Optimal positioning of a tubular continuum robot for resection of suprasellar brain tumors in consideration of task constraints

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Clinical Problem: Pituitary Adenoma

Surgical approaches

**Transcranial**
- Invasive
- Risk of infection
- Disfigurement
- Long recovery

**Endonasal**
- Minimally invasive
- Reduced complications
- Short recovery

[Burgner et al., IEEE/RSJ, 2011]
Tubular Continuum Robot

1. 2-4 concentric precurved, superelastic tubes
2. Smallest continuum robot (diameter < 2.5mm)
3. 2 DOF per tube:
   - Rotation $\alpha$
   - Translation $\beta$
4. Teleoperable

[Observation]

[Burgner et al., IEEE/RSJ, 2011]

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Motivation

Resort to invasive surgery

- Wide tumors
- Tumors located deep into the brain

Advantages of robot assisted surgery

- Better reachability
- Augmented manipulability
- Less fatigue for the surgeon
- Avoid invasive surgery

[Burgner et al., IEEE/RSJ, 2011]
Goal: Maximization of Target Coverage

3 design parameters per tube (9 in total):
- Length of the straight section $L_i^s$
- Length of the curved section $L_i^c$
- Curvature parameter $k_i$

Robot base placement with respect to reference frame:
- Position $t$
- Orientation $R$

Robot design optimization

Robot base placement optimization
State of the Art

- Collision-free pathways [Torres et al., IROS, 2012]
- Reachability of target points [Burgner et al., ICRA, 2013]
- 2 separate problems: navigation and manipulation [Bergeles et al., T-RO, 2015]

Robot design optimization

Robot base placement optimization: actual issue
Materials

Medical imaging datasets

Micro-adenoma

- Carlo Besta Neurological Institute, Milan, Italy
- 6 subjects (2 micro-adenomas + 4 macro-adenomas)

Macro-adenoma

- 3T MR scanner with contrast agent
- CT scanner
Methods

1. 3D reconstruction of surgical workspace
2. Workspace modelling
3. Model discretization (1 mm³ voxels)

- Tumor
- Sphenoid sinus
- Nasal passage
Definition of Admitted Base Placements

Initial base placement

- Tumor
- Sphenoid sinus
- Nasal passage

9 additional base placements

- Sphenoid sinus upper base center
- Insertion points
- Transformed frames

$9 \times (t, R)$

CS$_{\text{robot}}$ → CS$_{\text{global}}$
Definition of Admitted Base Placements

Initial base placement

- Tumor
- Sphenoid sinus
- Nasal passage
- Patient’s nostril

9 additional base placements

- Insertion points
- Transformed frames

CS_{robot} \rightarrow CS_{global}

9 \times (t, R)

Sphenoid sinus upper base center
Definition of Admitted Base Placements

Initial base placement

- Sphenoid sinus
- Nasal passage
- Tumor

9 additional base placements

- Insertion points
- Sphenoid sinus upper base center
- Transformed frames
Set of Admitted Base Placements

Initial base placement

- Tumor
- Sphenoid sinus
- Nasal passage
- Patient’s nostril

Definition of 8 base placements \((t, R)\)

- 8 insertion points at patient’s nostril
- Direction of insertion towards sphenoid sinus upper base center

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Optimization Algorithm

Random initial design

Selection of base placement

Generation of configuration samples

For each sample

Check of workspace boundaries

Computation of reached tumor voxels

Sequential Quadratic Programming (SQP)

Stopping criteria

Optimal design and base placement

New design
Optimization Results

1. Design
   - Before optimization
   - After optimization

2. Robot placement
   - Before optimization
   - After optimization

3. Reached tumor points (10,000 samples)
   - Before optimization
   - After optimization
   - x/y plane
   - x/z plane

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Algorithm Evaluation: Comparison with Previous Work

Previous surgical workspaces

3 workspace models taken from [Burgner et al., ICRA, 2013]: A, B, C

(A) (Micro-adenoma)

(B) (Macro-adenoma)

(C) (Macro-adenoma)

Tumor coverage comparison

Improvements with respect to [Burgner et al., ICRA, 2013]:

+ Consideration of robot base placement
+ Optimization of all robot tube components

Comparison of median tumor coverages

<table>
<thead>
<tr>
<th>Workspace model</th>
<th>Previous median coverage [%]</th>
<th>Actual median coverage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>67.5</td>
<td>92.5</td>
</tr>
<tr>
<td>B</td>
<td>70.0</td>
<td>95.0</td>
</tr>
<tr>
<td>C</td>
<td>75.0</td>
<td>79.5</td>
</tr>
</tbody>
</table>
Towards an Application-Specific Approach

**Generic representations**

2 workspace models using mean dimensions from literature: D, E

- **D** (Micro-adenoma): 7.5 mm, 7.5 mm, 13.6 mm, 17.5 mm
- **E** (Macro-adenoma): 11.5 mm, 11.5 mm, 13.6 mm, 17.5 mm

**Design shape comparison**

- Comparison of optimized design shapes using mean distance (MD)
- Interchange of similar designs (MD < 0.015 cm)

\[ MD = \frac{\sum_{k=1}^{K} \sqrt{(y_{1k} - y_{2k})^2 + (z_{1k} - z_{2k})^2}}{K} \]

The designs optimized for model D fit all other micro-adenoma cases considered.

Can these models be representative of more clinical cases?
Influence of Model Geometry on Tumor Coverage

Tumor volume $V_t$

Correlation test (Pearson coefficient): $p$-value > 0.05

Tumor access constraint $A_c$

Correlation test (Pearson coefficient): $p$-value < 0.05
Linear regression model: $R$-squared = 73%
Conclusions and Future Developments

Conclusions

- Robot base placement increases target coverage
- Robot performance depends on the space available at the base of the tumor

Future developments

- Increase number of tube components
- Multi-objective optimization
- Collision-free pathways for insertion
Thank you for your attention!