Segmentation algorithms

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Outline

- Definition
- Data
- Methods classification
- Examples
- Algorithms
- Conclusion
Image segmentation

Definition

\[ S : I \rightarrow R \quad I \text{ image} , \ R = \{1, \ldots, n\} \]

Alternatively

\[ \bigcup_{i=1}^{n} R_i = I \]

\( R_i \) is connected

\[ R_i \cap R_j = \emptyset \quad \forall_{i, j} \quad i \neq j \]

Background/Foreground

Many segments → over-segmentation

Regions, surface, lines
Applications

- Volume measurement
- Visualization improvement
  - Removing unimportant, uninteresting parts
- Early step of image understanding
  - Classification of segments
- Dual to image registration
  - Better registration ↔ Better segmentation
- Information reduction
  - Compression algorithms
- There is no ideal algorithm
Data

- **Raster image**
  - Matrix of picture elements
  - Digital image theory
  - High frequency (edges) vs. Low frequency (regions)

- **Volumetric data**
  - Volume elements
  - Edges $\rightarrow$ Border surfaces

- **Vector data**
  - Meshes

- **Multidimensional data**
  - Clustering
Methods classification

- **Edge based**
  - “An edge separates two regions”
  - Edge in 3D?
  - Image enhancement & Edge extraction algorithms

- **Region based**
  - “Region is a continuous set of similar pixels”
  - Homogeneity criterion
Image information

- **Noise**
  - Everytime & Everywhere & Everyscale
  - Different characteristics

- **Decision about element's regions based on**
  - Intensity
    - Global methods, global information
  - Intensity & position
    - Local methods, local information
  - Intensity & position & region shape
    - Methods with prior information
Speed of segmentation

- **Real-time**
  - Simple and rough methods
- **Interactive**
  - User assistance
- **Off-line**
  - Parallelization
  - Multiple phases, scales
  - Combination of different algorithms
# Autonomy

- **Manual**
  - Tedious user interaction

- **Semi-automatic**
  - Parameter tweaking
  - Initialization (position, first approximation)

- **Interactive**
  - Continuous interaction, acknowledgement

- **Automatic**
  - Fully autonomous
  - Less important part of production or QA process
  - Reliable
Examples

- Automatic
  - Palatum
- Semiautomatic
  - Kidneys
  - Cranium
- Interactive
  - Hip joint
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Segmentation pipeline

- Complicated algorithms
- Preprocessing
  - Image enhancement
- Scaling
  - Information reduction
  - Speedup
- Rough segmentation
- Segmentation refinement
- Segmentation enhancement
  - Isolated pixels removal, Holes filling, Morphological operations - erosion/dilatation/thinning/...
Thresholding

\[ S(x) = \begin{cases} 
  r_1 & \text{if } x < \text{threshold} \\
  r_2 & \text{if } x \geq \text{threshold}
\end{cases} \quad x \in I \]

- Frequently used
  - Simple, Manual
- Global method
  - Localized methods exist
- Automatic
  - Histogram based, Statistics
  - Sezgin & Sankur: Survey, 2004, 40 methods
- Multiple regions – multiple thresholds
Thresholding algorithms

- Simple algorithm
  1) Initial threshold $T_0$
     \[ m_i = \frac{1}{\| M_i \|} \sum_{x \in M_i} I(x) \]
  2) Means of two groups
  3) New threshold
     \[ T_t = \frac{1}{2} (m_1 + m_2) \]
  4) Repeat from 2. until $T$ changes

- Otsu's algorithm
  1) Normalized histogram
  2) Cumulative sums, means
     \[ P_i = \sum_{k_{i-1}}^{k_i} p_i \]
     \[ m_i = \sum_{k_{i-1}}^{k_i} j p(j|C_i) \]
  3) Between-class variance
     \[ \sigma^2_B = P_1 (m_1 - m_G)^2 + P_2 (m_2 - m_G)^2 \]
  4) Maximize between class variance
Region growing

- Similar to flood fill algorithm
  - seed(s) initialization – manual/automatic
  - one adjacent element per step
- Propagation depends on homogeneity criterion
  - Involves tresholds
- Variations
  - Adaptive homogeneity, Pohle 2001
  - Sphere of elements in one step, Fiorentini 2001
Region growing - example
Watershed segmentation

- Multiple regions (catchment basins) segmentation
- Gradient of preprocessed image
- Two phase process
  - Minima detection (manual → markers, automatic)
  - Watershed lines construction
  - Vincent & Soille 91
- Various modifications
- Subsequent post-processing
Watershed segmentation
Splitting & Merging

- Region based technique
- Unary predicate Q which is
  - TRUE if the parameter is likely to be region of segmentation
  - FALSE otherwise
- Image is recursively divided into quadrants
  - Splitting as long as Q is FALSE
  - Merging as long as Q is TRUE
- Various modification of the scheme
Hough transformation

- Edge based technique
- Connect several edge pixels to lines/curves
- “Which pixels form a line/curve?”
- Dual idea (lines example)
  - Each pixel possibly belongs to infinite number of lines
  - Which line has the most pixels?
  - Space of all lines $\rightarrow$ discretization $\rightarrow$ accumulator
    - Angle and shift
- Extendable to arbitrary dimension/shape
  - Computationally expensive
Hough transformation
Graph based methods

- Dijkstra shortest path algorithm
  - Limited to 2D data
  - Path between two points locally separating two regions
    - Does not separate two regions in the image
    - In polar space it does
  - Graph (V,E)
    - V pixels
    - E between adjacent pixels (4-, 8- adjacency)
  - Weight of edges depends on application
  - Heuristics (A* algorithm)

- Dynamic programming
Dijkstra shortest path
Graph based methods

- **Graph cut**
  - Partition of the graph into two sets
  - Minimum cut
    - sum of edge weights between partitions is minimum
  - Virtual sink & source connected to each image element
  - Minimum cut algorithm finds partitioning (segmentation)
    - Depends on weights of edges (application dependent – intensity, color, position, motion, fit into intensity model)
  - Partitioning into multiple segments is possible
  - Arbitrary dimension
Graph cut

(a) Image with seeds.

(b) Graph.

(c) Cut.

(d) Segmentation results.
Clustering

- Clusters are regions of segmentation
- Clusters are sets of pixels with the same properties (position, color)
- K – means clustering
  - Assign each pixel to cluster minimizing variance
- Lloyd's algorithm
  1) Cluster centers initialization – random/heuristic
  2) Assign each pixel to cluster minimizing distance
  3) Recompute cluster centers
  4) Repeat from point 2) until center positions change
Mean shift

- Cluster analysis method
- Each member of a data cloud undergoes an iterative procedure → shifting to a certain point of convergence
- All points shifting to one point of convergence belong to the same cluster (region of segmentation)
Mean shift - algorithm

For each pixel → $x_0$
- Until converged
  \[ x_{i+1} = x_i + \nabla f(x_i) \]
  \[ f(x_i) = \frac{1}{nh^d} \sum_{y \in I} K\left(\frac{y-x_i}{h}\right) \]

  \[ i = i + 1 \]

- Merge pixels which are close
  - Under certain threshold

- Remove small regions
Mean shift - examples
Active models

“Optimization of relation between geometrical representation of shape and sensed image”

Relation
  - Characteristics – edges, region intensity

Representation
  - Curves, Planes, Binary masks, Hypersurface

Optimization
  - Numerical method of finding function minimum
Active contours - snakes

- Generally for 2D data
  - Extendable to 3D via surfaces or slice-by-slice
- Optimization of (closed) curve to fit an object the best
  - Initial position - close to result, inside/outside result
  - Interactivity
Active contours - snakes

- Various criteria (parametrized by contour)
  - Edges
  - Smoothness
  - Area homogeneity

- Various contour representations

\[
E_{\text{edge}}(v) = \int_0^1 |\nabla I(v(t))| \, dt
\]

\[
E(v) = E_{\text{edge}}(v) + E_{\text{smoothness}}(v)
\]
Active contours - snakes

- Various extensions
  - Balloon force
  - Vector flow
  - Geodesic contours

- ITK – SNAP
  - Software
  - Experimental
Level sets

- A set of points induced by real valued function

\[ v = L_c = \{(x_1, x_2, \ldots, x_n) \mid f(x_1, x_2, \ldots, x_n) = c\} \]

- Other application
  - Shape representation for active models segmentation
  - Fluid simulations, PDE solution, Implicit surfaces

- Pros
  - Arbitrary dimension (2D, 3D, 4D), topology

- Cons
  - Slow, but easily parallelizable
Basic level sets segmentation

- Initialization
  - Regular shape (circle, sphere), user input
  - Construction of a level set
- Until converged
  - For each grid point $x_0$

$$f_t(x) = f_{t-1}(x) + \frac{\partial f(x)}{\partial t} \quad \iff \quad c_t(x) = c_{t-1}(x) + \frac{\partial c(x)}{\partial t}$$

$$\frac{\partial f(x)}{\partial t} = F(x) |\nabla f(x)|$$

$$F(x) = F_{balloon} + F_{curv} + F_{region}$$

- Reconstruct curve(s) $c$
Level set speed up techniques

- Narrow band
- Fast marching front
- Sparse fields
- Octree
- Distance transform
Off topic – Level set morphing
Active shape

- Prior information incorporated into active models
  - Shape

- Two phases
  - Model construction/learning from training set
  - Segmentation – model fitting to data

- Shape representation
  - PDM
Active shape - learning phase

- Set of examples
  - Big enough, distributed well

- Alignment - registration

- Mean shape

- PCA
  - Covariance matrix, eigenvectors, eigenvalues

- Model

\[ \text{shape} = \text{meanshape} + \sum b_i \text{component}_i \]
Active shape - segmentation phase

- Optimize shape and position parameters
  - Minimizing criterion
    \[ E_{fit}(a, b) = S(I, T_a(m + \sum b_i c_i)) \]

- Strategy of minimization depends on application
  - Edge guided
  - Genetic approach
  - Numerical optimization

\[ E_{fit}^{k+1}(a, b) = E_{fit}^k(a, b) + \nabla_{a, b} E_{fit}^k \]
Active appearance

- Shape and intensity prior information active models
  - Intensity profiles along the contours – mean profiles
  - Intensity of the whole image – mean image
Atlas-based segmentation

- Shape, intensity, spatial relations, ... priori information
- Loosing ability to segment extreme cases
  - Pathological subjects
- Registration of atlas (labeled) subject to segmented
  - Corresponding elements induce segmentation
Atlas-based approaches

**IND:** Segmentation using a single individual atlas.

**SIM:** Segmentation using the “most similar” individual atlas.

**AVG:** Segmentation using an average shape atlas.

**MUL:** Independent segmentation using multiple individual atlases with decision fusion.
Conclusion

- Good segmentation algorithm is
  - Robust
  - Fast (useful)
  - Precise

- Good segmentation way
  - Combination of several methods
  - Incorporation of prior information

- Implementation
  - MedV4D interface to ITK (segmentation and registration algorithms)
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