DSM / DTM Filtering

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Risk area map: Rosenberg a.d. Drau (Carynthia)

Data: GeoConsult (Austria)
Overview

• Problem
  – DTM required
  – Observation by Laser Scanning
  – but: obstacles along the laser beam path

• Solution - Extract terrain information
  a number of different approaches can be identified
  – Block minimum filters
  – Morphological filters
  – Progressive densification
  – Surface based filtering
  – Segmentation based filters

• Improvements
  – Break lines … higher geomorphological quality
  – Thinning … efficiency w.r.t. data volume/point number
Data Acquisition

- Sampling according to system parameters
- Points lie on different objects/surfaces
- Examples:
  - terrain, vegetation, low vegetation, understorey, houses, (light) poles, … (what else?)
  - multi path effects (long ranges)
- First/last detected echo
DEM / DTM / DSM / nDSM

Digital models of topographic surfaces

• Digital Elevation Model
• Digital Terrain Model
  (=DEM, sometime + break lines, peak points, …)
• Digital Surface Model
• normalized Digital Surface Model
• Digital Canopy/Situation/… Model
DSM  DEM  nDSM  DSM  DTM
DSM from Laser Altimetry

Useful for
- Check completeness
- Check overlap (extent, errors, ...)
- visualization
- manual interpretation
  (e.g. measure distances)

capturing geometry  Summer/Winter  Density of crop
Problem definition

• Given:

• Required:
Filtering - result driven definition

- Filtering to extract ground points
- Filtering to extract ground surface
- Classification to label points

- Filtering requires terrain assumption
  e.g.:
  - No height jumps
  - Smooth surface
  - No points below terrain
  - ... (what else?)
Filter algorithms overview

- Morphological filters
  Example: slope based filtering (Vosselman) + mathematical morphology

- Progressive densification
  Example: TIN densification (Axelsson)

- Surface based filters
  Example: robust interpolation (Kraus) + hierarchic extension

- Segmentation based filters
Block minimum filters

- Define regular mesh edge length =
- Take lowest point in each cell
- Compute DTM by interpolating set of these lowest points
- Problems:
Approach 1
Slope based filtering

- Principles of mathematical morphology (Slides from Prof. Vosselman)
- Binary, rasterized data
  … continuous domain
- Slope based filtering
- Relation to mathematical morphology
- Derivation of filter kernel
- Example
Mathematical morphology

Original

Kernel

Erosion

Dilation
Morphological opening

Original

Erosion followed by dilation
Morphological closing

Original

Dilation followed by erosion
More formally

**Erosion**

\[ e(x, y) = \min_{\Delta x} \min_{\Delta y} h(x + \Delta x, y + \Delta y) \]

**Dilation**

\[ d(x, y) = \max_{\Delta x} \max_{\Delta y} h(x - \Delta x, y - \Delta y) \]

\[ \Delta x, \Delta y \text{ - for all pixels inside structure element} \]

**Opening** - Min/Max filter
Grey scale erosion
Grey scale dilation

Width of dilating kernel:

Intensity

X Coordinate

Intensity

X Coordinate
Grey scale mathematical morphology

Kernel function \[ k(\Delta x, \Delta y), \quad -\frac{K}{2} \leq \Delta x, \Delta y \leq \frac{K}{2} \]

Erosion \[ e(x, y) = \min \min_{\Delta x, \Delta y} \left[ h(x + \Delta x, y + \Delta y) - k(\Delta x, \Delta y) \right] \]

Dilation \[ d(x, y) = \max \max_{\Delta x, \Delta y} \left[ h(x - \Delta x, y - \Delta y) + k(\Delta x, \Delta y) \right] \]

Min/Max \[ k(\Delta x, \Delta y) = 0, \quad -\frac{K}{2} \leq \Delta x, \Delta y \leq \frac{K}{2} \]
Filtering with mathematical morphology

Single opening \((\text{min}/\text{max})\)

- Selections
  - Window size
  - Height tolerance

Openings with multiple kernel sizes

- Increasing height tolerance with increasing window size

Structure element
Slope based filtering

- Optimal filter depends on terrain type
- Reject large height jumps
- Take distance between points into account

Filter function: \( \Delta h_{\text{max}}(d) \)

Let \( A \) be the set of all points. Define DEM* as

\[
DEM = \left\{ p_i \in A \mid \forall p_j \in A : \Delta h_{ij} \leq \Delta h_{\text{max}}(d_{ij}) \right\}
\]

* DEM = ground point set
Erosion with a kernel function

Terrain properties encoded in structure element.

Example:
Maximum terrain slope

Structure element

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Erosion with a kernel function

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Example:
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Structure element
Erosion with a kernel function

Terrain properties encoded in structure element.

Example:

Maximum terrain slope

Structure element

Height $\leq$ eroded height
More formally

For images: \( e(x, y) = \min_{\Delta x} \min_{\Delta y} [h(x + \Delta x, y + \Delta y) - k(\Delta x, \Delta y)] \)

For sets: \( e_{p_{i}} = \min_{p_{j} \in A} \left[ h_{p_{j}} - k(\Delta x_{ij}, \Delta y_{ij}) \right] \)

\[
k(\Delta x, \Delta y) = -\Delta h_{\text{max}} \left( \sqrt{\Delta x^2 + \Delta y^2} \right)
\]

\[
e_{p_{i}} = \min_{p_{j} \in A} \left[ h_{p_{j}} + \Delta h_{\text{max}} (d_{ij}) \right]
\]

\[
DEM = \left\{ p_{i} \in A \mid h_{p_{i}} \leq e_{p_{i}} \right\}
\]
Filter functions

• Theoretical
  – Assume maximum slope, e.g. 30%
  – Assume standard deviation $\sigma$ and a confidence interval, e.g. 95%.

\[ \Delta h_{\text{max}} (d) = 0.3 \, d + 1.65 \, \sqrt{2\sigma} \]

• Preserving important terrain features
  – Training set with ground points only
  – For each distance interval $d$, determine $\max(\Delta h)$
Filter functions (II)

• Minimising classification errors
  – Effect of type I error equals effect of type II error

 – For each $d$, determine $\Delta h$ for which

\[
P(p_j \in DEM \mid \Delta h, d, p_j \in DEM) = 0.5
\]
Filter functions (III)

The graph shows the relationship between the allowed height difference and the distance between points in meters. The graph compares two functions: "Maximum" and "Probabilistic". The x-axis represents the distance between points (m), while the y-axis represents the allowed height difference (m). The graph indicates how the allowed height difference changes with increasing distance for both functions.
morphological filtering
Example

Area: partly open, wooded, with a dike
Filter kerner: use training data set
  maximum filter (i.e. no ground points lost)
Tested also with reduced resolution
Approach 2
Robust interpolation

• Principle
• Mathematical description
• Hierarchic extension
• Example
Robust interpolation

- interpolation: surface $f(x,y)$ “through” points filtering of measurement errors

- robust: residuals (surface – laser point)
  weight function:
  points above/below surface
  - small/high weight

- iterate

- General principle: weight function interpolation method
Mathematical formulation

\[ z(x,y) = c^T C^{-1} z \]

\[ c = ( C(p, p_1), \ldots, C(p, p_n) )^T , \quad z = ( z_1, \ldots, z_n )^T \]

\[ C = \begin{pmatrix}
V_{zp1} & C(p_1, p_2) & \cdots & C(p_1, p_n) \\
C(p_1, p_2) & V_{zp2} & & \\
& \ddots & \ddots & \ddots \\
C(p_1, p_n) & C(p_2, p_n) & \cdots & V_{zpn}
\end{pmatrix} \]

\[ V_{zp_i} = \sigma_z^2 / w_i + C(0) \]

\[ w(r) = \begin{cases}
1 & : \quad r < g \\
1 / \left(1 + (a(r - g))^b\right) & : \quad g \leq r \leq g + h \\
0 & : \quad r > g + h
\end{cases} \]
Robust interpolation

Simple kriging (=linear prediction)
- random measurement errors

Histogram of residuals

Origin of the weight function
- statistical method
- penetration rate
- histogram analysis
Robust interpolation

Weight function
- Half weight width
- Slant

Graph showing the relationship between $p$ and $x$ with a shaded region indicating the half weight width and slant.
Hierarchic filter strategy

- Robust interpolation requires good mixture of ground and off-terrain points
- Hierarchic approach guarantees mixture
- Hierarchic approach speeds up process
Hierarchic filter strategy I

- Compute data (point set) at different niveaus:
  - Select
    - Lowest point or barycenter
  for each cell (define edge length)

- Process (filter) different niveaus coarse to fine
  e.g.: 20m → 4m → original data
Hierarchic filter strategy II

Iteration

1. Robust interpolation for coarsest niveau
   → first DTM

2. Select points of next (finer) niveau within a tolerance band of DTM

3. Robust interpolation for selected points

4. Iterate from step 2
Hierarchic robust interpolation

Niveau 1
Hierarchic robust interpolation

Niveau 2
Example

5m level
- select mean point in 5m x 5m cell
- robust filtering
- weight function half weight @ 75cm
- weight function tolerance 1m
- select Points $\pm 3\text{m}$ of DTM

2m level
- select lowest point in 2m x 2m cell
- robust filtering
- weight function half weight @ 30cm
- weight function tolerance 60cm
- select Points $\pm 2\text{m}$ of DTM

original (0.5m level)
- robust filtering
- weight function half weight @ 20cm
- weight function tolerance 30cm
Approach 3
progressive TIN densification

- Select a few low points that are most likely terrain
- Build a TIN of the low points
- Add nearby points to TIN
TIN densification

1. Select lowest points in big areas
2. Triangulate points
3. Test: single point ★ triangulation angle: (single point, vertex) to triangle
4. Add accepted points to triangulation
5. Iterate from step 3

Variants:
• 1 point / more points per iteration
• criterion: angle, distance, ...
TIN densification
Approach 4
Segmentation Based Filters
What Is Segmentation?

- Partitioning of a data set $R$ in object space (image, point cloud) into $N$ disjoint, coherent subsets $R_i$.

1) $\bigcup R_i = R$

2) $R_i$ is a connected region for all $i$

3) $R_i \cap R_j = \emptyset$ for $i \neq j$

4) $P(R_i) = true$ for all $i$ and a coherence predicate $P$

5) $P(R_i \cup R_j) = false$ for all adjacent regions $R_i, R_j, i \neq j$
What Is Segmentation?

• Partition data into smaller, coherent and "meaningful" subsets
  – Prerequisite for reconstruction (instantiation of geometric primitives)

• In the simplest case, segments correspond directly to objects of interest
  – Blob analysis in image processing
What Is Segmentation?

- Example: Image Segmentation + Blob Analysis

Grayscale Image → Binary Image → Detected Blobs (Objects)

Thresholding → Postprocessing + Labeling
What is Segmentation?

- **Classification vs. Segmentation**
  - segmentation: assignment to (parts of) objects, e.g., roof plane #117
  - classification: assignment to thematic groups, e.g., vegetation, roof
  - segmentation ~ classification + connected components analysis

Classification example

ISODATA clustering of height and intensity values + manual annotation of clusters

Hala & Brenner, ISPRS, 1999
What is Segmentation?

- Complex objects/scenes are broken down into simpler parts/subregions
  - Polynomial surface patches in 2.5 D range data segmentation
  - Example: 2.5 D segmentation of range data into planar patches (images taken from the USF database)
Range Data Segmentation

- Range image segmentation is a very active research area since the mid-1980ies.

- Seminal paper by Besl and Jain (1988, PAMI) “Segmentation Through Variable-Order Surface Fitting”

- Main idea
  - Surfaces are modeled locally by bivariate polynomial patches
  - Centers of individual surface patches (seed regions) are determined by Gaussian Mean/Curvature
  - Each patch is “grown” iteratively around its seed region
    - Region growing and model selection (polynomial degree) proceed according to the chi-square statistics of the residuals
Segmentation based filtering

What is a segmentation?
Example
Comparison of Filtering Approaches

• Concept of surface

• Reducing / adding information

• Experimental comparison
• What do we have now?
  Ground points …

• What do we want?
  Model of the terrain surface =
  = continuous function
  \[ \rightarrow \text{Interpolation / Approximation} \]
  – Consideration of measurement errors …
  \[ \ldots \text{geostatistics} \]
  – Special character of terrain surface
    • Lineaments
    • Varying variability
Lineaments in the terrain

Extraction of break lines from high resolution laser scanning data

- Breakline **definition** + motivation
- Breakline **extraction** in **range** images
- Extension: extraction in **point** clouds
Examples for breaklines

http://www.niger-uc.net/minta/tourisme/DESERT/desert.htm

http://home.wanadoo.nl/e.dejong2003/landschap.htm

Jump Edge
Crease Edge
Curvature Edge
Breakline definition

- General observation: terrain is a smooth surface
- Exception: breaklines, peaks, dolinas, ...
- Linear feature (3D line)
- Found at curvature “maxima” (curvature not well defined!)
- Morphological terrain descriptors
- Appear often pair-wise (upper/lower or left/right)
- Most important morphological DTM information
- Contour lines turn sharply (high curvature or apex)
Purpose of breaklines

- Morphologically correct DTM
- Data reduction
  (high number of points required for implicit description)
- Data analysis
  - object recognition
  - terrain characterization (e.g. in geology)
- Water run-off modelling
Breaklines in laser scanner data

Breakline network
Noise
Extraction principle (approach of Brügelmann)

- Dike cross-section with breakline points
- 1st derivative
- 2nd derivative with threshold values
• Range image with dike
• Higher altitudes are shown brighter

• Curvature measure per pixel
• Filter operation: 2\textsuperscript{nd} derivative with smoothing

• Statistical testing (threshold values)
⇒ possible breakline regions
• Nonmaxima suppression
• Thinning
⇒ Raster breaklines

• Raster-vector conversion
⇒ raw vector breaklines

• Splines through x,y - coordinates
• z-coordinate from ‘smoothed surface’
⇒ ‘smooth’ vector breaklines
Exact position and height

• Previous slide:
  - Spline through $x,y$-coordinates
  - $z$-coordinate from ‘smoothed surface’
  $\Rightarrow$ ‘smooth’ vector breaklines

• Breakline point not measured by laser (only adjacent surfaces are measured)
• Improved location of breakline
• Improved elevation of breakline
Exact breakline determination (approach of Briese)

- Use previous result as 1st approximation
- Use model of breakline: intersection of 2 smooth surfaces
- Determine breakline patch-wise
- Current breakline defines left vs. right points
- Determine surface patches from left/right pts.
- Intersect in breakline
- Renew left/right classification
- Iterate

Advanced DTM generation from LIDAR data by K. Kraus, N. Pfeifer IAPRS Vol XXXIV, 3/W4, Annapolis, Maryland, USA, 2001
Modeling – plain pair I
Results per break line

- One representative point per patch
- Edge direction per point
- Intersection angle of planes along the break line
- Adjustment information (precision, redundancy, …) along the break line
Automation – Growing of the edge

- Growing on the basis of 1 start segment:

**PROCEDURE:**

1. Determine patch/Break line edge with robust planar elements
2. Determine buffer zone for next/adjacent patch (Extrapolation)
3. Export (collect) unclassified ALS-point cloud within the buffer

These steps are repeated until a certain criterion is reached (e.g., intersection angle, precision, …)
Automation – Growing of the edge

- Growing on the basis of 1 Start-Point:
  Adjusting Quadric:

Edge direction: direction of the eigenvector of the smallest eigenvalue (after principle axis transformation)
Automation – Example
Full automation

Start-Segments:

EuroSDR, Testdataset Vaihingen
Full automation

Entirely automated derived break lines
Practical Example I

BfG (Bundesanstalt für Gewässerkunde, Federal Office of Water Ways, Germany), Testd ata Lahn
Practical Example II

Österr. Wasserstraßendirektion, Hainburg
Classification on the basis of the intersection angle
Practical Example – DTM after Filtering
Different point density!
Different point density!
Different point density!
Accuracy assessment

Comparison to terrestrial determined break lines
Last Example

start with manual approximation of breakline
5m point distance, digitized in shading
use of filtered point cloud
Break line Summary

• Automatic extraction of breaklines is possible
• Quality of breakline depends on density and accuracy of data (and pixel size)
• Improvement especially in geomorphologic DTM quality
• Regular grid becomes a hybrid grid
  ... = grid with lines meshed into it
DTM data reduction – requirements

- Base data: DTM = set of elevations in a matrix structure possibly augmented by lines
- Height tolerance ($L^\infty$-Norm) vs. RMS approximation
- Maintaining a maximum point distance ($\Delta^0$ niveau) [can be omitted]
- Splitting:
  - Hierarchic (quad tree, „inverses progressive sampling“)
  - Irregular
- Reduction criteria:
  - Curvature (in original DTM)
  - Slope (in original DTM)
  - Vertical distance
    (between original and reduces DTM)
Data reduction

• Basic ideas:
  – Surface approximation piecewise by linear surface patches (TIN)
  – Mesh refinement: coarse-to-fine
  – Mesh decimation: fine-to-coarse

• Reduction approach suggested [within $\Delta^0$ niveau]:
  – Conceptual: dense terrain model $\rightarrow$ simplified TIN (fine-to-coarse)
  – Algorithm: refinement of a generalized DTM (coarse-to-fine)

• Reduction criteria:
  – Vertical distance of the DTM grid points to the TIN
  – Guaranteeing a maximum height tolerance ($L^{\infty}$-Norm)
Datenreduction – original mesh

DTM in Original resolution (32,768 triangles)

Data: GeoConsult, Drau (Austria)
Datenreduktion – Mesh refinement

Reduced TIN
Maximum height tolerance = 25cm

Hierarchic splitting
5.496 Triangles (=17%)

Irregular splitting
1.192 Triangles (=6%)

+) regular triangles
-) Less compression

+) High compression
-) irregular triangle shapes
Summary on Filtering and DTM

- Filtering is operational
- Manual checking and improvement of filter results required for high quality
- Improvement options
  - FWF: other presentation in the Lidar Technology School 2008
  - Other sensors:
- Commercial implementations:
  SCOP++: hierarchic robust interpolation
  Terra Modeler: progressive densification
- Overview on filters
- Break lines for geomorphologically correct terrain representation
- Thinning for reducing data volume