Medical Imaging and Virtual Medicine

Lecture 1:
Volume data, Sampling theorem, Artifacts, Filtering

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Wilhelm Schickard, 1592 - 1635

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1623 invention of first calculation machine

(Blaise Pascal's Pascaline 1642)
Einführung (1)

Literature:

D. Bartz: Advanced Virtual Medicine
ACM SIGGRAPH Course 52, 2002

http://www.gris.uni-tuebingen.de/~bartz/tutorials
Einführung (2)

Literature:


Einführung (3)

Literature:

Proceedings:

• MICCAI
• EG/VGTC EuroVis
• IEEE Visualization
• CURAC: http://www.curac.org
• Computer Aided Radiology and Surgery
• Medicine meet Virtual Reality
Web Resources

- VTK: Visualization Toolkit: www.kitware.com/vtk
- NLM ITK: Insight Segmentation and Registration Toolkit: www.itk.org
- Registration Toolkit: www.image-registration.com
- OFFIS / DICOM Toolkit: www.offis.de/projekte/dicom/project_dicom4.htm
Volume Data (1)

Volume Data / Image Stack:

• Images/slices are composed of **image elements** – Pixel (Picture Element)

![Image of 2D pixel grid]

Pixel, Grid point/ Data point

Volume Data (2)

• **Volume Data** (Volume) are composed of stack of images.

• Volume elements are called **Voxels**.

![Image of 3D voxel grid]

Voxel, Grid point/ Data point
Terminology:

• **Volume cell** or simply cell

• Voxel distances or **voxel spacing**
  • **Pixel distance** (x/y) - distance with a slice
  • **Slice distance** (z) – distance between slices

Terminology, cont’d:

• **Isotropic** datasets: Pixel- and slice distance are equal

• **Anisotropic** (non isotropic) datasets: Pixel- and slice distance are different
Interpolation in Volume Data:

- Nearest Neighbor (non-continuous)
- Data points has voxel value of voxel closest to him (Clamping)
- Outdated concept

Trilinear Volume Interpolation:

- Four linear interpolations on edges
- On top of that, two linear interpolations (two bilinear interpolations)
- On top of that, one linear interpolation
Grid Types:

- **Regular** grids
  - **Cartesian, uniform** grids:
    - Spacing: regular
    - Geometry: regular
    - Topology: regular
    - Cell type: same

- **Non-Uniform** grids:
  - Spacing: irregular
  - Geometry: regular
  - Topology: regular
  - Cell type: same

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Grid Types, cont'd:

- **Regular** grids

- **Curvilinear** grids:
  - Spacing: irregular
  - Geometry: irregular
  - Topology: regular
  - Cell type: same
Grid Types, cont’d:

• **Irregular** grids
  - **Unstructured** grids:
    - Spacing: irregular
    - Geometry: irregular
    - Topology: irregular
    - Cell type: same

• **Hybrid** grids:
  - Spacing: irregular
  - Geometry: irregular
  - Topology: irregular
  - Cell type: mixed
Volume Data Acquisition (1)

In Scientific Computing/Visualization:

- **Measured** (measured value, scanner)
- Simulated (CFD, Physics, chemistry, etc.)
- Modeled (CAGD, CSG, etc.)

In Medical Imaging: Mostly scanned data

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Volume Data Acquisition (2)

**X-Rays (Röntgen)**

2D projection images based on absorption and scattering

- Very high resolution (now)
- Bone/tissue contrast due to choice of hard/soft radiation
- Only 2D
- 1895 discovered by Conrad Röntgen

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Volume Data Acquisition (3)

X-Rays:

- Pelvis overview
- Hand of wife of C. Röntgen

Volume Data Acquisition (4)

Computed Tomography (CT):

3D Volume is reconstructed from series of x-ray profiles (covering 360°).

- 1972 demonstrated by Godfrey Hounsfield
- Based on work of J. Radon (1917), A. Cormack (1963), and H. Lorenz (1905)

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Volume Data Acquisition (5)

**Computed Tomography (CT):**

- Radon-Transformation reconstructs cartesian grid data from projection profiles
- Based on Fourier transformation

![Diagram of X-ray emitter and detector with intensity profile / projection data](image)

Volume Data Acquisition (6)

**Computed Tomography (CT):**

- Spiral- (helical) and Multi-Slice CT (4, 16, ...)
- Cone beam reconstruction
- Planned: 256 slices (full detector array)
- Pro’s:
  - Better usage of radiation
  - Faster
  - Higher resolution
- But of course also more expensive

![Diagram of single, dual, and quad CT scans](image)

© Philips Medical Systems
Volume Data Acquisition (7)

Computed Tomography (CT):
- First images from Hounsfield
- Multi-Slice CT of Lungs

Volume Data Acquisition (8)

Computed Tomography (CT):
- Abdomen (belly)
- Tumor in ventricular system
Volume Data Acquisition (9)

Rotational Angiography / 3D X-ray (C-Bow):

3D Volume is reconstructed from a series of x-rays (ca. 160°)
- Very high resolution
- But alas, only bone and contrasted structures
- Isotropic datasets (little artifacts)
- Scan direction is important

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Volume Data Acquisition (10)

Rotational Angiography / 3D X-Ray:
Volume Data Acquisition (11)

Rotational Angiography / 3D X-Ray:
• Slice from angiography dataset
• Rotation over 160°

Volume Data Acquisition (12)

Rotational Angiography / 3D X-Ray:
• 3D visualizations
Volume Data Acquisition (13)

Magnetic Resonance Tomography (MRI, Nuclear Magnetic Imaging NMI):

3D Volume is reconstructed from measured proton spin in magnetic field (1.5T, 3T, ...)

- Relatively slow image acquisition
- Resolution strongly depends on magnetic field strength
- Many different acquisition protocols

Volume Data Acquisition (14)

Magnetic Resonance Tomography

- Exploits nucleon spin of hydrogen protons (human body consists of approx. 70% of water)
- Also nuclei of other elements utilizable
- Nucleon spinning in precession around longitudinal axis with specific angle (precession frequency, Larmor frequency)
- Build weak magnetic field
- Align in stronger magnetic field in parallel (or anti parallel)
Magnetic Resonance Tomography:

- **High frequency pulse** distorts protons about 90° or 180°, if initiated with precession frequency, creating **resonance** (multiples of).
- After pulse, nuclei return back in balance: **relaxation**
- **Longitudinal** relaxation: T1-weighted
- **Transversal** relaxation: T2-weighted
- Proton-weighted
- Diffusion estimation

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Magnetic Resonance Tomography:

- T1-weighted MRI image (MR-Flash)
- T2-weighted MRI image (3D-CISS)
- Sagittal Orientation
Many more acquisition modalities:

- (3D) Ultrasound
- fMRI / DTI
- Positron-Emission-Tomography (PET)
- SPECT
- ....

Slice images depicted according to orientation to body:
- **Axial** / transversal: separates up/down
- **Sagittal**: separates left/right body halves
- **Coronal** / frontal: separates front/back

Slice images are oriented according to scanning direction:
- CT: Images always axial
- MRT: flexible
- Rotational Angiography: flexible
Volume Data Acquisition

Volume Data

Volume Data Acquisition

Sampling Theorem / Artifacts

Filtering
Sampling Theorem / Artifacts (1)

Limits of volume data or **aliasing** issues

Source of most artifacts can be traced back to the following phenomena:

• Violations of the **sampling theorem**, or
• **Partial Volume Effects**
• **Interpolation Artifacts**

Sampling Theorem / Artifacts (2)

**Sampling Theorem (Nyquist, Shannon):**

For a sufficient reconstruction of a signal, it must be sampled **at least twice as fast**

(Nyquist - Rate)

\[ 1x + 1x \Rightarrow 2x \]
Sampling Theorem:
• Sampling rate at least twice as fast
• Better three times as fast

Alias-Effects at Undersampling
• Moiré-Artifacts disappear if sampled sufficiently
Undersampling Artifacts:

- Structures **below Nyquist-Rate** cannot be reconstructed savely.
Partial Volume Effects:

- Basically due to **undersampling** at Volume reconstruction
- High **intensity differences** between neighboring materials
- Sampling does not reflect these high frequencies

→ **Artifacts of material interface** (eg. holes, false connections) due to inherent smoothing
Staircase Artifacts:

- Interpolation issues in anisotropic datasets
- Possibly violation of Nyquist-Rate in slice direction

Outline

Volume Data
Volume Data Acquisition
Sampling Theorem / Artifacts
Filtering
What is a Filter?
GDV-2 Applets, Glassner 1995

• Every system that changes a signal; the signal is filtered.

• The filtering operation is also described as, a signal that is convolved with a filter (frequency domain)

Why Filtering?

• To avoid aliasing issues: Removal of high frequencies by applying:
  • Lowpass filter
  • Blurring
  • Contrast enhancement
  • Filter can also cause problems
Filtering (2)

Our focus – Image and Volume Filter:

• Image-/volume filter are usually defined as **matrices**, which “run” **pixel-** or **voxel-wise**

• Are usually normalized

• Also called a **filter kernel**

Filtering (3)

• Volume Data can be affected by noise
  ➔ Lowpass filter can remove or at least reduce noise

• But data lose accuracy

• Small features disappear might be below Nyquist-Rate anyway

• Careful filter design
There are many different Filter:

- Low Pass/Blurring/Smoothing
- High Pass
- Contrast enhancement
- Edge enhancement
- Reconstruction filter
- ...
Filtering (6)

Over Smoothing:

- Some features are lost at over smoothing

Filtering (7)

Smoothing Filter (Lowpass):

Respective matrices
- Gauß filter:

- Average filter: takes average of all pixel /voxel values
Filtering (8)

Smoothing Filter (Lowpass):

- Median filter:
  - Sorts all pixel /voxel values below filter kernel into value bins (value, not frequency)
  - Takes average value bin
- Anisotropic Diffusion:
  - Adaptive filter
  - Strong smoothing in homogeneous regions only – regions with small gradient magnitude

Filtering (9)

Smoothing Filter – Average
Filtering (9)

Smoothing Filter – Gauß

Filtering (9)

Smoothing Filter – Median
Filtering (9)

Smoothing Filter – Anisotropic Diffusion

Filtering (10)

More Filter:

• Contrast enhancement
• Histogram stretching (coming up)
  • Piecewise linear /logarithmic scaling
  • Histogram equalization
• Image sharpening by edge enhancement
Image Source

- http://www.ctisus.com – CT is us, CT Teaching Files
- Institute of Neuroradiology, University Hospital Frankfurt
- Department of Neuroradiology, University Hospital Tübingen
- Department of Radiology, University Hospital Tübingen
- Department of Radiology, University Hospital Mainz
- Siemens Medical Solutions, Erlangen
- Philips Medical Systems (Marconi Medical Systems), Eindhoven