Segmentation of point clouds

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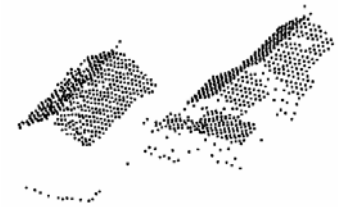
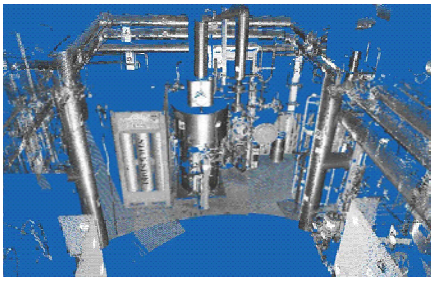
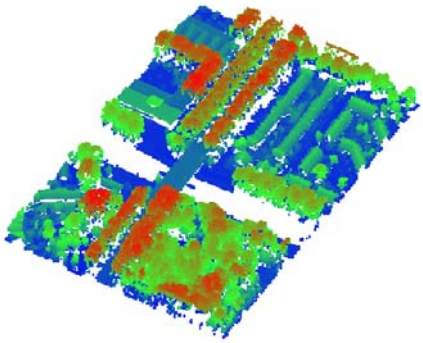
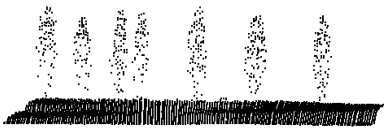
Extraction of information from point clouds







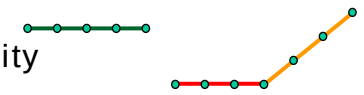


Segmentation algorithms

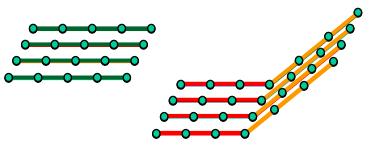
- Extraction of smooth surfaces
  - Scan line segmentation
  - Surface growing
  - Surface merging
  - Voxel space analysis
- Extraction of parameterised surfaces
  - Planes
  - Cylinders
  - Spheres

Scan line segmentation

- Independent segmentation of each scan line based on
  - Proximity
  - Curve fit / height continuity
  - Normal vector direction

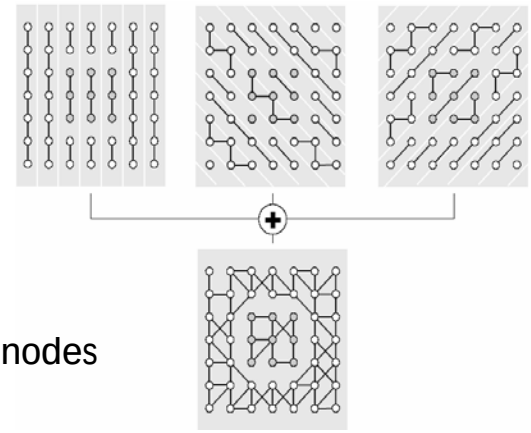


- Merging of scan line segments across neighbouring scan lines



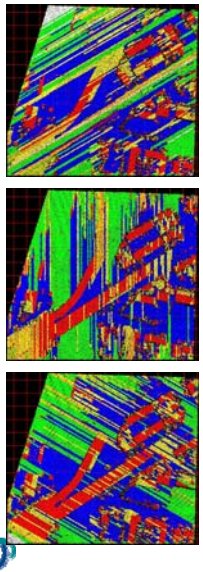
Using multiple scan line segmentations

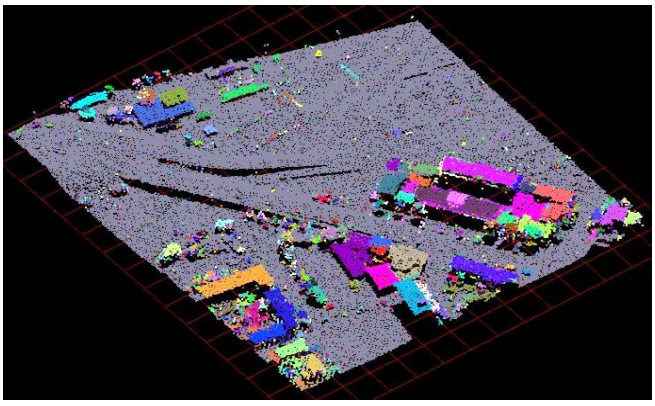
- Independent segmentation for multiple scan line orientations



- Join segments with common nodes

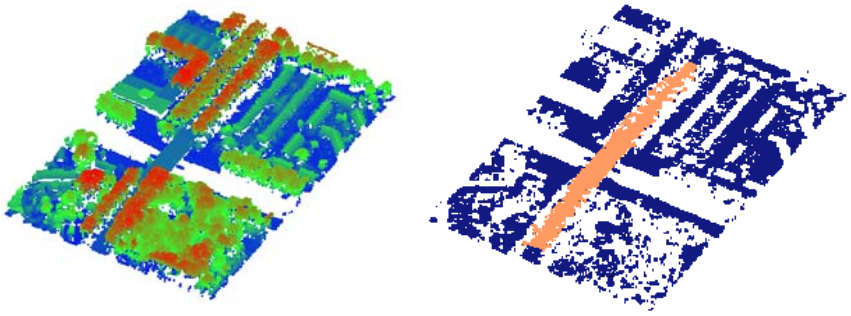
Using multiple scan line segmentations (II)





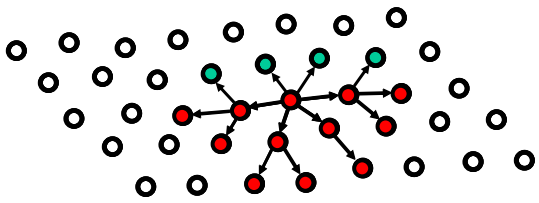
Example scan line segmentation

- Extraction of large smooth surface
- Decomposition into terrain and bridge



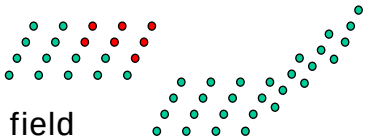
Surface growing

- Select arbitrary point
- Select a few neighbouring points
- If plane fitting results in low residuals use these points as seed surface
- Try to expand this planar surface with further neighbouring points

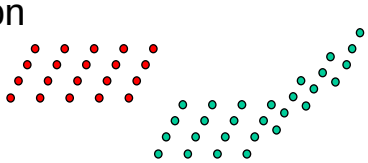


Surface growing (II)

- Determination of seeds – locally smooth patches
  based on
  - Local surface fitting
  - Local smooth normal vector field
  - Detected planes

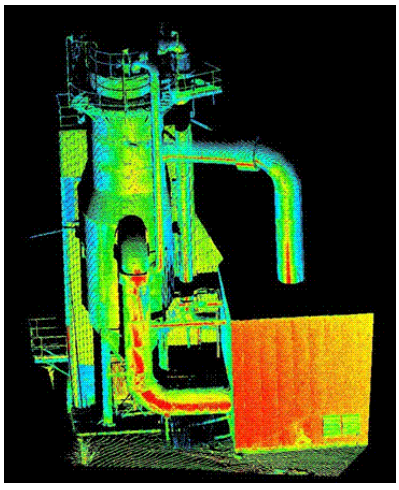


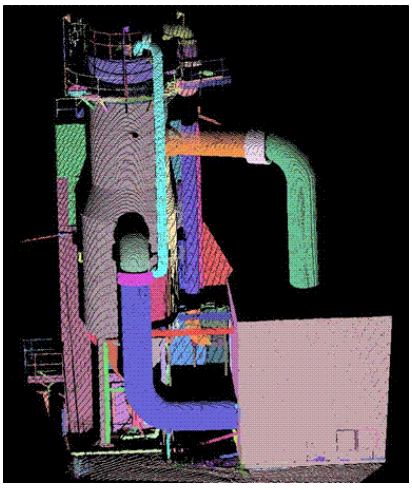
- Growing of surfaces based on
  - Proximity (TIN, kNN)
  - Surface fit / height continuity
  - Normal vector direction



Example surface growing

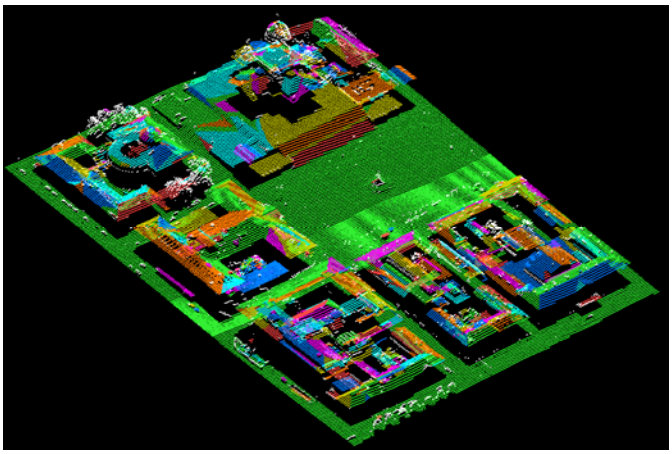
- Segmentation of an industrial installation





Example surface growing (II)

- Smooth surfaces in the EuroSDR test data on building extraction

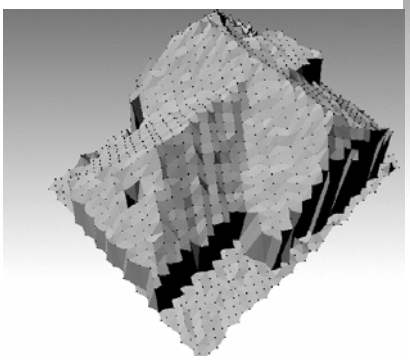


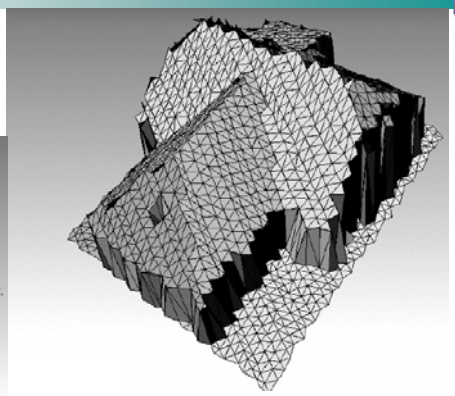
Surface merging

- Split point cloud into triangles (Delaunay triangulation)
- Iterative merging of surfaces based on
  - Adjacency
  - Surface to surface distance

Example surface merging

- Roof surfaces





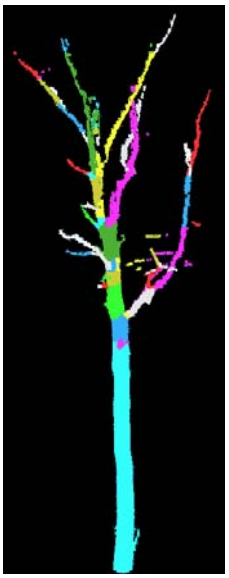
- Problems with multi-layered surfaces

Voxel space analysis

- Rasterise data into voxels
- Connected component analysis
- 3D image processing
  - Mathematical morphology
  - Skeletonising

Example voxel space analysis

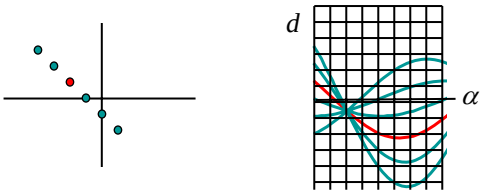
- Tree segmentation



Extraction of parameterised surfaces

Hough transform

Detection of straight lines in 2D space $X\cos\alpha + Y\sin\alpha = d$



Generalised Hough transforms for

- Planes
- Cylinders
- Circles

Detection of planes

Duality between points and planes in 3D space

- Plane in object space – point in Hough space

$$Z = s_x X + s_y Y + d$$

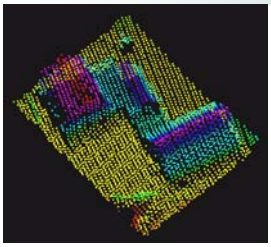
- Point in object space – plane in Hough space

$$Z = s_x X + s_y Y + d$$

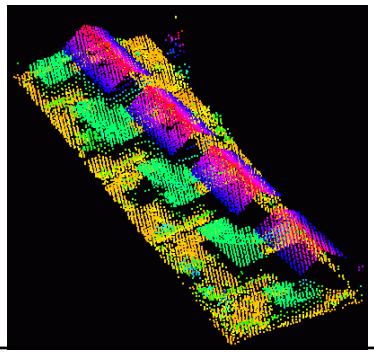
Two cases:

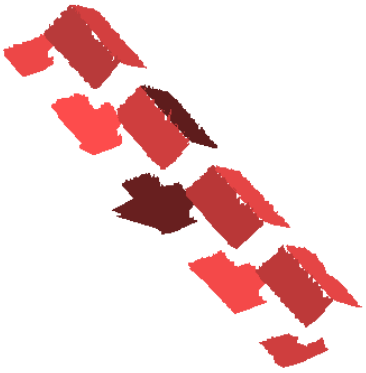
1. *Without normal vectors:*
   Point X, Y, Z corresponds to plane in Hough space
2. *With normal vectors:*
   Point X, Y, Z with normal vector defines a plane in object space. This plane corresponds to a point in Hough space.

Example plane detection



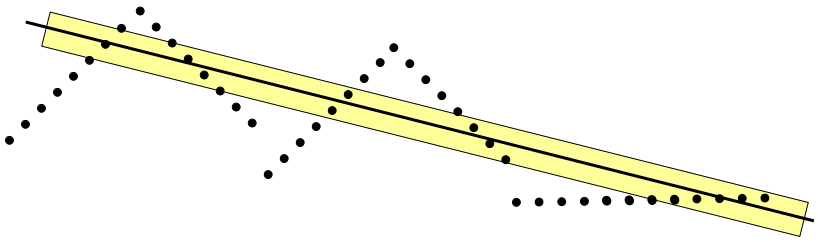
Roof surfaces





Detection of planes (II)

Problems with a global 3D Hough transform



Detection of cylinders

Cylinder described by five parameters

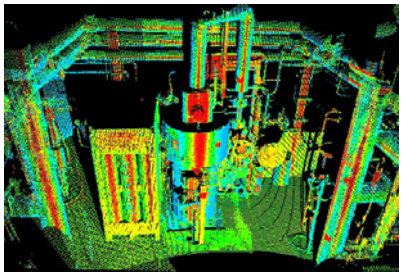
Two step Hough transform

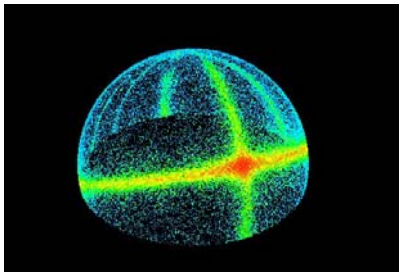
- Detection of orientation (2 parameters)
- Detection of position and radius (3 parameters)

Detection of cylinders (II)

Step 1: Detection of orientation

- Projection of normal vectors onto Gaussian sphere
- Detection of great circles on Gaussian sphere





Detection of cylinders (III)

Step 2: Detection of cylinder position and radius

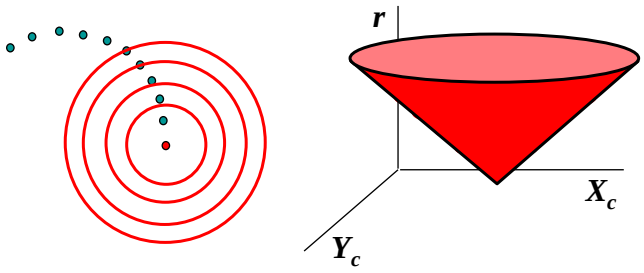
- Projection of points onto plane perpendicular to cylinder axis
- Detection of circle in 2D space, Hough space X_c, Y_c, r

Two cases:

1. *Without normal vectors*
2. *With normal vectors*

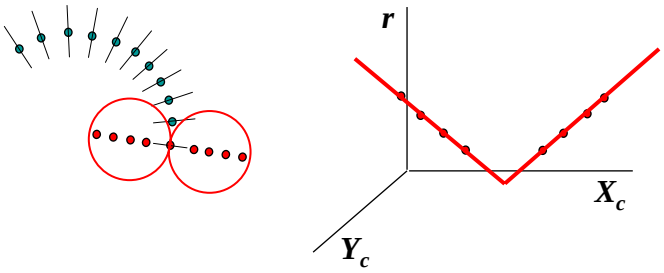
Detection of cylinders (IV)

1. *Without normal vectors:*
   Point X, Y corresponds to cone in parameter space

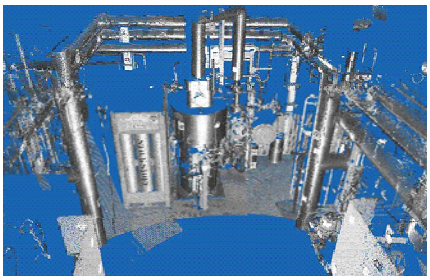


Detection of cylinders (IV)

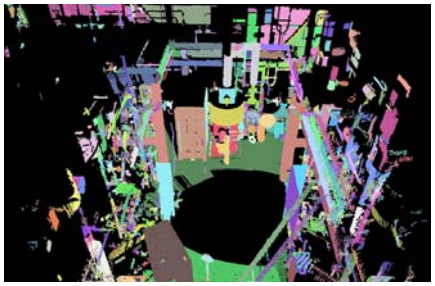
2. *With normal vectors:*
   Point X, Y corresponds to two lines in parameter space

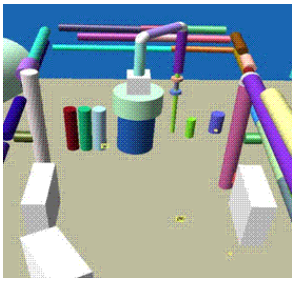


Example cylinder detection



- Segmentation into smooth connected components
- Cylinder detection for each component





Detection of spheres

Four dimensional parameter space X_c, Y_c, Z_c, r

Two cases:

1. *Without normal vectors:*
   Point X, Y, Z corresponds to sphere for each r

2. *With normal vectors:*
   Point X, Y, Z corresponds to two lines in 4D space

Summary

- A variety of algorithms is available for segmentation of point clouds.
- Smooth surfaces and parameterised surfaces can often be extracted reliably.
- The choice for the best method depends on the data quality and the application.

Building (change) detection in airborne laser scanning data

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3D city modelling

- Urban planning
- Planning for mobile communication
- Disaster management
- Noise and air pollution analysis
- Real estate market
- Cultural heritage
- Safety

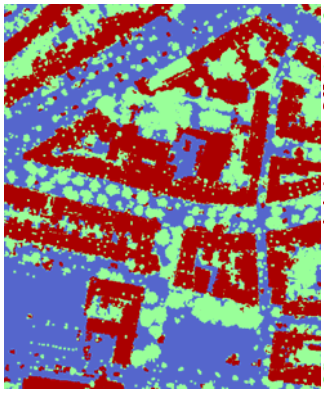
Building detection

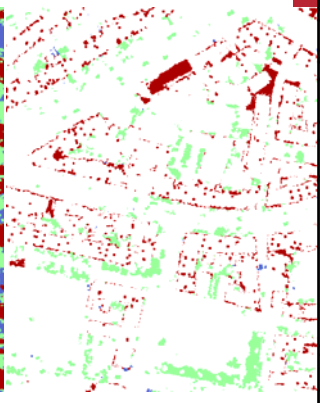
- Removal of terrain points from point cloud
- Segmentation of remaining point cloud into continuous surfaces
- Derivation of segment properties
- Classification of segments as building or vegetation

Classification of segments

Attributes

- roughness
- colour
- size

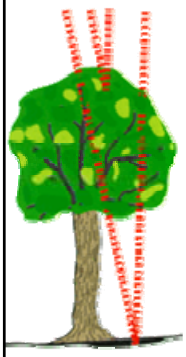


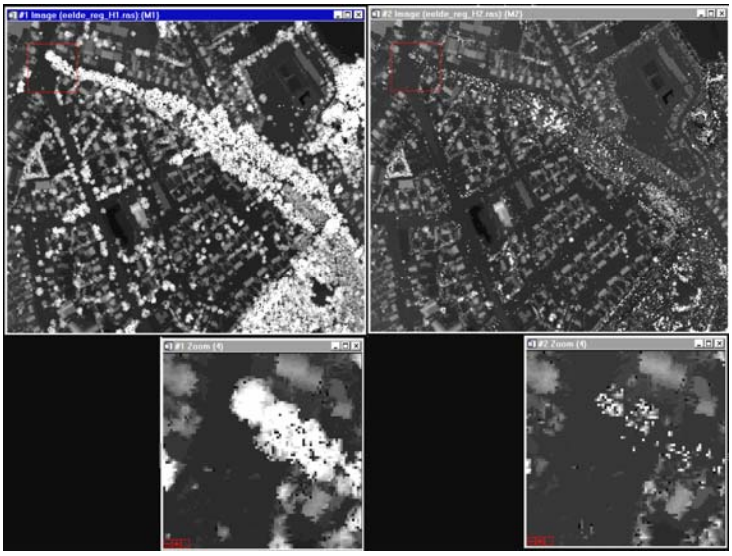


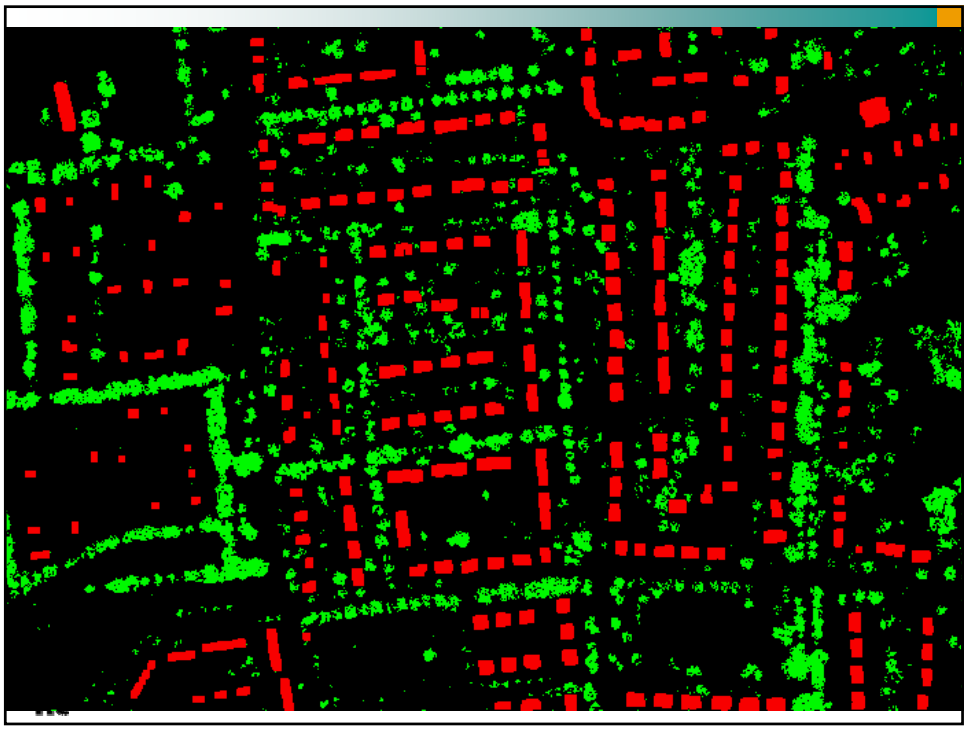
Accuracy

- initially 90%
- low vegetation
- wall points
- after post-processing 95%

First and last pulse differences

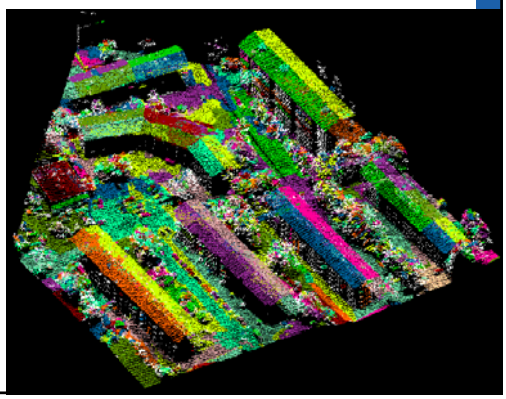






Building detection using point cloud segmentation

- Segmentation of a point cloud by surface growing
- Remove points in small segments
- Remaining segments are
  - Pieces of terrain
  - Roof faces
- Classification by examining height differences between segments



Change detection after disasters

Rapid acquisition of 3D data after disaster

- Earthquakes
- Explosions (industry accidents, terrorist attacks)
- Landslides

Change detection with laser scanning

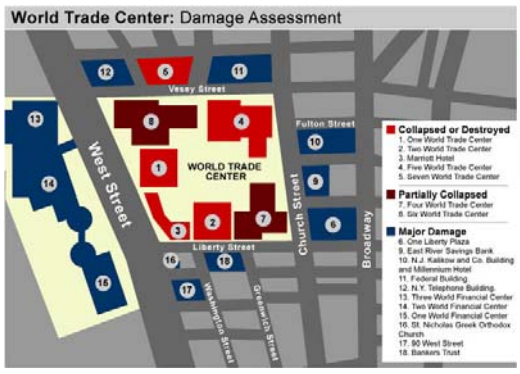
Laser scanning – Accurate surface models
Construction activities – Surface model changes

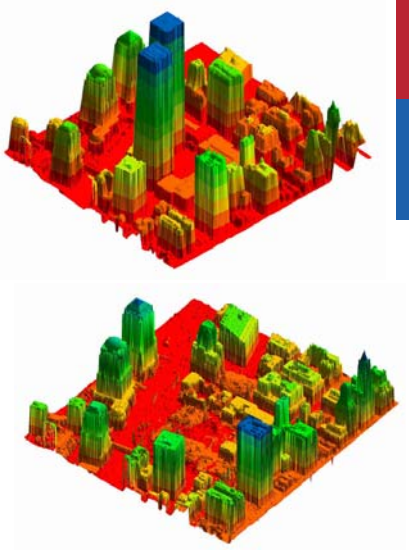
Two approaches

- Multi epoch data (difference DSM)
- Single epoch data and an outdated map
  - Segmentation and classification of laser data
  - Formalisation of mapping rules (selection, generalisation)
  - Change detection

Multi-epoch laser scanning data

- World Trace Center





Change detection pilot

Data

ALTM1225 scanner

1.4 m point spacing

Results

- All buildings detected
- Some vegetation attached

Mapping rules

Generalisation

- Protrusions and intrusions up to 3x3 m are omitted

Selection

- Buildings larger than 3x3 m
- Only buildings visible from the road

Change detection

- Demolished buildings
- Old buildings (map)
- New buildings
- Old buildings (laser)

Results

- All new buildings detected
- All demolished buildings detected
- Some sheds detected

Change detection (II)

- Changed buildings (map)
- Old buildings (laser)

Detected “changes”

- Real changes
- Trees attached to buildings
- Mapping errors
  - Rigorous generalisation
  - Interpretation error

Interpretation error

- Map data
- Laser data

Conclusions change detection pilot

- Point spacing of 1.4 m not high enough for detecting small changes
- Additional usage of imagery could improve classification
- Implementing mapping rules may be difficult
- Change detection with laser data valuable as quality control tool

Extraction of 3D building models from airborne laser scanning data

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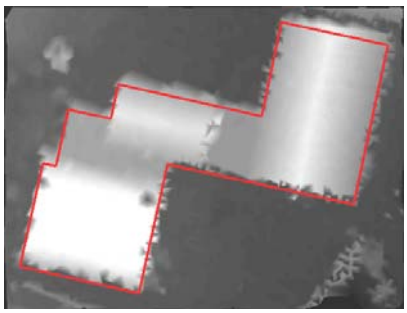
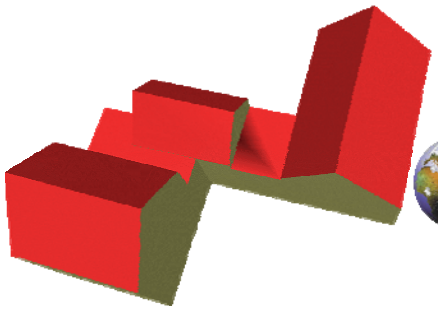
Building model reconstruction



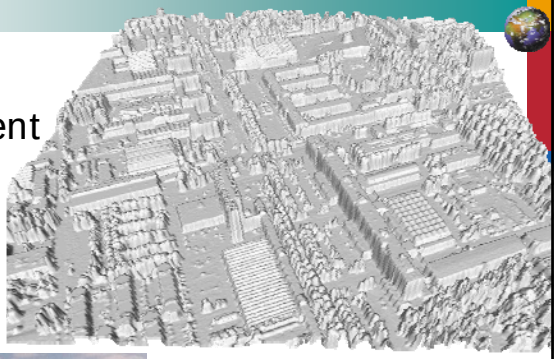


Model, data and map driven approaches

3D city modelling

Modelling required for

- accuracy improvement
- data reduction



Christo's wrapped Reichstag

Building reconstruction from laser data

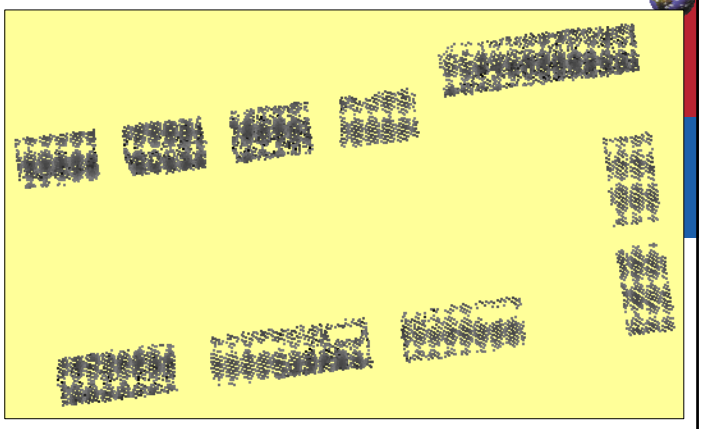
- Reliable 3D coordinates
- High point density required
- Assumptions on building shapes needed
- Usage of building ground plans

Case studies

- Model based approach using moments
- Data driven approach
- Map guided reconstruction
  - Data driven
  - Model driven

Model based approach using invariant moments

Invariance of
- shift
- scale
- rotation

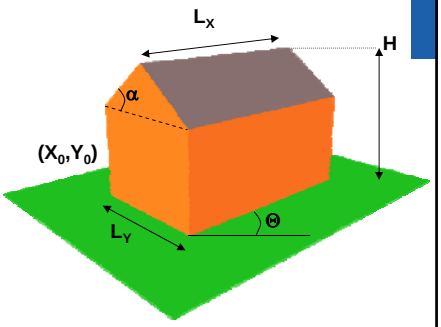


Irregularly distributed point data

$$M_{ij} = \sum_{P=P_1}^{P_n} {X_P}^i \cdot {Y_P}^j \cdot H_P$$

Building reconstruction using moments

- 7 building parameters for gable roof
- 1st and 2nd order invariant moments as a function of building parameters
- solve equation system (express building parameters as function of moments)



Building reconstruction using moments

- segmented point cloud $(X,Y,H)_l$
- binarized moments m_{ij} (with H = 1) for ground plan, position and orientation
- height-weighted moments M_{ij} for roof model model

Position: $X_0 = \frac{m_{10}}{m_{00}}, \; Y_0 = \frac{m_{01}}{m_{00}}$

Shift invariance: $\overline{M}_{ij} = \sum_{P=P_1}^{P_n} (X_P - \overline{X})^i \cdot (Y_P - \overline{Y})^j \cdot H_P$

Orientation: $\Theta = \frac{1}{2} \cdot \arctan \frac{2\overline{m}_{11}}{\overline{m}_{20} - \overline{m}_{02}}$

Rotation invariance:

$$M'_{pq} = \sum_{r=0}^{p} \sum_{s=0}^{q} (-1)^{q-s} \cdot \binom{p}{r} \cdot \binom{q}{s} \cdot \Psi \cdot \widetilde{M}_{(p+q-r-s)(r+s)}$$

with $\Psi = (\cos\Theta)^{p-r+s} \cdot (\sin\Theta)^{q+r-s}$

Length: $L_X = \sqrt{\frac{12 \cdot m'_{20}}{m'_{00}}}$

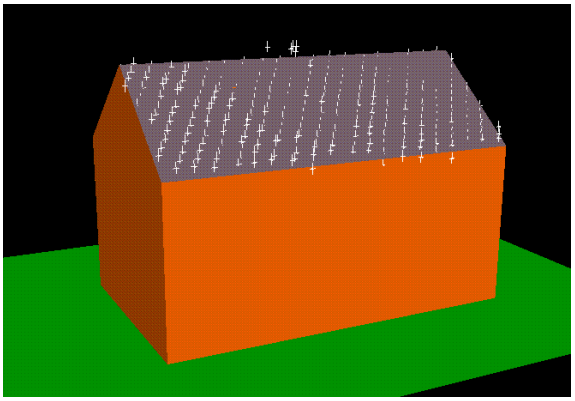
Width: $L_Y = \sqrt{\frac{12 \cdot m'_{02}}{m'_{00}}}$

Roof inclination: $\alpha = \arctan\left(8 \cdot \frac{M'_{00} \cdot \left(\frac{M'_{20}/M'_{02}}{m'_{20}/m'_{02}} - 1\right)}{\frac{M'_{20}/M'_{02}}{m'_{20}/m'_{02}} \cdot L_Y}\right)$

Height: $H = M'_{00} + \frac{L_Y}{2} \cdot \tan\alpha$

Data-driven model refinement

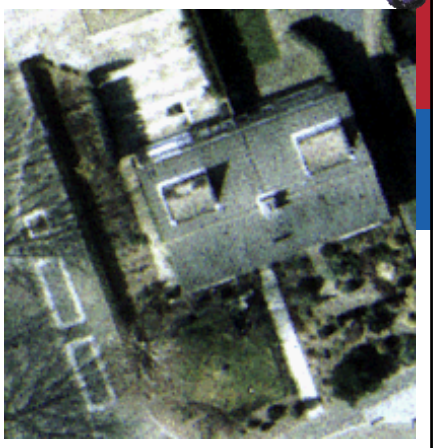
- Detection of regions with outliers
- Generation of refining hypotheses

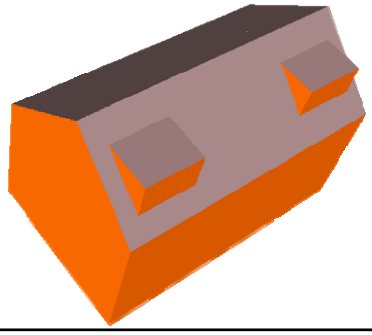


Modelling of dorms - example

Potential:

- minimum of 8-10 points per dorm needed
- dorms must be smaller than ~40% of roof surface





Point density

Simulations with reduced point densities

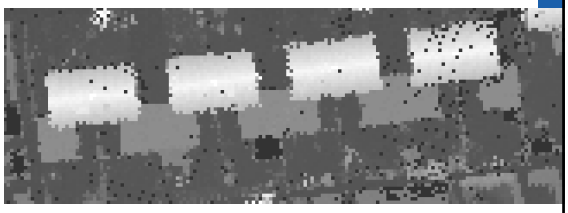
RMS derivations to parameters from high density

pts/m²	centroid		Θ	length	width	height	slope
2.6	0.03	0.01	0.2	0.09	0.03	0.03	0.3
1.3	0.10	0.06	0.4	0.19	0.08	0.04	0.5
0.65	0.23	0.14	1.0	0.28	0.16	0.07	1.5
0.33	0.40	0.20	1.9	0.57	0.20	0.19	3.2
0.17	0.95	0.39	2.9	0.85	0.50	0.41	6.9
0.08	1.32	0.61	6.0	1.13	0.68	0.73	12.1

Data driven approach

Assumptions:

- Roof described by planar faces
- Height jump edges parallel or perpendicular to main building orientation

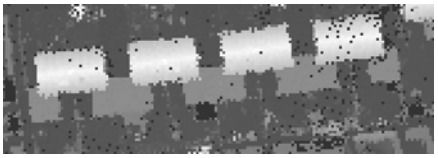


Steps:

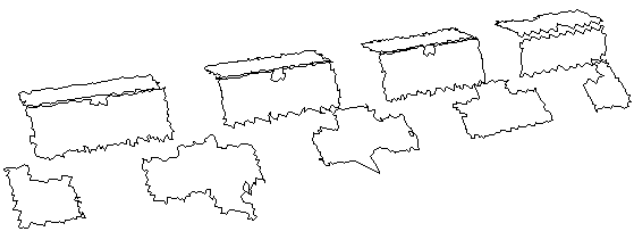
- Plane detection
- Initial face outlining in TIN
- Reconstruction of building outline
- Reconstruction of roof face edges

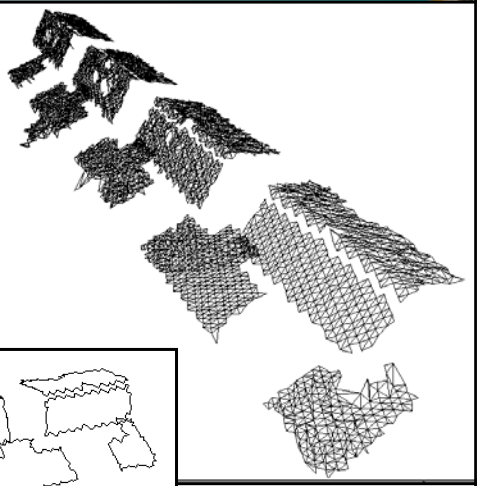
Initial roof faces

Height data



Rough face outlines

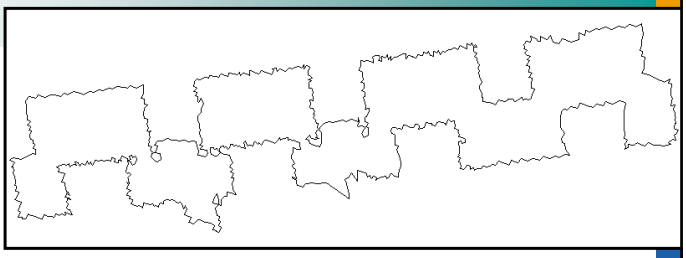




Connected components

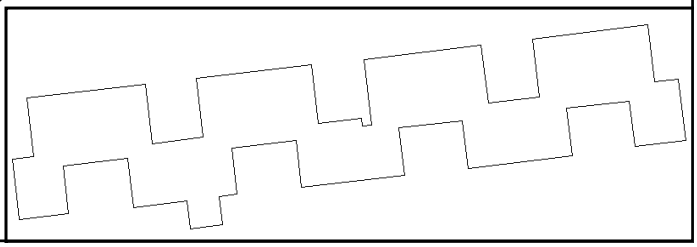
Reconstruction of roof outline

Union of faces



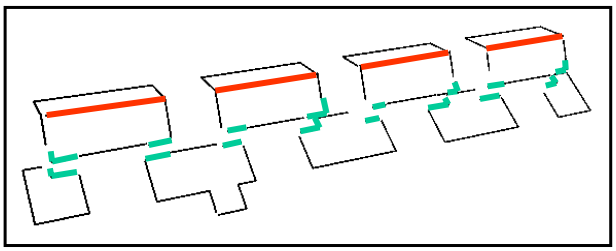
Approximation by straight lines

- main building direction
- minimum edge size
- most points inside building



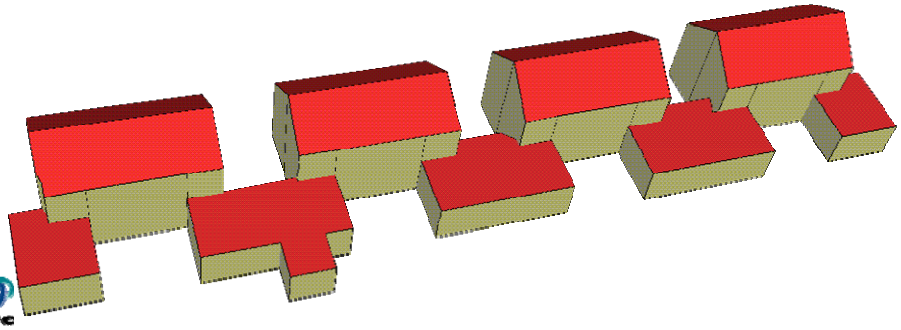
Reconstruction of face edges

- Ridges and valleys
  Intersection of planes of adjacent roof faces
- Roof outline
  Intersection of planes with adjacent walls
- Height jumps inside roof surface
  Straight lines aligned to main building directions



Reconstruction of 3D building

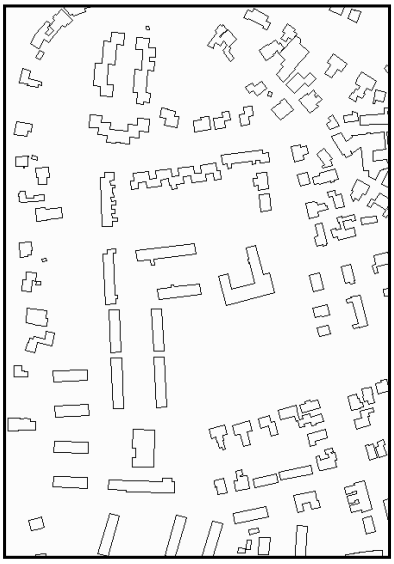
- Merging edges to faces
  - Joining parallel edges
  - Intersection of other edges
- Extraction of terrain height



Using ground plans

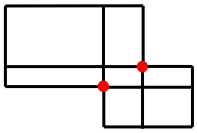
Benefits:

- Easy building location problem
  - Map and data inaccuracy
  - Roof extensions
- Constraints on roof plane orientations
- Indication of building composition

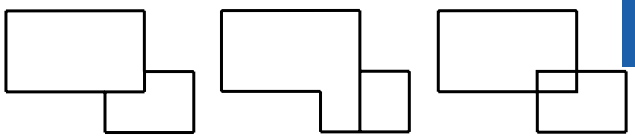


Decomposition of ground plans

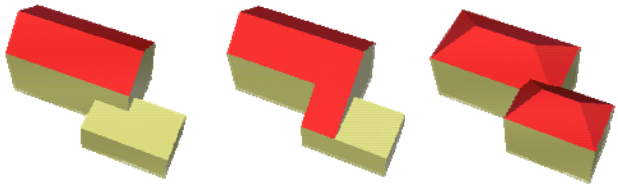
Ground plan



Decompositions

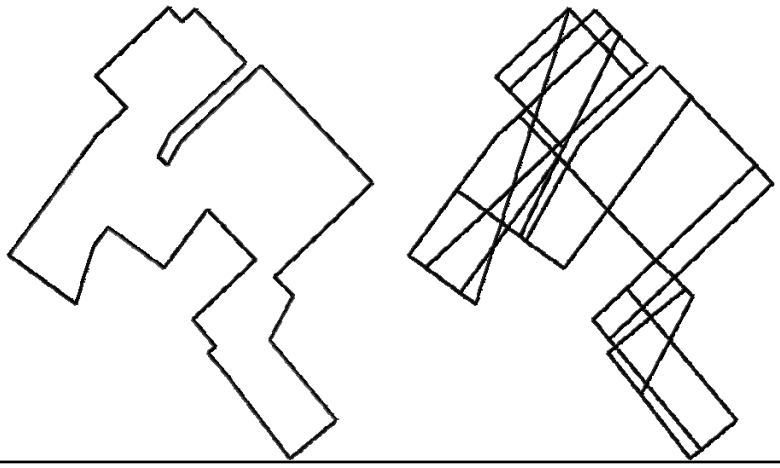


Building primitives on partitions



Decompositions of ground plans (II)

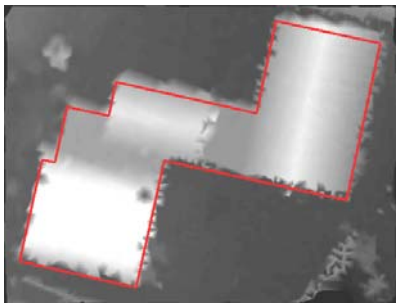
Extending edge segments at concave corners

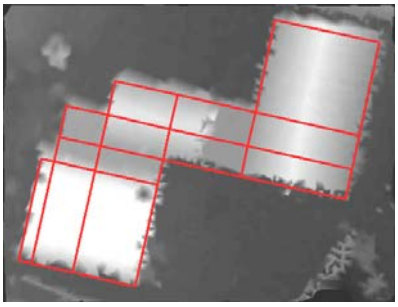


Combining maps with laser data

Processing steps:

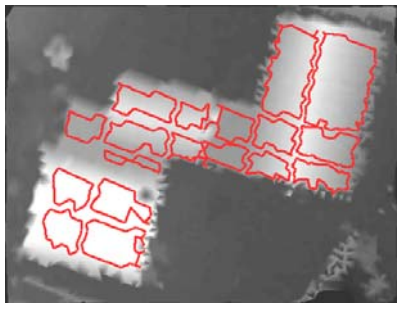
- Detection of planar faces
- Ground plan refinement
- Roof face reconstruction
- Initial 3D model
- Model refinement

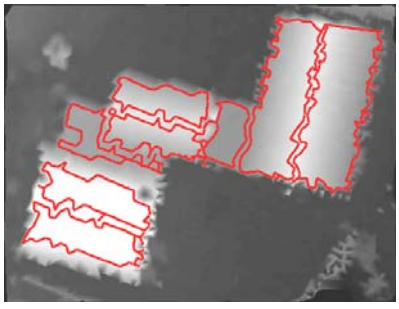




Detection of planar faces (II)

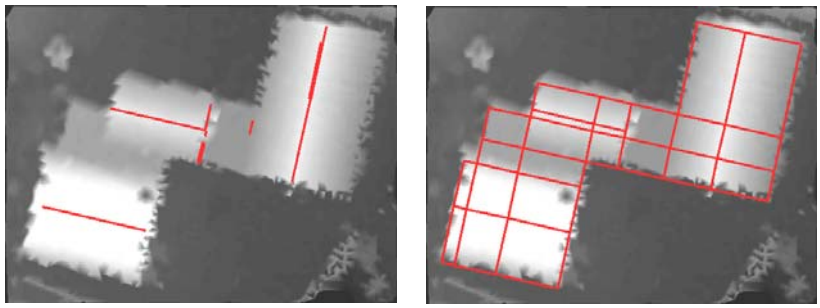
- 3D Hough transform in each ground plan segment
- Growing and merging of initial planar faces





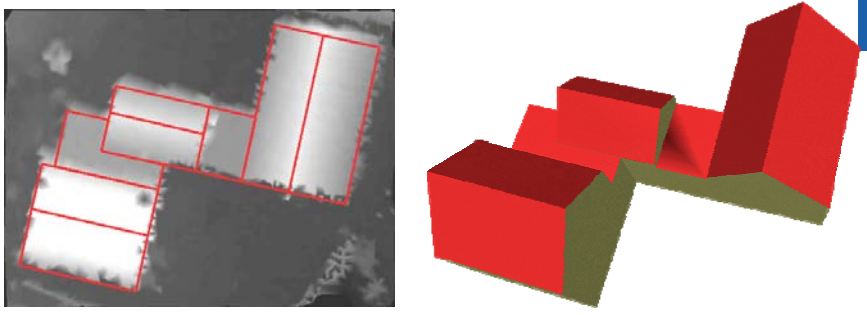
Refinement of ground plan segmentation

- One plane per segment
- Detection of intersection lines
- Detection of height jump lines
  - Constrained to segment orientation
  - Not near segment edge

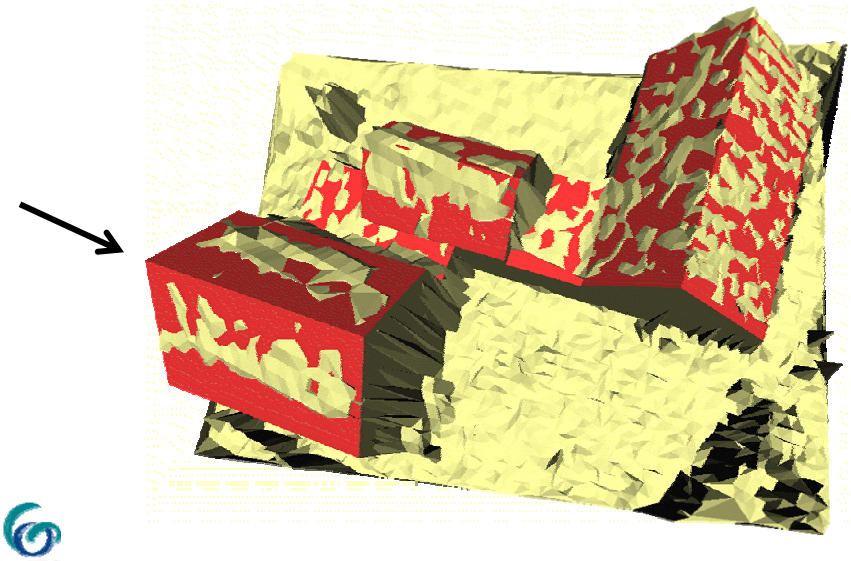


Reconstruction of roof face outlines

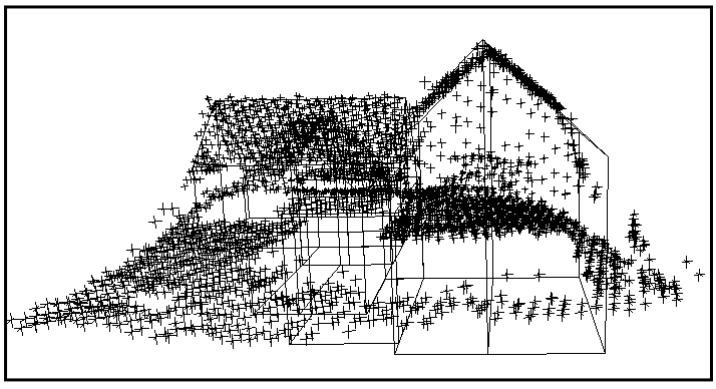
- Best fitting plane per segment
- Merging of segments of same plane



Difference to TIN



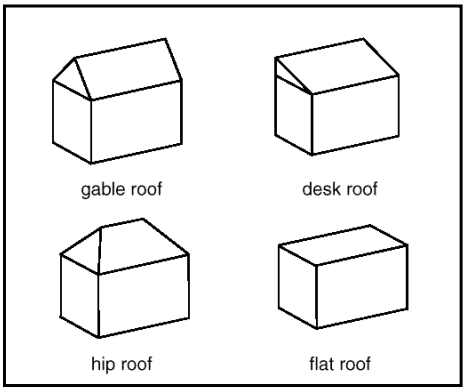
Point cloud view



Steep roof parts near edge with few points

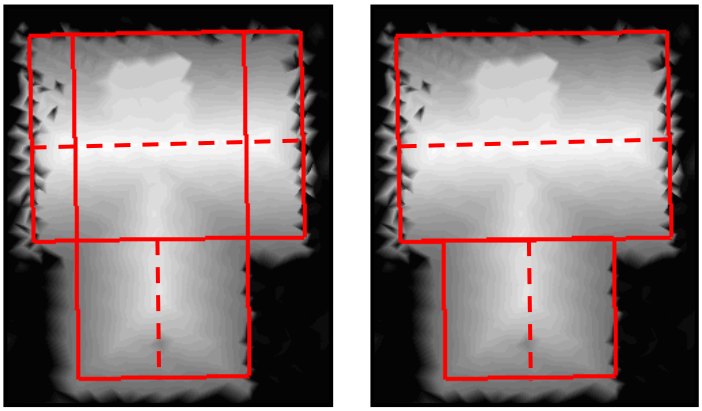
Model library

Best model per segment (flat, slanted, gable)



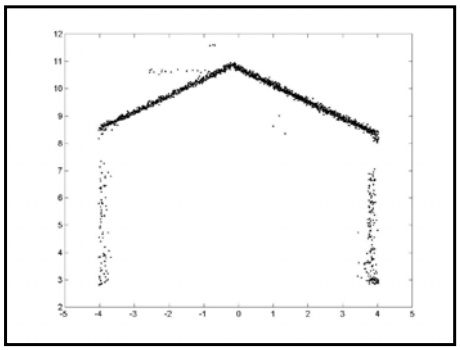
Initial 3D model

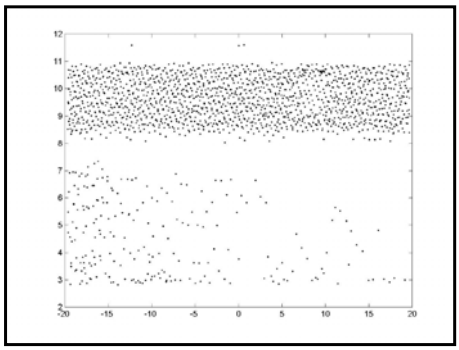
Merge similar models in adjacent segments



Reduction of Hough transform to 2D

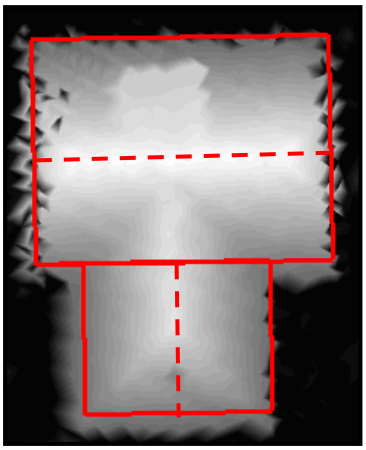
Point clouds projected onto walls

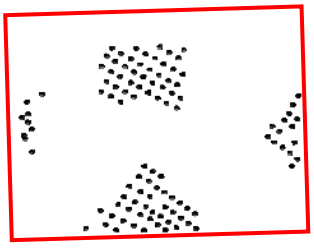


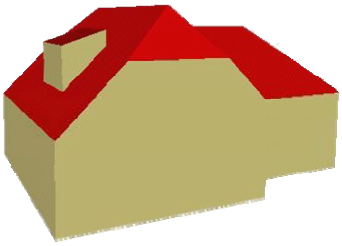


Refinement of 3D model

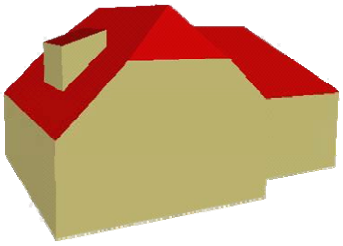
Outlier detection

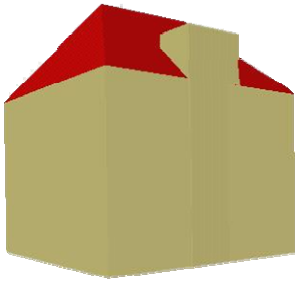


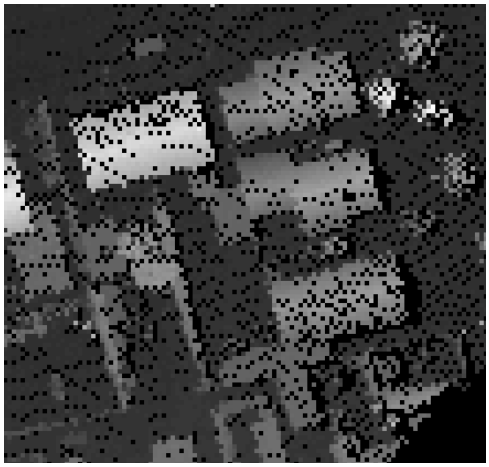


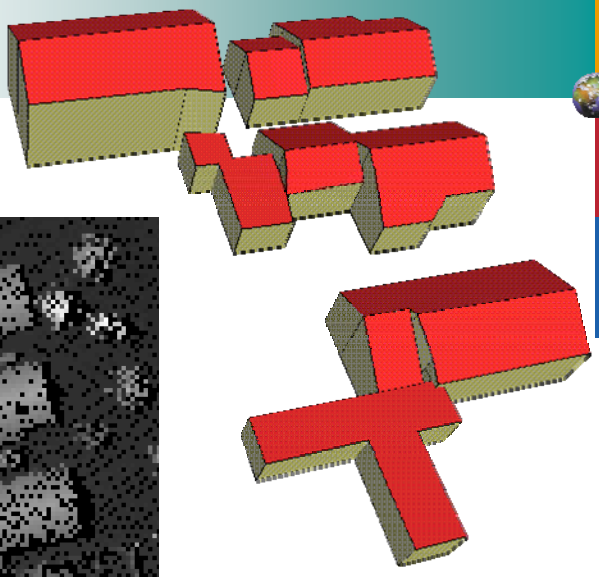


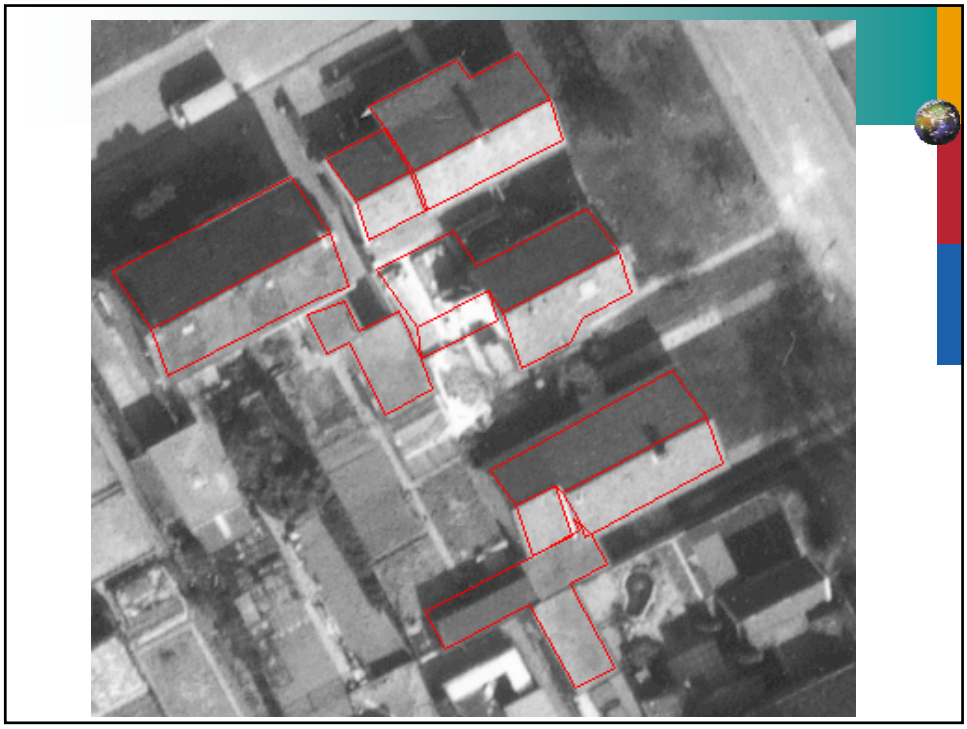
Comparison to photographs



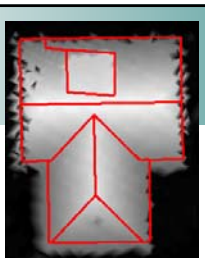


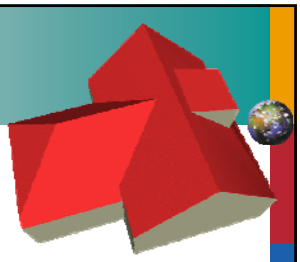


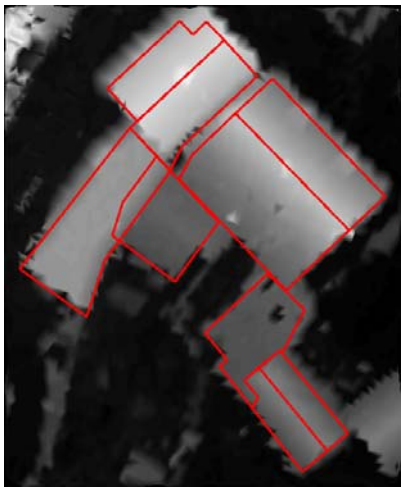


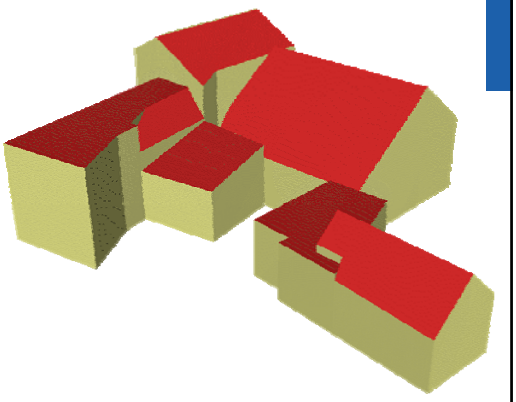


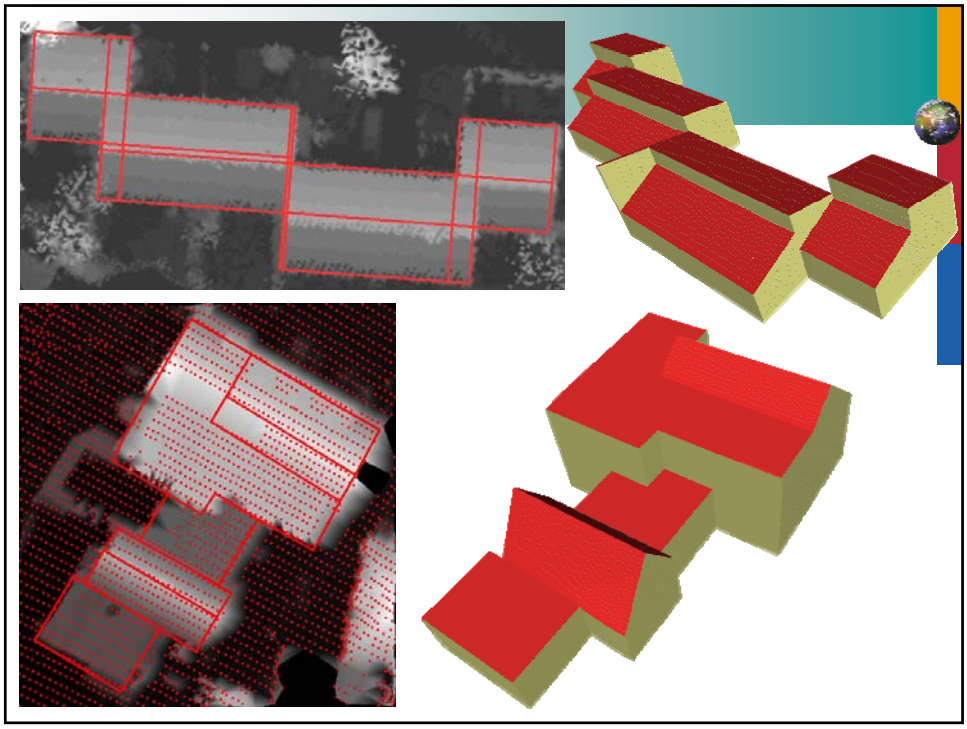
Some more results







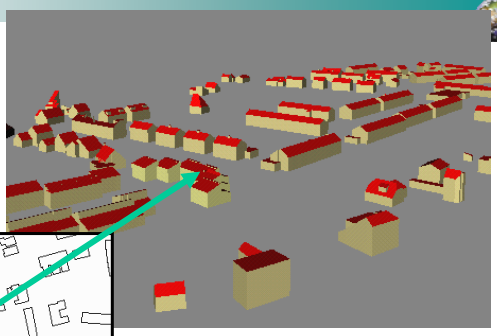




Overall results

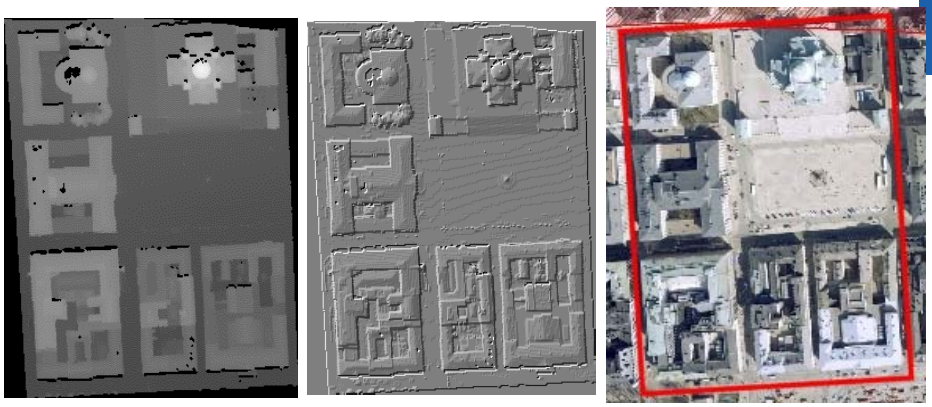
Out of 106 buildings

- 12 not suitable
- 11 failed
- 83 reconstructed



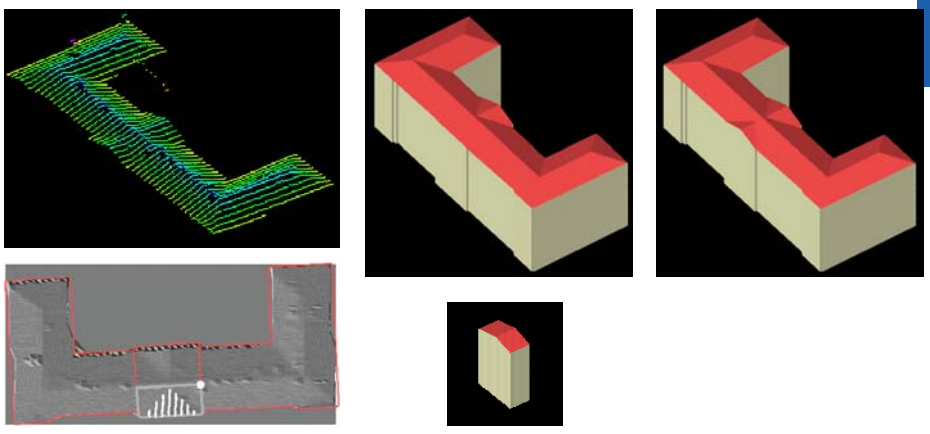
EuroSDR test on building extraction

Comparison of different building extraction techniques using laser scanner data and/or aerial photographs and maps.



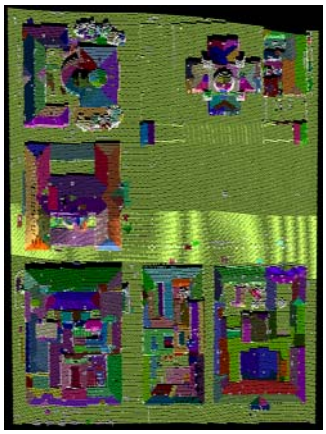
Semi-automatic building reconstruction

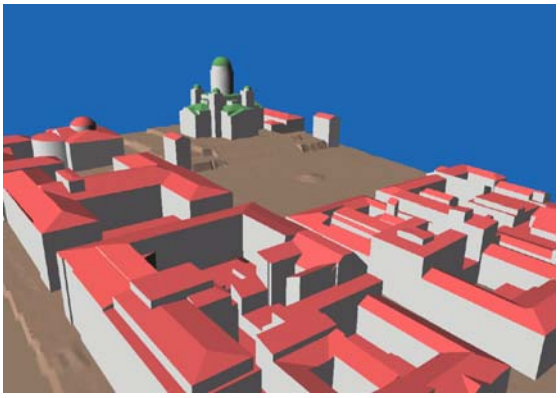
- Automatic reconstruction
- Interactive correction and extension of models



Semi-automatic terrain reconstruction

- Automatic extraction of smooth surfaces
- Interactive selection of terrain patches





Data integration

- Building ground plans
- Laser data
- Terrestrial imagery
- Aerial colour infrared image
- Computer graphics

ifp

Conclusions

- Map provides useful information on building composition.
- Planar faces are detected reliably in laser data.
- Data driven refinement of segmentation needed → high point density required, depending on application.
- Errors in reconstruction from laser data usually related to the number of points in a segment
  - small segment of ground plan
  - bad reflection properties (water on roof, slate roofs)

Outlook

- Sensor characteristics are still improving.
- Laser scanning data and photographs have complementary characteristics.
- Modelling tools for combined measurement processes in laser scanning data and imagery are to be developed.

Modelling roads and trees in urban areas

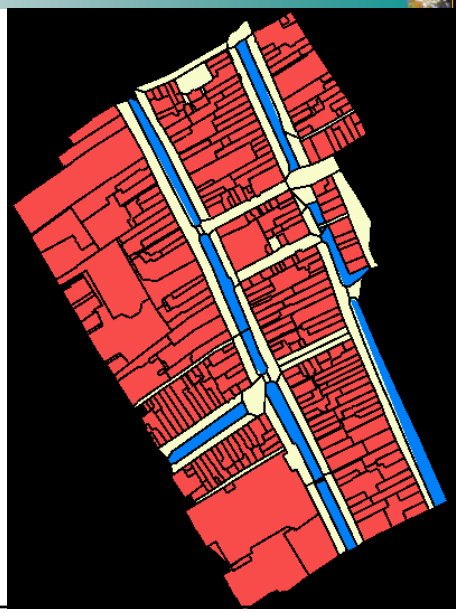
George Vosselman

INTERNATIONAL INSTITUTE FOR GEO-INFORMATION SCIENCE AND EARTH OBSERVATION

Road reconstruction at 1:1000 scale

Cadastral map with

- Roads
- Buildings
- Canals

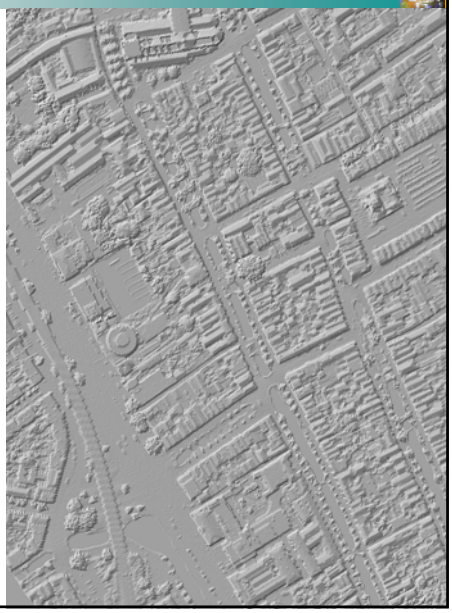


Laser scanning data

TopoSys data

Characteristics:

- Last pulse data
- 2 m point spacing in scan line
- 10 cm point spacing in flight direction

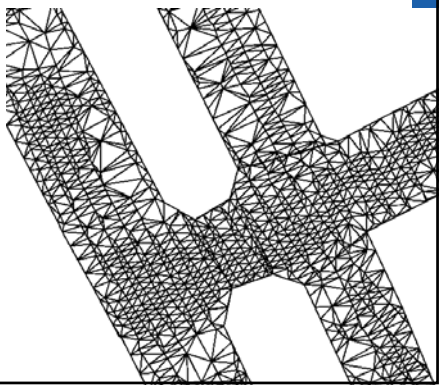


Reconstruction of the road surface

Points of the road surface

- Filtering of laser points
- Densification of map lines to one point every 2 m
- Constrained triangulation of map and laser points
- Variable point density

Assigning heights to road surface points



Nearest neighbour

For laser points:

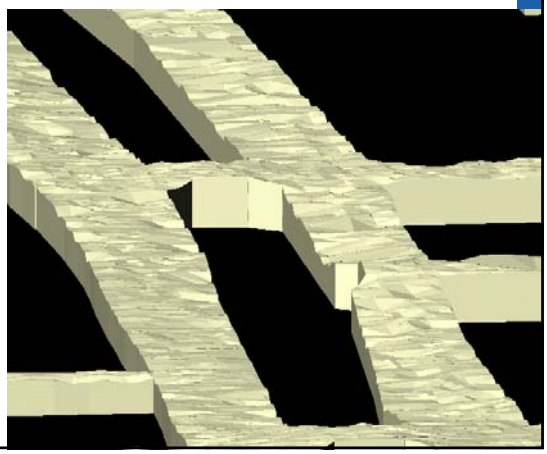
- Keep original height

For map points:

- Take height of nearest laser point

Result:

- Very noisy surface



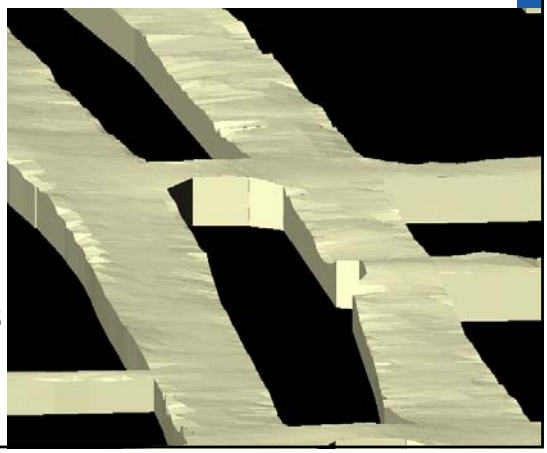
Fitting 2nd order polynomials

For each point:

- Select all laser points within some radius
- Fit polynomial
- Assign height

Results:

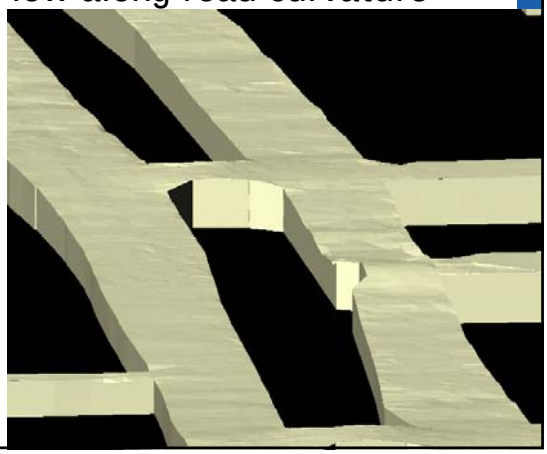
- Smoother road centres
- Extrapolation errors at road sides



Fitting constrained 2nd order polynomials

For each point:

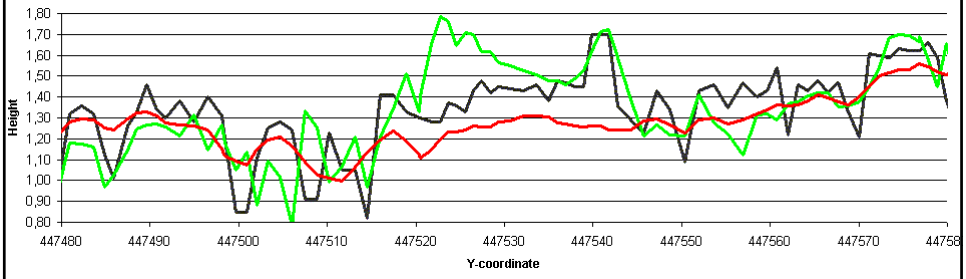
- Select all laser points within some radius
- Fit polynomial with low along road curvature
- Assign height



Results:

- Smoother road centres
- Extrapolation errors at road sides removed

Comparison of road side profiles



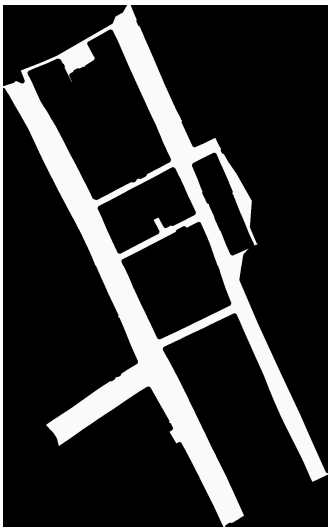
Original points

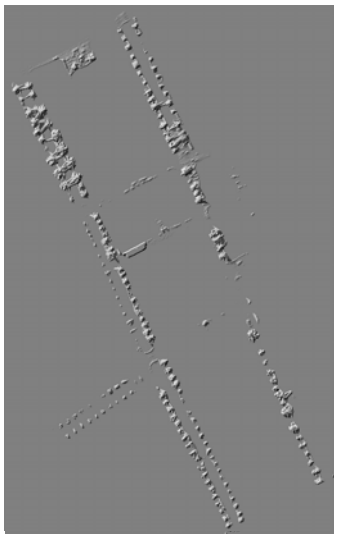
2nd order polynomial fit

Constrained 2nd order polynomial fit

Detection of trees

Map based selection of points





Detection of trees

Processing

- Minimum tree height
- Local maximum
- Grouping of points
- Estimation of tree location

Results

- 177 out of 182 detected
- 3 % omission error (5 trees)
- 5 % commission error (9 non-tree objects)

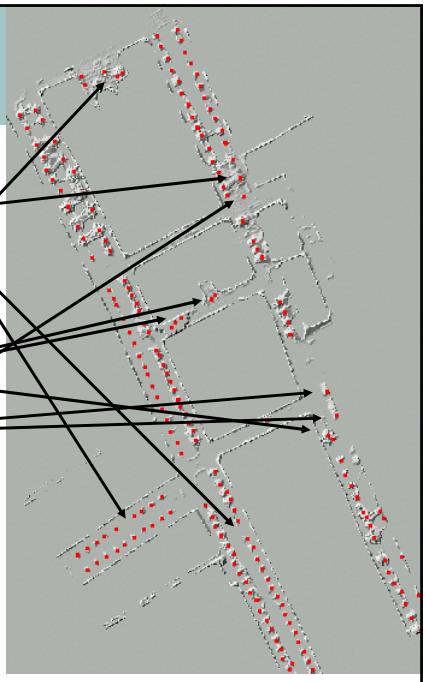
Tree detection results

Omission errors:

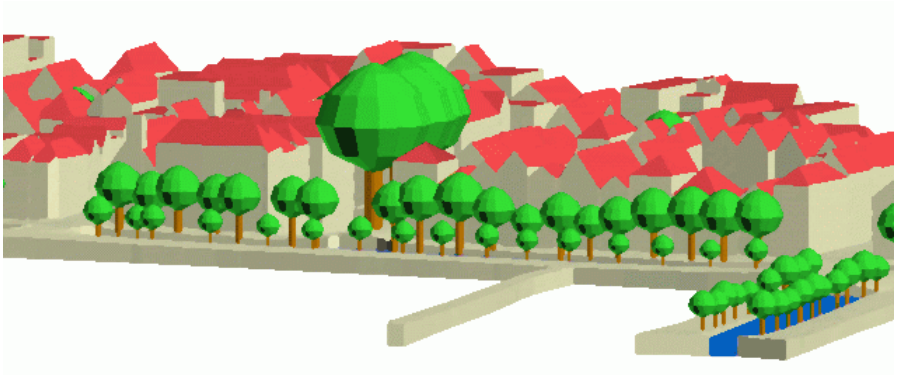
- Nearby trees seen as one tree
- No pulse reflection on tree

Commission errors:

- Double counted trees
- Small buildings
- Sun-shades
- Street light



Combining buildings, streets and trees



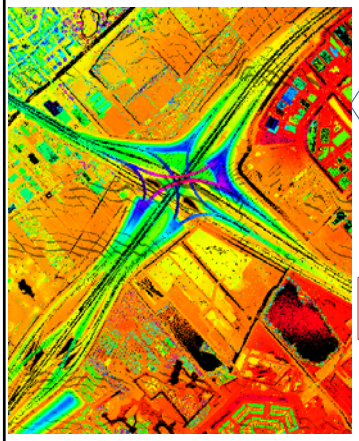
Conclusions on large scale modelling

- Large amount of information contained in laser scanning data sets.
- Accurate classification (>95%) of terrain, buildings and vegetation if high point density (>1 pt/m^2) is available.
- Extraction of 3D building models requires interactive methods.

Road reconstruction at 1:10.000 scale

Laser scanner data

Topographic database



Outlines
Classification
2D Semantics

Height to objects

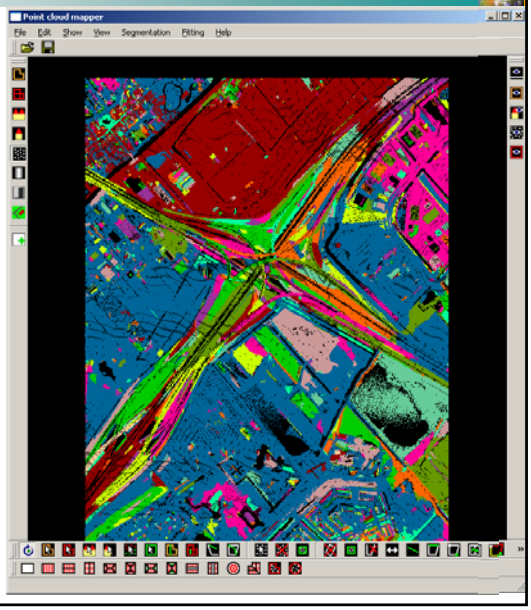
Point cloud
1 point / 9 m^2

Object based, 1:10.000

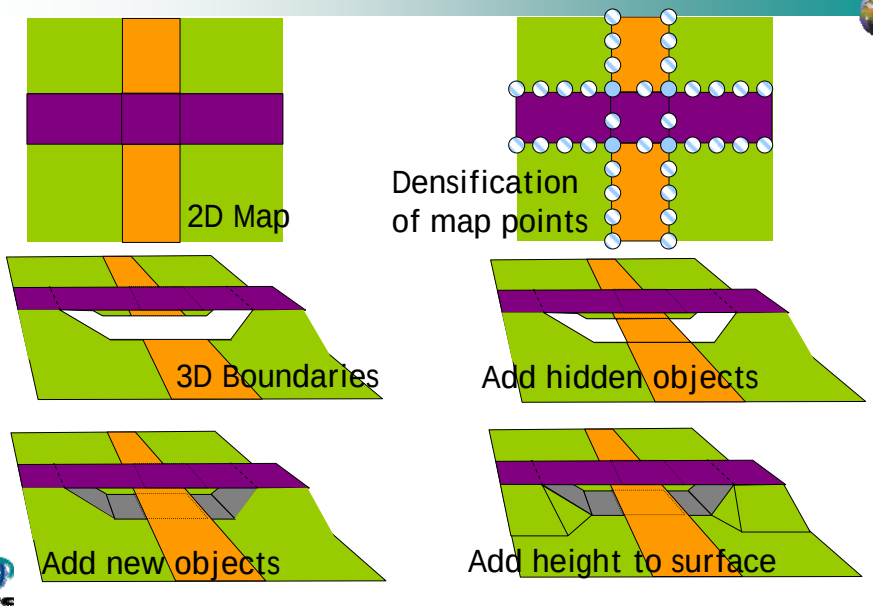
Preprocessing laser data

Extract smooth surfaces

- Seed surface detection by fitting planes
- Growing smooth surfaces
- Remove small segments

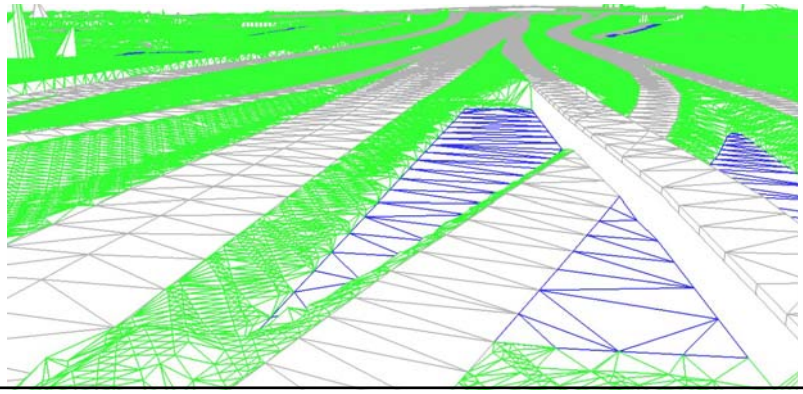


3D landscape reconstruction



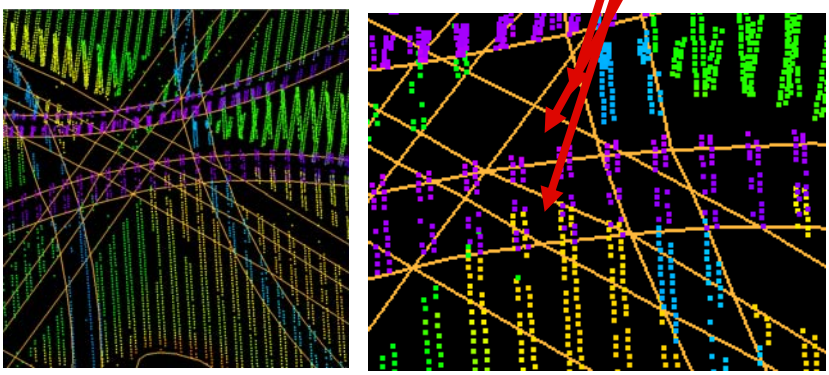
Utilisation of knowledge

- Water surfaces are horizontal
- Road surfaces are smooth
- Road heights are more accurate then grassland heights



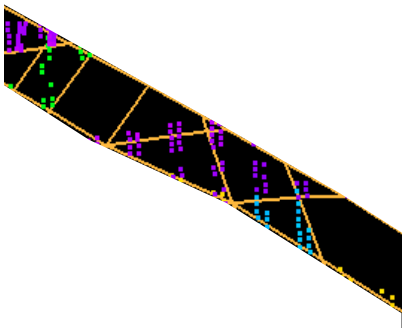
Complex cases

- No laser data in map segment
- Incorrect heights in map segment
- Multiple heights in map segment

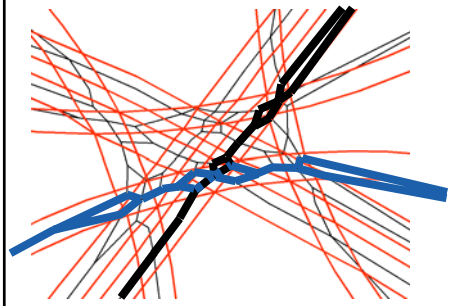


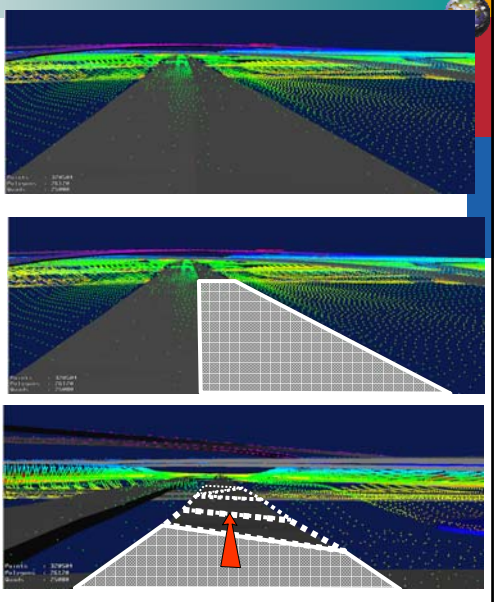
Complex cases (II)

- 1 road
- 12 polygons
- 1000 m2
- 5 correct laser points
- >150 false laser points

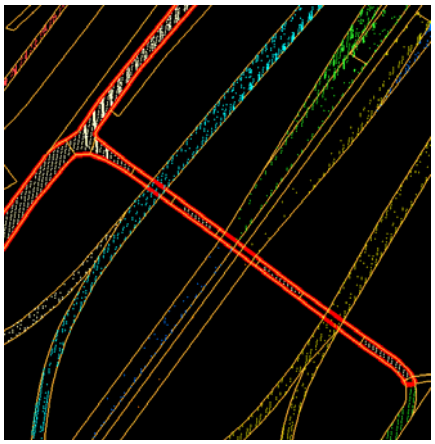


Combined map and laser growing



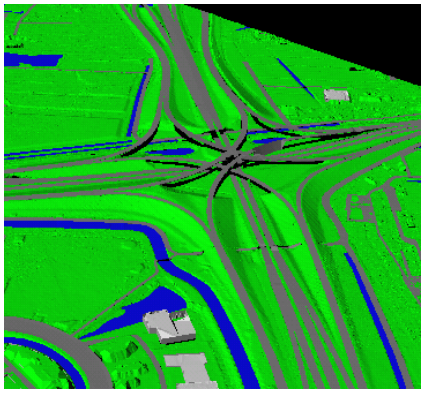


Laser points coloured by grown polygon



Results

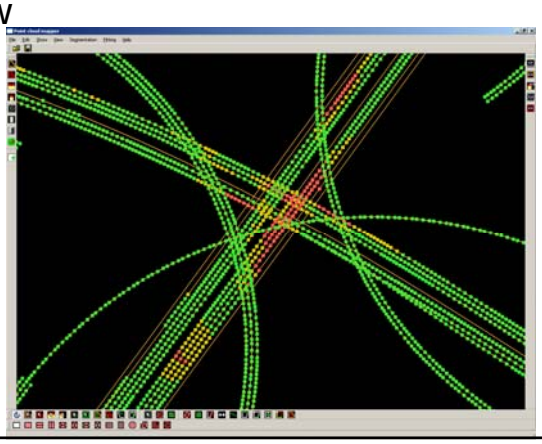
- Reconstructed road junction



Quality check

Comparison to large scale 3D road database

- <0.2 m green
- 0.2 – 0.5 m yellow
- >0.5 m red



Conclusions

- Airborne laser data contain large amount of information
- Extraction of surfaces is fairly reliable in case of high point densities
- Many features can be extracted (semi-) automatically
- Integrated processing of point clouds with imagery to be developed further