Multiray Photogrammetry and Dense Image Matching

Dense Image Matching - Application of SGM

- Stereo matching (1D) in epipolar image pairs
  - Application of Semi-Global-Matching
- Correspondences for each pixel
  - Parallax/disparity images
- 3D point cloud from spatial intersection
Multiray Photogrammetry and Dense Image Matching

- Highly overlapping aerial image blocks
  - Cost-free forward overlap for digital cameras
  - Sideward overlap for true-ortho generation
- 80% in-flight and 60% cross-flight
  - Object visibility in 2 strips, 5 images each
- Redundant matching for accurate and reliable point cloud generation

Dense matching using multiple-overlaps

- 80% in-flight and 60% cross-flight overlap provides 45 potential stereo combinations
  \[
  \binom{k}{r} = \frac{k!}{r!(k-r)!} = \binom{10}{2} = 45
  \]
- Suitability of different stereo combinations for 3D point cloud generation?
Suitability of different stereo combinations for 3D point cloud generation

- Large stereo base
  - Advantageous geometric configuration for 3D point measurement
  - Stereo matching aggravated by occlusions
- Short stereo base
  - Simplified automatic matching due to small image differences
  - Reduced accuracy for spatial intersection
- In-flight vs. cross-flight
- Influence of different combinations on accuracy, reliability, completeness of point measurement

Test area Gleisdorf

- UltraCamXp
  - flight height 1600m, GSD 0.1m
  - 413 images, 43 control points,
  - AAT by Match-AT
    - RMS of tie points 0.07pix
- Overlap 80% in-flight, 70% cross-flight
  - 5 images in flight, 3 strips
- Aim: Investigation of SGM matching quality for different configurations at potential problematic regions

- High frequent periodic patterns
- Small structures, shadows
- Vegetation
- Low texture Planar area
Evaluation of stereo matching quality: Disparity differences

- Disparity differences forward-backward matching as measure of consistency
- Filter out matches if difference exceeds certain threshold

Dense Stereo Image Matching

- Parallax image after filtering disparity differences > 1 pixel
  - A priori filter for all subsequent tests
Disparity differences as filter and quality measure

- Disparity differences of all matched pixels to compute $\sigma_{d_{\text{all}}}$
- Use $3\sigma_{d_{\text{all}}}$ as additional threshold to eliminate gross errors
- Disparity differences of remaining parallaxes to measure matching accuracy $\sigma_{d_{3\text{mv}}}$

$$\sigma_d = \frac{1}{\sqrt{2}} \sqrt{\frac{\sum_{i=1}^{n} \left( (d_{1i} + d_{2i}) - E[(d_{1i} + d_{2i})] \right)^2}{n}}$$

SGM performance from disparity differences

- Test with 5 images of same strip
- Stereo pairs with base-to-height-ratios from 0.12 to 0.48
  - Base-lengths from 192m – 768m
SGM performance from disparity differences

- Test with 5 images of same strip
- Accuracy and completeness of SGM decreases for larger baselines
  - Reliability of matching accuracy from forward-backward consistency?
- Evaluation of generated 3D point cloud in object space

<table>
<thead>
<tr>
<th>Base-to-height ratios</th>
<th>0.12</th>
<th>0.24</th>
<th>0.36</th>
<th>0.48</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward-backward matching $\sigma_{3mv}$[pix]</td>
<td>0.19</td>
<td>0.19</td>
<td>0.24</td>
<td>0.23</td>
</tr>
<tr>
<td>Completeness $n_{point%}$</td>
<td>86.2</td>
<td>82.5</td>
<td>65.6</td>
<td>53.7</td>
</tr>
</tbody>
</table>

Evaluation in object space: Test at planar area

- Estimate polynomial at planar surface from generated 3D point cloud
- Point accuracy from distances to estimated surface
- Error propagation to provide accuracy in image space for comparison
  - Spatial intersection from epipolar images as normal case of stereo photogrammetry

\[
Z = \frac{c \cdot B}{x' - x''} = \frac{c \cdot B}{p_x}
\]

\[
\sigma_z = \frac{Z \cdot Z}{c \cdot B} \cdot \sigma_{p_z} = m_b \cdot \frac{Z}{B} \cdot \sigma_{p_z}
\]

\[
\sigma_{p_A} = \frac{1}{m_b} \cdot \frac{B}{Z} \cdot \sigma_{Z}
\]
SGM performance at planar test area

<table>
<thead>
<tr>
<th>Base-to-height ratios</th>
<th>0.12</th>
<th>0.24</th>
<th>0.36</th>
<th>0.48</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward-backward matching $\sigma_{3mv}[\text{pix}]$</td>
<td>0.09</td>
<td>0.10</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>Point cloud to reference surface $\sigma_{3mv}[\text{cm}]$</td>
<td>9.15</td>
<td>5.44</td>
<td>6.23</td>
<td>5.11</td>
</tr>
<tr>
<td>Transformation to image space $\sigma_{3mv}[\text{pix}]$</td>
<td>0.12</td>
<td>0.14</td>
<td>0.24</td>
<td>0.26</td>
</tr>
<tr>
<td>Completeness $n_{\text{Points}}[%]$</td>
<td>97.79</td>
<td>98.05</td>
<td>96.63</td>
<td>97.31</td>
</tr>
</tbody>
</table>

- Decreasing SGM accuracy for larger baselines is compensated by better geometric configuration for spatial intersection
- Differences forward-backward matching and planar surface estimation provide similar accuracy values
- Difference between values for complete and planar test area

SGM performance
Completeness planar area vs. complete scene

<table>
<thead>
<tr>
<th>Base-to-height ratios</th>
<th>0.12</th>
<th>0.24</th>
<th>0.36</th>
<th>0.48</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane area $n_{\text{Points}}[%]$</td>
<td>97.8</td>
<td>98.0</td>
<td>96.6</td>
<td>97.3</td>
</tr>
<tr>
<td>Complete area $n_{\text{Points}}[%]$</td>
<td>86.2</td>
<td>82.5</td>
<td>65.6</td>
<td>53.7</td>
</tr>
</tbody>
</table>

- Restriction to planar area not representative for different surface types
Semi Global Matching (SGM)

- Semi-global Matching estimates disparities $D_p$ which minimize costs (e.g. grey value “differences”) for complete stereo pair
  - Costs of potential matches $(p,q)$ are assigned to 3d structure

Semi Global Matching (SGM)

- Ambiguities are avoided by additional continuity constraint
- Add costs (Penalty) for disparity changes of neighbouring pixels
- Constrain solution to planar areas by simply selecting large values for penalties $P_1$ and $P_2$!!

\[ L_r(p,d) = C(p,d) + \min \left( L_r(p-r,d), \right. \]
\[ \left. L_r(p-r,d-1)+P_1, \quad L_r(p-r,d+1)+P_1, \quad \min_{i,j}(L_r(p-r,i)+P_2) \right) \]
\[ - \min \left( L_r(p-r,k) \right) \]
Quality control by multi-ray photogrammetry

- Aerial triangulation / bundle block adjustment
  - Feature based matching to generate tie points at overlapping image patches
- Multiple rays to estimate camera parameters
  - Accuracy analysis
  - 3D coordinates of tie point as by-product
- 3D point clouds / DSM generation
  - Dense stereo matching between base image and respective stereo images
- Spatial intersection of multiple rays to estimate 3D point coordinates
  - Accuracy analysis
  - Elimination of gross errors

Multi-Stereo-Matching

- Transfer each pixel of the base image to multiple match images
- Redundant measures to determine 3D object coordinates for each pixel in the match image
Combination of two stereo matches

- Match base image against two neighbors
- Least squares spatial intersection of 3 image rays
  - Estimate object coordinate and corresponding point error
  - Determine $\sigma_{Z_{\text{all}}}$ from all pixels i.e. points of match image
- Eliminate gross errors $> \sigma_{Z_{\text{all}}}$
- Determine accuracy of remaining points $\sigma_{Z_{3mv}}$

Point determination from double matches

- Redundancy of 3 rays increases point accuracy and reliability
- Larger baselines increase 3D point accuracy but reduces number of successful matches
- Cross strip matching additionally reduces number of successful matches

$\sigma_z = 4.85\text{cm}$  $n_{\text{pts}} = 81.6\%$

$\sigma_z = 2.36\text{cm}$  $n_{\text{pts}} = 70.2\%$

$\sigma_z = 2.22\text{cm}$  $n_{\text{pts}} = 60.1\%$
Point determination from multiple matches
Increase to 5 or 7 image rays

- Use further increase of redundancy to eliminate single erroneous matches based on residuals in image space
- Remaining matches for “error free” 3D point coordinates
- Highest reliability and completeness

\[ \sigma_Z = 2.36\text{cm} \quad n_{Pts} = 70.2\% \]
\[ \sigma_Z = 3.67\text{cm} \quad n_{Pts} = 86.8\% \]
\[ \sigma_Z = 2.78\text{cm} \quad n_{Pts} = 91.6\% \]

Summary - Conclusions

- SGM stereo matching provides accuracies of 0.14 - 0.25 pixel
- Accuracy and number of successfully matched points decreases for larger base-to-height rations
- Better geometric properties for ray intersections of wide base lines partly compensate worse matching accuracy
- Multi-ray matching considerably improves accuracy, reliability and completeness of 3D point cloud generation
- “Pixel-wise bundle block adjustment” for refined error analysis
Other data sets: DGPF Project on Digital Photogrammetric Camera Evaluation
Comparison of results to commercial tool Match-T DSM (2009)
In our tests SGM provided
   - Higher completeness
   - Better accuracy
Planar test area prefers smoothness constraint

<table>
<thead>
<tr>
<th>Sensor</th>
<th>DMC</th>
<th>RMK</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD after filter [cm]</td>
<td>3.4</td>
<td>6.9</td>
</tr>
<tr>
<td>STD no filter [cm]</td>
<td>5.2</td>
<td>19.9</td>
</tr>
<tr>
<td>Density Pts/m²</td>
<td>23.39</td>
<td>5.35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensor</th>
<th>DMC</th>
<th>RMK</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMC</td>
<td>2.7</td>
<td>4.6</td>
</tr>
<tr>
<td>RMK</td>
<td>3.1</td>
<td>25.7</td>
</tr>
<tr>
<td>Density Pts/m²</td>
<td>102.99</td>
<td>103.06</td>
</tr>
</tbody>
</table>

Rothermel & Haala, 2011