Toward Safe Endonasal Surgery Using Teleoperated Continuum Robots

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Toward Safe Endonasal Surgery Using Teleoperated Continuum Robots

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Dr. J. Burgner, 9/30/11
Otolaryngology & Neurological surgery
Skull Base Surgery

- 1 of 5* people develop a pituitary tumor
- 39% of all brain tumors are at tuberculum sellae

* American Brain Tumor Association
The Endonasal Approach

tuberculum sellae meningioma

pituitary gland
sphenoid sinus
nasal cavity
Endonasal Surgery - Video
Challenges

- Only 14.5% of skull base surgeries are performed endonasally
  - Limited dexterity of current instrumentation
  - Small number of expert surgeons
  - Visualization

- Attempts to use the daVinci

Hanna et al.
Concentric Tube Robots
How We Address Safety

- Compliant, dexterous robot
- Modular actuation unit for custom designed active cannula robot
- Teleoperation
- Force sensing
- Image-guidance
- Virtual Fixtures
Robot Design - Workspace
Design Parameters

- Number of tubes
- Tube lengths
- Tube curves
- Overall robot stiffness
  - Tube diameters
  - Tube wall thicknesses
  - Tube configuration
Optimize Tube Parameters

- 3 tube design
  - Outer tube straight
    - Fixed length (100mm)
  - Middle and inner tube
    - Initial straight length
    - Curved part with constant curvature
- Optimize for maximum workspace coverage at region of interest
Teleoperated System
The Robot
Cadaver Setup Trial
How We Address Safety

- Compliant, dexterous robot
- Modular actuation unit for custom designed active cannula robot
- **Teleoperation**
- Force sensing
- Image-guidance
- Virtual Fixtures
Mechanics-Based Model

INPUTS:
Actuators $q$
Loads $w$

Model: Nonlinear BVP

OUTPUTS:
Robot Shape $g(s)$

$s$: Arc Length Along Robot
$g(s)$: Frame Along Robot
$q$: Translations and Rotations of Component Tubes
$V$: End Effector Motion
$w$: Applied Wrench

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Jacobian and Compliance Matrix

\[ V = J(s, q, w) \dot{q} + C(s, q, w) \dot{w} \]

Damped Least Squares Control

Objective Function

\[
F = \frac{1}{2} \left( (J\dot{q} - v_0)^T W_0 (J\dot{q} - v_0) + \sum_{i=1}^{m} (\dot{q} - v_i)^T W_i (\dot{q} - v_i) \right)
\]

Weighted Tracking Accuracy  
Damping & Avoiding

Minimize \( F \)

\[
\dot{q} = \left( J W_0 J^T + \sum_{i=1}^{m} W_i \right)^{-1} \left( J^T W_0 v_0 + \sum_{i=1}^{n} W_i v_i \right)
\]
Teleoperation Control

Damped Least Squares Control

PID Control

Kinematic Model

Surgeon’s Hand

Robot Tip

$g_d$, $q$, $F$, $L$, $g_m$, $J$
Teleoperation
How We Address Safety

- Compliant, dexterous robot
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Intrinsic Force Sensing

- Deflection based wrench estimation

\[ w_{e}^{k+1} \approx w_{e}^{k} + C^{-1} \left( g_{p}^{-1} g_{s} - I \right)^{\top} \]
Extended Kalman Filter Approach

- $g_s$ is subject to measurement inaccuracy

$$\mathbf{w}_{e}^{k+1} = \mathbf{w}_{e}^{k} + K \left( g_p^{-1} g_s - I \right)^{\top}$$

$$\Sigma^{k+1} = (I - KC)\Sigma^{k}_p$$

$$K = \Sigma_p C^T (C\Sigma_p C^T + \Sigma_s)^{-1}$$

Deflection based Force Sensing
Increase Safety

- Approached from the medical application
  - Current limitations
  - Lack of instrumentation

- Robotic design
- Ergonomics
- New camera views
- Improved image-guidance, virtual fixtures
Safe Robot – New Procedures

- „Turn corners“
- Dexterity in cranial area

- Potential applications
  - Fetal surgery
  - Lung surgery
  - Middle ear
  - Cardiac surgery
Conclusion

- Approach safety from the robot design perspective
- Consider safety in every development step
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http://research.vuse.vanderbilt.edu/MEDLab/