Medical Image Processing
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From Basics to Complex Algorithms

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Conflict of interest

I have previously worked for the company ContextVision
Outline

• What is an image? How is it represented?

• 2D, 3D, 4D data

• Basic operations
  (Fourier transform, filtering, interpolation)

• Complex algorithms (image registration, image segmentation, image denoising)
What is an image?

• An image is a 2D signal, where each pixel represents some property (e.g. light intensity)

• Most common case; images from a digital camera

• Each pixel is accessed by a 2D coordinate (x,y)

• Each pixel can store more than one value, colour images store red, green, blue values
2D Example (MRI)

For a 8 bit image

Black is represented as 0

Gray is represented as 128

White is represented as 255
2D Example
2D, 3D, 4D data

• Image processing normally refers to 2D images (e.g. Photoshop)

• Medical image processing is normally done on 3D or 4D datasets
2D, 3D, 4D data

• 2D images cannot represent parts of the human body, like the heart or the brain

• The image concept can be extended to 3 dimensions

• A volume is a 3D signal, where each voxel represents some property
3D Example - MRI
2D, 3D, 4D data

• Volumes can only represent static objects, not moving objects such as a beating heart (3D data can also be 2D + time, e.g. video)

• The image concept can be extended to 4 dimensions

• Several volumes can be seen as a 4D signal, where each dynamic voxel represents some property
2D, 3D, 4D data

2D
One image of size
512 x 512

3D
One volume of size
512 x 512 x 512

4D
Many volumes
128 x 128 x 64 x 1000
Basic operations – Fourier transform

• Sometimes it is beneficial to look at a signal in the frequency domain

• A Fourier transform changes the signal from a function of time (1D) or space (2D, 3D, 4D), to a function of frequency

• From a linear algebra perspective, a Fourier transform is a change of basis
Basic operations – Fourier transform

• 1D: Scalar product between the signal and sine / cosine basis functions of different frequency $(e^{iw} = \cos w + i \sin w)$

$$F(\omega) = \mathcal{F}(f(t)) = \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt$$

Scalar product

Signal as function of frequency

Signal as function of time

Basis functions
Basic operations – Fourier transform

• Fourier transforms are typically applied using the fast Fourier transform (FFT)

• 2D: First apply 1D FFT’s to each row, then to each column (or vice versa)

• 3D: First apply 1D FFT’s along x, then along y, then along z

• nD ...
Fourier transform – 1D Example

Signal was created using sines with 4 frequencies
Fourier transform – 2D Example
Basic operations - filtering

• Filtering is one of the most important operations in image processing

• Extract features from an image, like edges and lines, by applying a filter

• Often used as an important preprocessing step, or in every iteration of an algorithm
A Gaussian lowpass filter – Weighted averaging
Filters for edge detection (Sobel)

- Detect edges along $x$-direction
  - $\begin{bmatrix} 1 & 0 & -1 \\ 2 & 0 & -2 \\ 1 & 0 & -1 \end{bmatrix}$

- Detect edges along $y$-direction
  - $\begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix}$
Filtering – Edge detection

Edges along x-direction

Edges along y-direction
Filtering – Edge detection

• Combine edge images as $\sqrt{x^2 + y^2}$
• Bright pixels represent an edge
Convolution

- Convolution = scalar product between filter values and pixel values in each neighbourhood

- Slide the filter over all pixels, save each result in the center pixel

\[
(s * f)[x, y] = \sum_{f_x = -N/2}^{f_x = N/2} \sum_{f_y = -N/2}^{f_y = N/2} s[x - f_x, y - f_y] \cdot f[f_x, f_y]
\]
Convolution - Example

Filter (11x11)

Current filter response

Multiply each filter coefficient with the corresponding pixel value, store the sum in the center pixel
Basic operations - interpolation

- All original pixel values are located at integer coordinates.
- Interpolation is required for any operation that requires a pixel value at a non-integer coordinate.
- What is the pixel value at coordinate (223.22,140.92)?
Basic operations - interpolation

• When do we need interpolation?

• Changing the size of an image

• Rotations

• Translations

• Non-linear transformations
Vector field for rotation
Each vector describes how to move that pixel
Interpolation - Example

• Move the image 15 pixels in the x-direction, 20 pixels in the y-direction and rotate it 20 degrees
Interpolation methods

• Nearest neighbour

• Linear

• Cubic

• Spline

• Sinc
Interpolation – Nearest neighbour

• The interpolated value is given as the value of the nearest neighbour

• Quick, but bad quality

• Useful if you work with images that only should have integer values (e.g. a brain mask where each pixel is 0 or 1)
Interpolation – Bilinear

• Uses the 4 closest neighbours to calculate the interpolated value

• The neighbours are weighted with the inverse distance to the desired location

\[ I = (1 - \Delta x)(1 - \Delta y)I_{11} + \Delta x(1 - \Delta y)I_{21} + (1 - \Delta x)\Delta yI_{12} + \Delta x\Delta yI_{22} \]
Interpolation – Trilinear

• Interpolation in 3D

• Uses the 8 closest neighbours to calculate the interpolated value

• The neighbours are weighted with the inverse distance to the desired location
Complex algorithms

- Image registration, to align two images or volumes
- Image segmentation, to extract a certain part of an image or volume
- Image denoising, to suppress noise and improve image quality
Image registration

- Image registration is needed whenever you want to align two images or volumes
- Compare a subject before and after surgery
- Combine different medical imaging modalities
- Make a group analysis of fMRI data (transform all subjects to a brain template)
- Motion correction in fMRI, align each volume to the first one
Image registration - Example

Subject at timepoint 1

Subject at timepoint 2
Image registration - Example

T1-weighted MRI volume

T2*-weighted volume (fMRI)
fMRI – Head motion

Translation (mm)

Time
Image registration

• Use a similarity measure to calculate how similar two images are

• Maximize the similarity measure by keeping one image fixed, while changing the other one

• Use an optimization algorithm to find the best transformation parameters (e.g. translations, scalings and rotations)
Image registration - Algorithm

1. Calculate similarity measure between images

2. Calculate a new set of transformation parameters (using some optimization algorithm)

3. Apply transformation using interpolation

4. Go to 1
Image registration

• What kind of similarity measures can be used?

• Normalized cross correlation (NCC)

• Sum of squared differences (SSD)

• Mutual information (MI)

• …
Image registration - Example

• Movie created using normalized cross correlation, linear interpolation and the optimization algorithm fminsearch in Matlab
Image segmentation

• Image segmentation is needed whenever you want to study a specific part of a dataset

• How big is the brain tumour?

  Has it grown since a previous timepoint?

• How much white brain matter does a subject have?

• How large are the blood vessels?
Image segmentation - Example

Before and after surgery
There are many image segmentation algorithms. No algorithm can solve all problems.

- Thresholding
- Level sets
- Active contours
- Region growing
- Watershed
- Graph cuts
- ...
Active contours

• Represent a curve by a large number of nodes

• Move the nodes by minimizing different energy measures, energy of the contour, energy of the image, ...

• Calculate optimal forces for each node

• Move nodes according to the forces, iterate

Active contours – basic idea

Object to be segmented

Active contour
Active contours - Example
Image denoising

• Image denoising is used to suppress noise and improve the image quality

• Makes it easier for a medical doctor to do a diagnosis

• Often used before image registration or image segmentation, to improve the result
Image denoising - Ultrasound

- Images provided by ContextVision
Image denoising - MRI

- Images provided by ContextVision
Image denoising

• Just as for image segmentation, there are many image denoising algorithms
  • Bilateral filtering
  • Anisotropic diffusion
  • Adaptive filtering
  • Non-local means
  • …
Bilateral filtering

• Applying a lowpass filter is the most simple case of image denoising, since noise is high frequency

• Edges and lines are, however, also high frequency components, they will be blurred

• Can we somehow prevent this blurring?

Tomasi et al., Bilateral filtering for gray and color images, International Conference on Computer Vision, 1998
Bilateral filtering

• A Gaussian lowpass filter only weights neighbouring pixels by the spatial distance
Bilateral filtering

- A bilateral filter also looks at the **values** of the neighbouring pixels, how similar are they?
- Non-linear operation, the filter is different in each pixel

Center pixel is not close to an edge, average all neighbouring pixels

Center pixel is close to an edge, only average neighbouring pixels with similar intensity values
Bilateral filtering

(a) Noisy data  (b) After low-pass filtering  (c) After bilateral filtering

From the PhD thesis of Joakim Rydell
Summary

• Images are 2D signals, volumes are 3D signals

• CT, MRI and ultrasound are the most common medical imaging modalities

• Fourier transforms, filtering and interpolation can be applied in any dimension

• Image registration, image segmentation and image denoising are the most common algorithms
Questions?