CT-Video Registration Accuracy for Virtual Guidance of Bronchoscopy

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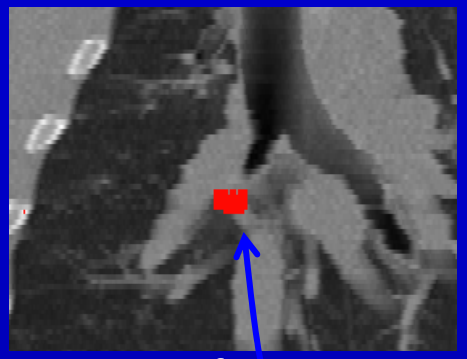
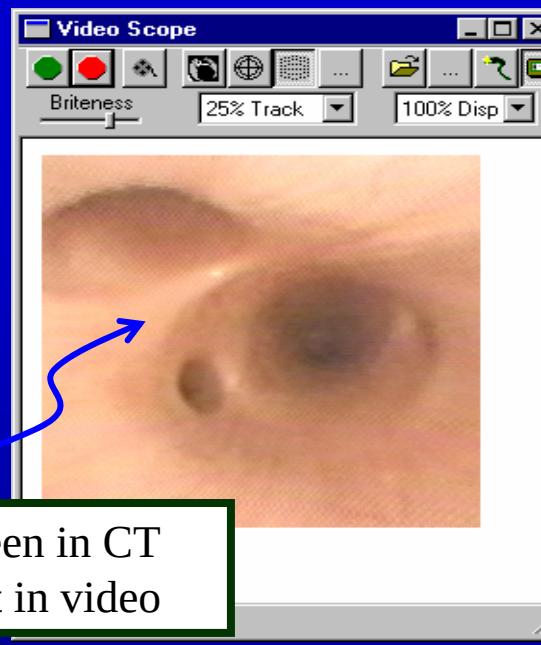
SPIE Medical Imaging 2004, San Diego, CA,
14-19 February 2004

CT-Guided Bronchoscopy for Lung Cancer Staging

- Bronchoscopic biopsy critical for staging.
- Physicians make errors when maneuvering bronchoscope to a biopsy site.
- Lymph nodes are hidden from endoscopic video, but visible in 3D CT analysis
  → *exploit CT using image guidance*
- CT-guidance of bronchoscopy
  → *reduce errors, improve biopsy success rate*



CT Scan of Chest



ROI seen in CT but not in video

Videoendoscopy Inside airways

Matching Video and CT Rendering

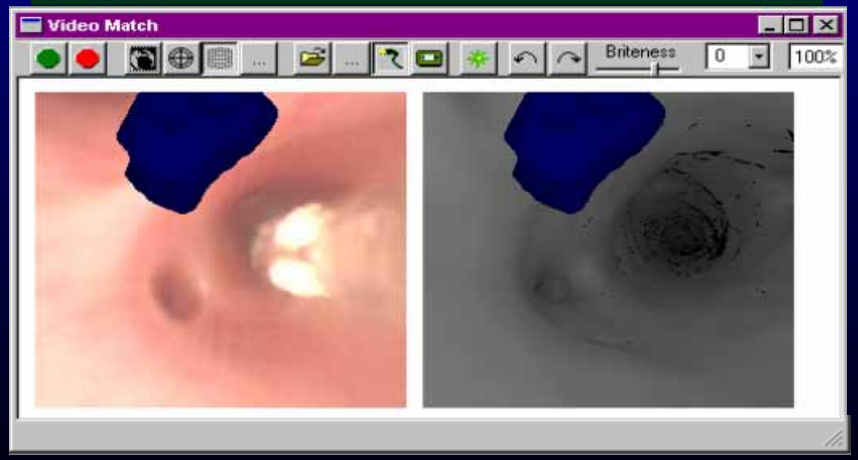


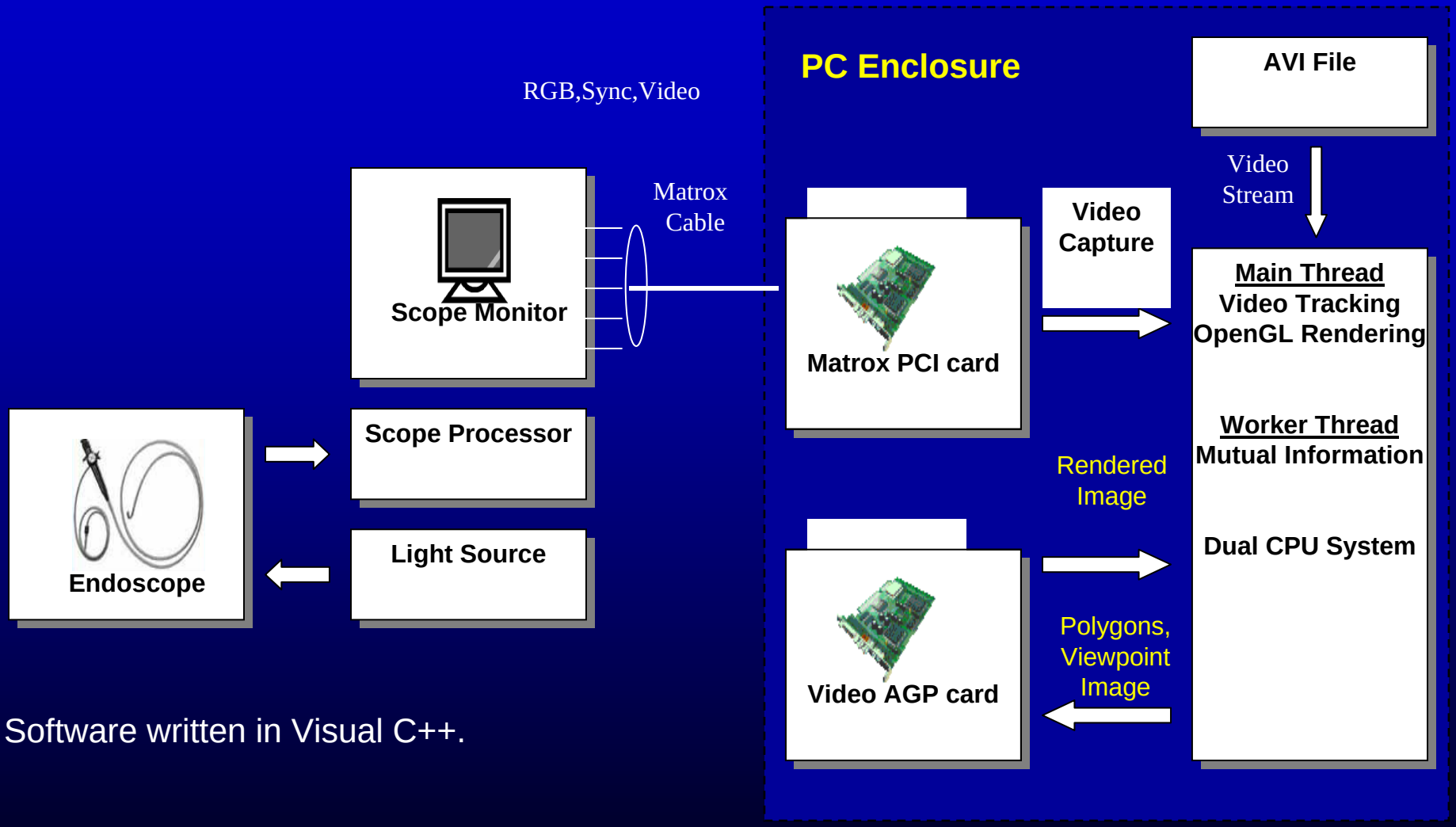
Image-Guided Bronchoscopy Systems

Show potential, but recently proposed systems have limitations:

- McAdams *et al. (AJR 1998)* and Hopper *et al. (Radiology 2001)*
  - Virtual bronchoscopy for lymph-node biopsy, but *no live guidance*.
- Solomon *et al.* (*Chest 2000*) – *E/M sensor attached to scope*
  - limited planning, many potential errors, limited guidance
- Bricault *et al. (IEEE-TMI 1998) – no device needed*
  - Registered videobronchoscopy to CT, but *no live guidance*.
- Mori *et al. (SPIE Med. Imaging 2001, 2002) – no device needed*
  - Registered videobronchoscopy to CT and tracked video.
  - Efforts not interactive: >20 sec to process each video frame.

No device needed

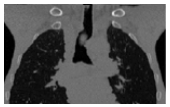
Our Group's Image-Guided Bronchoscopy System



Software written in Visual C++.

System Processing Flow

Data Sources



3D CT Scan

Bronchoscope

Image Processing

Stage 1: 3D CT Assessment and Planning

- Segment 3D Airway Tree
- Calculate Centerline Paths
- Define Target ROI biopsy sites

Stage 2: Live Bronchoscopy

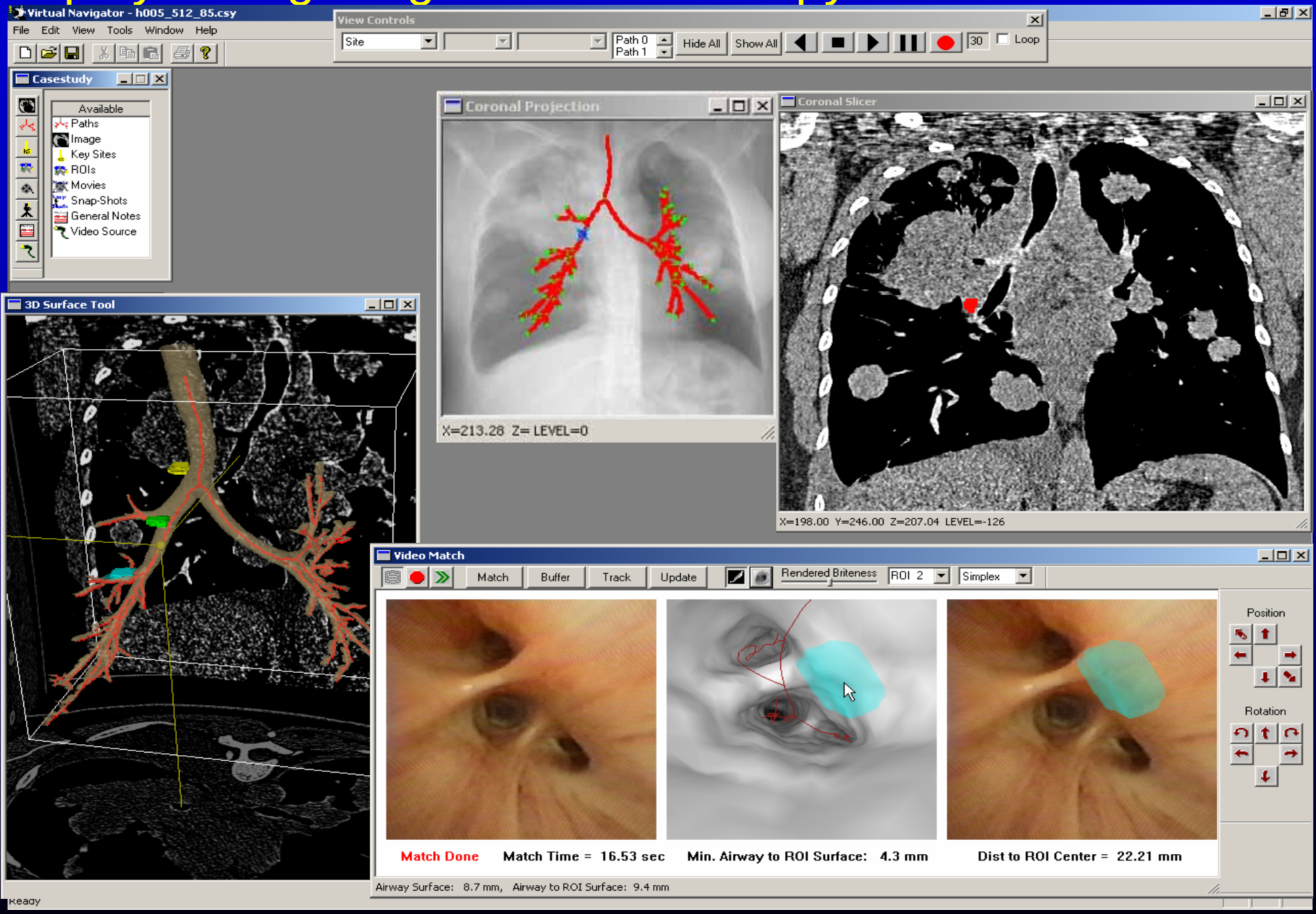
- Capture Endoscopic Video
- Correct Video's Barrel Distortion
- Track/Register Video and Virtual CT
- Map Target ROIs on Video

HTML Multimedia Case Study

Site List | Segmented Airway Tree | Centerline Paths | Screen Snapshots | Recorded Movies | Physician Notes

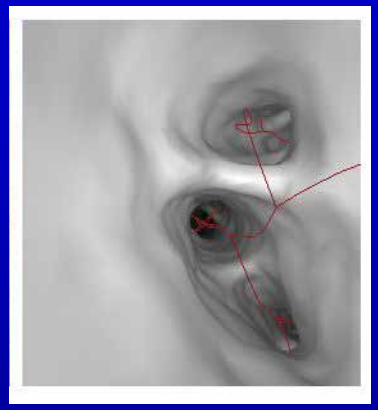
See: Helferty *et al.*, *SPIE Med. Imaging 2001*; Swift *et al.*, *Comp. Med. Imag. Graph*. 2002.

Display during Stage-2 Bronchoscopy

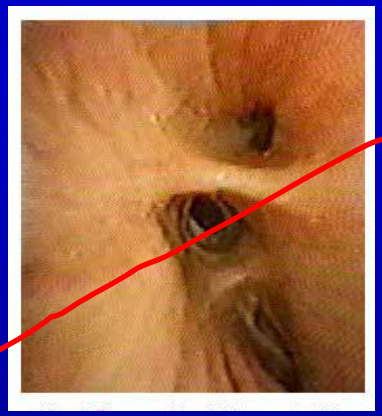


Case h005_512_85, Root site = (253,217,0), segger = (RegGrow, no filter), ROI #2 considered (Blue)

Stage 2: CT-Guided Bronchoscopy Protocol

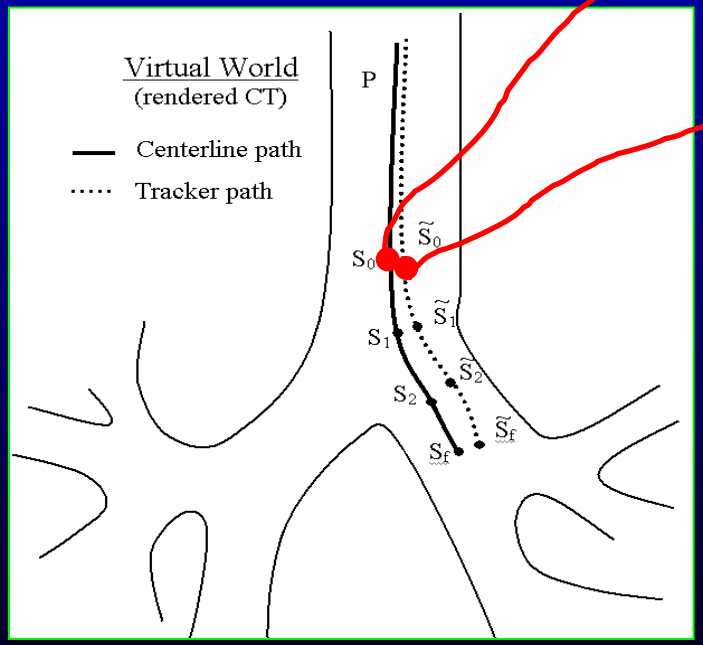


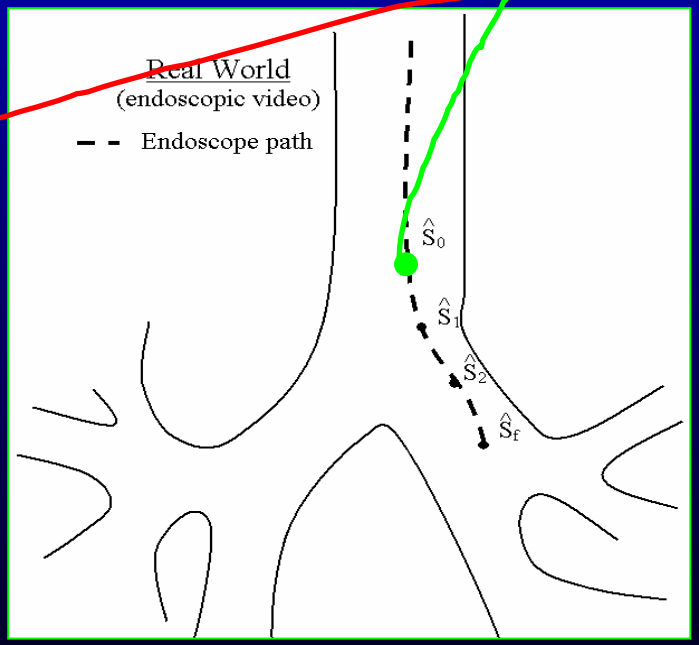
Endoluminal 3D CT rendering



Live video from bronchoscope

1. Provide Virtual-World CT rendering → I_{CT}
2. Move bronchoscope "close" to I_{CT} → target view I_V
3. Register Virtual World to target view I_V
4. Go to Step 1 unless biopsy site reached





Key Step:

CT-Video Registration

CT-Video Registration Problem: *Viewpoints*

Target video $I_V = I_V^{\chi_t}$

Optimal CT rendering $I_{CT}^{\chi_o}$

6-parameter viewpoint

$$\chi_t = (X_t, Y_t, Z_t, \alpha_t, \beta_t, \gamma_t)$$

$$\chi_o = (X_o, Y_o, Z_o, \alpha_o, \beta_o, \gamma_o)$$

3D position

$$p_t = (X_t, Y_t, Z_t)$$

$$p_o = (X_o, Y_o, Z_o)$$

3-angle direction

$$\mathbf{v}_o = \mathbf{v}(\alpha_o, \beta_o, \gamma_o)$$

$$\mathbf{v}_t = \mathbf{v}(\alpha_t, \beta_t, \gamma_t)$$

Standard camera direction matrix

$$\mathbf{v} = \begin{bmatrix} -\cos(\alpha)\sin(\beta)\cos(\gamma) + \sin(\alpha)\sin(\gamma) \\ \cos(\alpha)\sin(\beta)\sin(\gamma) + \sin(\alpha)\cos(\gamma) \\ \cos(\alpha)\cos(\beta) \end{bmatrix}$$

CT-Video Registration Problem:
Optimization Problem

Normalized Mutual Information (NMI):

$$S_{NMI}(I^{\chi}_{CT}, I_V) = \frac{h(V) + h(CT)}{h(V, CT)}$$

h(V), *h*(CT) – entropies based on image histograms (PDFs)

NMI Optimization:

$$\chi_o = \arg\left\{ \max_{\chi \in N_{\chi_i}} \left[S_{NMI}\left(I^{\chi}_{CT}(i,j), I_V(i,j)\right) \right] \right\}$$

χ_i – starting point for I^{χ}_{CT}

Ref: Studolme et al., *Pattern Recognition*, 1/99.

CT-Video Registration Problem:
Optimization Algorithms Tested

1. Steepest Ascent
2. Nelder-Meade Simplex
3. Simulated Annealing

CT-Video Registration Problem:
Error Measures for Tests

Position error $e_p = \|p_o - p_t\|$

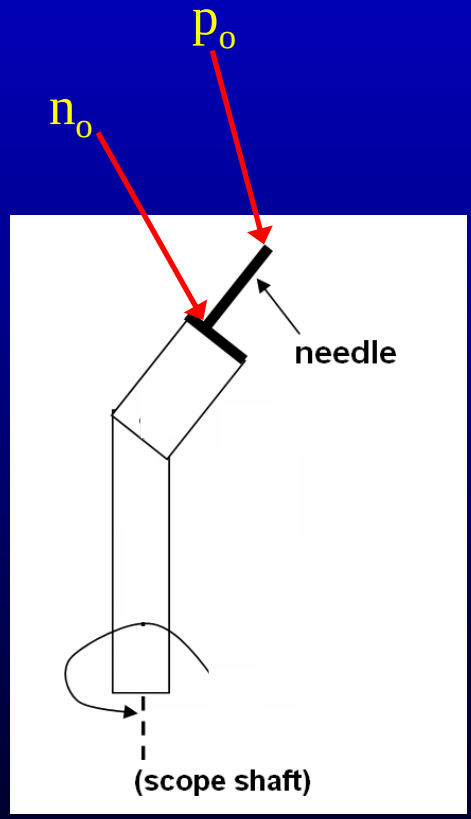
Angle error $e_a = \cos^{-1}(\mathbf{v}_o \cdot \mathbf{v}_t)$

Needle error $e_n = \|\mathbf{n}_o - \mathbf{n}_t\|$

where: $\mathbf{n}_o = \mathbf{p}_o + d_n \mathbf{v}_o, \quad \mathbf{n}_t = \mathbf{p}_t + d_n \mathbf{v}_t$

"needle" position for optimal CT view ($I_{CT}^{\chi_o}$)

needle position for bronchoscope (I_V)



Registration Protocol for Tests

1. Target video frame: I_V View to optimize: $I_{CT}^{\chi_o}$

2. Registration process:

   a. Fix 5 parameters of I_{CT}'s viewpoint to I_V's true viewpoint:
   $-10\ mm < \Delta X, \Delta Y, \Delta Z < 10\ mm$
   $-20^o < \Delta\alpha, \Delta\beta, \Delta\gamma < 20^o$

   b. Initialize I_{CT}'s remaining parameter away from true value

   c. Run NMI optimization until convergence

   d. Measure errors

errors for acceptable registrations →

$$\text{final } X, Y, Z \text{ position/needle errors } < 5mm$$
$$\text{final } \alpha, \beta, \gamma \text{ angle errors } < 5^o$$

Test #1: Performance of Optimization Algorithms

(a) Eliminate video and CT source differences

(b) Measure registration error precisely

1. Target video frame: I_V -- known fixed **virtual CT** view
2. View to optimize: $I_{CT}^{\chi_o}$ -- based on SAME 3D CT image as I_V
3. Test each optimization algorithms: stepwise, simplex, annealing

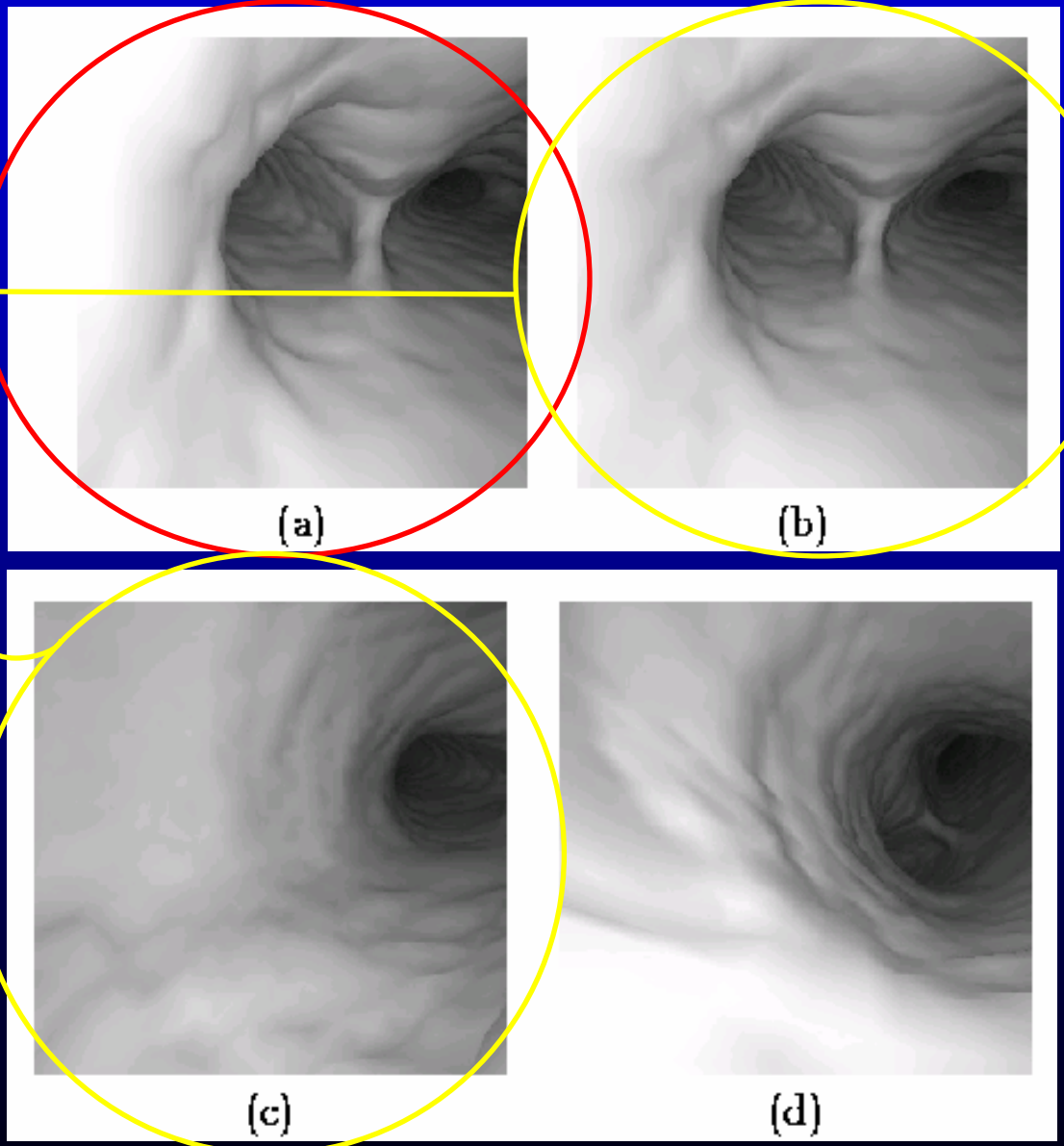
Test #1 -- Performance of Optimization Algorithms
Example Registrations $I_{CT}^{\chi_o}$

(a) Test "video" view I_V

(b) "Good" simplex result (ΔX=8mm) $I_{CT}^{\chi_o}$

(c) "Poor" annealing result (ΔY=10mm) $I_{CT}^{\chi_o}$

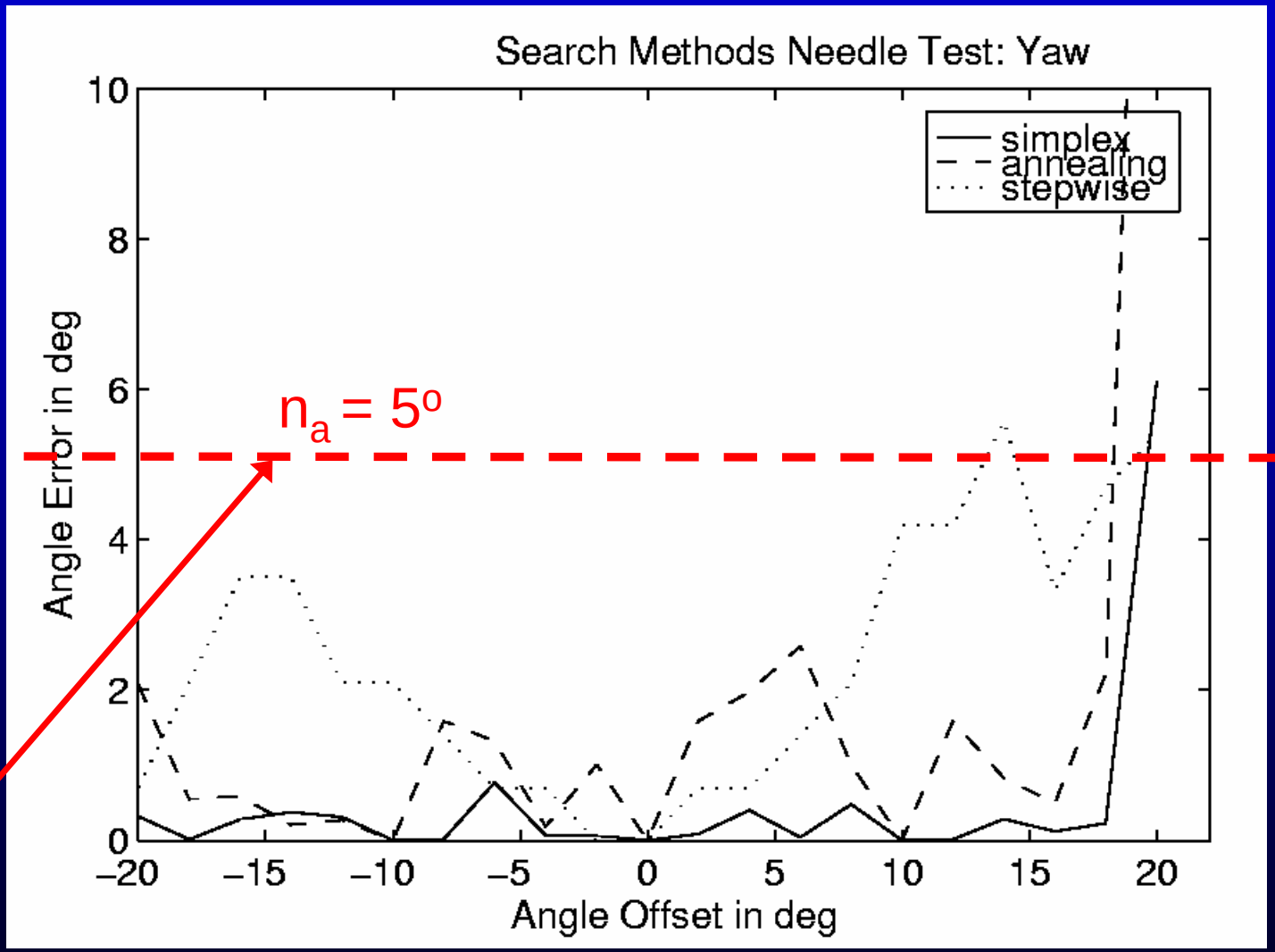
(d) "Poor" annealing result (Δ yaw = 20^o) $I_{CT}^{\chi_o}$



Test #1 -- Performance of Optimization Algorithms
Example Error Plot (n_a)

Initial $\Delta\beta$ (yaw) varied.

Other 5 parameters of I_{CT}'s viewpoint χ start at "true" values



Threshold for acceptable angle error n_a

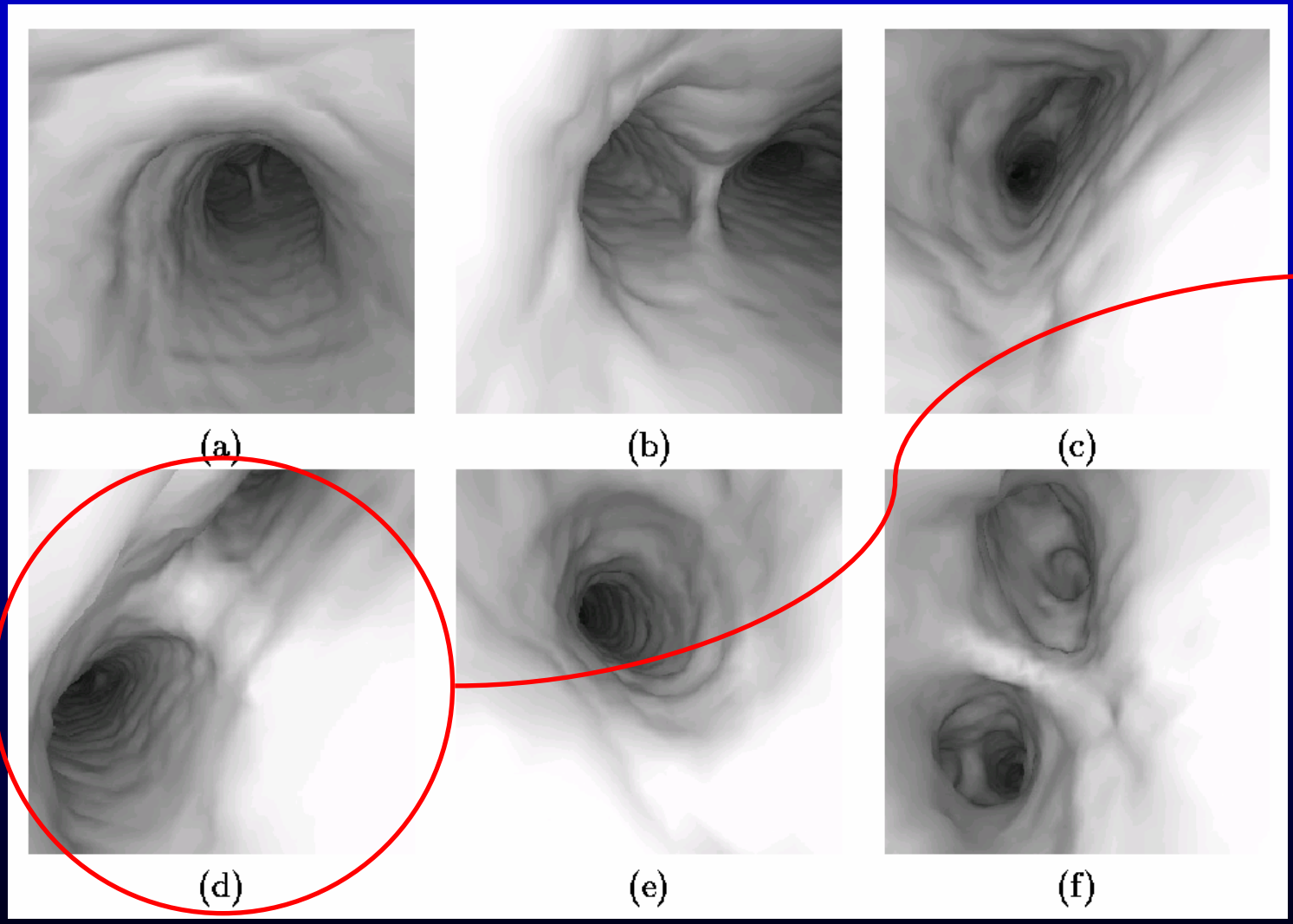
Test #2: Impact of Airway Morphology -- 6 Test ROIs

(a), (b) proximal and distal trachea

(c), (d) proximal and distal right main bronchus

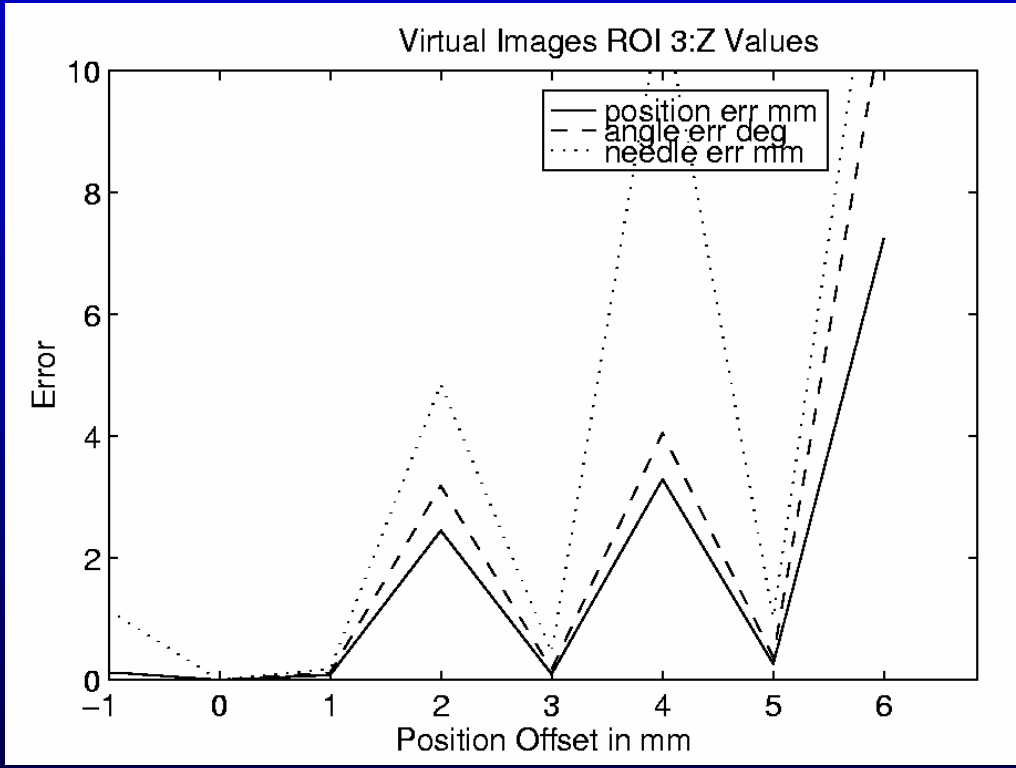
(e), (f) proximal and distal left main bronchus

→ Run Simplex Algorithm

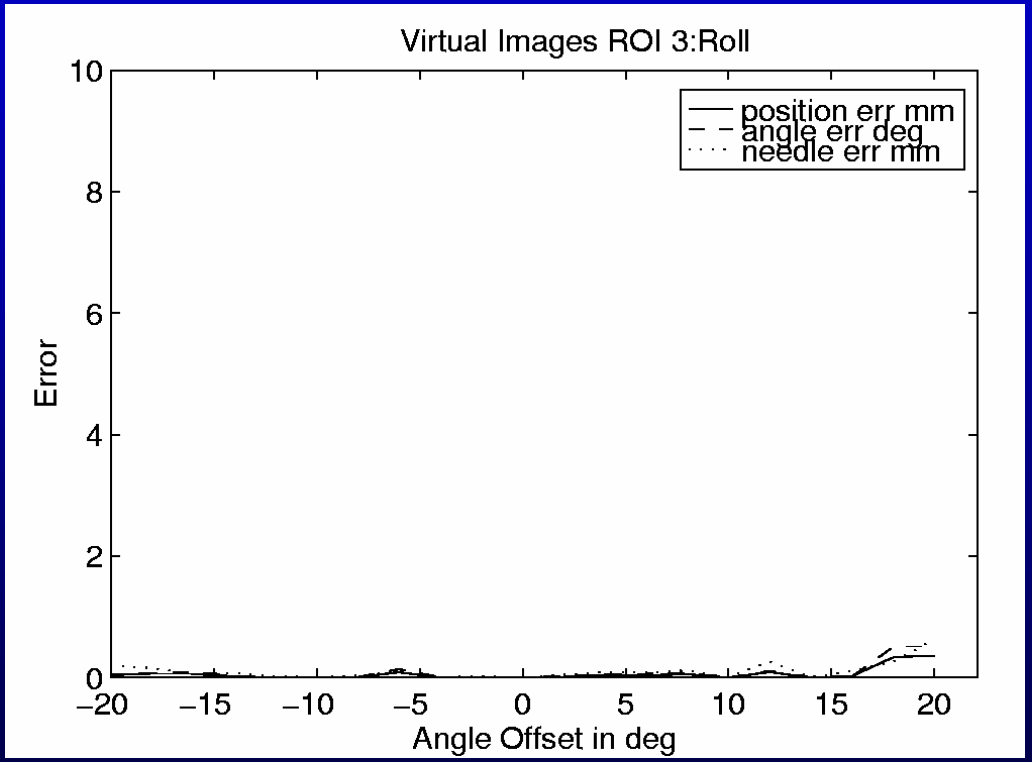


Test #2: Impact of Airway Morphology – ROI 3

ΔZ



Roll γ

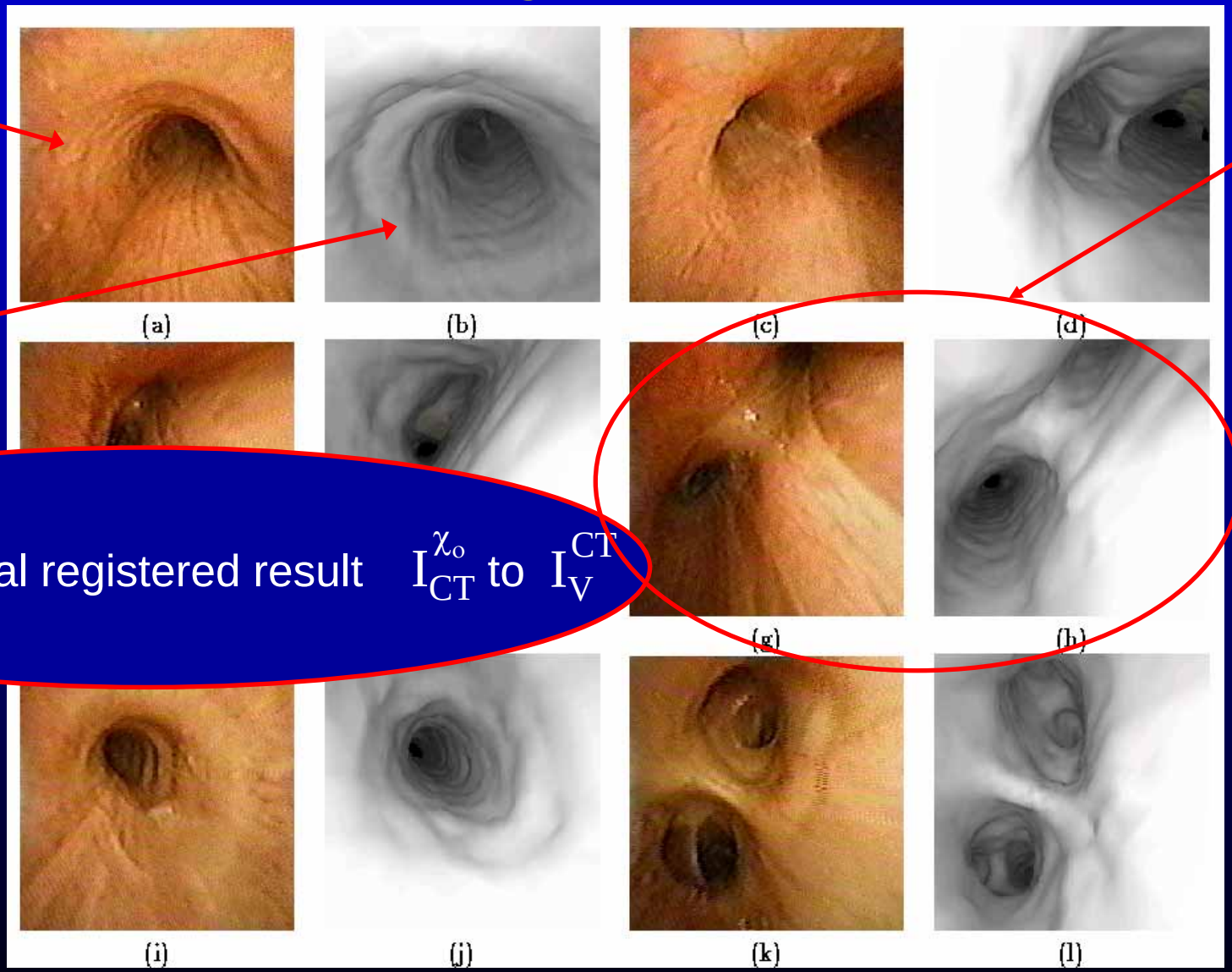


Test #2: Impact of Airway Morphology

Ranges of Starting Points that result in acceptable registrations

ROI Number	X bound min,max	Y bound min,max	Z bound min,max	Roll bound min,max	Yaw bound min,max	Pitch bound min,max
ROI 0	-10.0, 4.9	-10.0, 10.0	-10.0, 8.8	-20.0, 20.0	-20.0, 17.6	-20.0, 20.0
ROI 1	-7.6, 10.0	-10.0, 10.0	-10.0, 10.0	-20.0, 20.0	-20.0, 20.0	-20.0, 20.0
ROI 2	-10.0, 7.3	-6.4, 5.4	-5.1, 10.0	-20.0, 20.0	-20.0, 20.0	-20.0, 20.0
ROI 3	-10.0, 10.0	-10.0, 6.5	-10.0, 5.7	-20.0, 20.0	-20.0, 20.0	-20.0, 20.0
ROI 4	-10.0, 10.0	-7.1, 10.0	-10.0, 4.6	-20.0, 20.0	-20.0, 20.0	-20.0, 20.0
ROI 5	-10.0, 10.0	-10.0, 10.0	-10.0, 10.0	-20.0, 20.0	-20.0, 20.0	-20.0, 20.0
Average	-9.6, 8.7	-8.9, 8.6	-9.2, 8.2	-20.0, 20.0	-20.0, 19.6	-20.0, 20.0

Test #3: Registering CT to Real Video
* 6 Matching Test Pairs



I_V

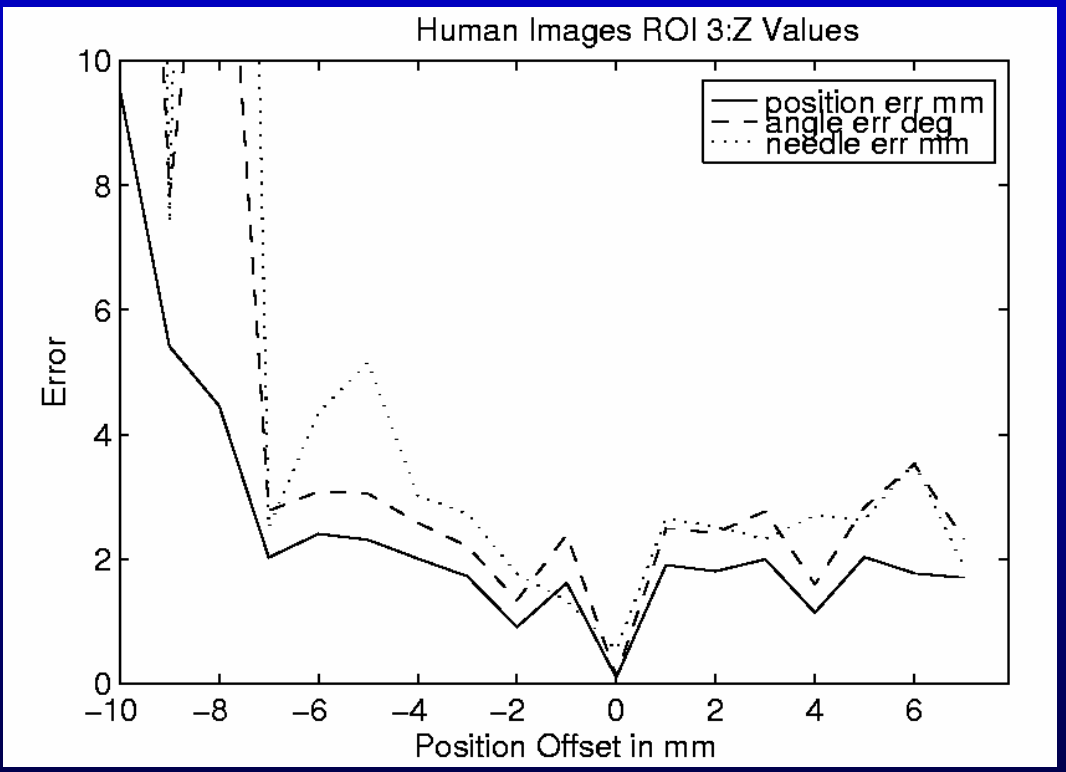
I_V^{CT}

ROI
Grp 3

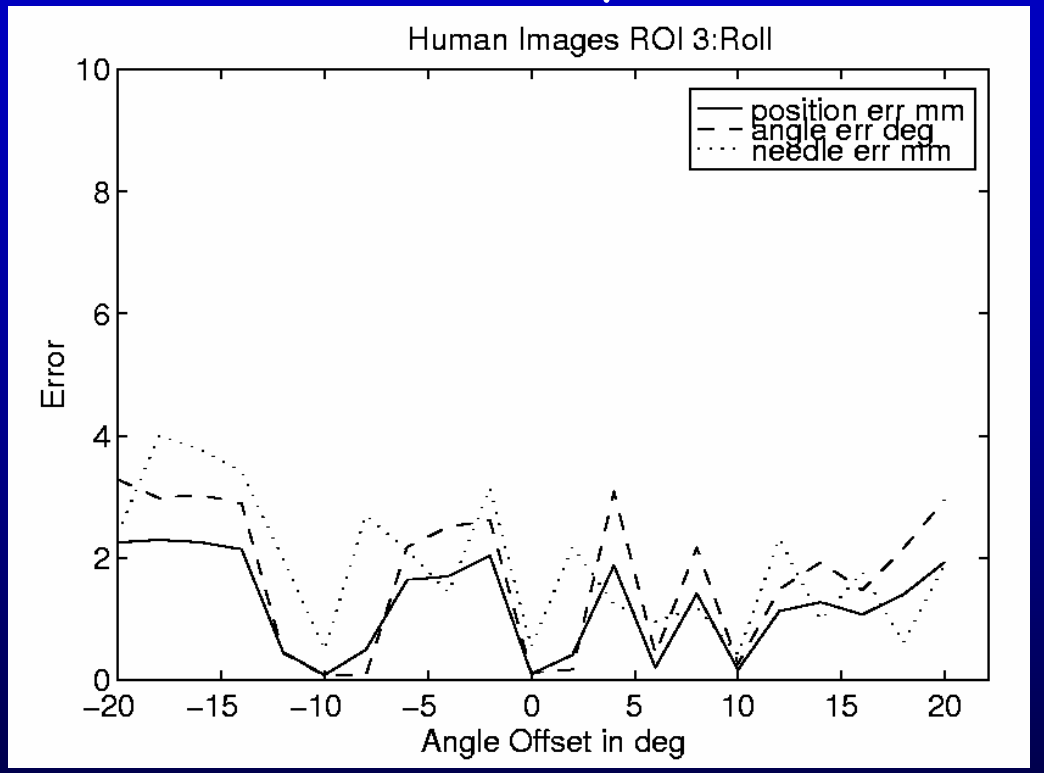
Compare final registered result $I_{CT}^{\chi_o}$ to I_V^{CT}

Test #3: Registering CT to Real Video * ROI-3 Pair

ΔZ



Roll γ



Test #3: Registering CT to Real Video
* Summary over 6 ROI Pairs

Ranges of Starting Points that result in acceptable registrations

error type	X bound min,max	Y bound min,max	Z bound min,max	Roll bound min,max	Yaw bound min,max	Pitch bound min,max
position	-9.7, 8.9	-8.9, 8.9	-7.3, 9.4	-20.0, 20.0	-20.0, 20.0	-20.0, 20.0
angle	-9.4, 8.0	-7.8, 7.9	-6.6, 7.7	-18.6, 20.0	-20.0, 20.0	-20.0, 20.0
needle	-10.0, 7.9	-7.7, 6.0	-6.1, 7.1	-15.2, 14.0	-11.0, 17.4	-11.1, 13.8

Test #4: Sensitivity to Different Lung Capacities

* CT scan – done at full inspiration (TLC)
* Bronchoscopy – done with chest nearly deflated (FRC)

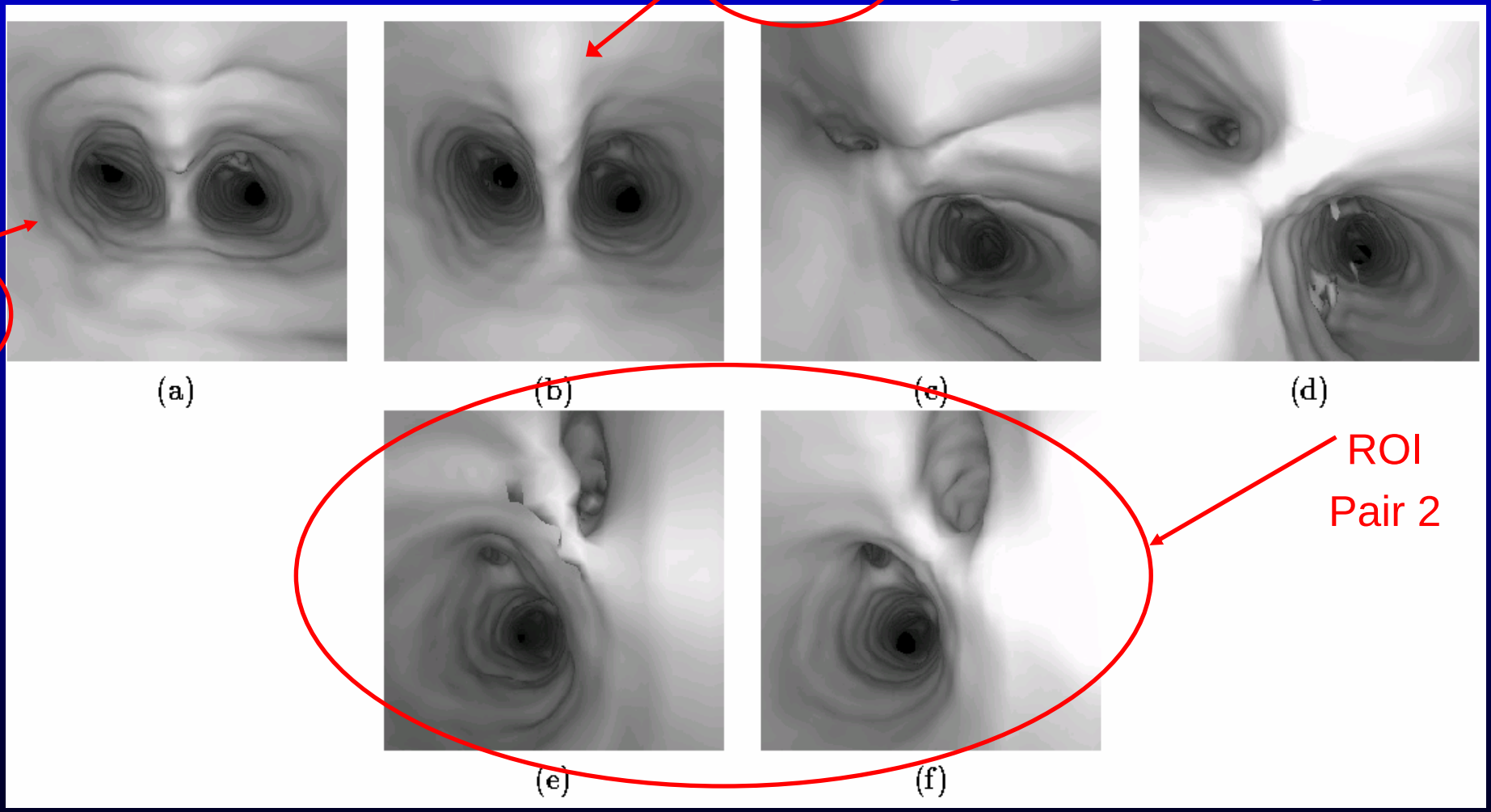
1. Target "video" frame: $I_V = I_{CT}^{FRC}$ -- known fixed CT view (from FRC CT volume)

2. View to optimize: $I_{CT}^{\chi_o}$ -- CT view from TLC CT volume

3. Run Simplex optimization algorithm:
   → Compare final result $I_{CT}^{\chi_o}$ to previously matched result I_{CT}^{TLC}

Test #4: Sensitivity to Different Lung Capacities

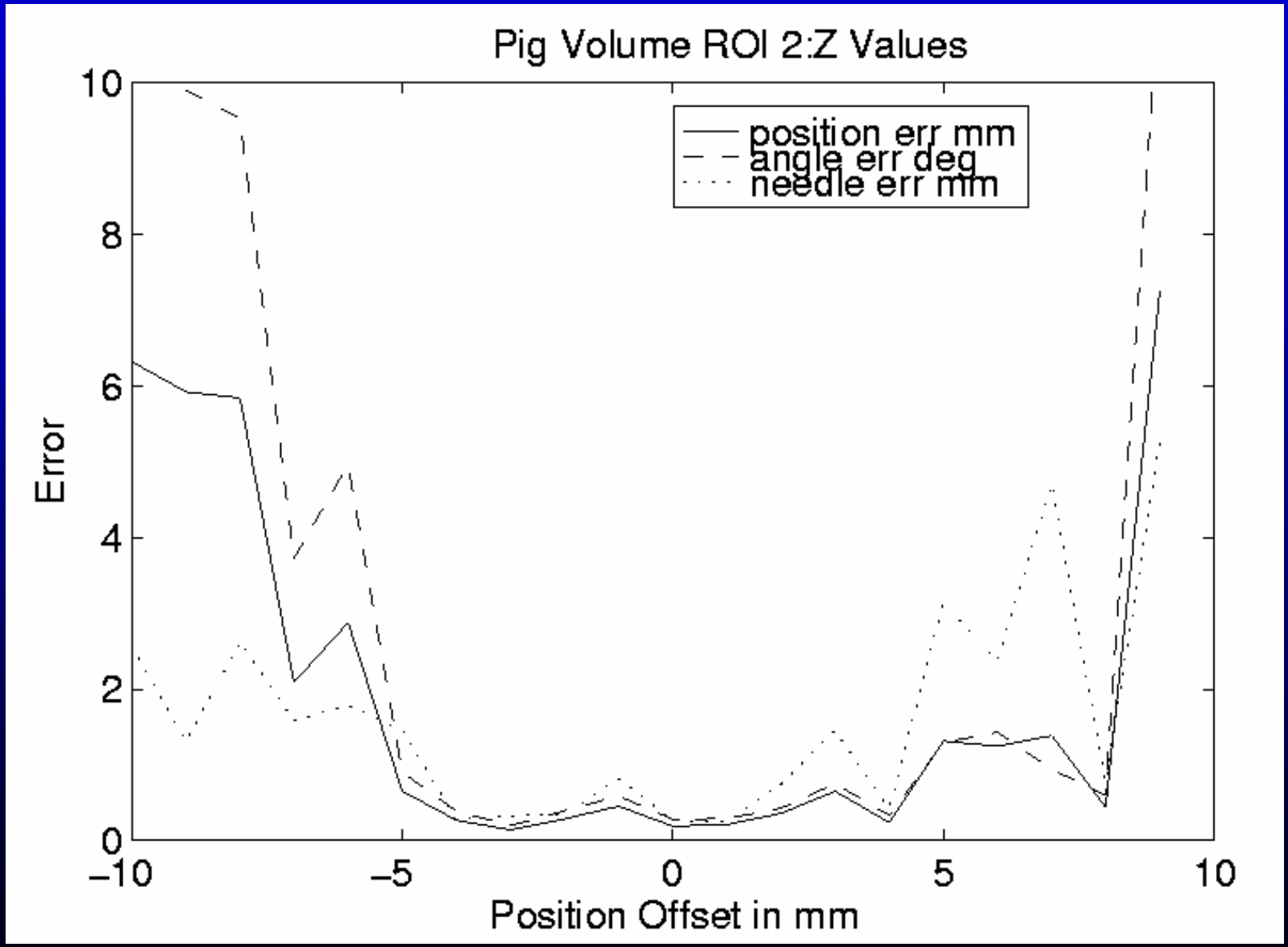
* 3 TLC/FRC Matching Pairs (Pig data; volume controlled)



Test #4: Sensitivity to Different Lung Capacities

* ROI Pair #2 (Pig data; volume controlled)

ΔZ



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Ranges of Starting Points that result in acceptable registrations

error type	X bound min,max	Y bound min,max	Z bound min,max	Roll bound min,max	Yaw bound min,max	Pitch bound min,max
position	-6.6, 10.0	-10.0, 8.3	-8.7, 8.5	-20.0, 20.0	-20.0, 20.0	-20.0, 18.9
angle	-6.5, 10.0	-8.0, 6.5	-8.1, 8.2	-20.0, 20.0	-19.5, 20.0	-19.9, 18.5
needle	-6.2, 7.6	-7.9, 6.3	-9.4, 7.0	-19.0, 20.0	-17.2, 20.0	-19.8, 17.3

Discussion

1. Method successful and runs in near real-time (5 sec per registration).
2. Good airway segmentation and video/CT “camera” calibration important.
3. Registration successful:
   a. over a wide range of anatomy
   b. Independent of lung volume
   c. +/- 8-10 mm position deviations, +/-15-20^{o} direction deviation
4. Head toward continuous video tracking and CT-video registration.

   → Helferty et al. *SPIE Med. Imaging 2003*

Acknowledgements

This work was partially supported by NIH grants #CA074325 and CA091534, and by the Olympus Corporation.

Steepest Ascent Algorithm

Initialize optimal viewpoint as initial viewpoint: $\chi_o = \chi_i = \{X, Y, Z, \alpha, \beta, \gamma\}$.
Compute $S_{max} = S^{\chi_o}_{NMI}$
iteration = 0
Do
    Compute $S^{\chi_i}_{NMI}, \quad i = 1, 2, \ldots, 12,$ where
        $\chi_1 = \{X + \Delta X, Y, Z, \alpha, \beta, \gamma\}, \quad \chi_2 = \{X - \Delta X, Y, Z, \alpha, \beta, \gamma\},$
        $\chi_3 = \{X, Y + \Delta Y, Z, \alpha, \beta, \gamma\}, \quad \chi_4 = \{X, Y - \Delta Y, Z, \alpha, \beta, \gamma\}, \ldots$
        $\chi_{11} = \{X, Y, Z, \alpha, \beta, \gamma + \Delta\gamma\}, \quad \chi_{12} = \{X, Y, Z, \alpha, \beta, \gamma - \Delta\gamma\}$
    $\chi = \arg\{\max_{\chi_i} S^{\chi_i}_{NMI}\}$
    If $(S^{\chi}_{NMI} > S_{max})$
        $S_{max} = S^{\chi}_{NMI}$
        $\chi_o = \chi$
    Else
        break; /* χ_o is the optimal viewpoint. */
    iteration = iteration + 1
While{iteration $<$ MAX_ITER}

Also tested Nelder-Meade Simplex and Simulated Annealing

Test #2: Impact of Airway Morphology

Consider 6 Varied Airway Locations (ROIs)

1. Target video frame: I_V -- a known fixed virtual CT view

2. View to optimize: $I_{CT}^{\chi_o}$ -- based on SAME 3D CT image as I_V

3. Run Simplex optimization algorithm.

Test #3: Registering CT to Real Video

1. Target video frame: I_V -- known fixed video frame; have matching I_{CT}^{V}
2. View to optimize: $I_{CT}^{\chi_o}$ -- from corresponding CT image
3. Run Simplex optimization algorithm:
   a. Fix 5 parameters of I_{CT}'s viewpoint to I_V's true viewpoint
   b. Run optimization
   c. Compare final registered result $I_{CT}^{\chi_o}$ to I_{CT}^{V}
4. Test on three target "video/CT" matching pairs

Test #4: Sensitivity to Different Lung Capacities

* CT scan – done at full inspiration (TLC)
* Bronchoscopy – done with chest nearly deflated (FRC)

1. Target "video" frame: $I_V = I_{CT}^{FRC}$ -- known fixed CT view (from FRC CT volume)

2. View to optimize: $I_{CT}^{\chi_o}$ -- CT view from TLC CT volume

3. Run Simplex optimization algorithm:
   a. Fix 5 parameters of I_{CT}'s viewpoint to I_V's true viewpoint
   b. Run optimization
   c. Compare final result $I_{CT}^{\chi_o}$ to previously matched result I_{CT}^{TLC}

4. Test on three "FRC/TLC" matching pairs