System for Live Virtual-Endoscopic Guidance of Bronchoscopy

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Lung Cancer

• Lung Cancer: #1 cancer killer, 30% of all cancer deaths, 1.5 million deaths world-wide, < 15% 5-year survival rate (nearly the worst of cancer types)

• To diagnose and treat lung cancer,
  1) 3D CT-image assessment – preplanning, noninvasive
  2) Bronchoscopy – invasive

→ Procedure is LITTLE HELP if diagnosis/treatment are poor
3D CT Chest Images

Typical chest scan $V(x,y,z)$:
1. 500 512x512 slices $V(x,y,z)$
2. 0.5mm sampling interval
3D Mental Reconstruction

→ How physicians assess CT scans now
Visualization Techniques — see “inside” 3D Images

- Multi-planar reconstruction\(^2\)
- Projection imaging\(^1\)
- Volume/surface rendering\(^4\)
- Virtual endoscopic rendering\(^5\)
- Curved-section reformatting\(^3\)
- STS-MIP (sliding-thin-slab maximum intensity projection)\(^6\)

1{Hohne87,Napel92}  2{Robb1988,Remy96,McGuinness97}  3{Robb1988,Hara96,Ramaswamy99}  
4{Ney90,Drebin88,Tiede90}  5{Vining94,Ramaswamy99,Helferty01}  6{Napel,92}
Bronchoscopy → For “live” procedures

video from bronchoscope

$I_v(x,y)$

Figure 19.4, Wang/Mehta ‘95
Difficulties with Bronchoscopy

1. Physician skill varies greatly!

2. Low biopsy yield. Many “missed” cancers.

3. Biopsy sites are beyond airway walls – biopsies are done blindly!

“Let’s just start cutting and see what happens.”
Virtual Endoscopy (Bronchoscopy)

- Input a high-resolution 3D CT chest image
  - virtual copy of chest anatomy
- Use computer to explore virtual anatomy
  - permits unlimited “exploration”
  - no risk to patient

Endoluminal Rendering
\[ I_{CT}(x,y) \]
(inside airways)
Image-Guided Bronchoscopy Systems

Show potential, but recently proposed systems have limitations:

• CT-Image-based

  • McAdams et al. (AJR 1998) and Hopper et al. (Radiology 2001)
  
  • Bricault et al. (IEEE-TMI 1998)
  
  • Mori et al. (SPIE Med. Imaging 2001, 2002)

• Electromagnetic Device attached to scope

  • Schwarz et al. (Respiration 2003)

→ Our system: reduce skill variation, easy to use, reduce “blindness”
Our System: Hardware

Endoscope

Scope Monitor

Scope Processor

Light Source

Matrox PCI card

Video Capture

Main Thread
Video Tracking
OpenGL Rendering

Video Stream

Worker Thread
Mutual Information

Rendered Image

Polygons, Viewpoint Image

Dual CPU System

PC Enclosure

AVI File

Video AGP card

Matrox Cable

RGB, Sync, Video

Software written in Visual C++. 

Our System: Work Flow

Stage 1: 3D CT Assessment
1) Segment 3D Airway Tree
2) Calculate Centerline Paths
3) Define Target ROI biopsy sites
4) Compute polygon data

→ Case Study

Stage 2: Live Bronchoscopy
For each ROI:
1) Present virtual ROI site to physician
2) Physician moves scope “close” to site
3) Do CT-Video registration
4) Repeat steps (1-3) until ROI reached
Stage 1: 3D CT Assessment (Briefly)

1. Segment Airway tree (Kiraly et al., Acad. Rad. 10/02)
2. Extract centerlines (Kiraly et al., IEEE-TMI 11/04)
3. Define ROIs (e.g., suspect cancer)

4. Compute tree-surface polygon data (Marching Cubes – vtk)

→ CASE STUDY to help guide bronchoscopy
Stage 2: Bronchoscopy - Key Step: CT-Video Registration

Register

Virtual 3D CT World

$I_{CT}^X(x, y)$ (Image Source 1)

Maximize normalized mutual information to get

$\hat{I}_{CT}^X(x, y)$

To the

Real Endoscopic Video World

$I_V^E(x, y)$ (Image Source 2)
CT-Video Registration: 1) Match viewpoints of two cameras

Both image sources, $I_V$ and $I_{CT}$, are cameras.

6-parameter vector representing camera viewpoint

$\chi = (X, Y, Z, \alpha, \beta, \gamma)$

3D point $p = (X_p, Y_p, Z_p)$ mapped to camera point $(X_c, Y_c)$ through the standard transformation

$$
\begin{bmatrix}
X_c \\
Y_c \\
Z_c
\end{bmatrix} = R(\alpha, \beta, \gamma)
\begin{bmatrix}
X_p - X \\
Y_p - Y \\
Z_p - Z
\end{bmatrix}
$$

The final camera screen point is given by $(x, y)$ where

$$
x = \frac{fX_c}{Z_c}, \quad y = \frac{fY_c}{Z_c}
$$
Make FOVs of both Cameras equal

To facilitate registration, make both cameras $I_V$ and $I_{CT}$ have the *same* FOV.

To do this, use an endoscope calibration technique (Helferty et al., *IEEE-TMI* 7/01).

Measure the bronchoscope’s focal length (done off-line):

$$f = \frac{(x_r - x_l)Z_m}{(X_r - X_l)}$$

Then, the angle subtended by the scope’s FOV is

$$\theta_{FOV} = 2 \tan^{-1} \left( \frac{x_r - x_l}{2f} \right)$$

Use *same* value for endoluminal renderings, $I_{CT}$. 
Normalized Mutual Information

*Mutual Information* (MI) – used for registering two different image sources:

a) Grimson et al. *(IEEE-TMI 4/96)*

b) Studholme et al. *( Patt. Recog. 1/99)*  → normalized MI (NMI)
Normalized Mutual Information

Normalized mutual information (NMI):

\[ S_{NMI}(I_V, I_{CT}) = \frac{h(V) + h(CT)}{h(V, CT)} \]

where

\[ h(V) = - \sum_{k=0}^{M-1} \sum_{l=0}^{M-1} p_{V,CT}(k, l) \log p_V(k) \]

\[ h(CT) = - \sum_{k=0}^{M-1} \sum_{l=0}^{M-1} p_{V,CT}(k, l) \log p_{CT}(l) \]

\[ h(V, CT) = - \sum_{k=0}^{M-1} \sum_{l=0}^{M-1} p_{V,CT}(k, l) \log p_{V,CT}(k, l) \]

and

\[ p_V(k) = \sum_{l=0}^{M-1} p_{V,CT}(k, l) \]

is a histogram (marginal density)
Given a fixed video frame $I^F_V(x, y)$ and starting CT view $I^{X_i}_{CT}(x, y)$

Search for the optimal CT rendering $I^{X_o}_{CT}(x, y)$ subject to

$$
\chi_o = \arg \left\{ \max_{\chi \in N_{\chi_i}} \left[ S_{NMI} \left( I^X_{CT}(x, y), I^F_V(x, y) \right) \right] \right\}
$$

where viewpoint $\chi = (X, Y, Z, \alpha, \beta, \gamma)$ is varied over neighborhood $N_{\chi_i}$ about $\chi_i$

Optimization algorithms used: Simplex and simulated annealing
System Results

Three sets of results are presented:

A. Phantom Test
   controlled test, free of subject motion

B. Animal Studies
   controlled in vivo (live) tests

C. Human Lung-Cancer Patients
   real clinical circumstances
A. Phantom Test

Goal: Compare biopsy accuracy under controlled stationary circumstances using (1) the standard CT-film approach versus (2) image-guided bronchoscopy.

Experimental Set-up:

Rubber phantom - human airway tree model used for training new physicians.

CT Film - standard form of CT data.
Computer Set-up during Image-Guided Phantom “Biopsy”
## Phantom Accuracy Results (6 physicians tested)

<table>
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<tr>
<th>Physician</th>
<th>Film accuracy (mm)</th>
<th>Guided accuracy (mm)</th>
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<tbody>
<tr>
<td>1</td>
<td>5.80</td>
<td>1.38</td>
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<tr>
<td>4</td>
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<tr>
<td>5</td>
<td>8.62</td>
<td>2.45</td>
</tr>
<tr>
<td>6</td>
<td>3.19</td>
<td>1.24</td>
</tr>
</tbody>
</table>

→ ALL physicians improved greatly with guidance

→ ALL performed nearly the **SAME** with guidance!
B. Animal Studies

**Goals:** Test the performance of the image-guided system under controlled in vivo circumstances (breathing and heart motion present).

**Experimental Set-up:**

- Biopsy dart
- Computer system during animal test (done in EBCT scanner suite).
Composite View after All Real Biopsies Performed

Thin-slab DWmax depth-view of 3D CT data AFTER all darts deposited at predefined sites. Bright “flashes” are the darts.

Rendered view of preplanned biopsy Sites
C. Human Studies
Stage 2: Image-Guided Bronchoscopy

Real-World target video $I_V$

Virtual-World CT rendering $I_{CT}$

Registered Virtual ROI on Video

(case h005 [UF], mediastinal lymph-node biopsy, in-plane res. = 0.59mm, slice spacing = 0.60mm)
Case p1h013: performing a biopsy

Left view: Real-time bronchoscopic video view; biopsy needle in view
Center: Matching virtual-bronchoscopic view showing preplanned region (green)
Right: Preplanned region mapped onto bronchoscopic view, with biopsy needle in view.

Distance to ROI = scope’s current distance from preplanned biopsy site (ROI).

→ 40 lung-cancer patients done to date
Comments on System

- Effective, easy to use
  - A technician – instead of $$ physician – performs nearly all operations
- Gives a considerable “augmented reality” view of patient anatomy
  - less physician stress
- Fits seamlessly into the clinical lung-cancer management process.
- Appears to greatly reduce the variation in physician skill level.

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Thank You!
Bronchoscope Video Camera Model

Following Okatani and Deguchi (*CVIU* 5/97), assume video frame $I(p)$ abides by a Lambertian surface model; i.e.,

$$I(p) = \sigma \frac{L \cos \theta_s}{\pi R^2}$$

where

$p = (X_p, Y_p, Z_p)$

$\theta_s = \text{light source-to-surface angle}$

$R = \text{distance from camera to surface point } p$
Lung Cancer

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- To diagnose and treat lung cancer,
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  2) Bronchoscopy – invasive

- 500,000 bronchoscopies done each year in U.S. alone

- A test for CT Image-based Lung-Cancer Screening in progress!
  - 10-30 million patient population in U.S. alone!
  - Screening is WORTHLESS if diagnosis/treatment are poor
Normalized Mutual Information

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We use normalized mutual information (NMI) for registration:

\[
S_{NMI}(I_V, I_{CT}) = \frac{h(V) + h(CT)}{h(V, CT)}
\]