The Role of Computing in Image-guided Surgery

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Image-guided Interventions

• Surgery is a side-effect of therapy!!

• Identify targets based on pre-operative or intra-operative images rather than direct vision

• Enter body via small incision

• Avoid large access wound

• Improve healing

• Reduce hospital stays

• Increase patient comfort
Image-guided Interventions

- Usually minimally invasive
  - But can help open interventions also
    - Identify lesion locations beneath organ surface
- Enter body through ports
- Direct visualization lost or compromised
- Complement with virtual view
- Intra-op visualization alone
  - Video, US, MRI, Xray
- Pre-op images alone
- Fusion of both
IGI areas

- Neurosurgery
  - Movement disorders
  - Epilepsy
- Cardio–Thoracic
  - Intra Cardiac
  - Robotic CABG
- Abdominal
  - Kidney
  - Liver
  - Prostate
  - Gall Bladder
- Radiation oncology
- Radio Surgery
- Orthopedics
- Anesthesia
  - Spinal facet joints
  - Central line insertion
Role of Computing

- Image Acquisition
- Image Processing
- Image Registration
- Instrument tracking
- Tissue modeling
- Image Visualization
Image Acquisition

• Computed Tomography (CT)
• Magnetic Resonance Imaging (MR)
• Ultrasound (US)
• X-ray fluoroscopy
• Positron Emission Tomography (PET)
• Single Photon Emission Tomography (SPECT)
• Endoscopy
2 Minutes of CT Physics
“Conventional” CT

- Rotate–rotate geometry
- 1–320 “slices”
- Sub–second data acquisition
- Dynamic scanning
- Volume reconstructions
2-D Fourier Transform

Horizontal Projection

1-D Fourier Transform

Interpolate in Fourier Transform Space

Vertical Projection

1-D Fourier Transform

2-D Inverse FT

2-D Fourier Transform
\[ g(r, \theta) = \int_0^\pi \int_{-\infty}^{\infty} \left[ \int_{-\infty}^{\infty} f(\xi, \phi) e^{-i2\pi \rho \xi} \, d\xi \right] |\rho| e^{i2\pi \rho r \cos(\theta - \phi)} \, d\rho \, d\phi \]

~1 GB data collected per 3D image  
~250MB data in reconstructed image  
Acquisition < 1 sec  
Reconstruction ~1 sec
MRI Scanner

MRI Scanner Cutaway

- Radio Frequency Coil
- Gradient Coils
- Magnet
- Patient
- Patient Table
- Scanner
MRI (formally NMR imaging)

- Paul Lautebur 1975
  - Presented at Stanford CT meeting
  - "Zeugmatography"
    - Magnets?!
    - Gradients?!
    - Clinical Applications?
- Raymond Damadian 1977
  - relaxation times and cancer
- Sir Peter Mansfield 1980
  - Slice-selection
  - Echo-planar imaging

Lautebur and Mansfield
Shared Nobel Prize in Medicine for MRI in 2003

Zeugmatography
image of water-filled test tubes

Early Mansfield Thorax Image
Two minutes of MR Physics!
Spinning nuclei generate rf signals.
Gradients provide spatial information

Sample tube with three regions with different Proton densities
Place in Magnetic field + gradient
Protons in all regions precess with different frequencies
Can now differentiate between regions by examining Frequency content of signal (Fourier Transform)
The Math

\[ f(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(k_x, k_y) e^{-i2\pi(k_xx + k_yy)} \, dk_x \, dk_y \]
Two minutes of US Physics!
Scanning and Display Modes

M mode  B mode  A mode

Time  Depth

Stationary Transducer
Composite B-Mode display of interfaces
The Math

\[
\Psi(r, \theta, \phi) = -\frac{1}{i \lambda} \int_{A} w(x, y) e^{i(2\pi \omega t + \phi(x, y))} \frac{e^{ikr}}{r} \cos \theta \cos \phi \, dS
\]

\[
f(x, y) = w(x, y) e^{i(2\pi \omega t + \phi(x, y))}
\]

Each element individually powered TX and RZ
Ultrasound Images

This is a color flow ultrasound image of the carotid bifurcation.
Tracking Technology
Tracking systems

- Key to bridging the gap between patient and image
- Ideal tracking system should be:
  - Unobtrusive
  - Accurate
  - Isotropic
  - Passive
- Need relative position of tool(s) wrt patient
- Track patient and tool
- No current solutions satisfy all of above criteria
Contemporary Tracking

• **Optical e.g. NDI Polaris,**
  - Accuracy ~0.3mm
  - Active
    - Tracks IR emitters
  - Passive
    - Tracks IR reflected from retro-reflectors
  - Depends on field of view
  - Suffers from line-of-sight restrictions

• **Magnetic e.g. NDI Aurora,**
  - Accuracy ~0.7 – 0.9mm*
  - Requires magnetically “clean” environment
  - No line of sight constraint

• **Image-based**
  - Identify position of instruments from 2D or stereo video; 2D or 3D ultrasound.
Optical Tracking Systems
(Electro?) Magnetic Tracking Systems
Registration Technology
Registration of Patient to Image

• **Point-based**
  - **Fiducials**
    - Attach fiducial marker point objects to patient skin or frame
    - Identify them with tracked tool in OR (X), cursor on image
  - **Create transformation matrix**
    - Solve system of equations for three translations, three rotations (scaling)
    - Generally least-squares solution because of measurement errors

• **Feature-based**
  - As above but identify homologous *features* in image and object
    - Tip of nose; canthi of eyes, etc

• **Surface based**
  - Trace surface in object with pointer or laser scanner
  - Fit to surface extracted from image
    - Best fit, least squares solution
Mapping patient space to image

• Different coordinate systems
  – Tracker
  – Patient
  – Pointer tip
  – Pointer body
  – 3D image

• Need to relate \((x, y, z)\) coordinates of patient to \((x', y', z')\) coordinates of pointer

• Rotate, translate, scale coordinates of pointer tip to 3D image
Transformation Matrices

\[
T_{\text{rigid}} = \begin{pmatrix}
    x' \\
    y' \\
    z' \\
    1
\end{pmatrix} = \begin{pmatrix}
    r_{11} & r_{12} & r_{13} & t_x \\
    r_{21} & r_{22} & r_{23} & t_y \\
    r_{31} & r_{32} & r_{33} & t_z \\
    0 & 0 & 0 & 1
\end{pmatrix} \cdot \begin{pmatrix}
    x \\
    y \\
    z \\
    1
\end{pmatrix}
\]

\[t_x, t_y, t_z\] translation vector components

\[r_{11}, \cdots, r_{33}\] orthogonal matrix rotation components
Co-ordinate System Transformation

Tracking camera

M_{WT}

M_{LT}

M_{LP}

M_{PW}

patient

image

pointer

Tracked probe
Image Registration
Image registration

- **Image to patient**
  - Linking coordinate systems

- **Image to image** – linear, static
  - Anatomy + function

- **Image to patient** – dynamic
  - Maintain registration while moving
    - Cardiac
    - Respiration
    - Surgical interaction

- **Image to image** – nonlinear (warping)
  - Atlas to patient

- **Surface to surface**
  - Image volume to patient surface
Registered images

• Basis of navigation
• Points in physical space identified by pointer can be mapped to image space
• Merge information from different modalities.
  – Identify where to make incision
  – See buried targets relative to pointer
  – Map extent of resection
  – Identify no–go zones in resection volume from registered pre–operative images
    • Eloquent tissue in brain (from fMRI)
    • Critical nerve pathways (from DTI)
    • Important blood vessels (from MRA)
PET/MRI Registration
2D–3D image registration

Intraoperative Imaging plane A

2D-3D REGISTRATION $T_{\text{rigid}}$

Intraoperative Imaging plane B

Pre-operative 3D coronary tree

$F_{\text{pre}}$

$F_B$

$F_A$
Visualization Technology
Visualization

• Display information to observer
• Manipulate information
• Multi-modality
  – Anatomical/functional
• Guidance – display tools
• Augment real view
• Minimize information overload
Visualization

- 2-D slice stacks
- Multi-planar 3-D view
- Surface rendering
- Volume rendering
- Virtual instruments combined with above
Integrate 3-D MRI and Ultrasound
Fused PET – CT images

• Planning for Colorectal Cancer Surgery

Ardeshir Goshtasby Intelligent Systems Lab, Wright University
Examining tractography maps in 3D
• Combine US with Pre-op MRI
• Identify individual components using pre-masking
• Introduce surgical tools
Lesion image registered with patient

Courtesy Dr P Edwards KCL
Augmented Reality

Birkfellner

DiGioia

Fichtinger

Navab
Back to Surgery!!
Applications of IGS

• Neurosurgery
• Orthopaedic Surgery
• Radiation therapy
• Radiosurgery
• Cardiac Surgery
• Abdomino/Thoracic Surgery
• Prostate surgery
• NOTES/SPA surgery
IGI in the Brain

Stereotactic approach

Open Craniotomy
In the very beginning

- Nov 8, 1895. Röentgen discovers X-rays
- Jan 13 1896 Needle extracted from hand under x-ray guidance (Bristol)
- Feb 1896 bullet removed from leg (Montreal), guided by an X-ray image
Making Image-guidance Robust

• Need to relate images to patient
• Provide a common coordinate system
  – Relate points in image unambiguously to points in patient
• X-ray only available modality for first 70 years
  – 2D image
  – Diverging beam image acquisition
  – Differential magnification
  – Film based – development time
  – Qualitative image registration at best
Relating Images to Patients

• Place markers on patient skin
• Identify markers in images
• Locate markers on patient
• Register image to patient via markers.
  – Difficult with just x-rays
  – Easy with slice or 3D images (CT, MRI)
Modern Stereotactic Frame

Frame base with Instrument holder

Frame base with imaging fiducials

Leksell AB Stockholm, Sweden
Stereotactic Frame

- Provides rigid coordinate system
- Equipped with coordinate marks
- Can be imaged
- Can hold instruments
- Accommodate isocentric targeting system
- Can facilitate targeting
  - Ablation
  - Stimulator implant
  - EP electrode guidance
Navigation

• Navigate inside target organ
• Brain example
  – Stereotactic techniques
  – Set up coordinate frame
  – Measure position of instruments within frame
  – Ideally register 3D image to same frame
• Attach rigid device to patient’s head
• Support for instruments
• Reference markers for imaging
Tomographic Imaging

- Key to 3D navigation
- Initially 13mm slices with early CT scanners
- Today
  - Volumetric imaging, isotropic 0.5 – 1.0mm voxels with CT and MRI
Functional Stereotactic Neurosurgery
Frame-to-Image Registration

Rigid patient-to frame registration

Assign frame coordinates to every position (voxel) in the MRI volume
Stereotactic Neurosurgery

- Electrode implantation
  - Epilepsy
- Ablation planning
  - Parkinsons disease
- Radiotherapy
  - Tumours
- Radiosurgery
  - Arterio-venous malformations
Surgical treatment of Parkinson’s disease must target specific functional regions in the deep brain.
EP Stimulation

Stim Off

Stim On
Electrophysiological Data

1. Microelectrode Recording: Listen for characteristic firing pattern
2. Electrical Stimulation: Evoke sensory or motor response

Recording:

Stimulation:
“*I feel/hear/taste*...”

Parkinson's Disease and Movement Disorders Center
Recording Stimuli/Responses

“Monkey Man Interface”

Use for data input and extraction

Patient # + Trajectory # + Body Side + Exploration Method + Body Part # + Response

CODE = 111_4_50uA_R_112_PE
Neurophysiological Atlas Construction

- Record positions relative to images of stimulus/response from multiple patients
- Enter data into database
- Map database info to standard space
- Map new patient to standard space
- Map previous procedure stimulus/response data to new patient
- Use data to guide new procedure.
Patient MRI & functional data (n = 161)

Patient data coded and annotated to their respective pre-op MRI

Apply to each new patient

Functional data warped to Standard Brain image space
Typical IGNS platform

Medtronic Inc
Breaking away from the frame...

- **Stereotactic frame**
  - Tracking of tools
  - Mounting of tools
  - Maintain rigid transform between tools and patient
  - Cumbersome for patient and imaging

- **Frameless**
  - Markers attached directly to patient
  - Patient skull tracked
  - Pointer tool tracked
Frameless Stereotactic surgery

Registration

Navigation
Heart Surgery – Traditional vs Minimally-invasive

Median Sternotomy for Cardiac surgery

“Maximally Invasive”

“Minimally Invasive”

Robot Ports for Robotic CABG
Imaging for Robot Port-placement Planning
Intra–Cardiac Surgery
Intra cardiac Surgery
Repairing heart valves inside beating heart

- Bi-plane echo navigation
- 3D echo positioning
- Doppler validation
- Bi-plane echo leaflet capture
Intra-cardiac Navigation
Prostate Brachytherapy
Prostate Biopsy Robot
Intra-biopsy Guidance

Courtesy Aaron Fenster
Check the proposed planning. If necessary, modify the implant position with the appropriate buttons. Press the blue pedal to validate.
Spinal intervention
Global challenges

- Registration accuracy
- Motion compensation
- Dynamic registration
- Modeling effect of resections
- Intuitive display
- Reducing information overload
- Seamless introduction into workflow
- Overcoming conservative attitudes
- Validation
The Future??

- Robust Dynamic Image Registration
- Ubiquitous instrument and imaging system tracking
- OR “aware” of all instruments and imaging devices
- Non–intrusive immersive displays
- Better awareness of psychophysical issues
- “Invisible” technology
- Continuum between training and guidance systems
Thank You

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