Medical Images, Medical Models and Simulation: A Cook's Tour

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Medical Images

What is a Medical Image?

DEFINITION A **Medical Image** refers to an image of the human body, or parts thereof, for clinical purposes, that is, for medical procedures seeking to reveal, diagnose or examine disease, or medical science including the study of normal anatomy and function.

Medical Imaging in the Wider Sense

- **Endoscopy** - A minimally invasive technique used to assess the interior surfaces of an organ by inserting a tube (flexible or rigid) into the body.
- **Radiology** - include X-ray fluoroscopy, Computed Tomography (CT), Ultrasound (US), and Magnetic Resonance Imaging (MRI).
- **Thermography** - Sometimes called *Thermal Imaging*, are images produced from the *infrared* radiation emitted from a subject.
- **Microscopy** - is any technique for producing visible images of structures or details too small to otherwise be seen by the human eye, using a microscope or other magnification tool. It is often used more specifically as a technique of using a microscope.

The Language of Medical Imaging

- **Tomography** An image formed from a set of projected cross-sectional images. The Greek word *Tomo* means '*cut*'.
- **Modality** is a method of acquiring and image and includes *CT*, *PET* etc.
- **CT** means '*Computed Tomography*'.
- **MRI** means '*Magnetic Resonance Imaging*'. This was first called *NMR* for Nuclear Magnetic Resonance but anything *Nuclear* is scary so the 'N' was dropped.
- **OCT** which stands for Optical Coherence Tomography which involves the use of infrared light to create images particularly of the walls of an artery.
- **PET** stands for Positron Emission Tomography
- **SPECT** stands for '*Single Photon Emission Tomography*'.
- **Ultrasound** which is just sonar in the body.

Radiological Medical Images

Images of the human body are created by the interaction of energy with human tissue. The different types of energy used today:

(1) Radiation;

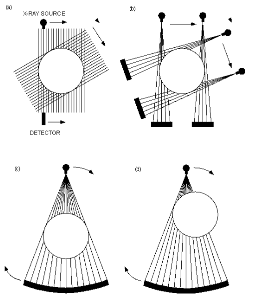
(2) Magnetic Fields;

(3) Electric Fields; and

(4) Acoustic Energy.

Note - X-Rays, CT, PET and SPECT are all *Ionizing* radiation modalities. They have sufficient energy to release positively charged ions from atoms that in turn damage human tissue. MRI and Ultrasound are *Non-ionising* modalities.

Computed Tomography



- The scanner consists of a X-Ray source and a detector. The scanner rotates around the subject to create a *slice* through the subject.
- A process referred to as *Tomographic Reconstruction* is used to recreate the image from the individual slices.
- Newer faster machines can process images faster as well as computing images as the gantry with the subject is moved smoothly through the scanner.

Computed Tomography

Simple Transmission

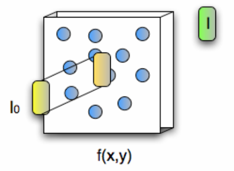
Assume that the shape of the object is given by f(x,y) and that it is composed of the same material.

Then the change in beam intensity is proportional to the cross-sectional area hit by the beam:

$$dI = -n\sigma I dx$$

Where *n* is the number of atoms in the area and σ is the cross-sectional area of an atom.

$$I(x) = I_0 e^{-\mu x}$$



Computed Tomography

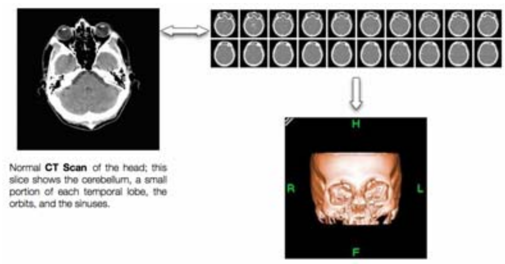
$$I(x,y) = I_0 e^{-\sum_i \mu(x_i, y_i, z_i) dz}$$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

The attenuation of the signal now results from the beam passing through materials of different densities such as bone, soft tissue, and fluid.

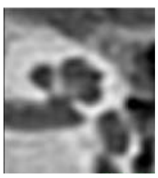
Consequently the attenuation of the signal is the sum of the losses due to each type of material.

Computed Tomography

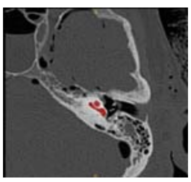


Computed Tomography

But what can be seen?



(A)



(B)

Medical Models

What is a Medical Model?

The image obtained through the various scanning modalities is only a collection of pixels or a collection of voxels.

- The aim is to produce more meaningful models!

Types of Models

- **3-D** Volume models obtained by thresh-holding
- Surface Models and deformable meshes
- Shape Models and Active Contours
- Functional Models - such as the Guyton Model for hypertension, models of Electrical Field strength around the cochlea.

Creating and Analysing Models

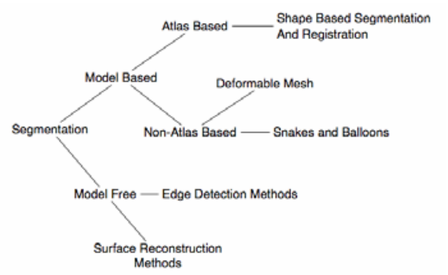
The image reconstruction process typically produces a collection of voxels I(x,y,z) of varying intensities.

The first aim is the *locate* the voxels that make up the objects of interest, that is the organs and the various structures in the body. This is the process of ***Segmentation***.

Some methods for segmenting images are:

- Surface reconstruction and Deformable meshes
- Shape Analysis - determine the *shape* of the organ and calculate a variety of metrics to analyse the organ shape such as its mean shape or its curvature.
- Model registration methods and atases.

Segmentation

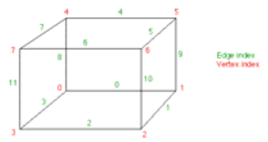


Surface Reconstruction

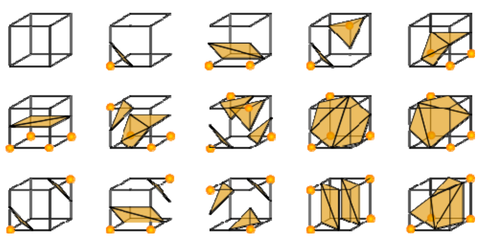
Surface reconstruction aims to find iso-surfaces - surfaces of constant density - in 3-D voxel sets or in a stack of 2-D slices. The iso-surface is defined externally, perhaps through a thresh-holding operation.

The classical *Surface Reconstruction* method is the *Marching Cubes* algorithm.

The algorithm works by considering a cube.



Surface Reconstruction



Snakes and Balloons

Snakes and balloons are a class of ***Deformable Model***.

Essentially, one starts by placing a curve within a region of interest and preferably close to the object to be segmented. The placement f the initial curve is usually done manually.

The *Snake* is a curve that has a number of internal forces prescribed at each point on the curve and an external force that draws the curve toward edges in the image space.

Balloons are the 3-D version of snakes.

Snakes and Balloons

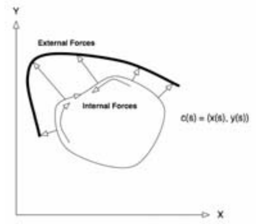
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

(a) *(b)* *(c)* *(d)* *(e)* *(f)*

In this figure (a) is an intensity image; (b) is created by 'Edge Detection' methods; (c)-(f) show a spherical snake expanding toward the boundaries of the chamber.

McInerney and Terzopolous

Snakes and Balloons



The Energy Functional

$$E = \int (\alpha(s)E_{cont}\beta(s)E_{curve}\gamma(s)E_{image}).ds$$

Where $s \in [0,1]$ and

- E_{cont} is the energy forcing the curve to be continuous;
- E_{curv} is the energy that forces the curve to be
- E_{image} is the energy that connects the curve to the image.

Snakes and Balloons

The aim is to *Minimise* the functional with respect to the curve parameters. For example, choosing the curve energy as follows

$$E_{cont} = \| \frac{dc}{ds} \|^2 \qquad E_{curve} = \| \frac{d^2c}{ds^2} \|^2 \qquad E_{image} = -\| \nabla I \|$$

means having to minimise these terms. Note that minimising the last term pulls the snake toward the contour with close to an edge.

Modelling Shape

The problem with surface models is that they give us a visual model of the organ but rarely give us any more morphometric information.

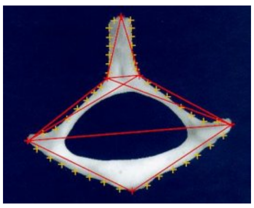
Shape models aim to go beyond surface models by seeking out parametric representations of anatomy that contain more useful information - for example, such that essential structures can be meaningfully compared.

Shape analysis goes back to D'Arcy Thomas in the early part of the 20th century (circa 1917).

Shape Definitions

- ***Shape*** is all the geometrical information that remains when location, scale and rotational effects are filtered out from an object.
- A ***Landmark*** is a point of correspondence on each object that matches between and within populations.
- An ***Anatomical Landmark*** is a point assigned by an expert that corresponds between objects of study in a way meaningful in the context of the disciplinary context.
- ***Mathematical Landmarks*** are points located on an object according some mathematical or geometrical property of the figure.
- ***Pseudo Landmarks*** are landmarks chosen by some other means.
- ***Configuration Space*** is the set of all landmarks.
- ***Configuration Matrix*** is the *k* by *m* matrix of the Cartesian coordinates of the *k* landmarks in *m* dimensions.

Shapes



A mouse vertebra with six mathematical landmarks and forty two pseudo landmarks.

The configuration space can consist of the 6 mathematical landmarks **or** the 42 pseudo landmarks or both (assuming that they are disjoint).

Dryden "Statistical Shape Analysis"

Shape and Morphometry

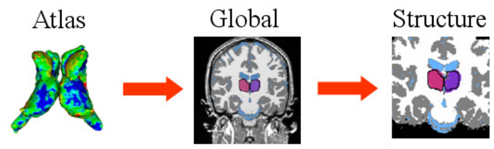
A number of measures can be used to analyse and compare shapes, for example the *Size* of the shape is given by any operator G such that G(aX) = aG(X).

An example of such as G is:

$$S(X) = \sqrt{\sum_{i=1}^{k} \| (X)_i - \overline{X} \|^2}$$

Other measures for comparing shape are possible also, such as estimates of the *Distance Between Shapes* and the *Mean Shape.*

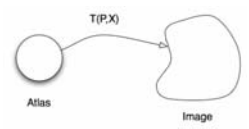
Atlases



Shape Atlases

Shape Atlases can be created as prior knowledge of anatomical structure. .

The key problem then is to map the shape atlas to the image!



The mapping **T** of the atlas to the image involves finding:

- The transformation of the shape parameters **P** to the image; and
- Finding the Translation, Scaling and Rotation of the atlas to fit the image.

Matching Shape Atlases to Images

A Typical Procedure for Matching Atlases:

1. Select a pair of corresponding landmarks in the Atlas and in the image
2. Choose a transformation - normally Affine transformations (rotation, translation and scaling) but transformation can also be *Rigid*.
3. Calculate the transformation parameters - normally this is done by a least squares fit of the landmarks.
4. Transform the Atlas to the image using and interpolation method such as nearest neighbor interpolation or cubic interpolation.

Matching Shape Atlases to Images

Alternatively, we can use Maximum Likelihood with a better chance of automating the matching!

More recent work attempts to use Bayesian probabilities to model the relationship between the *observed data I* (input image), the *hidden data T* (the labels), and the parameter space (S,R) with shape model S, and registration parameters R.

The optimal solution with respect to (S,R) is defined by:

$$(\overline{S}, \overline{R}) = \arg\max_{SR} \sum_{T} \log P\{T, S, B \mid I\}$$

Medical Simulation

Surgical Simulation Needs Interaction

Simulation needs models that are *Interactive*!

Models must be able to deform when forces are applied, and must be able to change their shape when drilled, palpated or cut.

How does the need to simulate and interact with a model affect the choice of model?

- Shape models contain only landmark points loose information.
- Can parametric shape models change in arbitrary ways to accommodate the effects of forces?
- Finite element models and Voxel based models seem to be the more common in simulation.

Simulation and Mastoidectomy

Voxel based models have been used for drilling simulations (Mastoidectomy and Dentistry) but less for soft tissue cutting.

The question is can we arrive at compact, computationally tractable methods of representing anatomical structures so that we can recreate models of patients and manipulate those models ‘*haptically*’?

Models for Shared Tasks

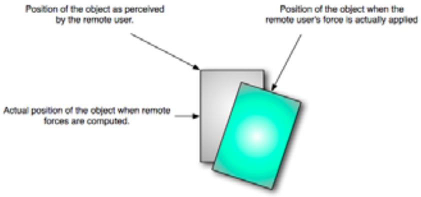


Figure 1 - Conflicting positions of an object as felt by a local user and a remote user.

Mastoidectomy with Voxels

Pflesser et. al. and Agus et; al. use voxel based methods. The amount of bone to be removed is expressed in terms of the number of voxels to be removed. But, how do we manipulate such a voxel set haptically?