Image Segmentation

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Objectives

Medical Image Segmentation

- Classify fundamental methods for image data segmentation
- Appraise efficacy and drawbacks of techniques according to the processing level
- Explain the inherent problems of robustness
- List algorithmic steps
  - Thresholding
  - Edge detection
  - Model generation

Low-level Segmentation Techniques

- Pixel-based
  - Thresholding
  - Clustering
- Edge-based
  - Livewire
- Region-based
  - Region growing
  - Region merging
- Draws
  - Semantic
  - Inherent
- Evaluation
  - Ground truth (?)

iconic

symbolic

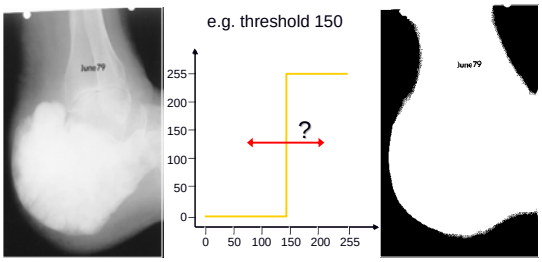
Definition

Image segmentation yields a

- Partitioning of image
  - complete
  - non-overlapping
- Mathematically, this means
  - complete $\bigcup_{i=1}^{k} R_i = f(m,n)$
  - non-overlapping $R_i \cap R_j = \emptyset$ $\forall i,j = 1,2,\ldots,k, \quad i \neq j$

Thresholding

- Separation of object and background



Approach by Otsu (1979)

- Assumption
  - *K* objects (different gray value)
  - Gaussian distributed histogram

$$h(g) \approx \sum_{k=1}^{K} a_k \cdot e^{\frac{(g-g_k)^2}{\sigma_k^2}}$$

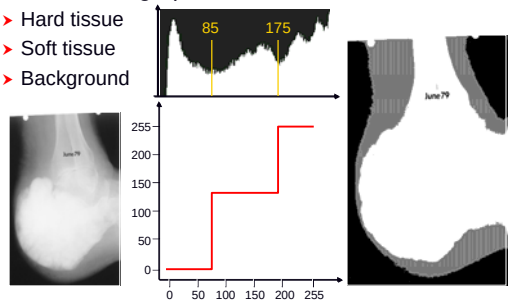
- Approach
  - Maximization of the inter-class variance
  - Minimization of the intra-class variance
- Type
  - Image-specific

Algorithm: $K = 2$

- Formulate as function of t
  - Frequency of gray values $H_0 = \sum_{g=0}^{t} h(g)$ $H_1 = \sum_{g=t+1}^{G-1} h(g) = 1 - H_0$
  - Mean gray values $\bar{g} = \bar{g}_0 H_0 + \bar{g}_1 H_1$
  - Variances $\sigma_0^2 = \sum_{g=0}^{t} (g - \bar{g}_0)^2 h(g)$ $\sigma_1^2 = \sum_{g=t+1}^{G-1} (g - \bar{g}_1)^2 h(g)$
- Compute for all t
  - Intra-class variance $\sigma_{\text{intra}}^2 = H_0 \sigma_0^2 + H_1 \sigma_1^2$
  - Inter-class variance $\sigma_{\text{inter}}^2 = H_0 (\bar{g} - \bar{g}_0)^2 + H_1 (\bar{g} - \bar{g}_1)^2$
- Select t such that $t_{\text{opt}} = \max_t \left\{ \frac{\sigma_{\text{inter}}^2}{\sigma_{\text{intra}}^2} \right\}$

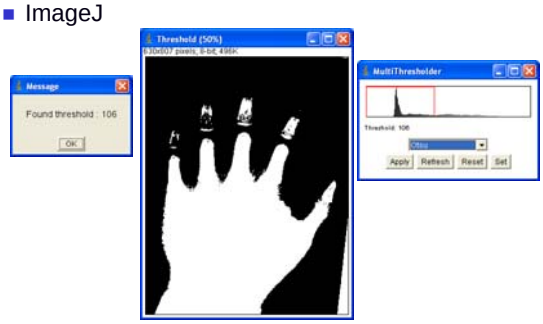
Example: $K = 3$

- Skeletal radiograph
  - Hard tissue
  - Soft tissue
  - Background



Otsu Thresholding: $K = 2$

- ImageJ



Example: Microscopy

- Task
  - Separation of cells and background
- Problem
  - Inhomogeneous illumination
- Result

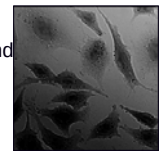


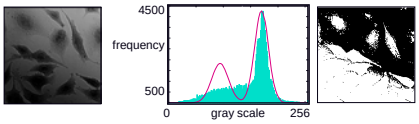
image-specific region-specific pixel-specific

Pixel-Specific Implementation

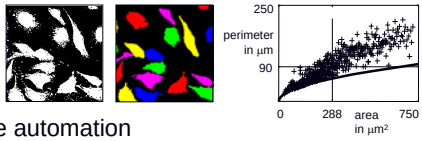
```
for m = 1 to M {                          // walk over columns
   for n = 1 to N {                         // walk over lines
      mask_size = 1
      while variance(mask) < variance(image) {
         mask_size++
         } // while
      thresh = compute_otsu(mask)
      if image(m,n) <= thresh
      then new_image(m,n) = 0
      else new_image(m,n) = 255
   } // for n
} // for m
```


Computational Complexity

- 1979 Nobuyuki Otsu: automatic threshold
  - O(n)



- 2000 Metzler et al: local dynamic implement.
  - O(n^3)



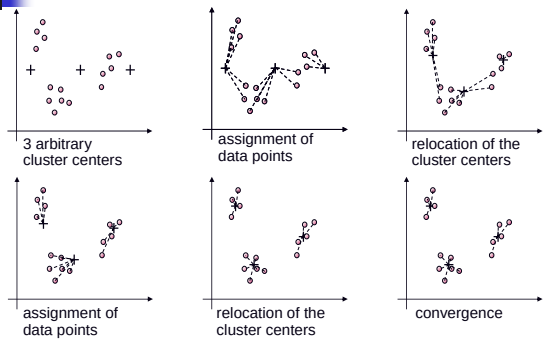
➔ Complete automation

Clustering

- Represent image in feature space
  - Gray value statistics (histogram)
  - Color bands of multi-band images
  - …
- Search for clusters in feature space
  - Compute cluster center
- Re-label pixels
  - update cluster membership

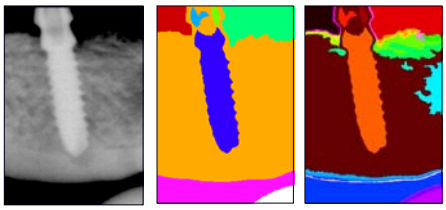
➔ Iso-data clustering
  - Image-specific

Example



Traps (Draws)

- Semantic: from the object ↔ segment gap
  - Over segmentation (one object → multiple segments)
  - Under segmentation (one segment → multiple objects)



Traps (Draws)

- Inherent: from the algorithm itself
  - Incoherent segments

➔ Post-processing required
  - Morphological filter sequences
  - Separation of different objects
  - Re-labeling of connected components
  - Pseudo-coloring of segments

Edge-Based Segmentation

- Edge detection
  - Local convolution
  - Binarization of edge image
  - Post-processing for noise reduction
- Edge tracking / contour completion
  - Detection of coherent edge pixels
  - Formation of a closed contour
- Application
  - Livewire

Edge Detection

- Sobel
  - 1st derivative with orthogonal smoothing
  - 8 directions
- Canny (1986) / Deriche
  - Non-maxima suppression
  - Hysteresis for edge following
- Laplace
  - 2nd derivative
  - Isotropic

-1	-2	-1
0	0	0
1	2	1

-2	-1	0
-1	0	1
0	1	2

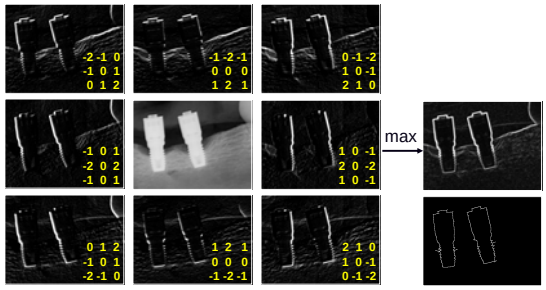
-1	0	1
-2	0	2
-1	0	1

2	1	0
1	0	-1
0	-1	-2

0	-1	0
-1	5	-1
0	-1	0

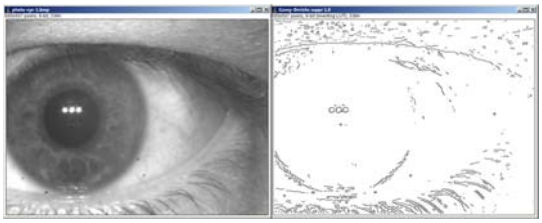
Edge Detection

- Example



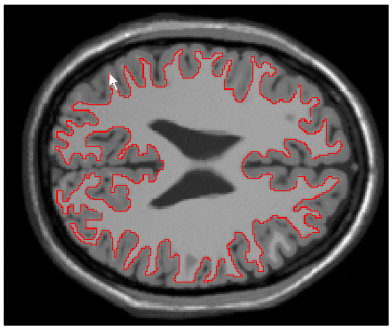
Edge Detection

- ImageJ



Edge-Based: Livewire

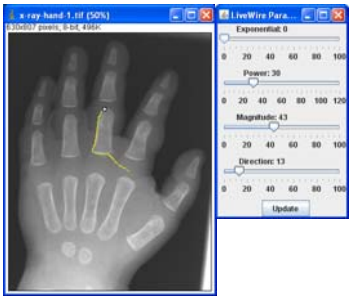
- Example



Sebastian König
Mannheim, 2003

Livewire

- ImageJ



Region-Based Segmentation

- Detection of connected regions
  - Agglomerative
    - region growing, region merging
  - Divisive
    - split, split & merge
  - Hierarchical
    - scale space, pyramid linking
- Distance or similarity measure
  - Pixel to pixel
  - Pixel to region
  - Region to region

Region Growing

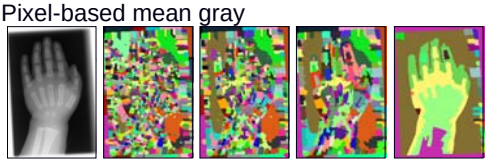
- Initialize all pixels as unlabeled
- Position labeled seed points (localization)
  - Manual
  - Heuristic
  - Complete (region merging)
- While unlabeled pixel neighbored and distance below threshold
  - Merge pixel to region
  - Update region mean
  - Update neighborhood

Seedless Region Growing

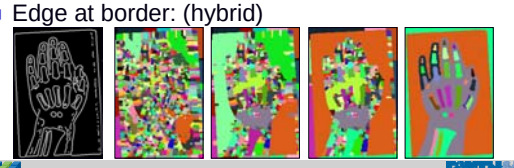
- Initialize all pixels as labeled
- Region adjacency graph (RAG)
  - Node: image region
    Property: e.g., mean gray value
  - Edge: neighborhood of regions
    Property: distance or similarity measure
- Sequentially sorted list (SSL)
  - Sort RAG according to smallest edge property
- While SSL first entry smaller threshold
  - Merge, update RAG and SSL

Region Merging

- Pixel-based mean gray



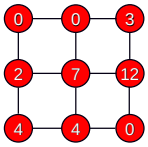
- Edge at border: (hybrid)



Traps (Draws)

- Inherent: from the algorithm itself
  - Type a: performing a merge changes all distances
  - Type b: equal distance to more than 1 neighbors

Example: Inherent Draw



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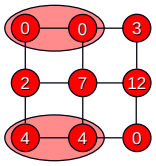

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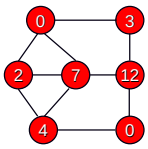
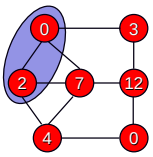


Example: Inherent Draw

raster scan



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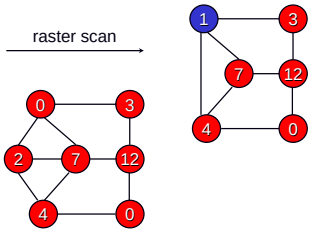

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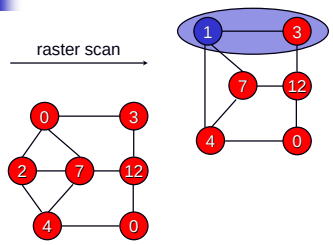
raster scan



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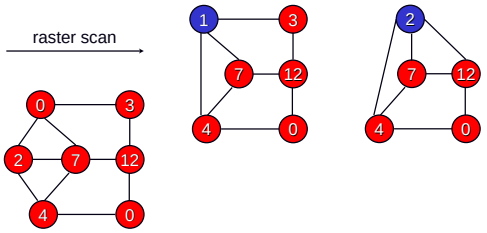

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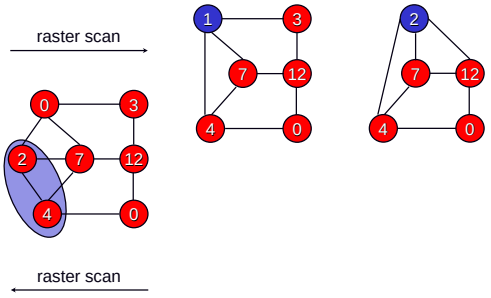

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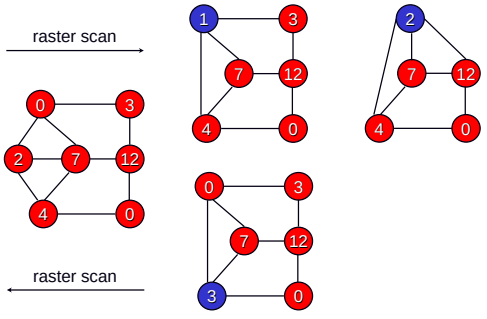
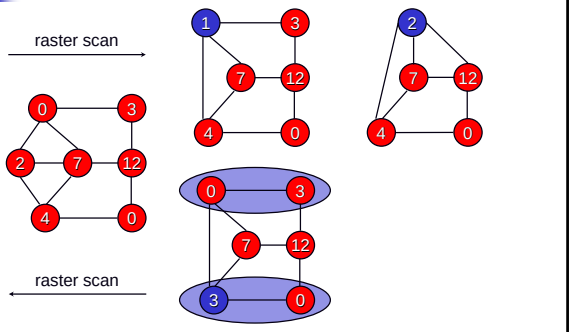


Example: Inherent Draw



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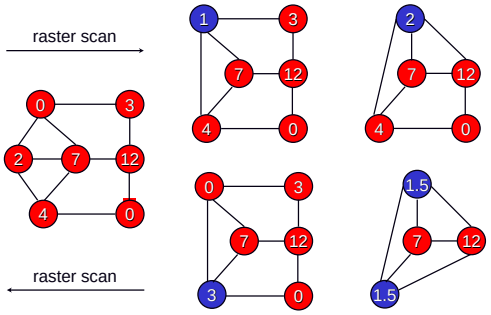

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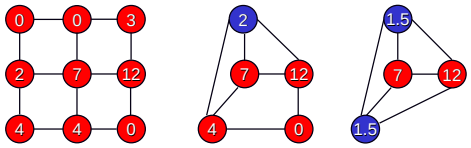
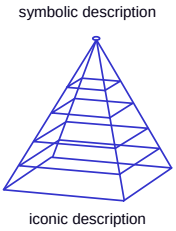


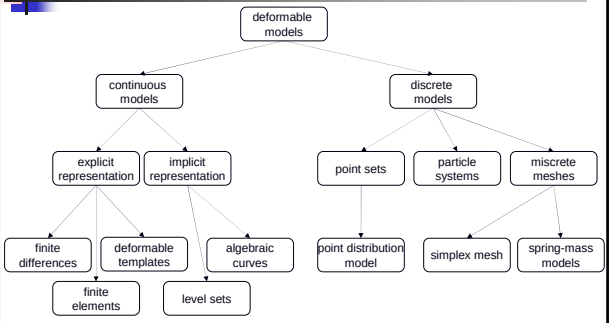
- Algorithmic: from implementation
  - E.g., caused by speed up strategies

Model-Based Segmentation

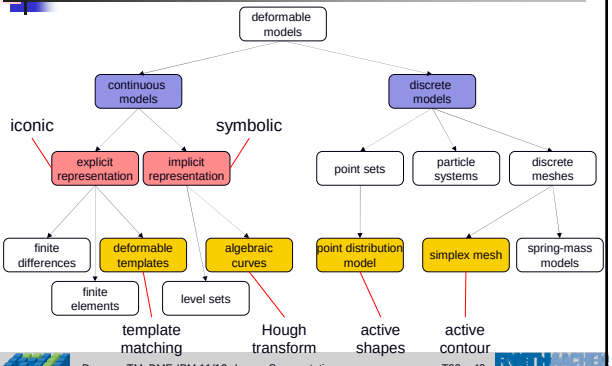
- Object (model)-based
  - Matched filter
  - Hough transform
  - Active shape model
- Scene-based
  - Structural prototype
- Hybrid
  - Watershed transform
  - Active contours



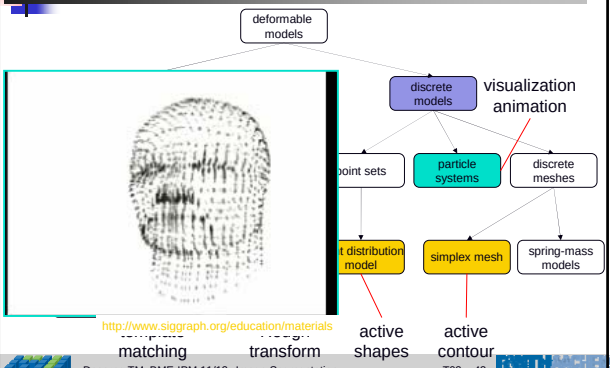
Model-Based Segmentation



Model-Based Segmentation

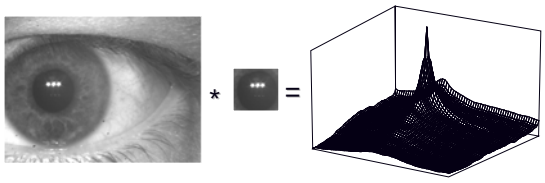


Model-Based Segmentation



Template Matching

- Matched filter
  - Generate search pattern (template)
  - Correlate image with template
  - Detect global maximum



Template Matching

- ImageJ

Hough Transform (Patent 1962)

- Detection of curves
  - Line, circle, ellipse, …
  - Points on curve vs. parameters of curve
- Hough space
  - Initialization
  - Accumulation of parameter hypotheses
  - Maxima indicate likely curves in pixel (voxel) space
- Preprocessing
  - Edge detection
  - Scaling

Hough Transform

- Line in Hesse's normal form:

$$x\cos\theta + y\sin\theta - \rho = 0$$

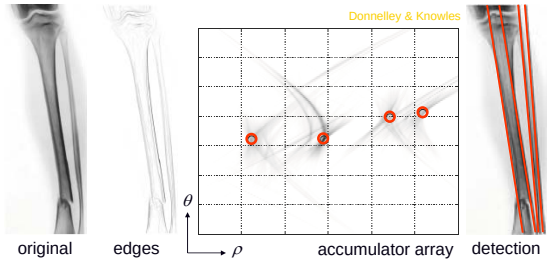
- Transform into accumulator array
  - Axis by parameters (ρ,θ)
  - For all pixels (x_i,y_i)
    - increment all (ρ,θ) belonging to a straight line that passes through pixel (x_i,y_i)

$$\rho = x_i\cos\theta + y_i\sin\theta$$

- Local maxima in accumulator array
  ⇒ Straight lines in pixel space

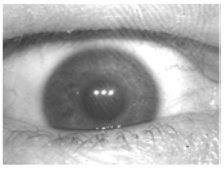
Hough Transform

- 2D Example (line detection)
  - Fracture detection using line approximations

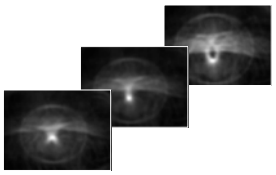


Hough Transform

- 3D Example (circle detection)
  - Detection of pupil in photographs of the eye
  - Measurement of the angle of squint (automatic strabometry)



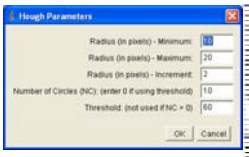
spatial domain



Hough space

Hough Transform

- ImageJ



Active Shape Models

- Idea
  - Fit prior model to image data along 'statistically plausible' deformations
- Point distribution model (PDM)
  - N shapes with n landmarks as m-dimensional points x_i

$$\mathbf{X} = (\mathbf{x}_1, \ldots, \mathbf{x}_{N-1})^T$$

- Principal component analysis (PCA)
  - Mean shape
  - Covariance matrix
  - Eigenvector Φ_i
  - Eigenvalue λ_i

$$\bar{\mathbf{x}} = \frac{1}{N}\sum_{i=0}^{N-1}\mathbf{x}_i$$

$$\mathbf{S} = \frac{1}{N}\sum_{i=0}^{N-1}(\mathbf{x}_i - \bar{\mathbf{x}})(\mathbf{x}_i - \bar{\mathbf{x}})^T$$

Active Shape Models

- Model generation
  - Base Φ of eigenvectors ϕ representing the principal modes of variation
  - to the t largest eigenvalues λ indicating the variance per mode
- Shape representation
  - Approximate $\mathbf{x} \approx \bar{\mathbf{x}} + \Phi\mathbf{v}$
  - Weighting vector v
- Model application
  - Determine v that minimizes a distance measure

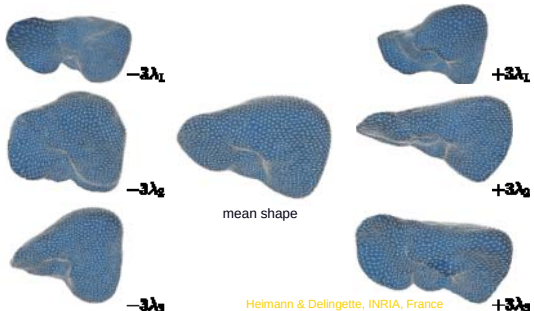
Active Shape Models

- 2D example: statistical bone model of the finger
  - 3rd proximal phalanx 7-13 years (male)
  - 3rd proximal phalanx 13-17 years (male)

BoneXpert Mature Technology

Active Shape Models

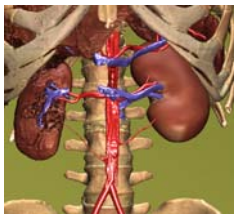
- 3D example: statistical liver model



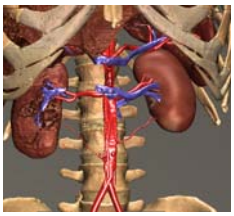
Heimann & Delingette, INRIA, France

Active Shape Models

- 3D example: statistical kidney model
  - Variation in “length”
  - Variation in “curvature”



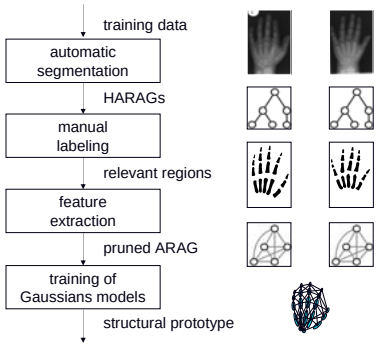
Hacker & Handels, Proc SPIE 2006



Hacker & Handels, Proc SPIE 2006

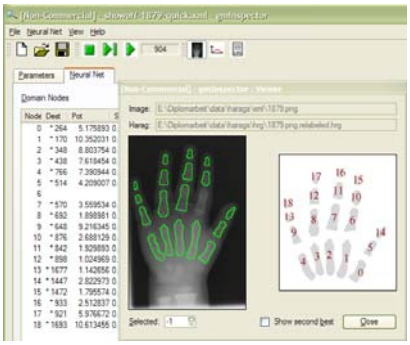
Scene-Based Segmentation

- High-level a-priori knowledge
  - Relevant objects
  - Spatial relation
- Variability of objects
  - Anatomy
  - Deformations
  - Pathology



Scene-Based Segmentation

- Example

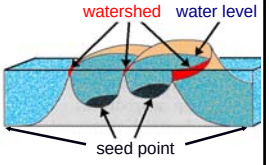


Hybrid Approaches

- Idea
  - Increase robustness
  - Combine advantages (but not drawbacks)
- Watershed transform
  - Agglomerative, regional approach
  - Extended with edge-based aspects
- Active contour model
  - Edge-based approach
  - Extended with region-based and object-based aspects (model of contour properties)
- Active appearance model

Watershed Transform

- Idea
  - Image as 3D topographic relief
    - height ≡ intensity of pixel
  - Flood valleys from seed points
    - catchment basins
  - Prevent merging of basins
    - raise dams (watersheds)
  - Image segments ≡ catchment basins



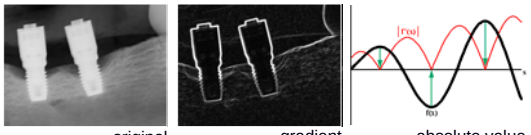
Watershed Transform

- Algorithm

```
// Seed point detection //

detect local minima;
assign each minimum own ID;

// Flooging //

sort seed points by increasing height;
waterlevel = global minimum;
repeat
  for each seed point
    for each neighbor
      if ( under water and no ID )
        assign same ID as seed point;
      else
        ignore;
  waterlevel++;
until (waterlevel == global maximum);
```

Watershed Transform: Gradient Image

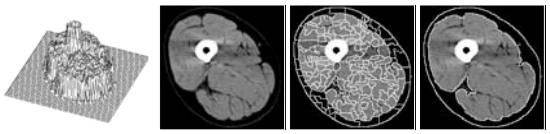
- Watershed-dams = edges
- Watershed-basins = regions
- ➔ Gradient image instead of image itself
  - Absolute value of 1st derivative of image
  - Local maxima = edges
  - Local minima = seed points



original gradient absolute value

Watershed Transform: Examples

- CT



- Photography

Watershed Transform

- ImageJ

Active Contours

- Segment
  - Defined by (closed) contour

Active Contours

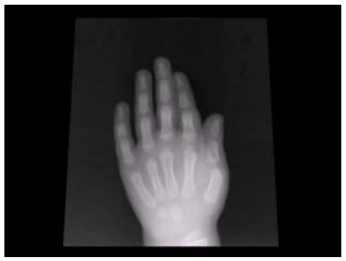
- Contour
  - Represented by single sampling points

Active Contours

- External forces
  - Gray scale gradient in image

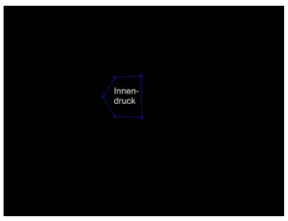
Active Contours

- Internal forces
  - Stiffness of the contour



Active Contours

- Global forces
  - Continuous drifting of the contour
    - expansion by inner pressure
    - inflation by outer pressure



Active Contours

- Iterative segmentation
  - Balance of forces
- Iterative control
  - Topology
  - Number of vertices

Active Contour Models

- Snakes
  - Internal and external energy
  - Initial contour required
  - Application: object tracking in image sequences
- Balloons
  - Model pressure or suction
  - initial contour can be omitted
- Extensions
  - Automatic determination of the many parameters
  - Integration of a-priori knowledge (e.g., shape)

Snakes

- Parametric contour $\vec{s}(s), \quad s \in [0,1], \quad \vec{s}(0) = \vec{s}(1)$
- Internal energy from elasticity α and stiffness β

$$E_{int} = \int_0^1 \alpha \left| \frac{d\vec{s}}{ds} \right| + \beta \left| \frac{d^2\vec{s}}{ds^2} \right|$$

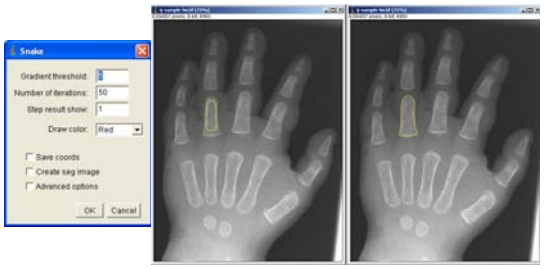
- External energy from edge filtered image

$$E_{ext} = \int_0^1 \text{grad}\left(f(\vec{s}(s))\right) ds$$

- Numerical minimum search of $\vec{s}(s)$
  - Requires good initial contour
- Different discrete implementations

Snakes

- ImageJ



Balloons

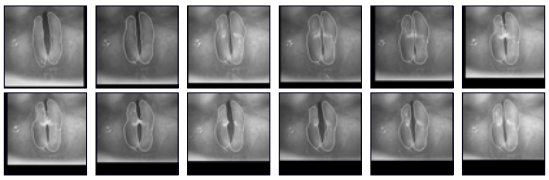
Directed movement of edges and vertices

- Pressure (orthogonal to contour) $\vec{F}^{p}$
- Stiffness (minimization of 2. derivative) $\vec{F}^{st}$
- Image influence $\vec{F}^{e}$
  - from gray scale potentials $\Phi(\mathbf{w})$
  - through rotation adaptive convolution with edge pattern (matched filter) $h(h)$

$$|\vec{F}^{e}| = \sum \Phi(\mathbf{w}) \cdot h(-h)$$

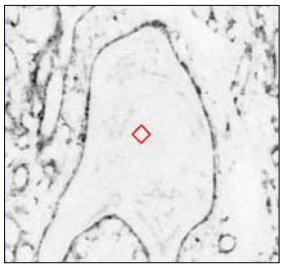
Example: Laryngoscopy

- Contour tracking of vocal cords
  - Snake



Example: Microscopy

- Segmentation of the cell membrane
  - Balloon with inner forces

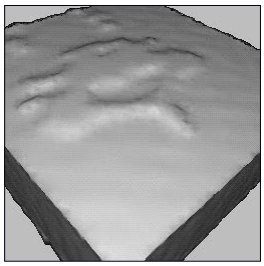


Example: Video

- Tracking of lip motion in phoniatrics
  - 2D snake approach

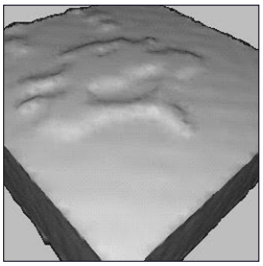
Example: CT

- 3D segmentation of spine
  - Deflating balloon



Example: CT

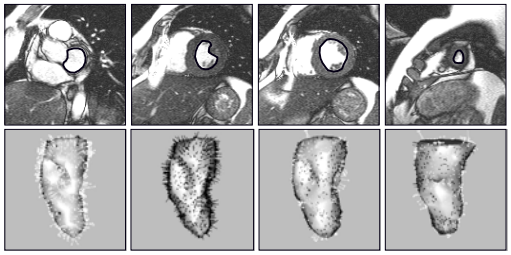
- 3D segmentation of spine
  - Deflating balloon



- 3D segmentation of orbita
  - Inflating ballon

Example: MRI

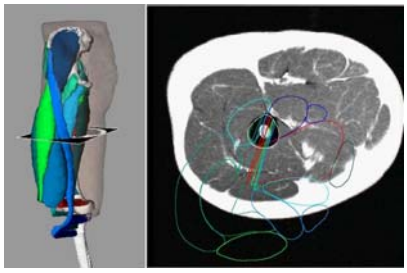
- 4D segmentation of the ventricle volume
  - Inflating balloon



Diastole Systole Cycle Cycle (rotation)

Example: MRI

- 3D segmentation of individual muscles
  - Multiple contours interacting in multi-resolutions



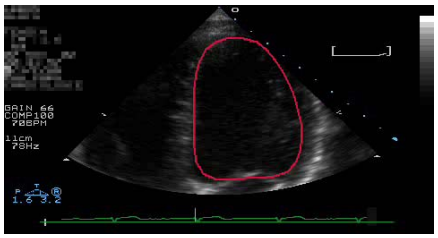
Active Appearance Models

- Cootes et al. IEEE PAMI 2001
  - Active shape model
  - Warp image into mean shape (shape-free model)
  - Principle component analysis
    - Shape
    - Texture (appearence)
  - Apply model to data (active)
- Application
  - Face recognition (eigenfaces)
  - Medial …

Fernando de la Torre

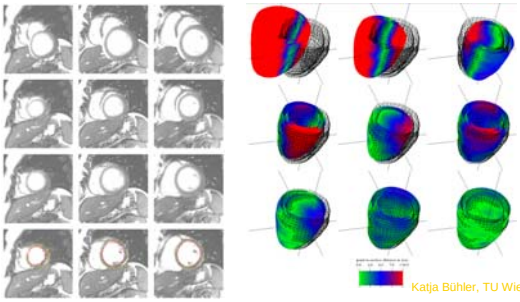
Active Appearance Models

- 2D example
  - Wall motion tracking in ultrasound



Active Appearance Models

- 3D example: left ventricle in MRI



Katja Bühler, TU Wien

Summary

- Segmentation
  - Localization (man)
  - Delineation (machine)
- Algorithms
  - Thresholding
  - Clustering
  - Region growing

Summary

- Traps (draws)
  - Semantic
    - Over segmentation
    - Under segmentation
  - Inherent
  - Algorithmic

Summary

- Methods
  - Thresholding
  - Clustering
  - Livewire
  - Region growing
  - Region merging
  - Template matching
  - Hough transform
  - Watershed transform
  - Active shape
  - Active contours
  - Active appearance
- Levels
  - Pixel
  - Edge
  - Region
  - Object
  - Scene