The Landscape of Dense Image Matching Algorithms

- Photogrammetric Week 2011
  - Carl Pulfrich Award Dr. Heiko Hirschmüller: "The application of Semi-Global Matching (SGM) for the generation of very dense surface models … is a game changer in the point cloud generation business"

- Photogrammetric Week 2013
  - Increasing number of solutions from industry and academia

- Evaluation of dense multi-image matching software systems: State-of-the-art, potential and limitations
  - EuroSDR Benchmark on Image Matching
EuroSDR Benchmark on Image Matching for DSM Computation

- Realization under the umbrella of independent organization
  - EuroSDR - European Spatial Data Research Network
    - Not-for-profit organization links national mapping agencies with research institutes and universities
- Project team
  - Prof. Dr. Norbert Haala, Mathias Rothermel, University of Stuttgart
  - Wolfgang Stößel, State Agency of Surveying and Geoinformation Bavaria
  - Dr. Michael Gruber, Microsoft Photogrammetry
  - Prof. Dr. Norbert Pfeifer, Vienna University of Technology
  - Michael Franzen, Federal Office for Metrology and Surveying, Vienna

- February 2013: Project definition and announcement
  - Provide test data, present test issues, motivate participants
- May 2013: Results from participants
  - Compute DSM raster at grid width of image GSD
  - Simplify evaluation, 3D point clouds not included
- June 2013: Joint evaluation
  - Workshop at BEV Vienna to present and discuss results
- July 2013: Preliminary report
  - Paper and presentation “The Landscape of Dense Image Matching Algorithms” at Phowo
Image based DSM generation:
Test issues

- Pixel-wise image matching
  - Correspondences for each pixel in epipolar image pairs
  - Parallax/disparity images

- 3D point cloud from spatial intersection
Dense Stereo Matching
Epipolar image pair and disparity image

3D Point Cloud
Dense image matching from highly overlapping imagery

- Highly overlapping aerial image blocks
  - Cost-free forward overlap for digital cameras
- 80% in-flight and 60% cross-flight
  - Objects visible in 2 strips with 5 images
- Redundant matching for accurate and reliable point cloud generation

Multi-stereo matching

- Match central base image against multiple neighbors
  - 80%/70% overlap depicts object in 3 strips with 5 images each
  - Base image can potentially be matched against 14 neighbours
Multi-stereo matching

- Match each base-image pixel against multiple neighbors
  - Multi-ray 3D surface reconstruction

Multi-stereo matching for redundant point determination

- Dense multi-stereo matching to generate 3D point clouds
  - Spatial intersection of multiple rays to estimate 3D point coordinates for each single pixel
  - Redundancy to increase accuracy and eliminate of mismatches
Multi-stereo matching for redundant point determination

- Dense multi-stereo matching to generate 3D point clouds
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\[
\begin{align*}
\sigma_Z &= 4.85\text{cm} \\
n_{\text{Pts}} &= 81.6\% \\
\sigma_Z &= 3.67\text{cm} \\
n_{\text{Pts}} &= 86.8\% \\
\sigma_Z &= 2.78\text{cm} \\
n_{\text{Pts}} &= 91.6\%
\end{align*}
\]

Design of a Benchmark on Image Matching for DSM Computation

- Evaluate state-of-the-art, potential and limitations of existing software systems
- Questions to be answered
  - Matching quality depending on surface types
    - Investigate different landuse
  - 3D accuracy and completeness depending on image overlap
    - Investigate different block configurations
  - Efficiency of software solution to provide and handle multiple matches
    - .....

- Motivate potential participants for voluntary work:
- Keep it simple, reduce the effort
  - Avoid handling large data sets
    - Limit number and size of test areas
  - Simplify comparison
    - Evaluate raster DSM - do not include 3D point clouds
Selected test areas

- Two aerial image blocks of moderate extent
  - Results from available AAT to be used during dense matching
- Semi-rural – Vaihingen/Enz
  - Moderate GSD and image overlap
  - Representative for statewide data collection
- Urban - München
  - Higher GSD and image overlap
  - Representative for data collection in dense urban areas

Test area Vaihingen/Enz

- Semi-rural: Moderate GSD and image overlap
  - Ultracam-X, 36 PAN images, GSD 20 cm, 8 bit/pix
  - 9420x14430 pixel, 180 Mbyte/image, 6.5GB
Test area Vaihingen/Enz

- Block of 3 strips with 12 images each
  - 63% in flight and 62% cross flight overlap
  - Overlap four-folded to nine-folded
- DSM grid 20cm, 7.5kmx3.0km

Test area München

- Dense urban area high overlap and small GSD
  - Occlusions, shadows, small structures
- DMC II 230, 15 PAN images, 10cm GSD
  - 16 bit/pix, 15kx14kpix, 220Mpix/img, 3.3 GB
Test area München

- Block of 3 image strips with 5 images each
  - 80% in flight 80% cross flight overlap
  - Typical overlap five-folded to fifteen-folded
- DSM grid 10cm 1.5kmx1.7km

EuroSDR Benchmark on Image Matching

Investigated results from participants

- Users of commercial software
  - SocetSet 5.6 (NGATE), BAE Systems
    - C. Ginzler (WSL, Swiss Federal Institute for Forest, Snow and Landscape Research)
  - UltraMap V3.1, Microsoft
    - B. Brunner (FMM, Forest Mapping and Management)
  - Match-T DSM 5.5, Trimble/inpho
    - C. Ressl (GEO TU Wien, Vienna)

- Commercial providers
  - ImageStation ISAE-Ext
    - R. Schneider (GEOSYSTEMS)
  - Pixel Factory
    - P. Nonin (Astrium GEO-Information Services)

- Research developments
  - Royal Military Academy RMA DSM Tool
    - M. Idrissa
  - Joanneum Research, Graz
    - K. Gutjahr
  - MicMac, IGN France
    - M. Pierrot-Deseilligny
  - SURE, ifp University of Stuttgart
    - M. Rothermel
  - DLR-SGM, German Aerospace Center (DLR)
    - H. Hirschmüller
Evaluation of DSM quality:
Reference from Airborne LiDAR?

- Main differences at vegetation due to growth and measurement principle
- LiDAR point density 6.7 pts/m² not sufficient to evaluate 10cm/20cm DSM
  - No ground-truth of suitable quality available

Test data: DGPF project on camera evaluation

Evaluation of DSM quality:
Difference of respective software solutions

- Generate “reference” DSM from all provided results
  - Median surface
- Color code differences between DSM and median surface
  - Restrict to -2m < Median < +2m
- Identification and further evaluation of problematic areas
Visual analysis of DSM differences

- Larger differences at
  - Steep slopes
  - Cast shadows
  - Vegetation
  - Small structures
  - Water surfaces
- Numerical values for offset and surface noise
  - Evaluation of extracted profiles

Evaluation of Profiles
Steep slope, cast shadow

- Gross errors: GeoSystems, MicMac
- Increased noise: RMA
- Smoothing at edges: Astrium
- NoData Values: SocetSet
Evaluation of Profiles
Steep slope, well illuminated

- Consistent reconstructions for complete profile

Evaluation of Profiles
Small Structures

- Roof of small hut from almost all solutions
- Row of vines with object size close to available GSD still resolved:
  - IfP-SURE, Astrium, MicMac,
- Smoothing
  - UltraMap
Evaluation of Profiles
Patches of trees

- Consistent reconstruction also at trees
  - Constant offset for DLR-SGM

Evaluation of Profiles
Buildings, trees, water surface

- Large differences for water surface
  - Smoothing for UltraMap
Test area München
Results from participants

- Visualisation of sub-part (170x150m)
  - Nominal overlap 11-13 fold
  - Further reduction at occlusions

- 9 DSM solutions available
  - No DMC II data for UltraMap
Match-T

Joanneum Research
Evaluation of profiles

- Differences at
  - Steep edges
  - Small structures
  - Cast Shadows
- Large differences for SocetSet
  - Not included for further evaluation
Cast shadow, step edge, small structures

- Increasing noise at cast shadow: RMA, MicMAc
- Deviation at step edge: Match-T
- Small structures resolved
- Differences almost at GSD level
Evaluation of Profiles
Fine structure

- Fine structures resolved almost all systems
- Differences on the ground in one pixel level
  - Noise for MicMac

Roof with cast shadow

- Increasing noise for shadowed surface
  - Larger deviations GeoSystems
- Differences at surface steps
**EuroSDR Benchmark on Image Matching for DSM Computation**

- Clear ranking for the respective results was avoided
- Growing number of software for high quality DSM generation
  - Vertical accuracies close to sub-pixel level
- Acceptable run-times even for standard hardware environment
  - München 10cm DSM grid 1.5x1.7km
  - Vaihingen/Enz 20cm DSM 7.5x3.0km

**IT environment and Processing Time**

- 32 Xeon E5-2630/i7 cores, 5 GPU’s (1 Tesla K10, 4 Tesla M2090).
  - Vaihingen/Enz: 35min data ingest and AAT, DSM 27min (UltraMap)
- Intel Core i7 CPU, 3GHz with 4 cores, 8GB memory
  - Vaihingen/Enz 23h, München 19h (Match-T)
- 2 Intel Xeon with 4 cores and 16GB memory
  - München limited to 6 stereo models, 40min per stereo model, 4h for complete block (GEOSYSTEMS)
- 2 Xeon E5-2640, 2.5GHz with 12 cores
  - München 2h 12min, Vaihingen/Enz 57 stereo pairs 3h 9min. (Pixel Factory)
- i7 CPU quadcore at 3.4GHz, 32GB Ram.
  - München 4h 13min, Vaihingen/Enz 4h 37min (SURE)
  - NVIDIA 580 GTX GPU implementation Vaihingen/Enz 2h 50min
- Virtex 6 FPGA board, 8GB Ram, connected to a Intel Xeon E5-1620 4 core PC via GigE.
  - München 5h 51min, Vaihingen/Enz 19h 31min (DLR – SGM)
Conclusion

- Many thanks to participants of EuroSDR benchmark!
  - Software development still subject to considerable momentum
- Processing takes advantage from large image overlaps
  - Economical flight scenarios?
- Difficult areas e.g. cast shadows and structures close to GSD
- From 2.5D to 3D (4D?) environments