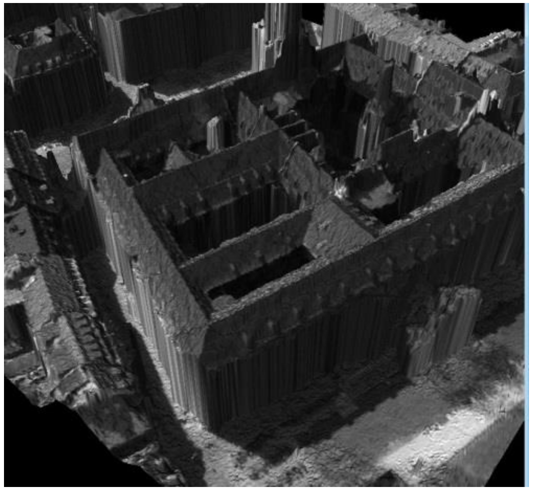
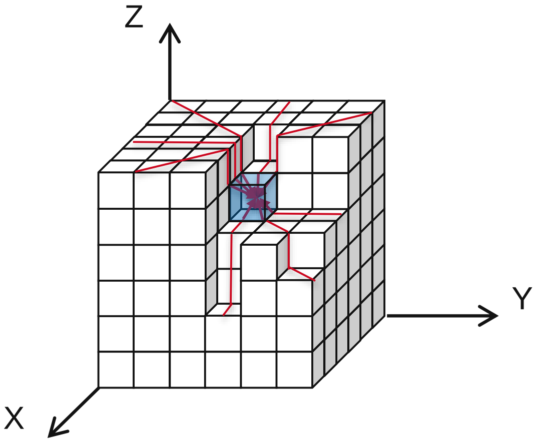
Dense pointclouds from combined nadir and oblique imagery by object-based semi-global multi-image matching





Thomas Luhmann, Folkmar Bethmann & Heidi Hastedt
Jade University of Applied Sciences, Oldenburg, Germany
Institute for Applied Photogrammetry and Geoinformatics

Photogrammetric Week
September 11-15, 2017
University of Stuttgart

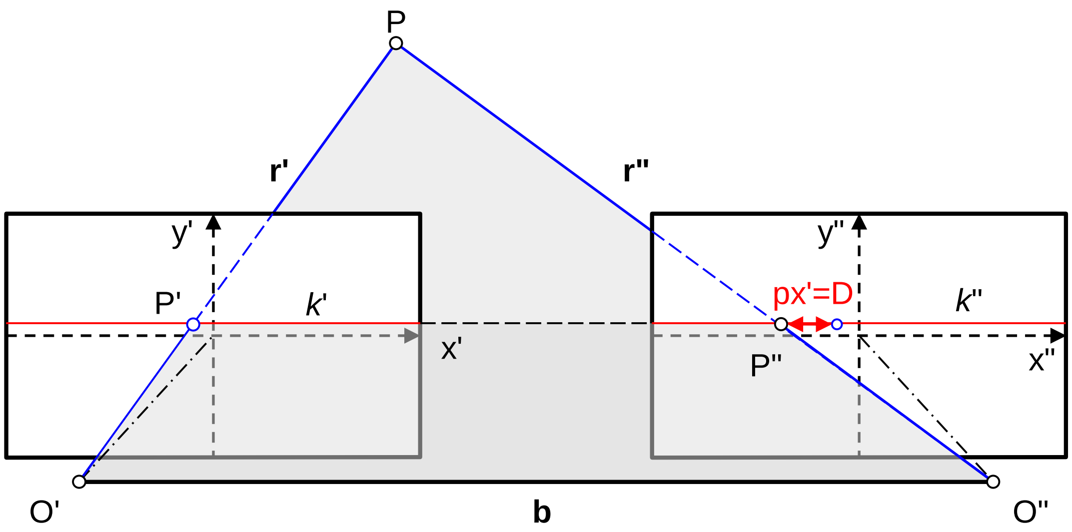
Content

- Introduction, motivation
- Semi-global matching in object space
- Matching of nadir aerial images
- Combined matching of nadir and oblique images
- Summary and outlook

Introduction

Semi-Global Matching (SGM) [Hirschmüller 2005, 2008]

- Common method for dense stereo matching (1 XYZ point per pixel)
- Usable for very different kind of applications (real-time applications, close-range reconstruction tasks, aerial image matching)
- Often used within multi-view stereo (MVS) approaches for complex 3D reconstruction tasks



Epipolar stereo pair with x-parallaxe (disparity) D

Introduction

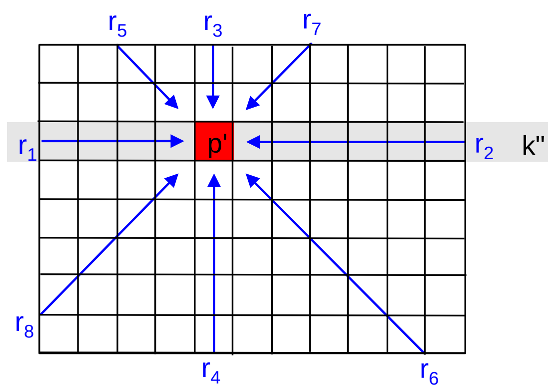
SGM: Minimization of a global energy function

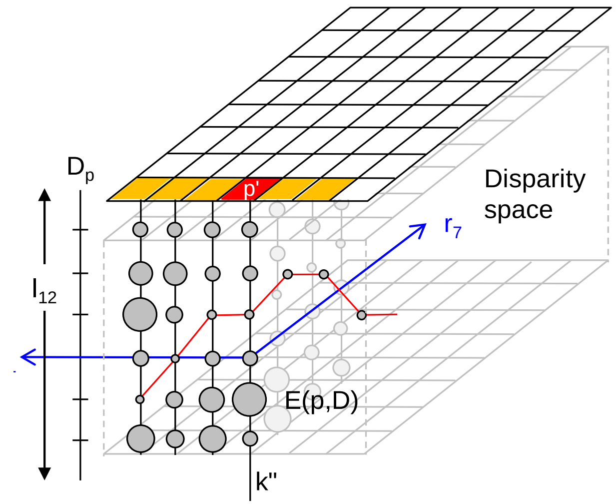
$$E(D) = \sum_{x',y'} C(x',y',D) + \sum_{q \in N_{x'y'}} P_1 \cdot \mathrm{T}[|D - D_q| = 1] + \sum_{q \in N_{x'y'}} P_2 \cdot \mathrm{T}[|D - D_q| > 1]$$

costs for disparity *D* — matching costs — terms for adding the penalties P_1 and P_2

Major idea of SGM:
Cost aggregation only in the direction of 1-dimensional paths („semi-global“ solution, approximation)

Path directions for cost aggregation (e.g. for 8 paths)





Recursive computation separately for each path *r* with:

$$L_r(p',D) = C(p',D)$$
$$+ \min[L_r(p'-r,D), L_r(p'-r,D-1) + P_1, L_r(p'-r,D+1) + P_1, \min_i L_r(p'-r,i) + P_2)]$$
$$- \min_k L_r(p'-r,k)$$

Introduction

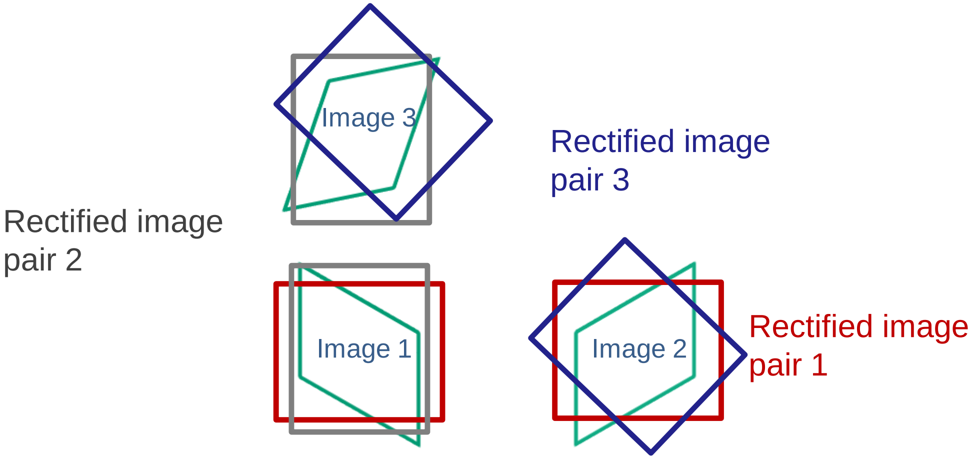
Advantages of SGM

- Robust results in non- and weak-textured areas (due to penalization of local disparity changes)
- Good modelling of depth discontinuities in areas with sharp object boundaries (low smoothing)
- High resolution, detailed reconstruction of even fine structures (dense matching)
- Good performance in processing speed
- Advanced software solutions: SURE, OpenCV and others

Introduction

Limitations of SGM:

- Matching always in stereo images, no simultaneous multi-image matching
- commonly rectified images are used for matching → in MVS approaches every image has to be resampled more than one time, e.g. with three images:



Example:
- Image bundle with15 images
- Number of all possible image pairs:
  $n \cdot (n-1) / 2 = 15 \cdot (15-1) / 2 = 105$ image pairs
  → Resampling of
  $n \cdot (n-1) = 210$ images (worst case)

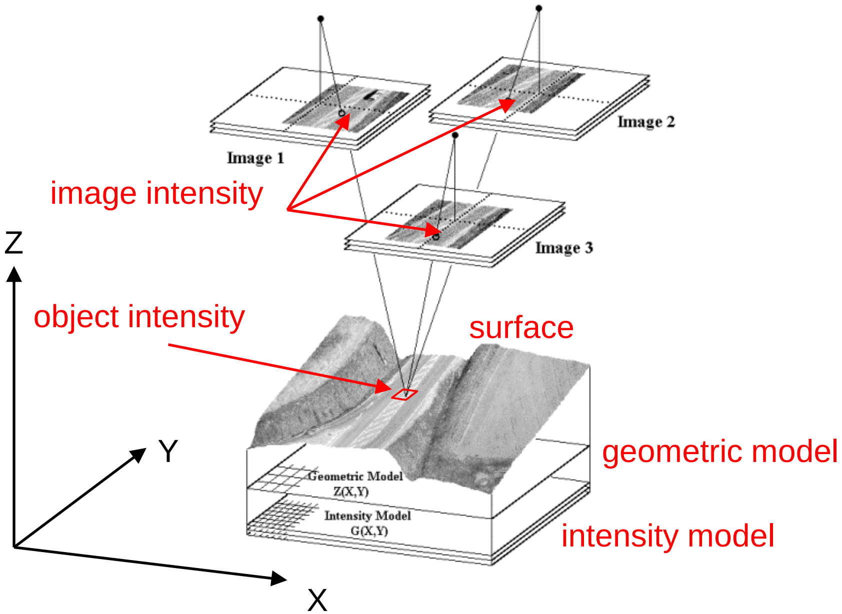
Motivation

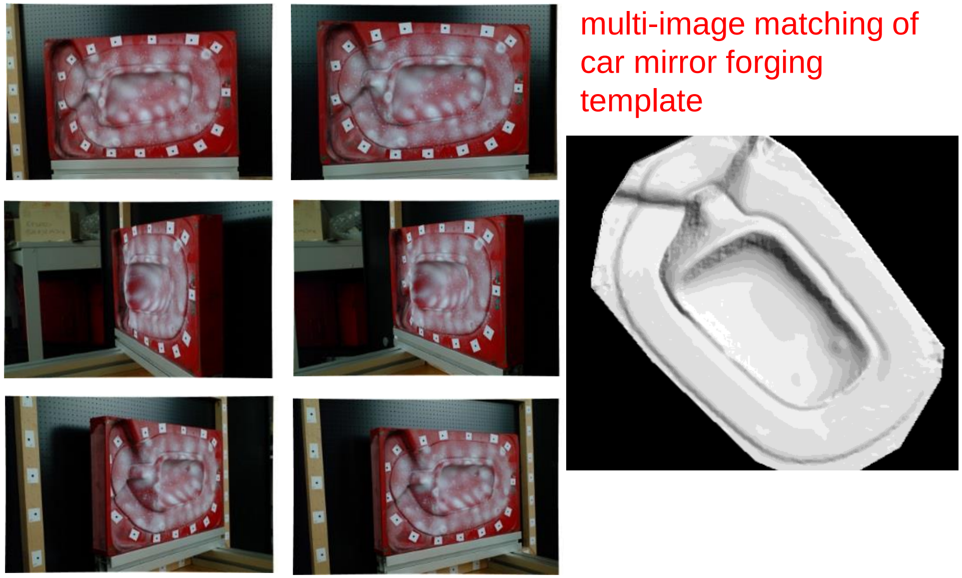
- Extension of SGM for multi-image matching
- Conversion to object space

Semi-Global Matching in Object Space

Our previous work on object-based matching

- Facet Stereo Vision (FAST vision) by Wrobel (1986), Weisensee (1991) and others
- New implementation and applications by Wendt et al. (2004)
- First implementation of OSGM by Bethmann & Luhmann (2015)





Semi-Global Matching in Object Space

Modified energy function:

$$E(D) = \sum_{x',y'} C(x',y',D) + \sum_{q \in N_p} P_1 \cdot \mathrm{T}[|D - D_q| = 1] + \sum_{q \in N_p} P_2 \cdot \mathrm{T}[|D - D_q| > 1]$$ Stereo SGM

$$E(Z) = \sum_{X,Y} C(X,Y,Z) + \sum_{q \in N_{X,Y}} P_1 \cdot \mathrm{T}[|Z - Z_q| = \Delta Z] + \sum_{q \in N_{X,Y}} P_2 \cdot \mathrm{T}[|Z - Z_q| > \Delta Z]$$ SGM in object space

Semi-Global Matching in Object Space

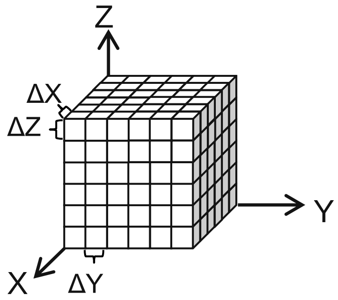
Modified energy function:

$$E(Z) = \sum_{X,Y} C(X,Y,Z) + \sum_{q \in N_{X,Y}} P_1 \cdot \mathrm{T}[|Z - Z_q| = \Delta Z] + \sum_{q \in N_{X,Y}} P_2 \cdot \mathrm{T}[|Z - Z_q| > \Delta Z]$$

Processing steps

1. Sub-division of the object space (discretization)

Spatial resolution (ΔX, ΔY, ΔZ) is defined in object space (adapted to the GSD and spatial configuration of the cameras)



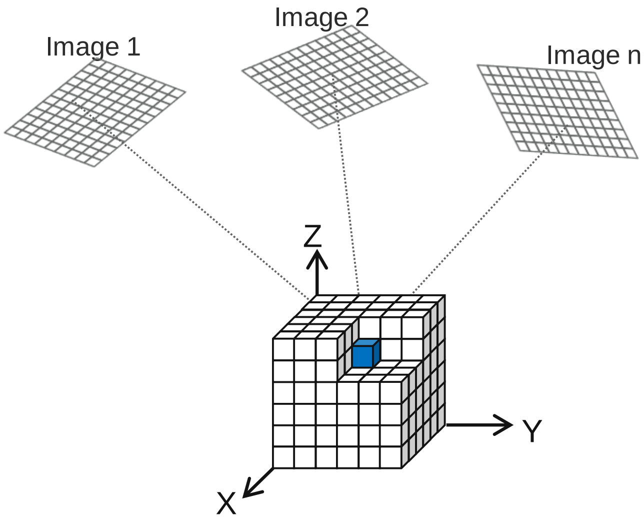
Semi-Global Matching in Object Space

Modified energy function:

$$E(Z) = \sum_{X,Y} C(X,Y,Z) + \sum_{q \in N_{X,Y}} P_1 \cdot \mathrm{T}[|Z - Z_q| = \Delta Z] + \sum_{q \in N_{X,Y}} P_2 \cdot \mathrm{T}[|Z - Z_q| > \Delta Z]$$

Processing steps

1. Sub-division of the object space (discretization)
2. Calculation of matching costs for each point / voxel



- No need for image rectification
- Matching within pairs, triples and so on
- → real multi-image matching possible

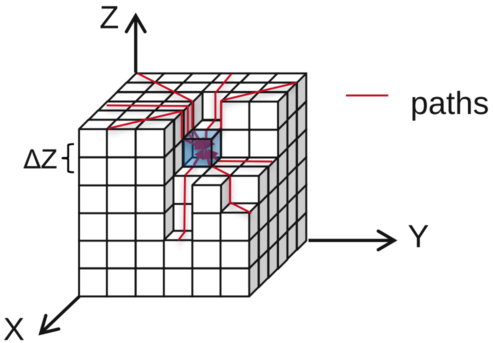
Semi-Global Matching in Object Space

Modified energy function:

$$E(Z) = \sum_{X,Y} C(X,Y,Z) + \sum_{q \in N_{X,Y}} P_1 \cdot \mathrm{T}[|Z - Z_q| = \Delta Z] + \sum_{q \in N_{X,Y}} P_2 \cdot \mathrm{T}[|Z - Z_q| > \Delta Z]$$

Processing steps

1. Sub-division of the object space (discretization)
2. Calculation of matching costs for each point / voxel
3. Aggregation of matching costs (in object space instead of disparity space)



Penalties effectuate smoothing with respect to a defined spatial axis (here: Z-axis)

$$L_r(v,Z) = C(v,Z) + \min[L_r(v-r,Z), L_r(v-r,Z-\Delta Z) + P_1, L_r(v-r,Z+\Delta Z) + P_1, \min_i L_r(v-r, i \cdot \Delta Z) + P_2)] - \min_k L_r(v-r, k \cdot \Delta Z)$$

Semi-Global Matching in Object Space

Modified energy function:

$$E(Z) = \sum_{X,Y} C(X,Y,Z) + \sum_{q \in N_{X,Y}} P_1 \cdot \mathrm{T}[|Z - Z_q| = \Delta Z] + \sum_{q \in N_{X,Y}} P_2 \cdot \mathrm{T}[|Z - Z_q| > \Delta Z]$$

Processing steps

1. Sub-division of the object space (discretization)
2. Calculation of matching costs for each point / voxel
3. Aggregation of matching costs (in object space instead of disparity space)
4. Summing up of path-wise aggregated matching costs, search of minimum in S

$$S(X,Y,Z) = \sum_r L_r(X,Y,Z) \qquad Z(X,Y) = \arg\min_Z S(X,Y,Z)$$

Result is a 2.5D point cloud
instead of a disparity map

Semi-Global Matching in Object Space

Results for close-range applications:

- Object: clay sculpture, 110mm x 70mm x 90mm
- Camera: Nikon D2x + 24mm Nikkor lens, GSD=0.1mm

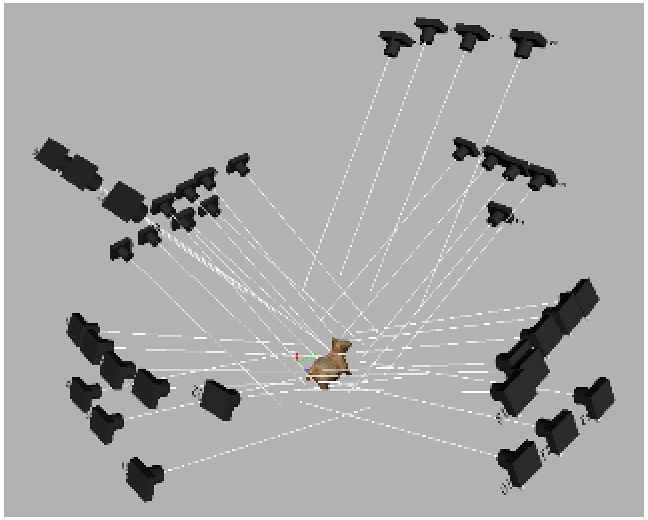
Bethmann & Luhmann 2015

Semi-Global Matching in Object Space

Results for close-range applications:

- Object: clay sculpture, 110mm x 70mm x 90mm
- Camera: Nikon D2x + 24mm Nikkor lens, GSD=0.1mm
- Image bundle with 38 images
- Reference data, captured with fringe projection system (accuracy 20-50µm)
- Matching
    - Resolution in object space
      $\Delta X = \Delta Y = \Delta Z = 0.3$mm (ca. 3x GSD)
    - Different reference planes for matching
    - Median filter for outlier removal
    - 110.000 object points

Bethmann & Luhmann 2015

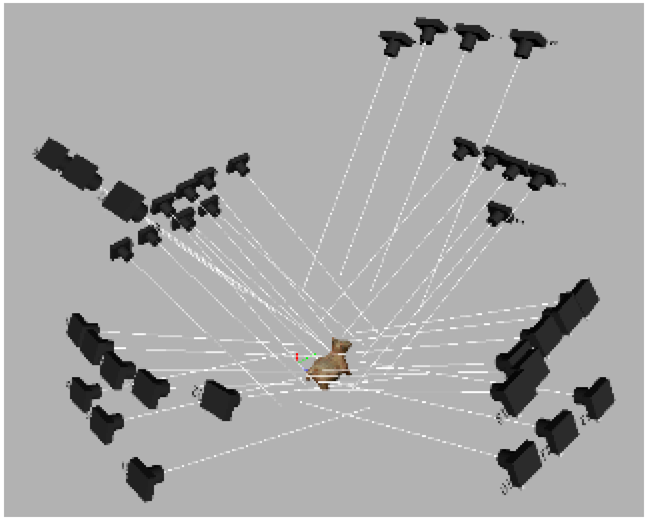


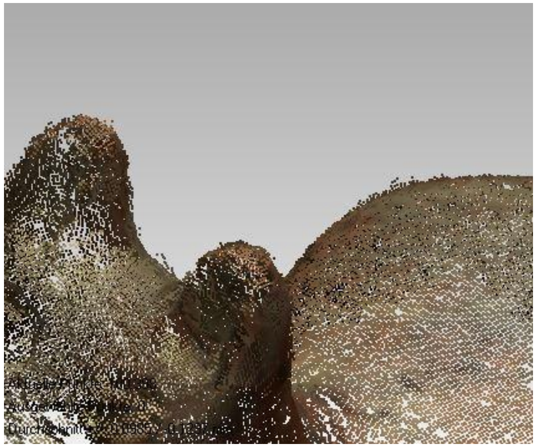
Semi-Global Matching in Object Space

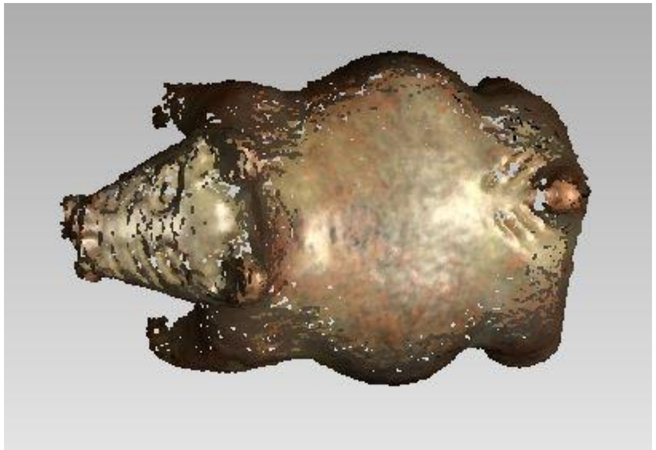
Bethmann & Luhmann 2015

Results for close-range applications:

- Object: clay sculpture, 110mm x 70mm x 90mm
- Camera: Nikon D2x + 24mm Nikkor lens, GSD=0.1mm
- Image bundle with 38 images
- Reference data, captured with fringe projection system (accuracy 20-50µm)
- Matching



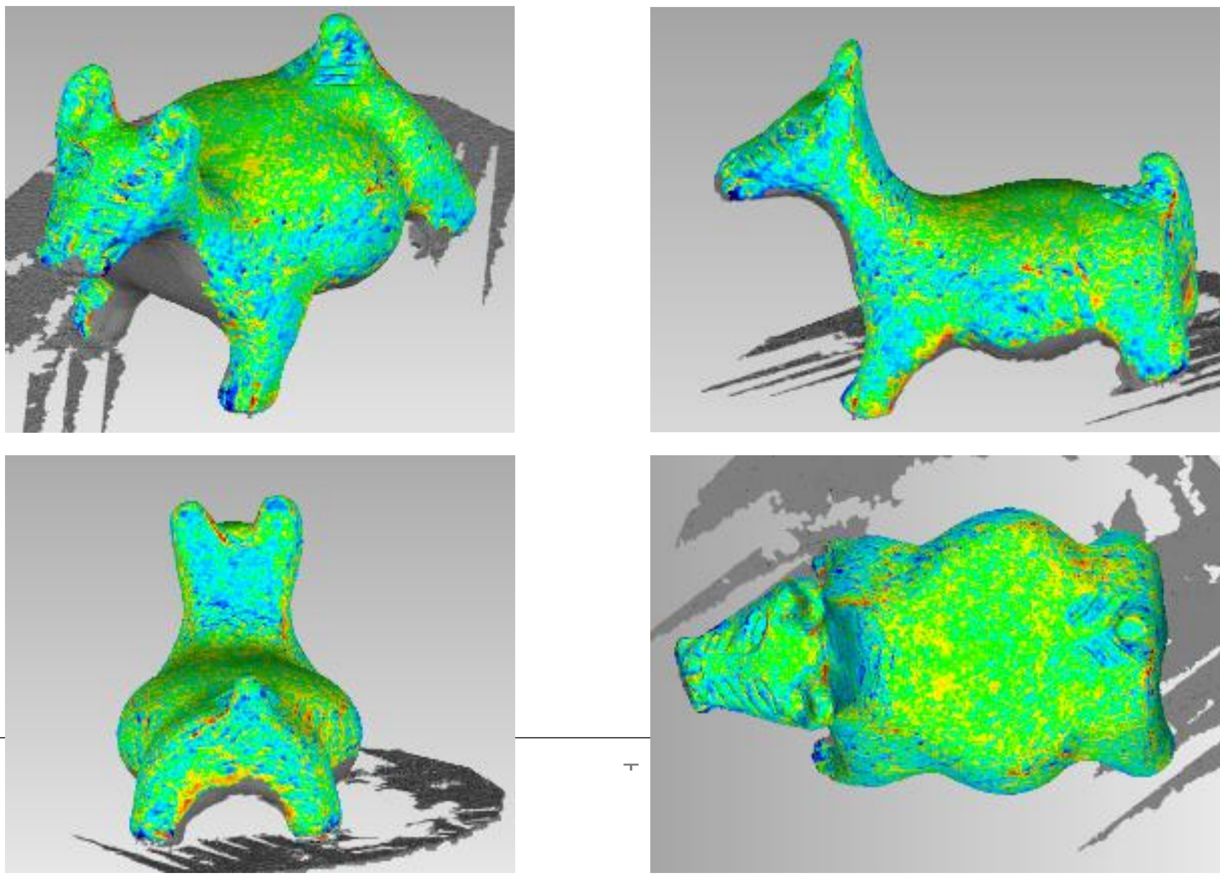


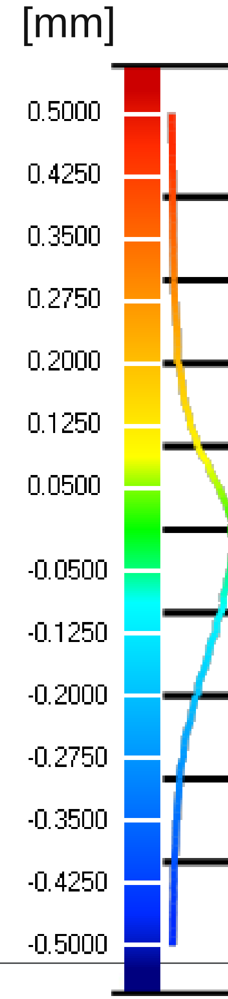


Semi-Global Matching in Object Space

Results for close-range applications:

- Comparison to TIN derived from fringe projection measurement
- Mean 3D deviations +0.098mm (pos) and -0.129mm (neg)
- Standard deviation: ±0.165mm

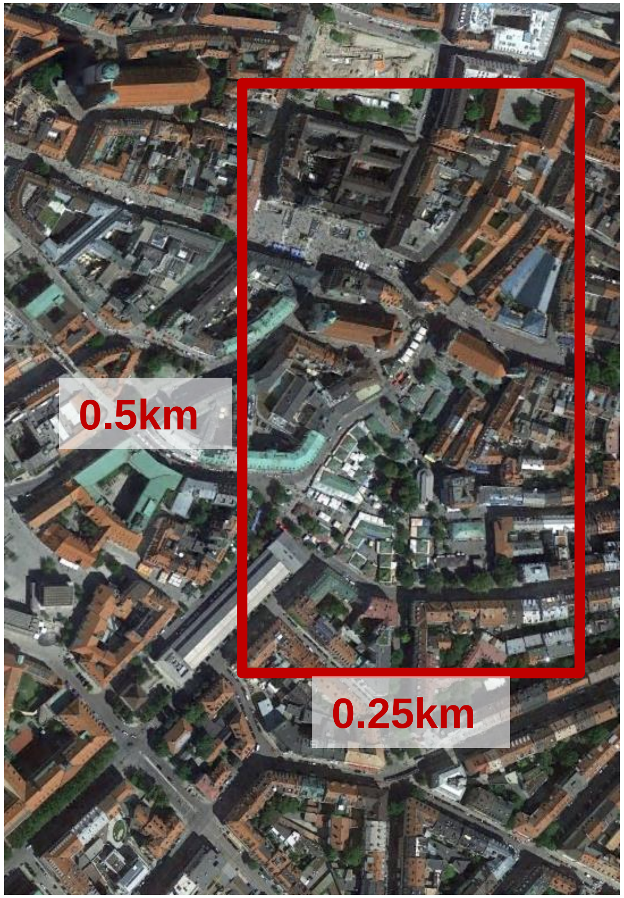




Matching of nadir aerial images

Aerial images (EuroSDR benchmark Munich):

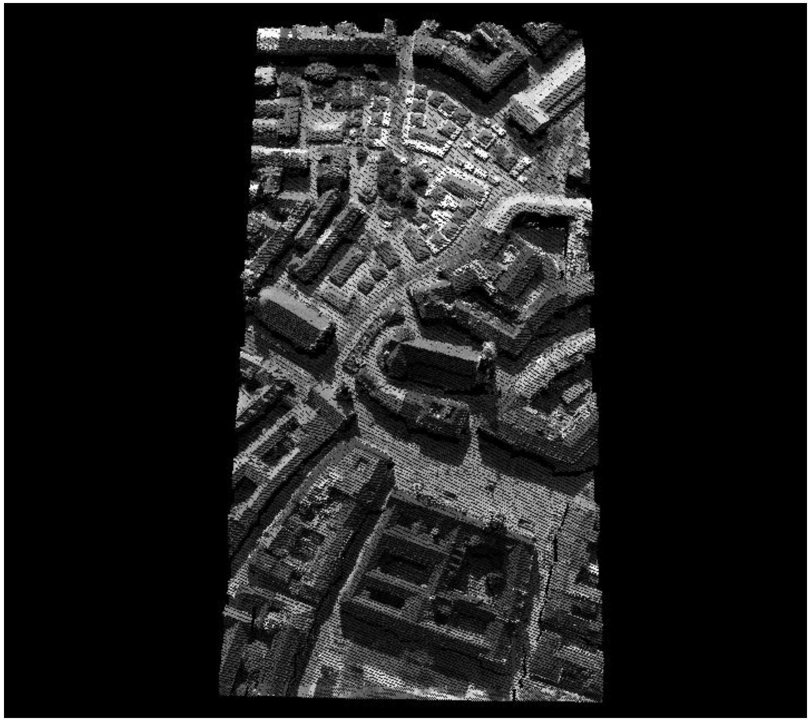
- Part of EuroSDR dataset, inner city of Munich
- Set of 15 aerial images, 16 Bit PAN
- Camera: DMC II 230, 15552 x 14144 Pixel, c=91mm
- GSD 10cm
- 80% overlap in flight and cross flight direction
- Urban area, flat topography but high buildings (up to 50m)



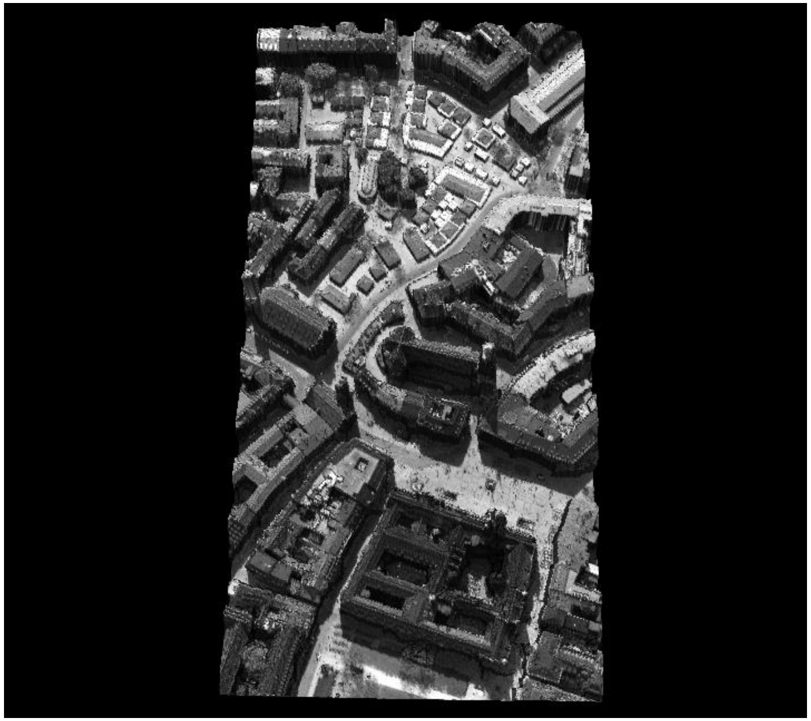
Matching of nadir aerial images

Aerial images (EuroSDR benchmark Munich):

- Voxel resolution in object space ΔX= ΔY= ΔZ=10cm (adapted to GSD)



Unfiltered point cloud (12 million points)



TIN derived from unfiltered point cloud

Matching of nadir aerial images

Aerial images (EuroSDR benchmark Munich):

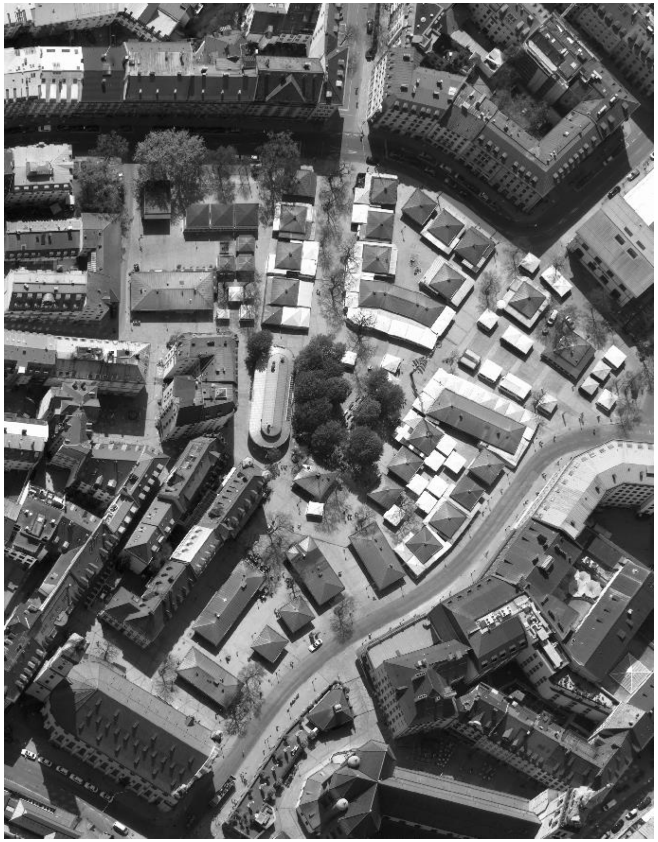


Image section

TIN derived from unfiltered point cloud

Matching of nadir aerial images

Aerial images (EuroSDR benchmark Munich):

- Voxel resolution in object space ΔX= ΔY= ΔZ=10cm (adapted to GSD)

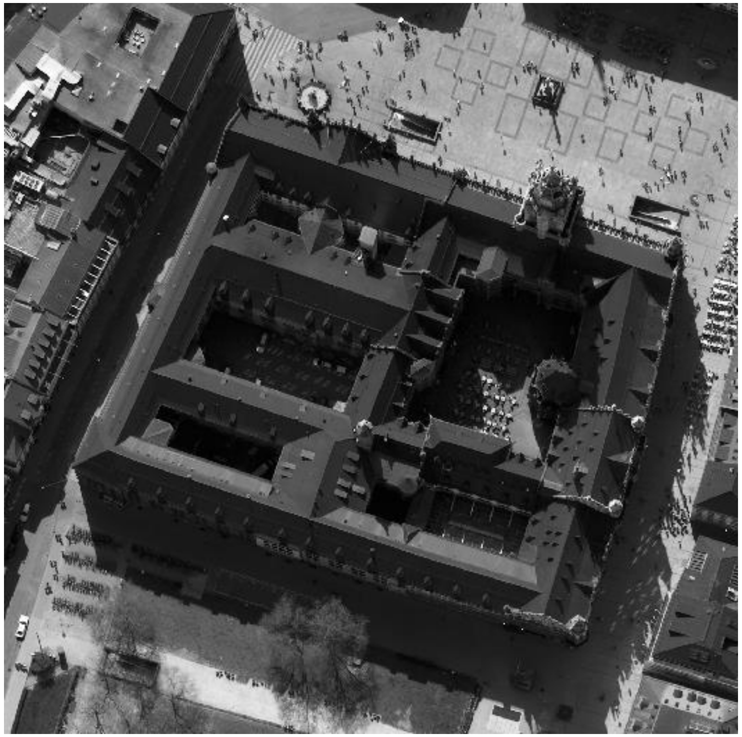
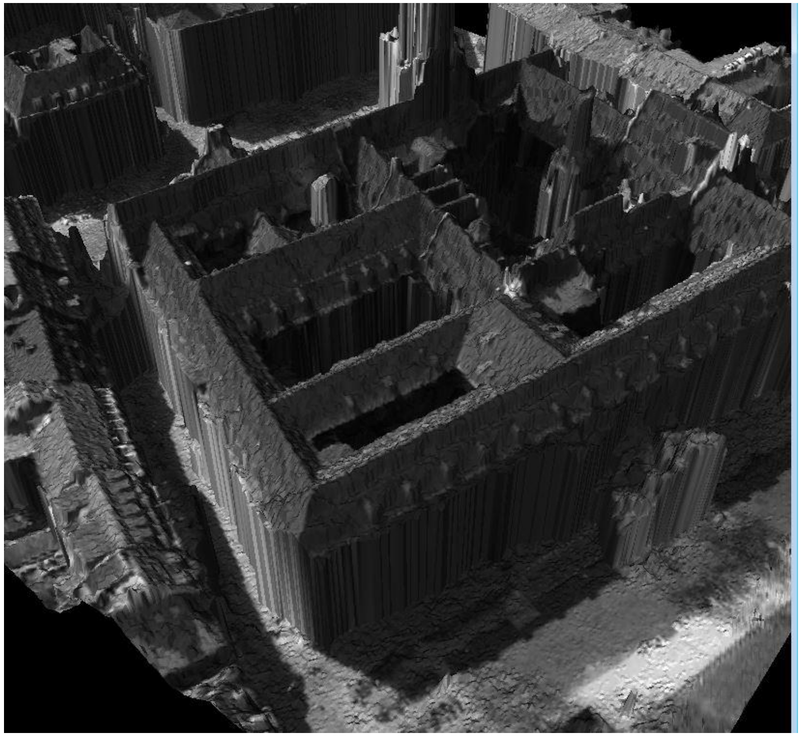


Image section

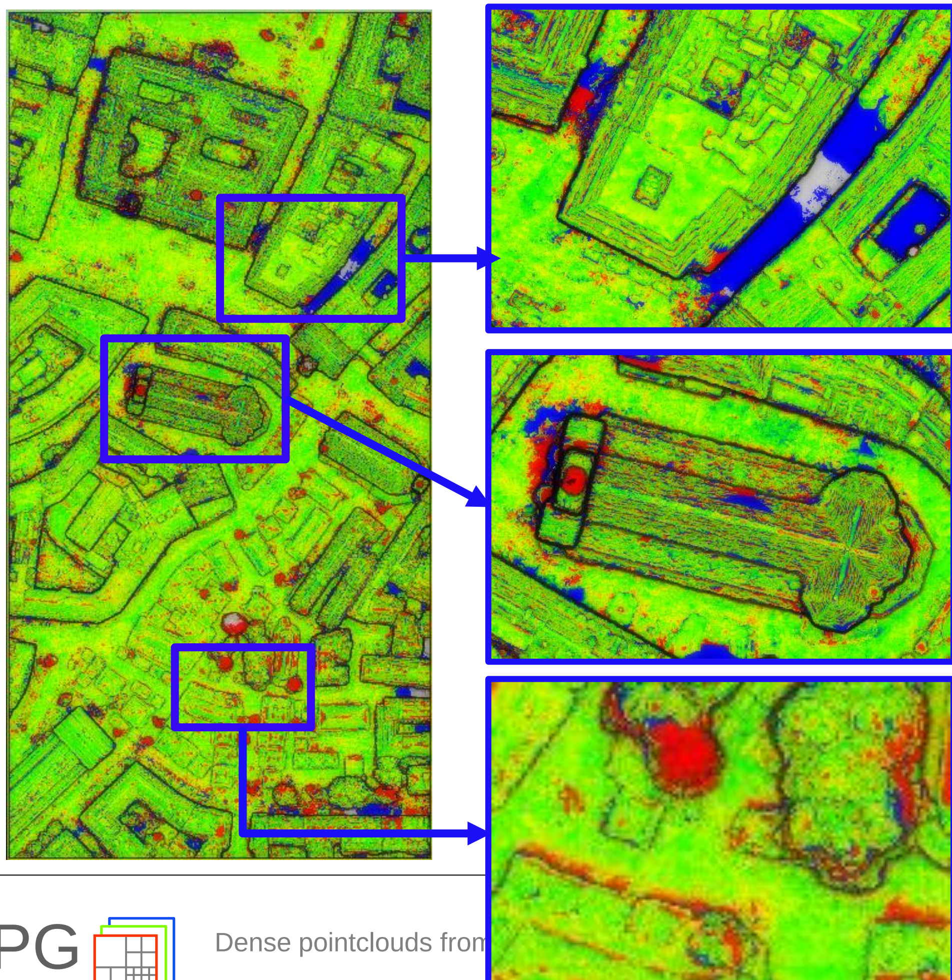


TIN derived from unfiltered point cloud

Matching of nadir aerial images

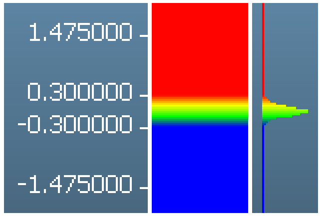
Aerial images (EuroSDR benchmark Munich):

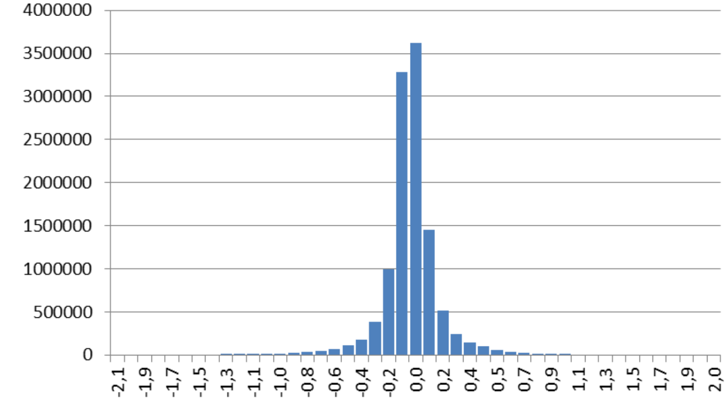
- Comparison to median DSM of the benchmark:



Red : deviations < 0.3m

Blue : deviations > -0.3m

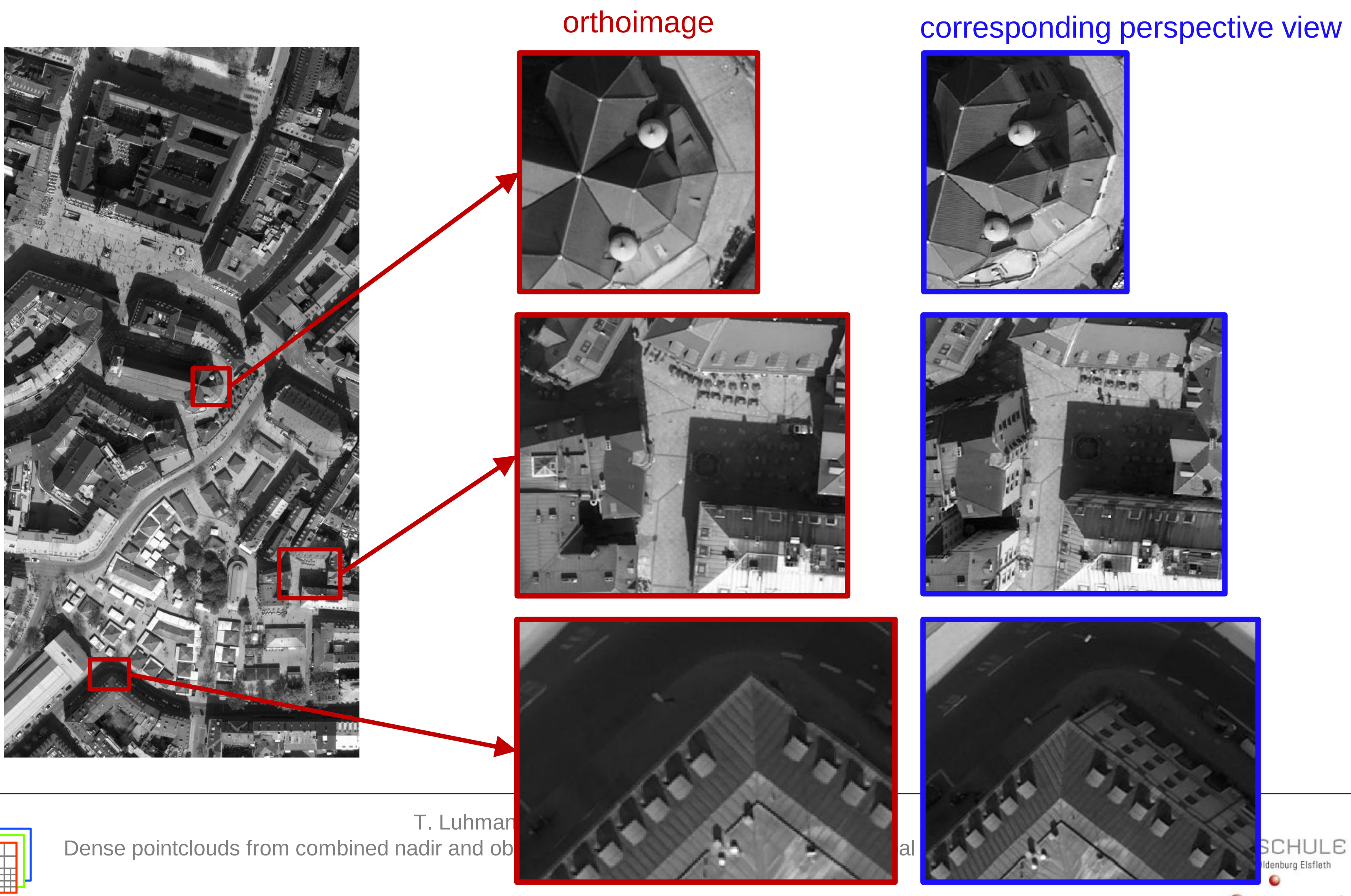




Range	**Number Points**	**%**
all	11790368	100
-0.1 to 0.1	8864297	75
-0.2 bis 0.2	9864876	84
-0.4 to 0.4	10829079	92

Matching of nadir aerial images

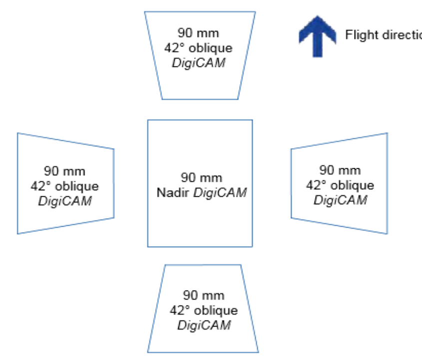
Aerial images (EuroSDR benchmark Munich): True orthoimage, based on DSM from matching



Combined matching of nadir and oblique images

Benefits of combined nadir and oblique image processing

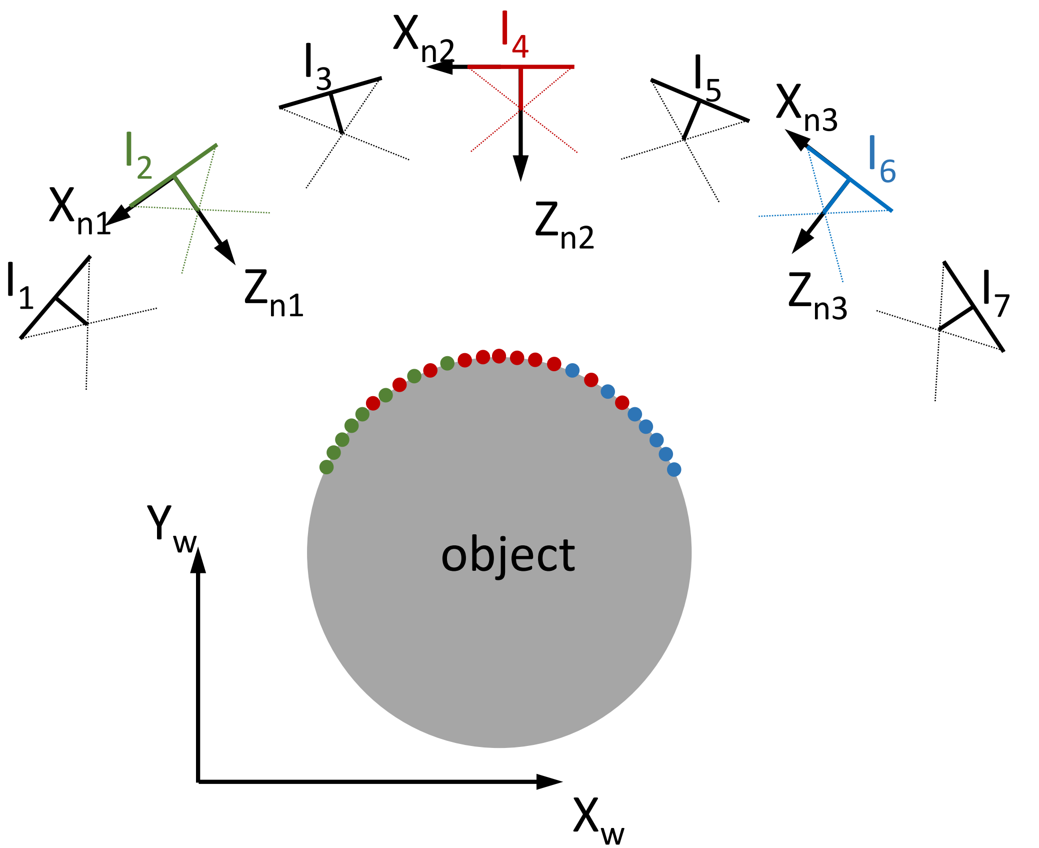
- Closing gaps from occlusions
- Improved texture mapping for vertical facades
- Convergent imaging angles for better intersection of rays
- Multi-image approach for higher accuracy
- Monoplotting for simple height measurements

Combined matching of nadir and oblique images

3D scenarios, oblique images

- Definition reference images (here e.g. in I_2, I_4 and I_6)
- Transformation of all other exterior orientations into the coordinate system of each reference image
- Multi-image matching in each system
- Back transformation of resulting point clouds into world coordinate system (X_W, Y_W, Z_W)



- Object point, matched in temporary coordinate system I_2
- Object point, matched in temporary coordinate system I_4
- Object point, matched in temporary coordinate system I_6

Combined matching of nadir and oblique images

Aerial and oblique images (benchmark dataset Zeche Zollern):

- provided by ISPRS Scientific Initiative "Multi-platform Very High Resolution Photogrammetry"
- test area: museum Zeche Zollern

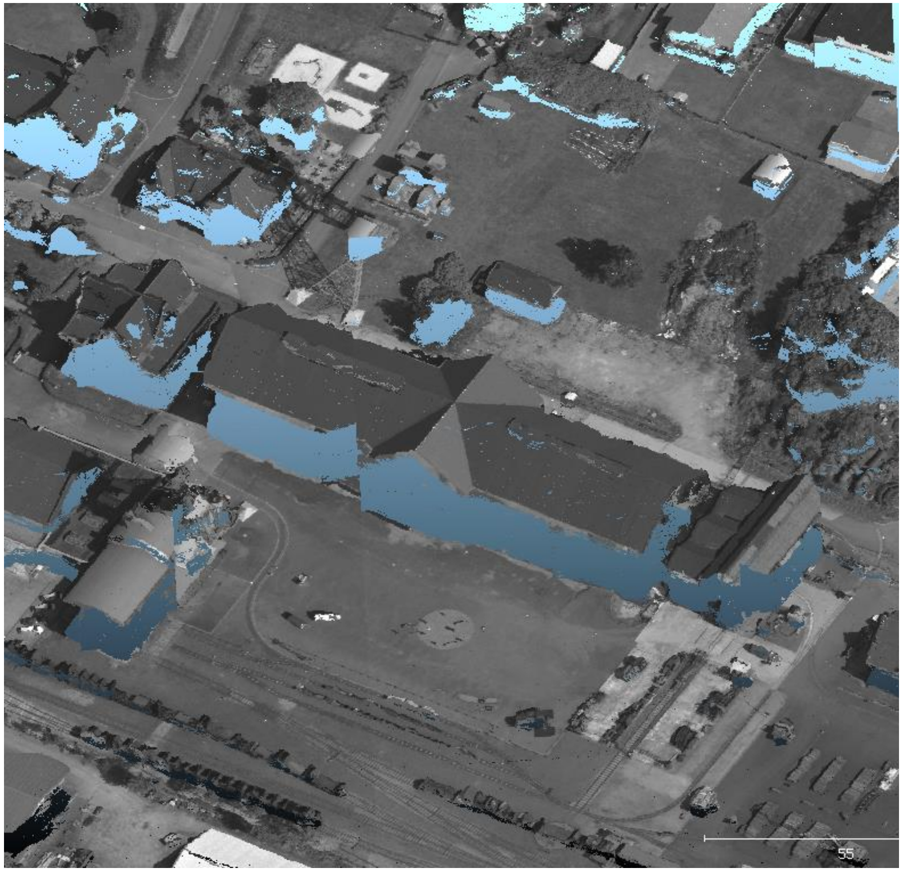
- industrial buildings of different complexity
- very challenging for matching algorithms due to fine object structures and occlusions
- GSD of nadir images: 10cm
- GSD of oblique images: 8cm – 12cm
- Overlap nadir: 75% (along track) and 80% (across track)
- Overlap oblique: 80% (along track) and 80% (across track)
- 85 images (nadir and oblique)
- Ground "truth" by ALS and TLS data

PentaCam (IGI)

Combined matching of nadir and oblique images

Aerial and oblique images (benchmark dataset Zeche Zollern): unfiltered point clouds

Matching with nadir images only



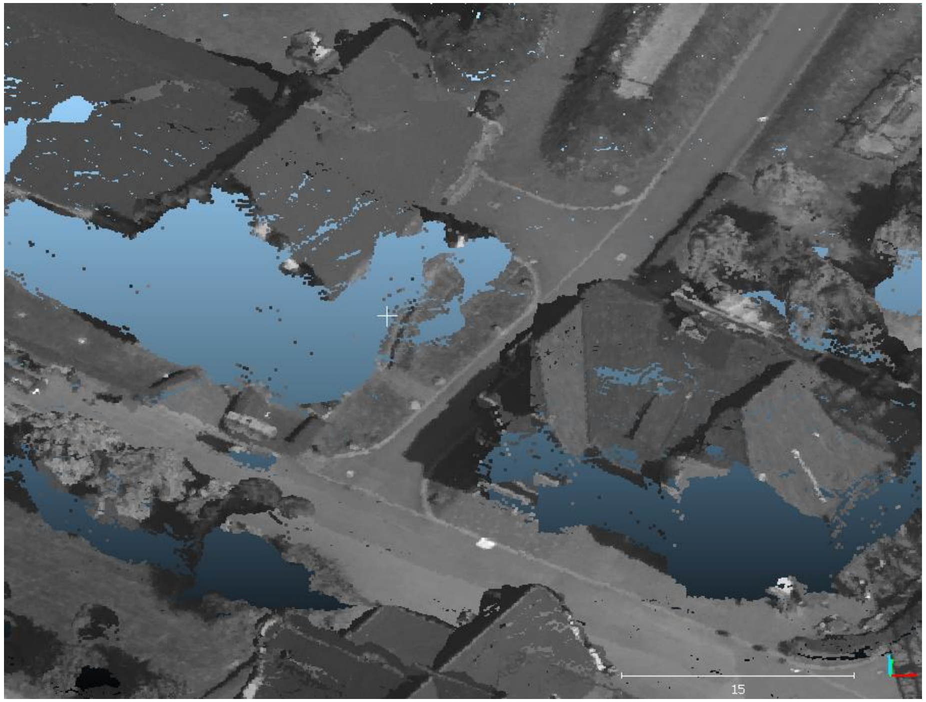
Combined matching with nadir and oblique images

unfiltered point clouds

Combined matching of nadir and oblique images

Aerial and oblique images (benchmark dataset Zeche Zollern)

Matching with nadir images only



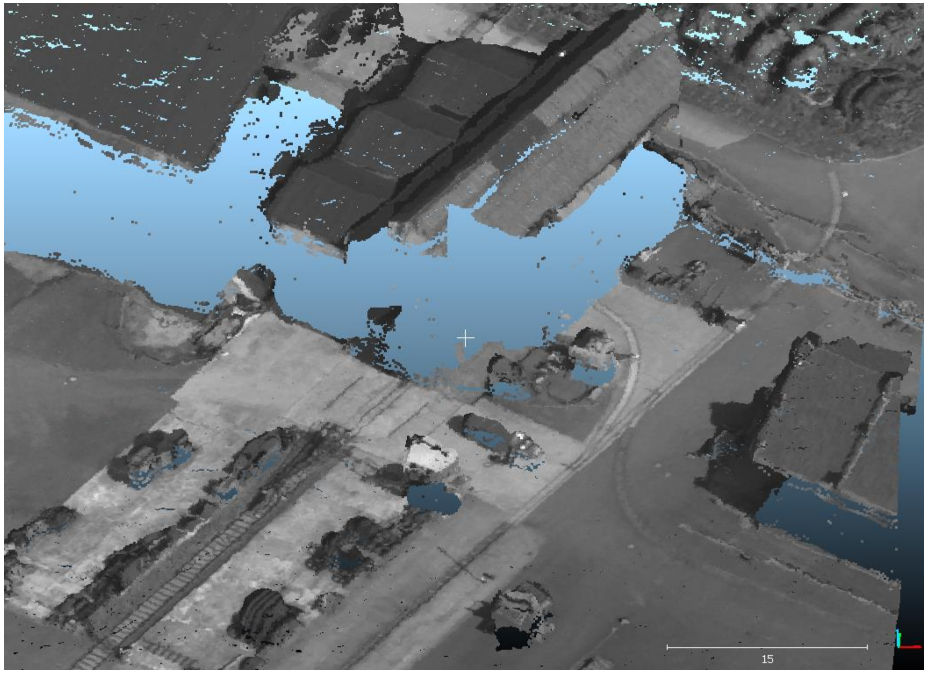
Combined matching with nadir and oblique images

unfiltered point clouds

Combined matching of nadir and oblique images

Aerial and oblique images:

Matching with nadir images only

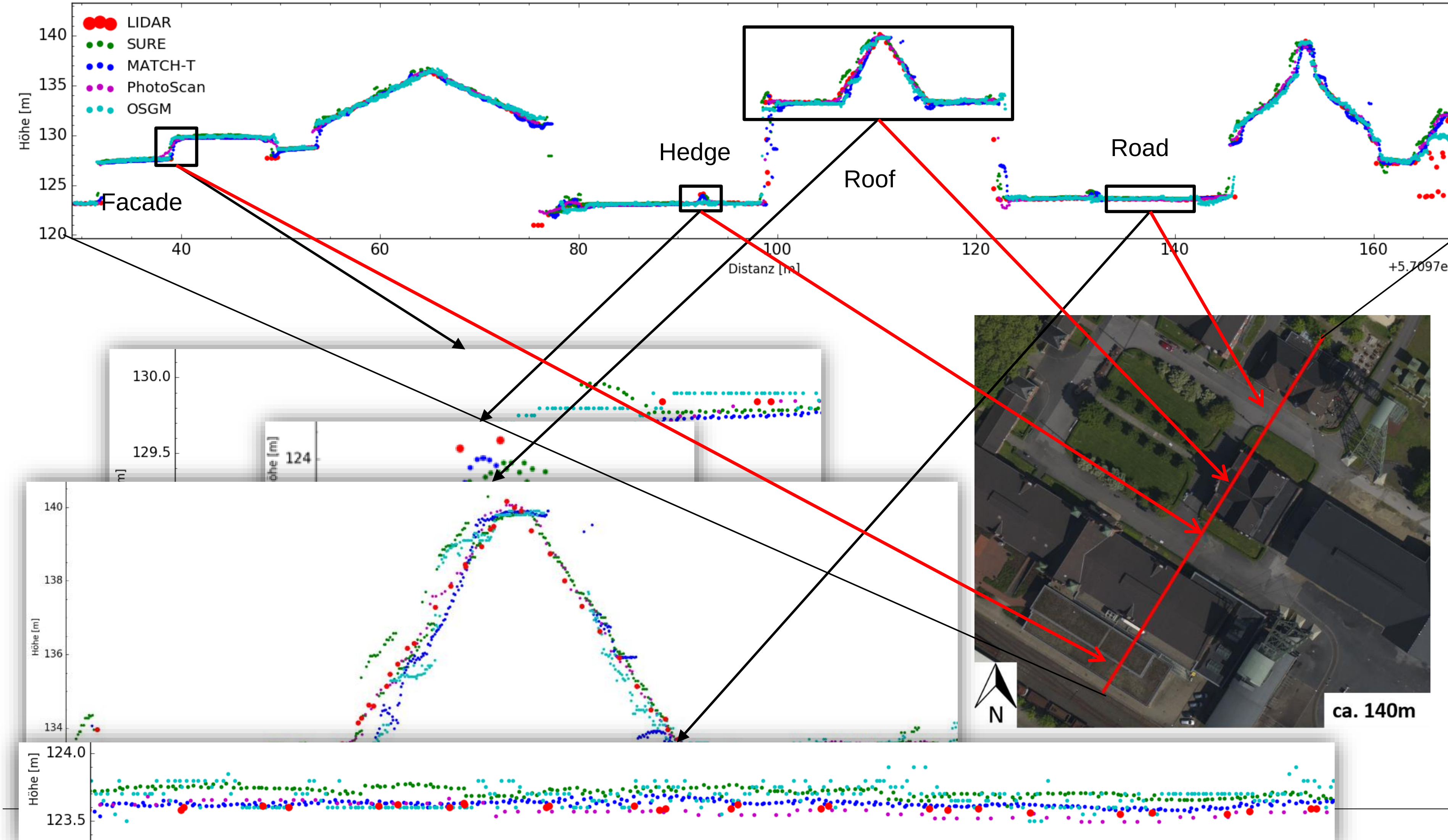


Combined matching with nadir and oblique images

unfiltered point clouds

Combined matching of nadir and oblique images

Comparison with different software packages



IAPG Institute for Applied Photogrammetry and Geoinformatics
JADE HOCHSCHULE Wilhelmshaven Oldenburg Elsfleth

Combined matching of nadir and oblique images

Comparison SURE vs. OSGM

Subset of 12 images









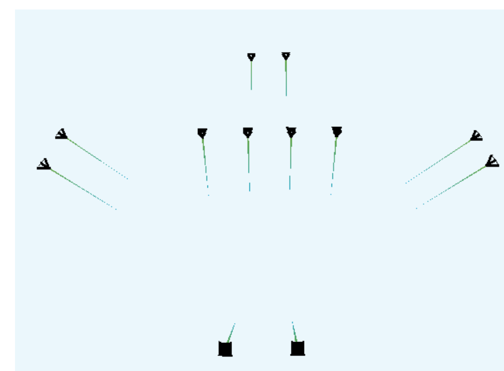

```
PS C:\Users\3D Station\ownCloud\_osgm\bilder> cd "H:\SURE\images"
PS H:\SURE\images> ls


    Verzeichnis: H:\SURE\images


Mode                LastWriteTime     Length Name
----                -------------     ------ ----
-a---        24.06.2014     15:51  300838368 001_008_145000298.tif
-a---        24.06.2014     15:51  300837688 001_009_145000297.tif
-a---        24.06.2014     16:29  300837388 005_004_147000362.tif
-a---        10.06.2014     18:35  300818264 005_013_148000353.tif
-a---        10.06.2014     18:44  300818264 006_004_148000369.tif
-a---        24.06.2014     16:30  300839064 006_013_147000378.tif
-a---        24.06.2014     16:13  300838284 010_008_145000493.tif
-a---        24.06.2014     16:13  300837692 010_009_145000494.tif
-a---        10.06.2014     13:35  300818265 006_007_163000372.tif
-a---        10.06.2014     13:36  300818265 006_008_163000373.tif
-a---        10.06.2014     13:36  300818265 006_009_163000374.tif
-a---        10.06.2014     13:37  300818265 006_010_163000375.tif


PS H:\SURE\images>
```



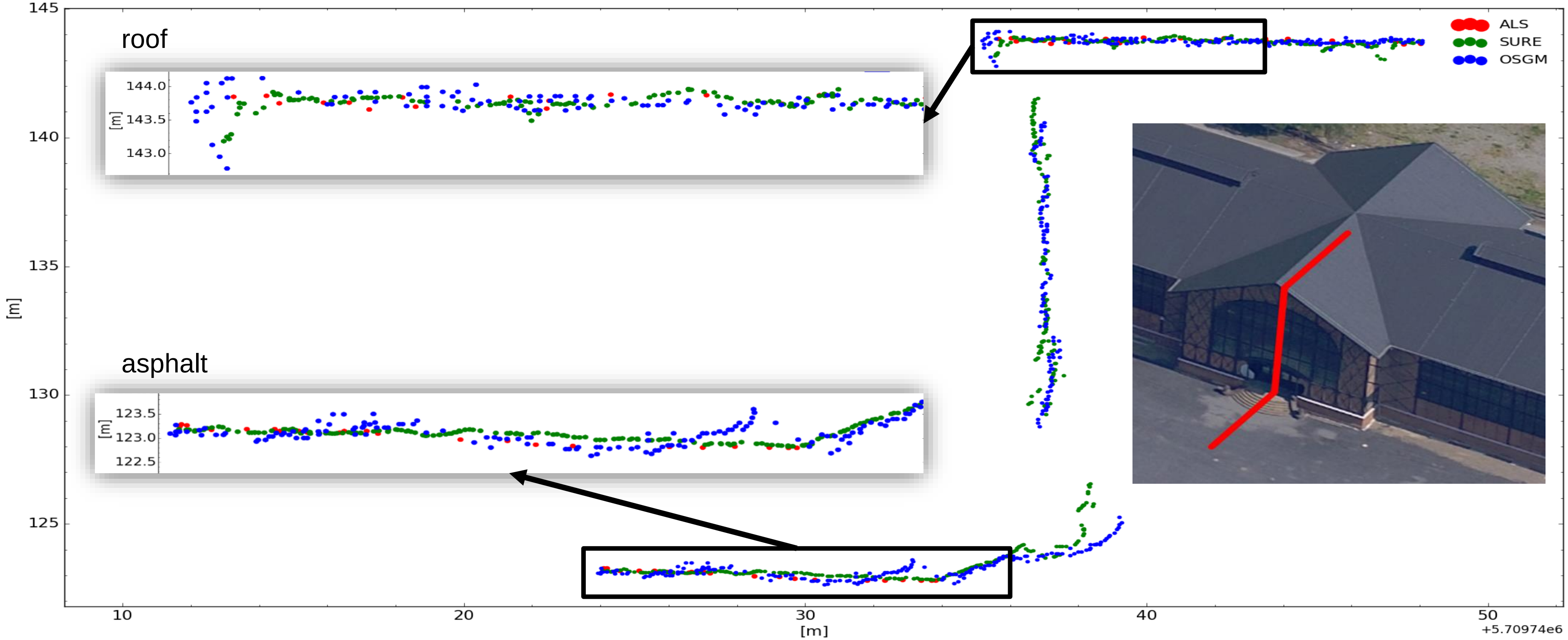


IAPG Institute for Applied Photogrammetry and Geoinformatics

JADE HOCHSCHULE Wilhelmshaven Oldenburg Elsfleth

Combined matching of nadir and oblique images

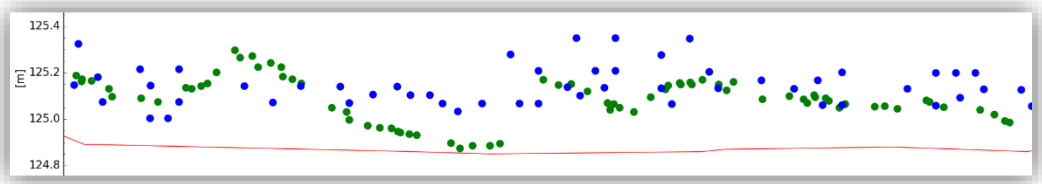
Comparison SURE vs. OSGM

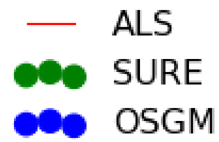


Combined matching of nadir and oblique images

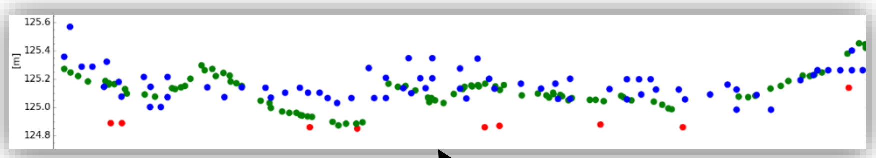
Comparison SURE vs. OSGM

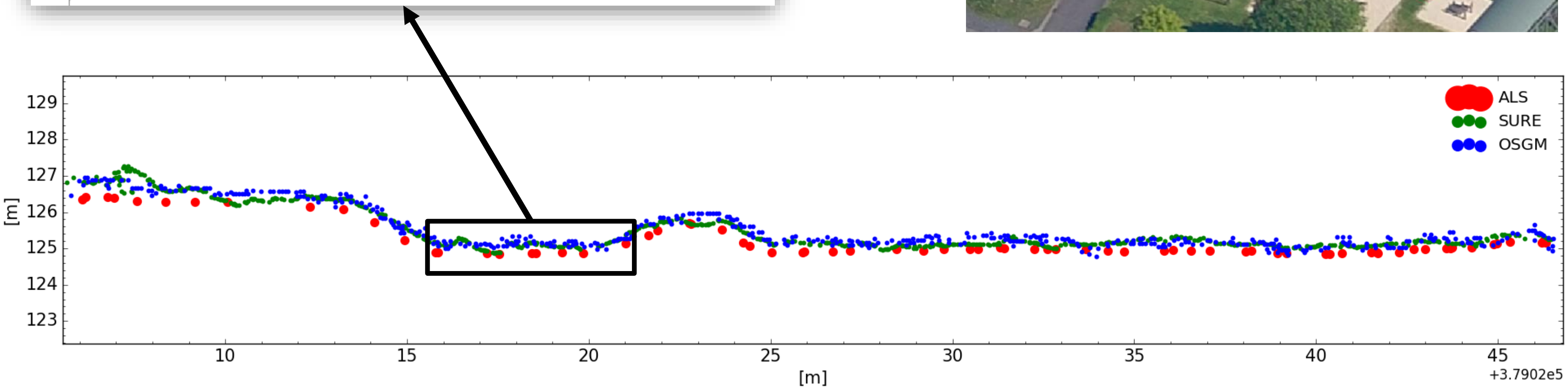
grassland





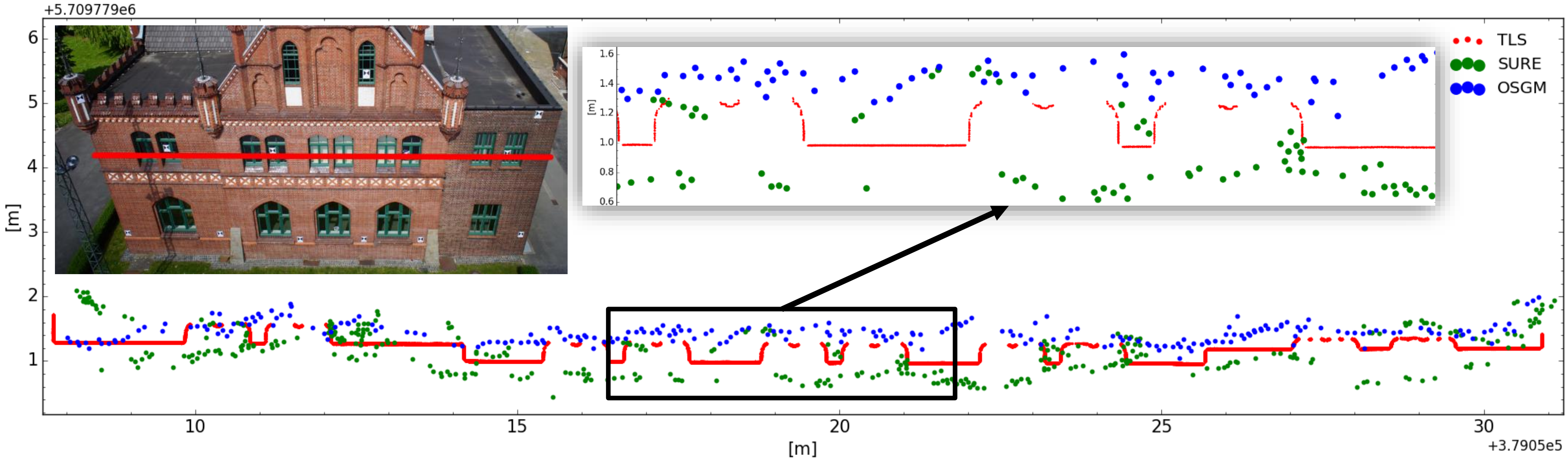
road





Combined matching of nadir and oblique images

Comparison SURE vs. OSGM



without UAV imagery

Summary and outlook

Advantages of the proposed approach

+ instead of pairwise matching, multiple images can be used simultaneously
+ benefits of SGM are maintained
+ (true-)orthoimage is generated as a by-product of the matching procedure
+ image rectification is not necessary any more
+ first results on different datasets are very promising (without any point cloud filtering in post-processing)

Outlook

+ combined processing of aerial and UAV images
+ integration of existing 3D object data into matching procedure
+ adaptive voxel resolution
+ optimized implementation

Thank you for your attention!

The research has been supported by the Lower Saxony program
for Research Professors, 2013-2018.

VolkswagenStiftung