Medical Imaging, Acquisition and Processing

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Overview

- Introduction and motivation
- Modalities (acquisition devices)
  - Microscopy, X-rays, CT, Ultrasound, PET/SPECT, EEG/MEG, …
- Data processing
  - Preprocessing, Reconstruction, Segmentation, Registration, Classification, …
- Conclusions
Medical imaging pipeline
Medical imaging pipeline example

- Patient/subject
  - Physical property
    - Imaging device
      - Raw data
        - Preprocessing
          - Improved data
            - Reconstruction
              - Images/volumes
                - Interpretation
                  - Quantitative/qualitative inf.
                    - Physician
                      - Decision
Medical imaging pipeline example

- Patient/subject
  - Physical property
    - Imaging device
      - Raw data
        - Preprocessing
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                  - Quantitative/qualitative inf.
                    - Statistical processing
                      - Decision

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Physical property:
density, absorbance,
conductivity, …

Examples:
- CT, X-rays, MRI, ultrasound, …
Preprocessing

A priori knowledge

Raw data  Preprocessed, cleaned, enhanced data

Preprocessing

Examples:
- Noise suppression, contrast enhancement, intensity equalization, outlier elimination, bias compensation, time/space filtering, ...
Reconstruction

Physics of the acquisition device

Preprocessed raw data

Reconstruction

Physically meaningful images, volumes, sequences

Inverse problem

Examples: Tomographic reconstruction

MRI, ultrasound …
Interpretation

A priori knowledge

Images, volumes, sequences

Interpretation
High-level processing

Quantitative & qualitative inf.

size, changes, metabolic inf.

Examples:
- Registration, segmentation, classification, tracking,...
Modalities
Microscopy

Optical microscopy – since 17th century; Jensen, van Leeuwenhoek, Galilei, …
Microscopy — examples

placenta cross-section
Microscopy — examples

muscle capillaries
Microscopy — examples

crocodile ear slice
Microscopy — examples

retina
Microscopy — types & trends

- Electron microscopy
  - Electron transmission microscopy
- Confocal microscopy – reject out-of-focus light, scanning
- Phase-contrast microscopy
- Fluorescence microscopy
  - fluorescent dyes
  - multiple sensing channels/filters
  - multiple light sources – visible, UV
- CCD cameras
  - supercooled
  - superresolution
- Moveable specimen tray
  - Auto-focussing
  - Automated acquisition, mosaicking
Microscopy

Advantages
- High-spatial resolution
- Colour and texture information
- Affordable (optical microscopy)
- Proven technique – large body of experts available

Disadvantages
- Difficulties of in-vivo observations
- Inherently 2D
- Missing large-scale perspective
X-rays / Radiography

1895, W. Röntgen  B. Röntgen hand  modern hand
X-rays / Radiography (2)

Modern chest radiography machine
X-rays / Radiography (3)

Chest X-ray:
X-rays / Radiography (4)

- Advantages
  - Widely used and available
  - Experts available
  - High-spatial resolution
  - Excelent imaging of hard tissues (bones)

- Disadvantages
  - Radiation exposure
  - Difficulty in imaging soft-tissues
  - 2D projection, hidden parts
X-rays / Radiography (5)

- New trends
  - CCD sensors replace film
  - higher sensitivity, faster exposure, lower dose
  - dynamic imaging
Computed tomography

The machine:
Computed tomography (2)

Principle:
Computed tomography (3)

Example, lungs:
Computed tomography (3)

Example, head:
Computed tomography (4)

- Advantages
  - 3D volume
  - High-spatial resolution

- Disadvantages
  - Increased radiation dose
  - Longer acquisition times
  - Shadows, difficulties imaging soft-tissues
  - Costly equipment
Ultrasound – Equipment
Ultrasound – Equipment
Ultrasound (2) – Examples

Fetus
Ultrasound (2) – Examples

Heart

LV

Shindler
Ultrasound (2) – Examples

Heart, Doppler
Ultrasound (3)

- **Advantages**
  - Low-cost
  - Proven technique – Experts available
  - Not invasive, no harmful effects
  - Good imaging of soft tissues
  - Easy dynamic acquisition

- **Disadvantages**
  - Low-signal quality, speckle noise
  - Low penetration depth or low spatial resolution
  - Shadows from bones and other thick tissues
  - Mostly 2D
Ultrasound (4)

- New trends
  - 3D ultrasound
  - High-frequency ultrasound
  - Doppler ultrasound
MEG and EEG

Magnetoencephalography  Electroencephalography
MEG sensors

SQUID array

Gradiometers
Currents in the brain

Quadripolar structure of action potential

Action Potential

Propagation

Axon Membrane

-80 mV

100 mV

1 ms

K+

Repolarization

Na+

Depolarization

K+

Ion-pump

Na+

Ion-pump

Primary currents $J^p[A/m^2]$
Magnetic measurements
Source localization

Surface field:

Brain field:
MEG and EEG

Advantages

- EEG widely available
- Excellent temporal resolution, can observe brain activities at ms resolution

Disadvantages

- MEG extremely expensive
- Poor spatial sampling / resolution
- Good reconstruction algorithms not yet available
- Necessity of a good head model
Magnetic resonance imaging (MRI)

MRI – Principles


2. Protons wobble in alignment with magnetic fields of varying intensity; frequency of wobble is proportionate to strength of individual magnetic field.

3. A brief radio signal, whose soundwave frequency equals the frequency of wobble of certain protons, knocks those protons out of alignment.

4. When radio signal ceases, protons snap back into alignment with magnetic field, emitting a radio signal of their own, that announces the presence of a specific tissue.

\[ \omega = \gamma B \]
CREATING Refined ANATOMICAL IMAGES

Within the metallic cocoon of an MRI scanner, the patient is surrounded by four electromagnetic coils and the components of a transceiver.

Scanner
Uses electromagnets and radio signals to produce cross-sectional images

Y Coil
Creates a varying magnetic field from top to bottom across the scanning tube.

Z Coil
Creates a varying magnetic field from head to toe within the scanning tube.

Transceiver
Sends radio signals to protonate and receives signals from them.

X Coil
Creates a varying magnetic field from left to right across the scanning tube.

Main Coil
Surrounds patient with uniform magnetic field.

Patient
Wears loose clothing; must empty pockets of metallic objects that could prove harmful if moved by magnetic force.

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MRI – Example

Brain slice:
MRI

- Advantages
  - Good spatial resolution
  - True 3D acquisition
  - Excellent contrast for all tissue types
  - In vivo, non-invasive, no radiation

- Disadvantages
  - Very expensive
  - Acquisition somewhat long (3D)
  - Poor temporal resolution (3D)
  - Patient discomfort — noise, claustrophoby
  - Strong magnetic field
MRI – Types and trends

- Sequences: gradient-echo, spin-echo,…
- Weighting: T1, T2, PD, BOLD,…
- Acceleration: EPI, FLASH, parallel, …
- Modalities: fMRI, perfusion, flow, …
Other imaging methods

- Positron emission tomography (PET)
- Single positron emission tomography (SPECT)
- Gamma camera
- Termography
- …
Medical data processing
Medical imaging specificities

(wrt. Computer vision)

- We want the physical reality, not to emulate human perception.
- We deal with many modalities, optical intuition often does not apply.
- Data are rare and expensive — maximum information must be extracted. Approximations to be avoided if possible.
- Data are continuous, result is continuous — we do not decide, we help to decide
- Algorithms must be robust and safe — give no answer or a conservative answer, rather than a wrong answer.
- Physician is the ultimate judge — computer is a tool.
- Accountability and verifyiability help credibility. Medical comunity wants clinical trials.
Basic data processing tasks

- Low level operations
- Segmentation
- Registration
- Classification
- Reconstruction / Inverse problems
- ...
Contract enhancement

original

enhanced
Edge detection

retinal cells
Segmentation

Divide image into classes.
Segmentation (2)

- Easy for humans, difficult for computers.
- We do not know how brain perform segmentation.
- Algorithm is image and task dependent, needs a priori knowledge.
- Useful for:
  - Separating objects, masking background
  - Image simplification
  - Shape, size and other statistics
How do we segment?

Cells are black.
How do we segment?

Cells are homogeneous connected components.
How do we segment?

Arteries are bright and elongated.
Segmentation from MRI (T1)

original, gray and white brain matter, CSF
Image registration

- Find corresponding points
- Manual, automatic, semi-automatic
- Useful for:
  - Comparing images from different times
  - Comparing images from different methods
  - Comparing images from different subjects
  - Analyzing movement
  - Segmentation
- Provides qualitative and quantitative information.
Image registration (2)

Reference image \rightarrow \text{registration} \rightarrow \text{deformation} \rightarrow \text{warped image} \\
\text{registration} \rightarrow \text{test image} \rightarrow \text{warping}
Image alignment

reference

before

test
Image alignment

reference

before

warped

test
Manual registration

- Landmark identification
- Landmark interpolation
Registration as minimization

Reference image → difference → optimization → criterion E → deformation function $g(x)$ → deformation → deformation function $g(x)$ → optimized image
Registration examples

- EPI distortion

After
Registration examples

- EPI distortion
- MRI atlas

Atlas
Registration examples

- EPI distortion
- MRI atlas
- CT alignment

After
Registration examples

- EPI distortion
- MRI atlas
- CT alignment
- SPECT atlas

(With University Hospital in Geneva)
Registration examples

- EPI distortion
- MRI atlas
- CT alignment
- SPECT atlas
- Ultrasound

velocity (with María J. Ledesma-Carbayo)
Registration examples

- EPI distortion
- MRI atlas
- CT alignment
- SPECT atlas
- Ultrasound
- MRI heart sequence
Registration examples

- EPI distortion
- MRI atlas
- CT alignment
- SPECT atlas
- Ultrasound
- MRI heart sequence
- MRI perfusion
Tomographic reconstruction

The problem
Tomographic reconstruction

Solution
Tomographic reconstruction

Another solution
The Radon transform is defined as

$$ (Rf)(\theta, u_j) = \int f(t \cos \theta - u_j \sin \theta, t \sin \theta + u_j \cos \theta) \, dt $$

for angle $\theta_i$. The figure illustrates the integration over a line $s_{i,j}$ in the $(t,u)$ plane.
The Radon transform for a function $f$ is defined as:

$$(\mathcal{R}f)(\theta_i, u_j) = \int f(\cos \theta_i - u_j \sin \theta_i, \sin \theta_i + u_j \cos \theta_i) \, dt$$

where $\theta_i$ is the angle of the line, and $u_j$ is a parameter.

The integral represents the projection of the function $f$ onto a line with angle $\theta_i$. The result $I$ is given by:

$$I = I_0 \exp \left(- \int_{\mathcal{S}} \rho(\mathbf{r}) \, ds(\mathbf{r}) \right)$$

where $\mathcal{S}$ is the support of the function $\rho(\mathbf{r})$. This expression models the attenuation of a ray traversing the object, with $I_0$ being the initial intensity and $\rho(\mathbf{r})$ the density of the object at position $\mathbf{r}$.
Reconstruction algorithms

Phantom

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Reconstruction algorithms

Backprojection

Variational reconstruction

8 angles (each 22°), 32 samples per angle
Other algorithms and topics

- Inverse problems – MEG, optical tomography, …
- Classification – is the patient/sample healthy?
- Optical, shape reconstruction — provide 3D shape
- Texture analysis
- Machine learning, uncertainty
- Related subjects:
  - Databases and information infrastructure — PACS (Picture Archiving and Communication Systems)
  - Expert systems, knowledge engineering, data mining. . .
Medical imaging – Conclusions

Medical imaging experiences a recent boom:
- Many modalities
- Instruments are digitalized and more widespread
- More powerful and affordable computers
- Large quantity of data is produced.

Computers can help to:
- make data meaningful
- extract previously unavailable information
- visualize, compare and analyse
- scan for abnormalities
- provide the right information for physicians to make the decision
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