3D simulator for intra-operative path planning with a deformable position-based dynamics environment in keyhole neurosurgery

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Brain surgery
a highly invasive procedure that allows accessing the brain to treat a variety of conditions

→ improve accuracy and quality through minimally invasive neurosurgery

KEYHOLE NEUROSURGERY (KN)
Access the brain through a burr hole in the skull

Procedures
• Biopsy
• Convection enhanced delivery CED
• Deep brain stimulation DBS

Advantages
✓ Lower complications
✓ Better post-operative outcomes
Introduction: problems

PROBLEMS OF A STATIC ENVIRONMENT

- No consideration of cerebral displacement (from MM to CM)
- Less precision in avoiding obstacles in intra-operative phase

DYNAMIC ENVIRONMENT

- Simulates the brain structures displacement

DIFFICULTIES

- Viscoelastic behaviour of the brain
- Computational resources
- Patient specificity
State of the art: soft tissue deformation in neurosurgery

**SYNTHETIC PHANTOM MODELS**
- Gelatine or hydrogels
- Replicate in vitro the brain’s behaviour
- Cope with deformations occurring during neurosurgical procedures

**LIMITATIONS**
- High computational time → unsuitable for real-time applications
- Complicated process
- Overshooting problem of equilibrium configurations

**FORCE-BASED DYNAMIC MODELS**
- Include finite element methods (FEM), mass-spring systems
- Model by manipulating internal and external forces (accelerations)
- Determine positions through numerical integration of the derived accelerations

**SOLUTION**
- POSITION-BASED DYNAMICS (PBD) APPROACH
Aim of the work

This thesis aims to develop a 3D simulator for pre-and intra-operative path planning with a dynamic environment based on a PBD approach to assist the surgeon during keyhole neurosurgery, ensuring realism during the procedure and a precise and safe setup to reduce the risks for the patient.

Pre- and Intra-operative path planning framework implemented in Unity with possibility to operate both manually, with the use of a joystick, and automatically.

Dynamic environment: an innovative approach is applied to the brain model to simulate needle-tissue and tissue-tissue deformation simulation.

Hardware integration (Neuromate) with EDEN2020 frameworks.
Methods: simulator architecture

1. START SIMULATION

2. SELECT THE PROCEDURE
   - Deep Brain Stimulation
   - Convection Enhanced Delivery

3. KINEMATIC CONSTRAINTS SELECTION
   - MAX CURVATURE: 0.014 mm
   - SPEED: 0.4 mm/s
   - OUTER DIAMETER: 2.5 mm

4. SELECT THE TARGET
   - Tumor
   - LF Pallidum
   - RH Pallidum
   - LF Thalamus
   - RH Thalamus
   - LF Ventricle
   - RH Ventricle

5. ENTRY POINT SELECTION

6. TRAJECTORY GENERATION

7. TRAJECTORY VISUALISATION

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Methods : Position-Based Dynamics (PBD)

PBD compute the time evolution of a dynamic system by directly updating positions. Objects are discretized as clusters of particles described by their positions $\mathbf{p}_i$, velocities $\mathbf{v}_i$, and mass $m_i$ subject to a set of $J$ positional constraints $C_j(\mathbf{p})$.

Deformation computation is a constraint-function optimization problem.

**GOAL OF THE SOLVER**

$$C(\mathbf{p} + \Delta \mathbf{p}) = 0$$

**$\Delta \mathbf{p}$ COMPUTED BY SOLVING**

$$C(\mathbf{p} + \Delta \mathbf{p}) \approx C(\mathbf{p}) + \nabla_p C(\mathbf{p}) \cdot \Delta \mathbf{p} = 0$$

$$C(\mathbf{p}_1, \mathbf{p}_2) = |\mathbf{p}_1 - \mathbf{p}_2|^2 - d^2$$
Methods: Position-Based Dynamics (PBD)

- Particle spacing
- Cluster spacing
- Particle radius
- Cluster radius
- Collision distance
- Cluster stiffness
- Link radius
- Link stiffness
- Collision distance

Mesh of the object

NVIDIA Flex UNITY PLUGIN

Flex Soft Actor + Flex Container

Deformable object
Experimental setup: workflow

Catheter insertion
PBN

SIMULATED TISSUE
DEFORMATIONS

REAL TISSUE
DEFORMATIONS

Human White matter parameters

In-vitro experiments: gelatin phantom

Human Gray deep matter parameters

Simulation experiments: Human brain

Human brain parameters

In-vivo experiments: ovine brain

CALIBRATION

VALIDATION
Experimental setup: white matter calibration

**SIMULATION**
3D Flex Model of Brain with fiducial slice at the depth of 31.4 mm

**REAL**
tissue phantom in Hydrogel with fiducial slice at the depth of 31.4 mm

Calculation of this metrics at each frame $f$ and $k$ insertion:

- Penetration depth of the catheter
  \[ \Delta depth^k_f = \| q^k_{init} - q^k_f \| \]

- Average displacement of the $N$ particles of the phantom
  \[ \Delta disp^k_f = \frac{1}{N} \sum \| p^k_{init} - p^k_f \| \]

- Displacement of phantom particles center of mass (CoM)
  \[ \Delta centerDisp_f = \| c_{init} - c_f \| \]

Comparison between **REAL** and **SIMULATION** deformations

$q_{init}, p_{init}, c_{init}$ : catheter, particles, CoM initial positions

$q_f, p_f, c_f$ : catheter, particles, CoM final positions
Experimental setup: grey deep matter calibration

Tuning of the grey matter Flex parameters following knowing the differences in the various brain structures' behaviours:

Average displacement of the $N$ particles of the phantom

\[
\Delta disp_f = \frac{1}{N} \sum \| p_{init} - p_f \|
\]

Displacement of CoM of each brain structures

\[
\Delta disp_{l.f} = \| c_{l.init} - c_{l.f} \|
\]

Comparison between LITERATURE and SIMULATION range of deformations for each brain structures

**Human Brain Structures**

- Amygdala
- Brain Stem
- Caudate
- Cerebellum
- Hippocampus
- Gyri and Sulci
- Pallidum
- Putamen
- Thalamus
- Tumor

$p_{init}$, $c_{init}$: particles, CoM initial positions
$p_f$, $c_f$: particles, CoM final positions
Experimental setup: FleX model validation

For each \( k = 1, \ldots, 5 \) equally distanced points on each side \( s = 1, \ldots, 4 \) of the hole created from the catheter insertion for each frame \( f \) calculation of:

Average displacement of the \( N \) particles of the ovine phantom

\[
\Delta disp^k_f = \frac{1}{N} \sum \| p^k_{init} - p^k_f \|
\]

\( p^k_{init}, c^k_{init} \): particles initial positions
\( p^k_f \): particles final positions

Comparison between IN-VIVO and SIMULATED ovine experiments

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Results: FleX model calibration

White matter calibration with cube and hydrogel phantom

Displacement with respect to Insertion Depth

- Local peak with a subsequent decrease in deformation caused by the initial insertion of the catheter into the material.
- The deeper the catheter continues, the more the displacements increase.
Results: FleX model calibration

Fine tuning of the grey deep matter parameters

Brain structures shift heatmap

Reflects the expected values of deformations reported in literature

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## Results: FleX model calibration

### Optimal set of parameters for each brain structures

<table>
<thead>
<tr>
<th>Flex Objects</th>
<th>Particle Spacing</th>
<th>Cluster Spacing and Radius</th>
<th>Cluster Stiffness</th>
<th>Link Radius</th>
<th>Link Stiffness</th>
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<tr>
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<td>0,002</td>
<td>0,0065</td>
<td>0,001</td>
</tr>
</tbody>
</table>
Results: FleX model validation

The deformation ranges are comparable. The model can be applied to different types of datasets and represents a suitable model for the simulation of cerebral deformations induced by the catheter's insertion.

Mismatch: 5.16%
Discussion

INTEGRATION
UNITY-ROS

rosbridge_websocket

ROS

ubuntu
Conclusions and future work

The simulator accurately mimics cerebral deformations and viscoelastic brain behavior providing important visual feedback in order to reach the target precisely. ROS-Unity integration makes it applicable to real situations for both pre- and intra-operative phases.

- User friendly interface with possibility to use directly MRI volume
- Automation of FleX parameters calibration procedure

ACHIEVEMENT:
- Submitted to IROS conference and RAL journal
- Poster submitted to The Hamlyn Symposium on Medical Robotics 2021

FUTURE WORKS:

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