation solution (i.e., the trajectory), and, optionally, other parameters, such as inertial sensor biases, fusing all the available sensor readings in a single step "tight fusion" between inertial and image measurements.

• each “raw” sensor reading corresponds to an observation model, which forms the vector of unknowns:
  ▪ Sensor poses (exterior orientations),
  ▪ 3D position of the map-fixed features (object points) and
  ▪ calibration parameters (interior orientation, boresight, lever-arms, IMU sensor biases)

• high number of unknowns because of high IMU rate has to be reduced (otherwise ill-conditioning), i.e. IMU pre-integration or solving through regularization
Dynamic Networks – Integration of inertial raw data into sensor georeferencing

Object points

IMU position & orientation

Image EO params

$\Gamma^m_{b,j}$

$t$

image $i = 1$

$T_1$

$i = 2$

$i = 3$

$T_2$

chunk $k = 1$

chunk $k = 2$

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Dynamic Networks – Integration of inertial raw data into sensor georeferencing

Empirical UAV test flight – test layout

Remark: Data set already introduced before
Dynamic Networks – Integration of inertial raw data into sensor georeferencing

Empirical UAV test flight – tested scenarios

Case 0

Case 1

Case 2

Case 3

1 km

GCP

Chp

inertial/GNSS only

GNSS denied area
Dynamic Networks – Integration of inertial raw data into sensor georeferencing

Empirical UAV test flight – Case 0: Full photogrammetric block with GCP

Check point residuals

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Dynamic Networks – Integration of inertial raw data into sensor georeferencing

Empirical UAV test flight – Case 2: Corridor survey

Check point residuals

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Dynamic Networks – Integration of inertial raw data into sensor georeferencing

Empirical UAV test flight – Case 3: Corridor survey with GNSS blockages

Check point residuals

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Questions & Comments ?!
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