MEDICAL IMAGE COMPUTING (CAP 5937)

LECTURE 2: Digital Images, Imaging Software, and Medical Imaging Modalities

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Background Check

• X-ray?
• Ultrasound?
• Computed Tomography (CT)?
• Magnetic Resonance Imaging (MRI)?
• Positron Emission Tomography (PET)?
• Diffusion Weighted Imaging (DWI)?
• Diffusion Tensor Imaging (DTI)?
• Magnetic Particle Imaging (MPI)?
• Optical Coherence Tomography (OCT)?
Medical Imaging

• The most direct way to see inside the human (or animal) body is cut it open (i.e., surgery)
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- We can even see metabolic/functional/molecular activities which are not visible to naked eye
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where do radiologists interpret scans?

• Dedicated light source
• Darkened environment
• Limited distraction
PACS (example)
Medical Image Analysis

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- Improvements in image quality, changing clinical requirements, advances in computer hardware, and algorithmic progress in medical image processing all have a direct impact on the state of the art in medical image analysis.
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• Medical images are often **multidimensional (2D, 3D, 4D, nD)**, have a large dynamic range, are produced on different imaging modalities in the hospital, and make high demands upon the software for visualization and human–computer interaction.
  
  – A high resolution MR image of the brain, for instance, may consist of more than 200 slices of 512 x 512 pixels each, i.e., more than **50 million voxels** in total. (100MB)
  
  – In clinical studies that involve the analysis of time sequences or multiple scans of many subjects, the amount of data to be processed can easily exceed **10 GB**.
  
  – While 8 bits or 1 byte per pixel is usually sufficient in digital photography, most medical images need **12 bits** per pixel (represented by 2 bytes in the computer memory).
Medical Image Analysis-Manual

• Often accepted as surrogate of the truth (if biopsy or real ground truth is not available)
• However, manual analysis is highly subjective because it relies on the observer’s perception.
  – Intra and inter-observer agreements/variabilities
• It is highly tedious
Observer Variability – Example: Liver lesion

Intra- (one week interval)

Inter-
Medical Image Analysis-Automated

- Different strategies for image analysis exist. However, few of them are suited for medical applications.
Medical Image Analysis-Automated

- Different strategies for image analysis exist. However, few of them are suited for medical applications.
- The reason is that both the medical image data and the model or prototype (i.e., the a priori description of the features to be analyzed), are typically quite complex.
Digital Images

What computer sees!
Digital Images

• **Definition:** A digital image is defined by *integrating* and *sampling* continuous (analog) data in a spatial domain [Klette, 2014].
PIXELS are ATOMIC ELEMENTS of an image.
In late 1960s, terminology ‘pixel’ was introduced by a group of scientist at JPL in California!
Image Types

• A scalar image has integer values

\[ u \in \{0, 1, \ldots, 2^a - 1\} \]

a: level (bit)

Ex. If 8 bit (a=8), image spans from 0 to 255

0 black

255 white

Ex. If 1 bit (a=1), it is binary image, 0 and 1 only.
**Image Types-Color**

- Image has three channels (bands), each channel spans a-bit values.
- RGB, Hue-Saturation-Brightness
Brief Introduction to Imaging Modalities
ELECTROMAGNETIC SPECTRUM

Radio Waves | Micro waves | Infrared light | Ultraviolet light | X-rays | γ-rays

Wavelength (m)

Photon energy (eV)

MRI | endoscopy | radiography | CT | nuclear imaging

400nm |

700nm

(P. Suetens)
X-Ray Imaging / Radiography

- The first published medical image was a radiograph of the hand of Wilhelm Conrad Roentgen’s wife in 1895. *Nobel Prize in Physics 1901.*

Routine diagnostic radiography (2D images): chest x-rays, fluoroscopy, mammography, motion tomography, angiography, …
X-Ray Imaging / Radiography

\[ D = \log\left(\frac{I_{in}}{I_{out}}\right) \]

- **D** = Optical density
- **E** = Exposure \( (I_{in}/I_{out}) \)
- **I_{in}** = Incoming light intensity
- **I_{out}** = Outgoing light intensity
X-Ray Imaging / Radiography-Sensitometric Curve

- Maximum slope of the curve is known as the gamma of the film.
- A larger slope implies a higher contrast at the cost of a smaller useful exposure range.
- In low and high density areas, contrast is low and little information available.
- In linear part, slope characterize Contrast of the film. Max slope is known as Gamma of the film.

**Defn. Contrast:** is the intensity difference in adjacent regions of the image.
Basics Use of X-Rays

- Dental examinations
- Surgical markers prior to invasive procedures
- Mammography
- Orthopedic evaluations
- Chest examination (Tuberculosis)
- Age estimation (forensic, left hand)
Clinical Examples – X-Rays

- Wrist
- Hand
- Forearm
- Pelvis
- Elbow
How Radiologists Search Abnormal Patterns in Chest X-Rays?

Patterns belonging to Potentially Benign Lesions

Patterns belonging to Potentially Malignant Lesions
How Radiologists Search Abnormal Patterns in Chest X-Rays?

**Radiologists often report the following**
- Size, dimension, volume
- Pattern description,
- Location,
- Interaction with Nearby structures,
- Intensity distribution
- Shape
- ...

**Difficulties**
- Noise
- vessels can be seen as small nodules
- radiologists may miss the pattern
- patterns may not be diagnostic
- CT often required for better diagnosis
- size estimation is done manually in 2D
- Shadowing
- total lung capacity computation
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Computer algorithms can solve/simplify these problems for improved healthcare
Another Example for X-ray Imaging

Benign

Malignant
Ultrasound Imaging

• US is defined as any sound wave above 20KHz

1794-Lazzaro Spallanzani - Physiologist
First to study US physics by deducing bats used to US to navigate by echolocation

1826-Jean Daniel Colladon - Physicist
Uses church bell (early transducer) under water to calculate speed of sound through water prove sound traveled faster through water than air.

1880-Pierre & Jacques Curie
Discover the Piezo-Electric Effect (ability of certain materials to generate an electric charge in response to applied mechanical stress.)
1942-Karl Dussik - Neurologist  
First physician to use US for medical diagnosis  
1948-George Ludwig - MD  
First described the use of US to diagnose gallstones  
1958-Ian Donald  
Pioneers in OB-GYN
Principle of US Imaging

US equipment assumes that sound velocity is constant in the body.

<table>
<thead>
<tr>
<th>Body tissue</th>
<th>Acoustic impedance ($10^6$ Rayls)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.0004</td>
</tr>
<tr>
<td>Lung</td>
<td>0.18</td>
</tr>
<tr>
<td>Fat</td>
<td>1.34</td>
</tr>
<tr>
<td>Liver</td>
<td>1.65</td>
</tr>
<tr>
<td>Blood</td>
<td>1.65</td>
</tr>
<tr>
<td>Kidney</td>
<td>1.63</td>
</tr>
<tr>
<td>Muscle</td>
<td>1.71</td>
</tr>
<tr>
<td>Bone</td>
<td>7.8</td>
</tr>
</tbody>
</table>
Features of US Imaging

• Resolution:
  – direction of pulse propagation, pulse width 1-2mm
  – direction of scanning: beam width 2-3mm
  – low resolution and low SNR in deep region

• Ability of imaging soft tissue
• imaging in real time
• Doppler image
• Artefacts

Color flow mapping shows simultaneous amplitude (US) and velocity information (doppler)
Clinical Use of US Imaging
Clinical Use of US Imaging

Renal Artery Blood Flow

manual measurements? can computer help calculating all blood flow and identify automatically the abnormal regions? (See Next Lecture, afternoon)

stenosis is seen
eca: external carotid artery
cca: common carotid artery
ica: internal carotid artery
Clinical Use of US Imaging

Bone, fat, and physical length Measurements – unborn babies
(Image Credit: S. Rueda, Oxford Univ.)

(a) Arm Composition
(b) Original Image
Computed Tomography (CT)

Tomo: slice/level (Greek)
Graphe: draw
CT Imaging (continue)

C-arm

CT

Micro-CT

~CAT Scan
(computerized Axial tomography)
3D Nature of CT
Remark: 3D View Terminology
I: Image
I(x,y,z) denotes intensity value at pixel location x,y,z
Clinical Use of CT Imaging

- Standard imaging technique in many organs, particularly gold standard for lung imaging
- Fast
- Radiation exposure
- Often used in surgery rooms
- Show anatomy and pathology
- Intensity values are (more-or-less) fixed, read as HU (Hounsfield Unit)
CT Imaging Example: Tumor

2D manual measurement of tumor size (short and long axis of tumor)
CT Imaging Example: Lung

(A) Normal
(B) Emphysema
(C) Ground Glass Opacity
(D) Fibrosis
(E) Micronodules
(F) Consolidation
CT Imaging Example: Cardiac

how to calculate the amount of fluid?
Magnetic Resonance Imaging (MRI)

- 1882-Nichola Tesla
- Discovered rotating magnetic field
- 1971-Paul Lauterbur  NOBEL PRIZE
- First invented MRI
- Late 1970-Sir Peter Mansfield (Nottingham)  NOBEL PRIZE
- Developed mathematical techniques to create clearer images and also in minutes rather than hours as Lauterbur did.

- CT is more widely used than MRI.
- MRI does not have ionizing-radiation.
- MRI has excellent soft tissue contrast, while CT is preferred for lung and bone imaging.
- CT is fast (few seconds), while MRI is slow (sparse MRI ~5-10 mins, abdomen or brain may take 30-40 mins).
MRI Basics
MRI Basics

No magnetization
Types of MRI

- **TE**
  - Short
  - Long

- **TR**
  - Long
  - Short

- **Images**
  - **PROTON DENSITY**
  - **T2-WEIGHTED**
  - **T1-WEIGHTED**
Brain MRI
Safety in MRI
Diffusion Tensor Imaging

- measures random Brownian motion of water molecules.
- useful for tumor characterization (densely cellular tissues exhibit lower diffusion).
Diffusion Weighted Imaging (DWI)

Glioblastoma Tumor
Clinical Use: Example
Clinical Use: Example

Myocardial Infarction Detection
Clinical Use: Example

rectal tumor
Functional MRI (fMRI)

- measures brain activity through oxygen concentration in the blood flow.
- relies on the fact that cerebral blood flow and neuronal activation are coupled.
- when area of the brain is active (in use), blood flow to that area also increases.

- which part/location of the brain is activated when reading?
- which part/location of the brain is activated when listening music?
- which part/location of the brain is activated when searching puzzle?
fMRI Settings

(a) Schematic of the fMRI setup showing the 4-channel flex coil, illuminator, stimuli, camera, fixation, and turntable. The lower portion (6 channels) of the 12-channel headcoil is also depicted.

(b) List of stimuli used in the experiment, including objects and colors.

(c) Timeline of the experiment showing the fixation LED and illuminator LED, with trial times of 500 ms and 20 sec ITI.

Active Regions
Nuclear Medicine Imaging – PET/SPECT

- Scint: Scintigraphy, two-dimensional images
- PET: Positron Emission Tomography
- SPECT: Single Photon Emission Tomography

**Table:**

<table>
<thead>
<tr>
<th>Year</th>
<th>Fixed PET</th>
<th>Fixed PET-CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>215</td>
<td>715</td>
</tr>
<tr>
<td>2011</td>
<td>120</td>
<td>1030</td>
</tr>
</tbody>
</table>

**Graph:**

(a) PET and PET-CT Sites in the US

(b) 1,744,000 Clinical PET and PET-CT Studies in 2011 (US Statistics)

- Oncology: 95%
- Cardiology: 3%
- Neurology: 2%
Nuclear Medicine Imaging – PET/SPECT

1,650,000 Clinical PET and PET-CT Studies in 2010 (US Statistics)

- Diagnosis: 33%
- Staging: 19%
- Treatment Planning: 10%
- Therapy Followup: 38%
Basics of PET Imaging

• uses short-lived positron emitting isotopes (produced by collimators)
• two gamma rays are produced from the annihilation of each positron and can be detected by specialized gamma cameras
• resulting image show the distribution of isotopes
• an agent is used to bind into isotopes (glucose, …)

Late 1950s, David L. Kuhl concept of emission and transmission molecular activity is measured.
PET/CT and MRI/PET (Hybrid Imaging)

PET/CT
-choice of modality for oncological applications (yet)

MRI/PET
-superior soft tissue contrast resolution
-minimized radiation
What to Measure in PET?

• **SUV** (standardized uptake value: voxel-wise or region-wise) \((\text{SUV}_{\text{peak}}, \text{SUV}_{\text{max}}, \text{SUV}_{\text{lbm}})\)

• Metabolic lesion/tumor volume (MTV)

• **Shape** information of (functional) lesion (spiculated vs focal)

• **Texture** information of lesion (heterogeneous vs homogeneous)

• **Number and distribution** of the lesions (focal, multi-focal)
Clinical Use of PET: Example
Clinical Use of PET: Example
Serial and Simultaneous MRI/PET

Past

Now!
# Shallow Comparison of Imaging Methods

<table>
<thead>
<tr>
<th></th>
<th>Chest</th>
<th>Abdomen</th>
<th>Head/Neck</th>
<th>Cardiovascular</th>
<th>Skeletal/muscular</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CT</strong></td>
<td>gold standard</td>
<td>Need contrast for excellency, widely used</td>
<td>Good for trauma</td>
<td>Gold standard</td>
<td>Gold standard</td>
</tr>
<tr>
<td><strong>US</strong></td>
<td>no use except heart or P.Effusion</td>
<td>Problems with gas</td>
<td>Poor</td>
<td>Poor</td>
<td>Elastography</td>
</tr>
<tr>
<td><strong>Nuclear</strong></td>
<td>Extensive use in heart and therapy in lung</td>
<td>CT or MRI is merged</td>
<td>PET</td>
<td>Perfusion</td>
<td>bone marrow</td>
</tr>
<tr>
<td><strong>MRI</strong></td>
<td>growing cardiac applications</td>
<td>Increased role of MRI</td>
<td>Gold standard</td>
<td>Will replace CT in near future</td>
<td>Excellent</td>
</tr>
</tbody>
</table>
Software to Use, and Coding Standards

• Free software (with GUI) you can use for analysis of medical images
  – ITKSnap, Slicer, MITK, ImageJ/Fiji, MIPAV, Osirix, FSL, SPL, Mango, and many others can be found in IdoImaging.com and NITRC website.
  – Preference: Slicer, ITKSnap, ImageJ/Fiji

• Coding (self): ITK/VTK libraries will be used
  – C/C++ and Python can be used to call libraries
  – SimpleITK with Python is simpler

• Image Format
  – DICOM
  – Analyze (.img/hdr)
  – Nifti
  – …
3D Slicer (Free to Use)
Use the mouse in the 3D window to rotate the volume rendered image.
ITK/VTK

- National Library of Medicine (of NIH) **Insight Segmentation and Registration Toolkit (ITK)**.
- ITK is an open-source, cross-platform system that provides developers with an extensive suite of software tools for image analysis.
- Many tutorials are available on the net!

The goals for ITK include:
- Supporting the [Visible Human Project](http://www.nlm.nih.gov/research/visible/visible_human.html) (visit their [webpage](http://www.nlm.nih.gov/research/visible/visible_human.html))
- Establishing a foundation for future research.
- Creating a repository of fundamental algorithms.
- Developing a platform for advanced product development.
- Support commercial application of the technology.
- Create conventions for future work.
- Grow a self-sustaining community of software users and developers.
What is ITK?

• Image Processing
• Segmentation
• Registration
• No Graphical User Interface (GUI)
  – Example: QT can be used to create GUI
• No Visualization → Use VTK
C++ Glue Code

ITK
Image Processing

GUI
{MFC, Qt, wxWin, FLTK}

Visualization
{OpenGL, VTK}

C++ Compiler
gcc 2.95 – 3.3
Visual C++ 6.0
Visual C++ 7.0
Visual C++ 7.1
Intel 7.1
Intel 8.0
IRIX CC
Borland 5.5
Mac – gcc

CMake
www.cmake.org
Installation Process (ITK and VTK)

• Google ITK and VTK, go to the download page, download the zip file
• Google cmake, go to the download page, get the binaries and install the binaries.
• Alternative (preferable): Use GIT repository to install.
• For Windows
  – Run Cmake
  – Select the SOURCE directory
  – Select the BINARY directory
  – Select your Compiler
  – Click “Configure” to configure
  – Click “OK” to generate project files
Build A Sample Project with ITK

- Set `ITK_DIR` to the binary directory where ITK was built
- Compile your code with Cmake!
- Run Executable!

- Linux and Mac installations are available on the net!
Example Project: myProject.cxx

```cpp
#include "itkImage.h"
#include "itkImageFileReader.h"
#include "itkGradientMagnitudeImageFilter.h"

int main( int argc, char **argv ) {
    typedef itk::Image<unsigned short,2> ImageType;
    typedef itk::ImageFileReader<ImageType> ReaderType;
    typedef itk::GradientMagnitudeImageFilter<ImageType,ImageType> FilterType;

    ReaderType::Pointer reader = ReaderType::New();
    FilterType::Pointer filter = FilterType::New();

    reader->SetFileName( argv[1] );
    filter->SetInput( reader->GetOutput() );
    filter->Update();
    return 0;
}
```

http://www.itk.org/ItkSoftwareGuide.pdf
Index to Physical Coordinates

\[
P[0] = \text{Index}[0] \times \text{Spacing}[0] + \text{Origin}[0] \\
P[1] = \text{Index}[1] \times \text{Spacing}[1] + \text{Origin}[1]
\]

\[
\text{Index}[0] = \text{floor}\left(\frac{P[0] - \text{Origin}[0]}{\text{Spacing}[0]} + 0.5\right) \\
\text{Index}[1] = \text{floor}\left(\frac{P[1] - \text{Origin}[1]}{\text{Spacing}[1]} + 0.5\right)
\]
Resample Image Filter Example

```cpp
#include "itkImage.h"
#include "itkResampleImageFilter.h"
#include "itkIdentityTransform.h"
#include "itkLinearInterpolateImageFunction.h"

typedef itk::Image< char, 2 >  ImageType;

ImageType::Pointer inputImage = GetImageSomeHow();

typedef itk::ResampleImageFilter< ImageType >  FilterType;

FilterType::Pointer resampler = FilterType::New();

ImageType::SizeType size;
size[0] = 200;
size[1] = 300;

ImageType::IndexType start;
start[0] = 0;
start[1] = 0;
```

ITK/Examples/Filtering/ResampleImageFilter.cxx
Resample Image Filter

ImageType::PointType origin;
origin[0] = 10.0; // millimeters
origin[1] = 25.5; // millimeters

ImageType::SpacingType spacing;
spacing[0] = 2.0; // millimeters
spacing[1] = 1.5; // millimeters

resampler->SetOutputSpacing( spacing );
resampler->SetOutputOrigin( origin );

resampler->SetSize( size );
resampler->SetOutputStartIndex( start );

resampler->SetDefaultValuePixelValue( 100 );
resampler->SetInput( inputImage );
typedef itk::LinearInterpolateImageFunction<
    ImageType,
    double > InterpolatorType;

InterpolatorType::Pointer interpolator = InterpolatorType::New();

typedef itk::TranslationTransform< double, 2 > TransformType;

TransformType::Pointer transform = TransformType::New();

transform->SetIdentity();

resampler->SetInterpolator( interpolator );
resampler->SetTransform( transform );

resampler->Update();

const ImageType * outputImage = resampler->GetOutput();
SimpleITK

• New Wrapper for the insight segmentation & registration toolkit
• **Goal:** to help rapid prototyping and expand the user based of ITK by exposing the algorithms to new users

• Simplify the algorithms so they don’t depend on types of images.
• Binary built in distributions
• Supports 2D & 3D images, multi component images
• Easy importing & exporting
• data through Numpy
Simpler!

```c++
// Setup image types.
typedef float InputPixelType;
typedef float OutputPixelType;
typedef itk::Image<InputPixelType, 2> InputImageType;
typedef itk::Image<OutputPixelType, 2> OutputImageType;
// Filter type
typedef itk::DiscreteGaussianImageFilter<
    InputImageType, OutputImageType > FilterType;
// Create a filter
FilterType::Pointer filter = FilterType::New();
// Create the pipeline
filter->SetInput( reader->GetOutput() );
filter->SetVariance( 1.0 );
filter->SetMaximumKernelWidth( 5 );
filter->Update();
OutputImageType::Pointer blurred = filter->GetOutput();
```

V.S.

```java
import SimpleITK
input = SimpleITK.ReadImage ( filename )
output = SimpleITK.DiscreteGaussianFilter( input, 1.0, 5 )
```
Summary

• Medical image analysis/computing is a highly active research field.
• Measurement is the key in MIC! Volumetry, morphometry, quantification, visualization are all necessary methods in diagnostic radiology applications.
• Different imaging modalities are in use for different clinical purpose
• Imaging modalities have distinct properties from each other
• ITK/VTK libraries simplify processing of medical images, and provides standardized platform for analysis of medical images
References and Slide Credits

• P. Suetens, Fundamentals of Medical Imaging, Cambridge Univ. Press.
• M. Fasihi, PhD Student, Group presentation CRCV.
• A. Mortazi, PhD Student, Group presentation CRCV.
• ITK.org
• siemens.com
• slicer.org

• Read the additional lecture notes given in the web-course and course webpage.
• When you send email, please put “MIC:…” into subject line