Automated and deterministic Trajectory Planning for Stereotactic Brain Biopsy

Using Patient-Specific Anatomical Modeling and Exhaustive Discrete Search

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Presentation Roadmap

01 **Clinical Motivation**
Why safe biopsy trajectory planning matters

02 **Related Work**
Previous navigation and path planning methods

03 **Automated Planning**
From MRI to entry zone and anatomical modeling

04 **Deter. Optimization**
Risk map, exhaustive search & multi-path planning

05 **Results**
Performance, feasibility, limitations and future work

UnERD

01

Clinical Motivation

Introduction, stereotactic surgery explanation. Why safe biopsy trajectory planning matters and the contributions of this work.

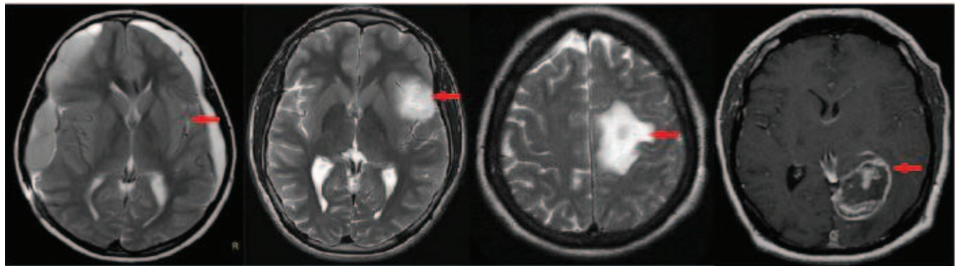
Tumour Surgery

Why trajectory planning matters:

- **Stereotactic brain biopsy is minimally invasive, but trajectory choice determines safety.**

Carries inherent risks, with hemorrhagic complications occurring in 0.7–5.2% of cases.

A LOT IN BRAIN SURGERY.



Extracted from [2]

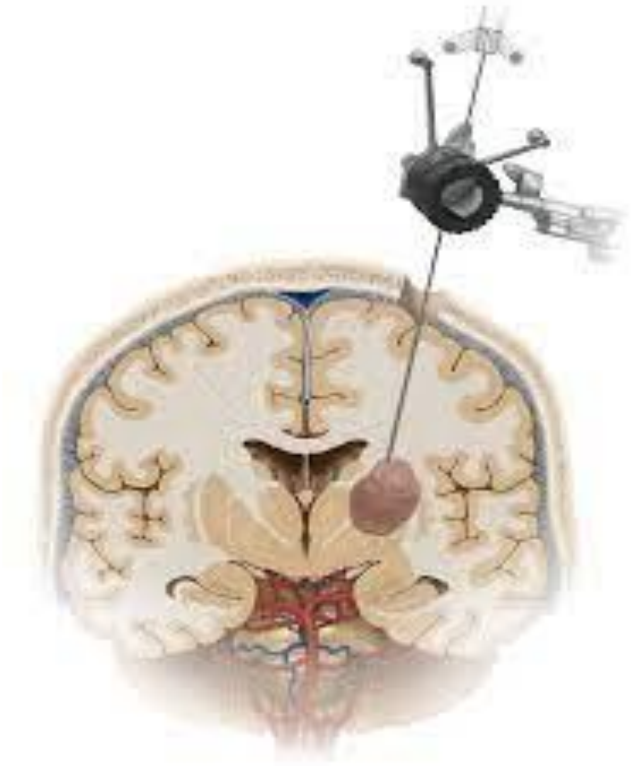
Stereotactic Operation

Stereotactic biopsy procedure is used for:

- Sampling of abnormal tissue
- Large and deep-seated tumors

Limited surgical access

Located in eloquent brain areas, such as the motor cortex



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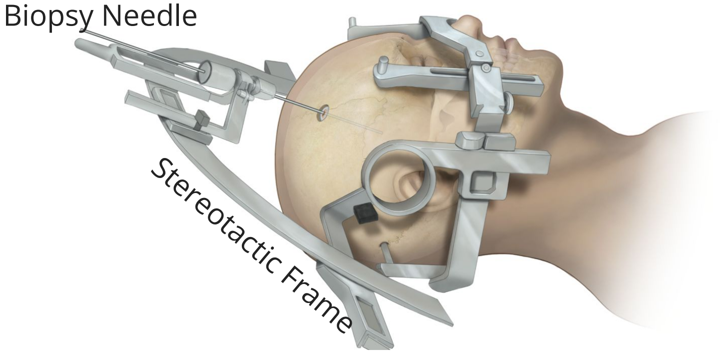

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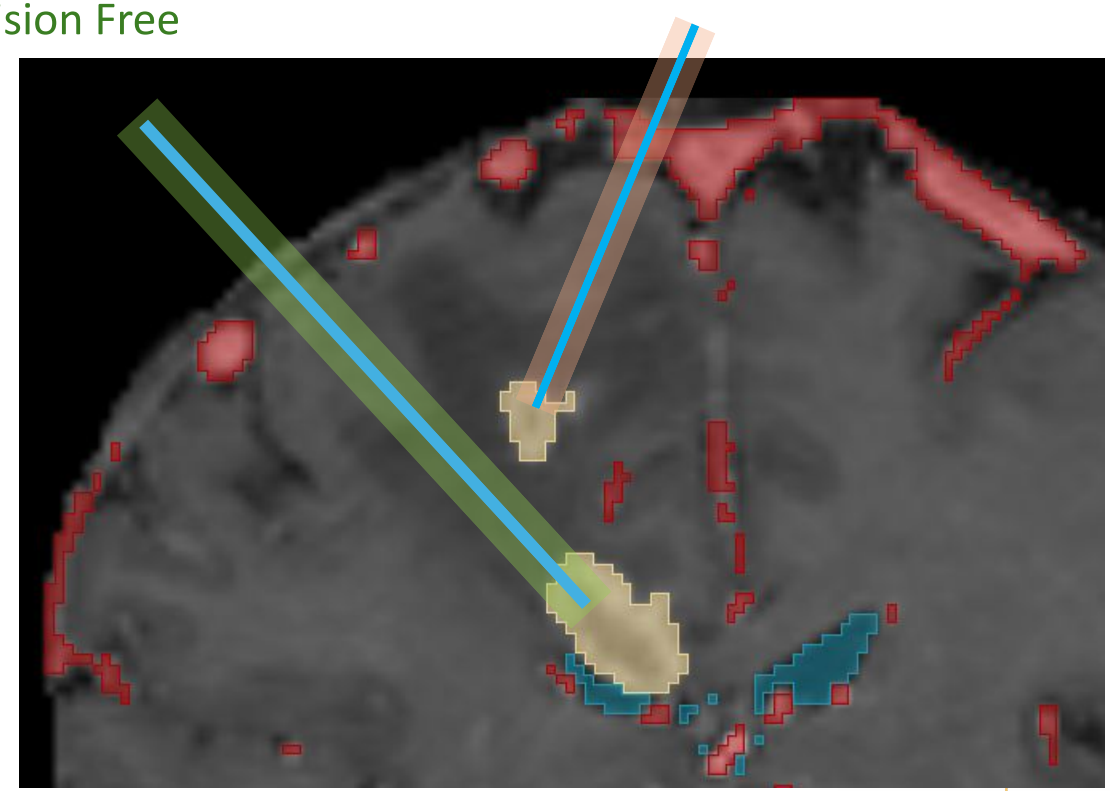
Goals

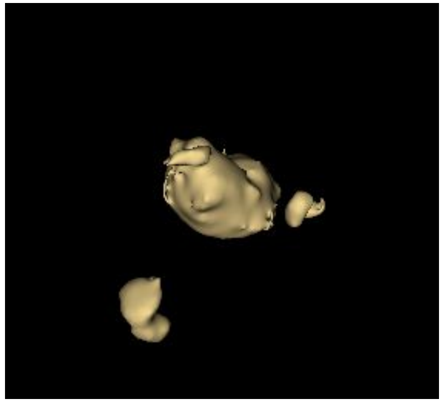
1. Needle path needs to be straight
2. Defining tumor target point and optimal entry
3. Single or multi-path planning
4. Risky region (vessel, CSF) collision avoidance
5. Minimizing time



Conditions

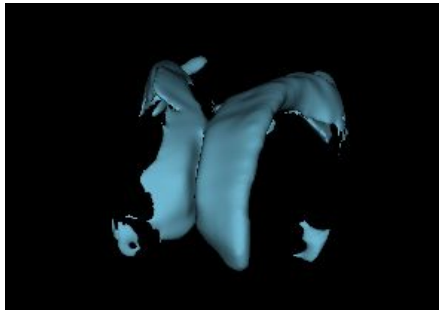
For optimal path-planning and entry point extraction:

1. Tumour cluster(s) as target points



2. Obstacles are defined as risky regions:

- Vascular structures
- Ventricle regions



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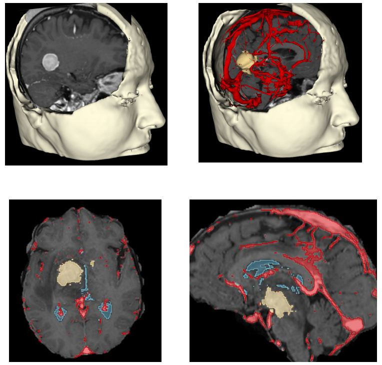
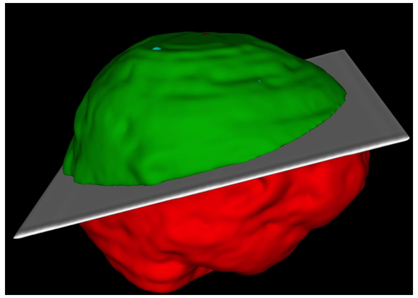
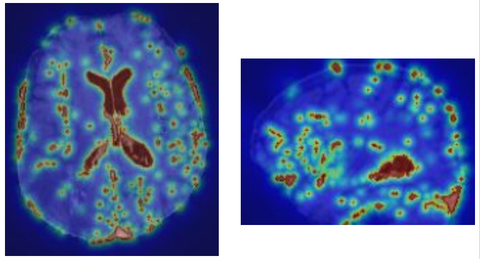
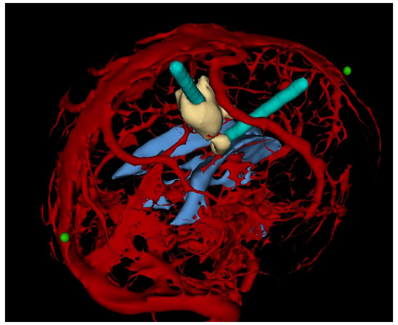
Current Work Contribution









01 Patient-Specific Modeling

T1CE MRI⟶ vessels, tumor, CSF

02 Automatic entry-zone Generation

Hairline based anatomical modeling

03 Probe-Aware risk map

EDT + Clearance envelope

04 Deterministic exhaustive Search

Globally optimal+ multi-path output

02

Relative Works

Previous navigation and path planning methods
Explaining exhaustive search and manual ROI

Approaches

Automated planning has advanced, but clinical biopsy workflows still need full automation, reproducibility, and transparent safety guarantees.

Table1. Trajectory planning navigation approaches

Approach	Limitation
Manual trajectory planning	Slow and operator-dependent
Manual ROI-based automation	Search space depends on user-defined entry regions
TOF-MRA / semi-automatic segmentation	Limited venous/peritumoral modeling or added expert correction **Small number of patients**
Sampling or genetic optimization	No deterministic global-optimality guarantee
Single-trajectory systems	Limited intraoperative flexibility

Optimization

Many systems still require the surgeon to define an entry region ROI or target manually.

Others rely on stochastic or metaheuristic optimization, which can be fast but does not guarantee the global optimum.

Distance

Extracted from [4]

$$\begin{cases} d_{k(v)} = \sqrt{(x_k - x_i)^2 + (y_k - y_i)^2 + (z_k - z_i)^2} \\ g(d_{k(v)}) = \dfrac{1}{d_{k(v)} + \epsilon}, \\ R_{\text{sum}(v)} = \sum_k w_k g(d_{k(v)}). \end{cases}$$

Risk Term

Extracted from [18]

$$C(\tau) = \sum_{v \in \tau} R(v)\Delta\ell$$

Extracted from [4]

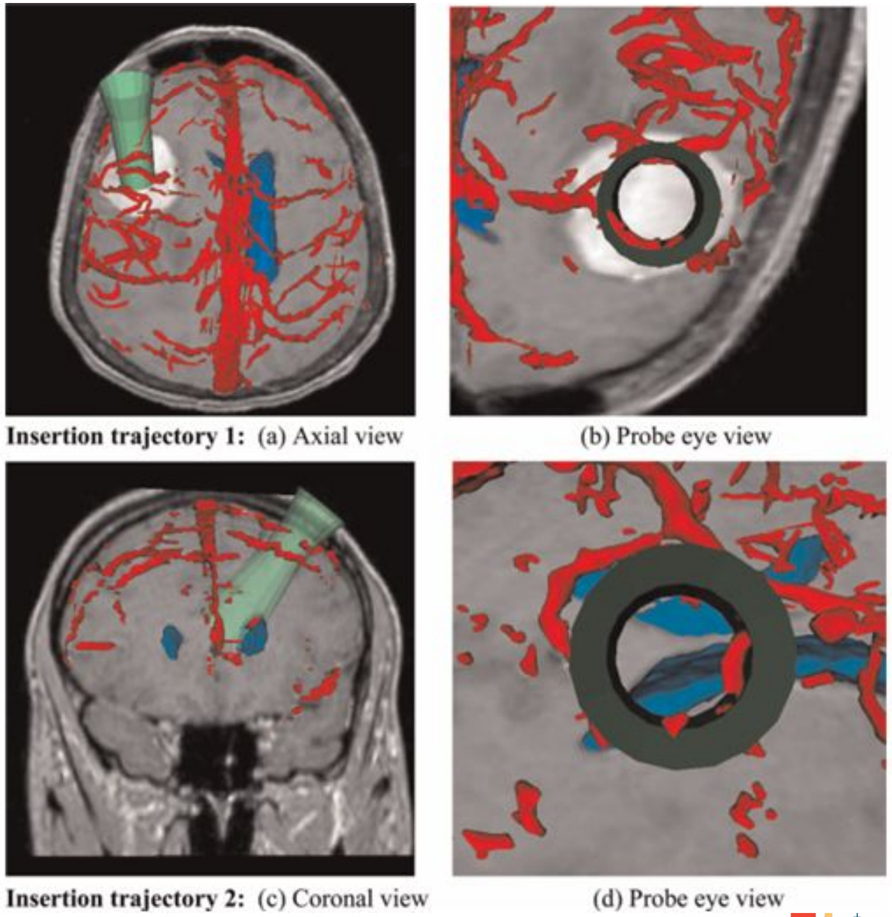
Exhaustive search

Extracted from [4]

$$\tau^* = argmin_{e \in E}\ C_{\lambda(\tau(e,t))}$$

Gaps in Existing Planners

1. Manual entry ROI region for every case
2. Manual segmentation of structures such as vessels (T1CE)
3. TOF-MRA data has venous under-representation
4. Limited number of patients
5. Time-consuming and operator-dependent for manual planning 12-30 min per path.
6. Usually single trajectory output



Extracted from [5]

03

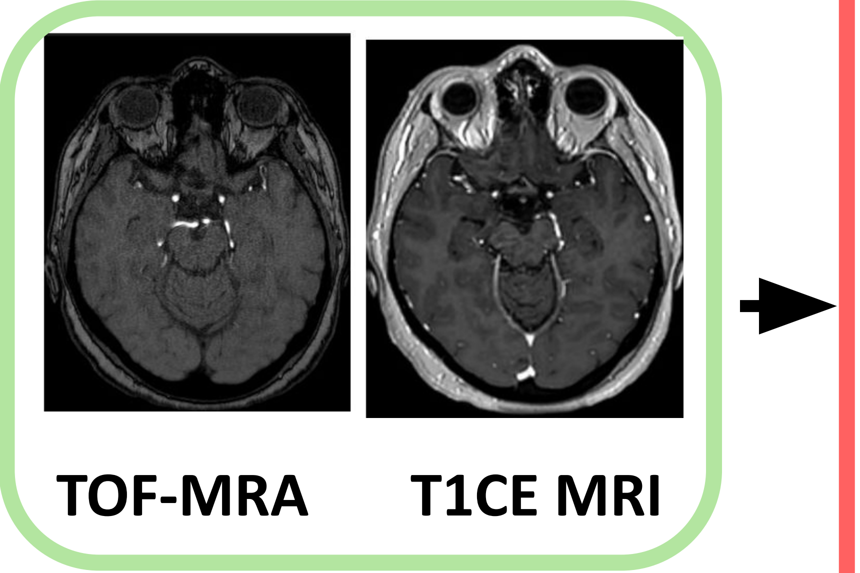
Automated Planning

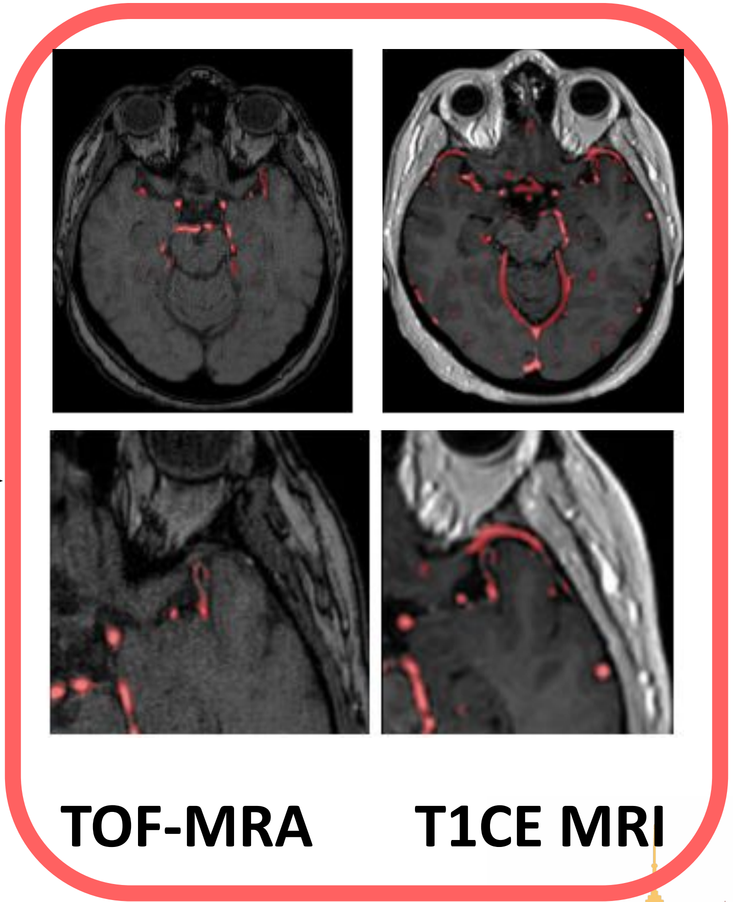
Skull stripped MRI will be processed and Entry + target points will be automatically be extracted via anatomical modeling

Dataset and Annotations

- 137 Stereotactic biopsy patients
- 402 tumor clusters total
- 1.5T T1CE MRI
- 160 slices per volume
- Semi-automatic expert annotation of vessels, tumor core, and CSF

- Skull stripped via HD-BET and Swiss skull-stripper





Segmentation Pipeline

- Architecture:

Neuro-Vasc U-net

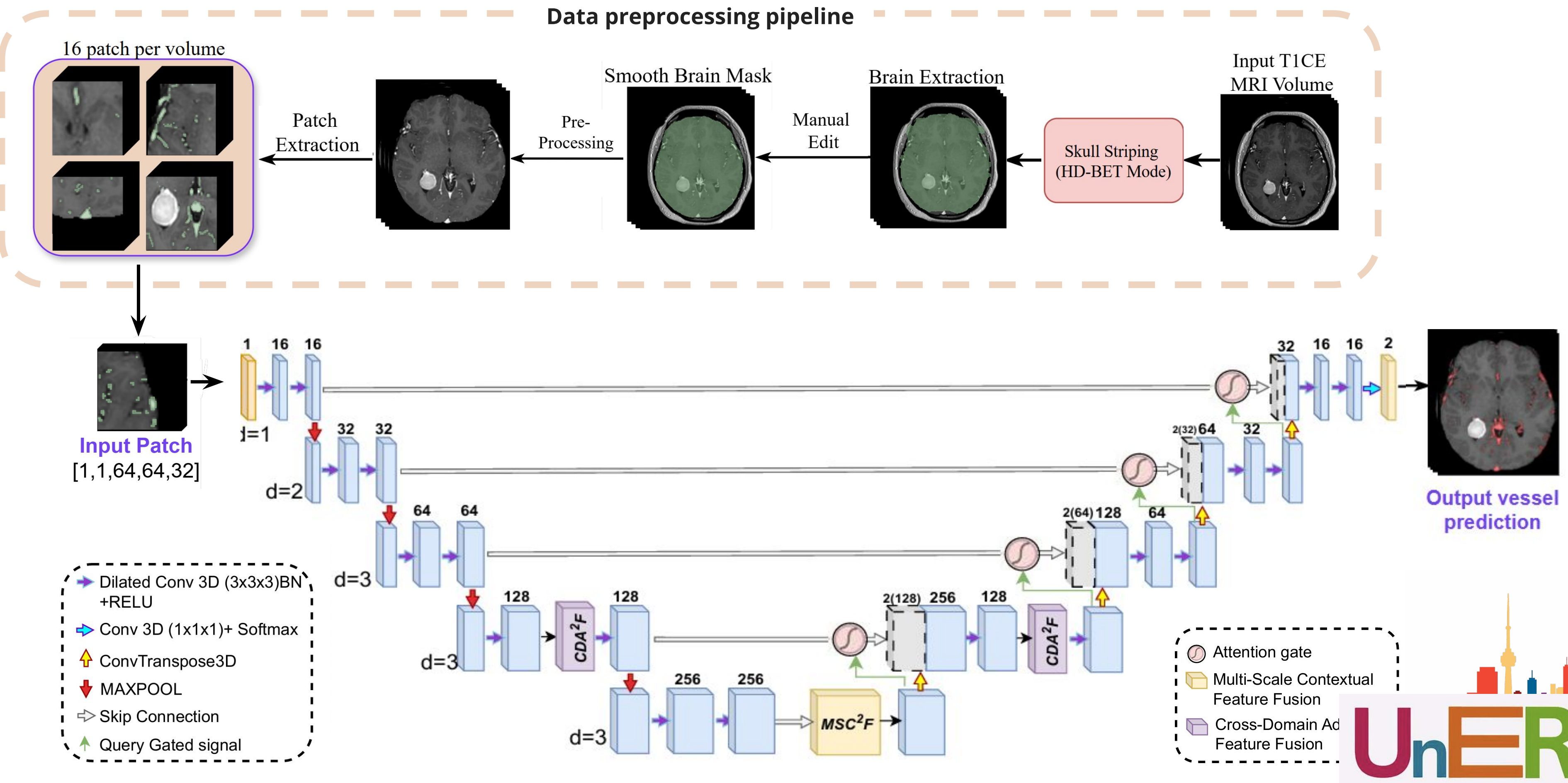
DSC: 86.09%

- Trained on 108 T1CE volumes
- Loss:

WCE+Dice

Lr= 8×10^{-5}

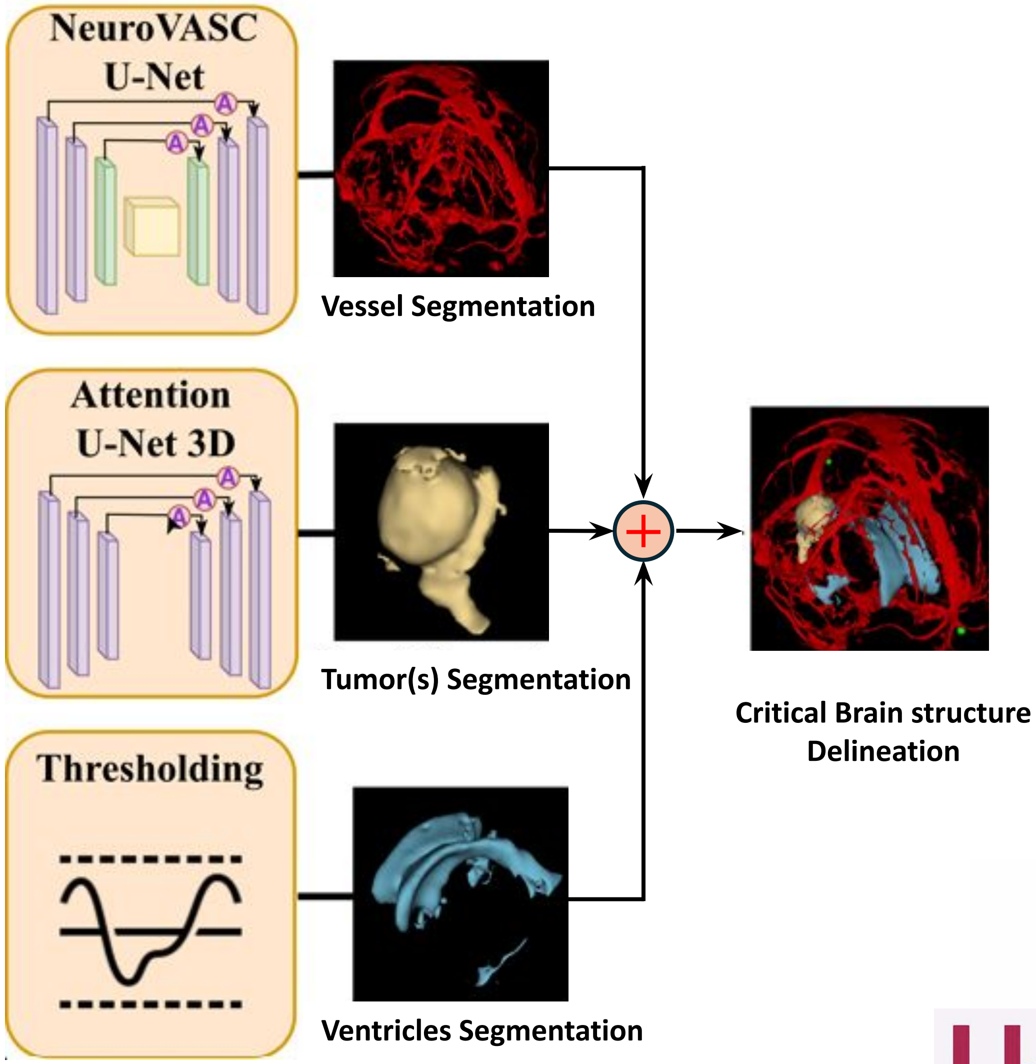
Adam optimizer



Extracted from [6]

Segmentation Pipeline

- Tumor core used for surgery. For sampling, tumor core is used
- 3D Attention U-Net, DSC: 75.79%
- CSF / ventricles: thresholding + morphology + expert correction



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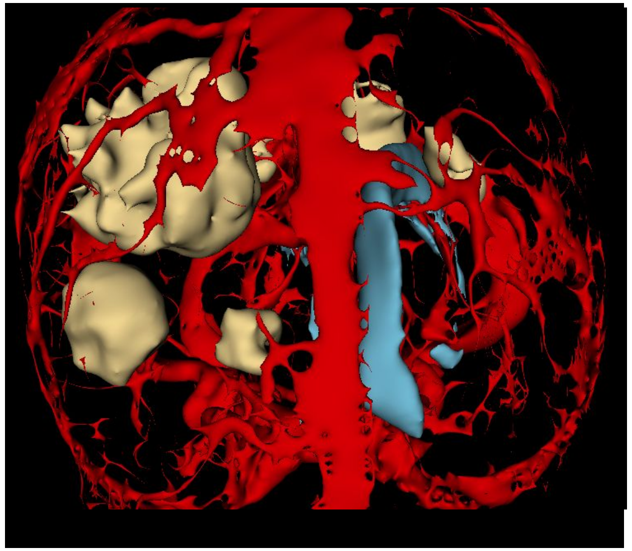
Segmentation Pipeline

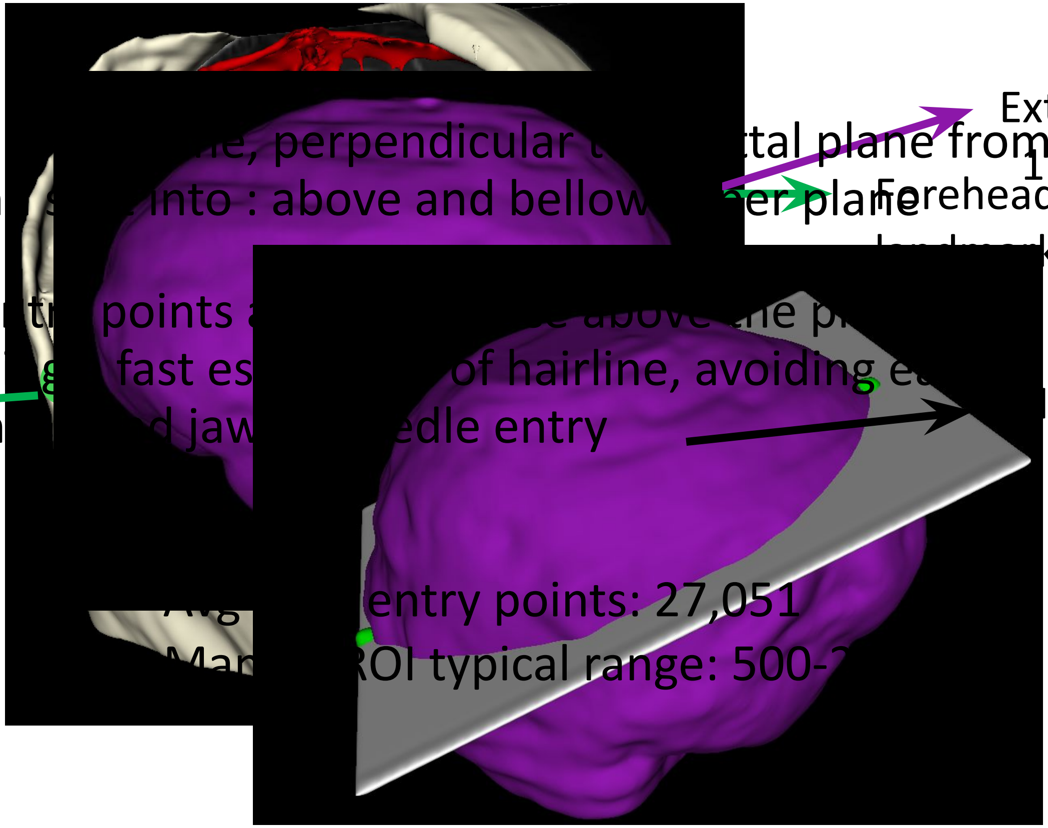
Target Points:

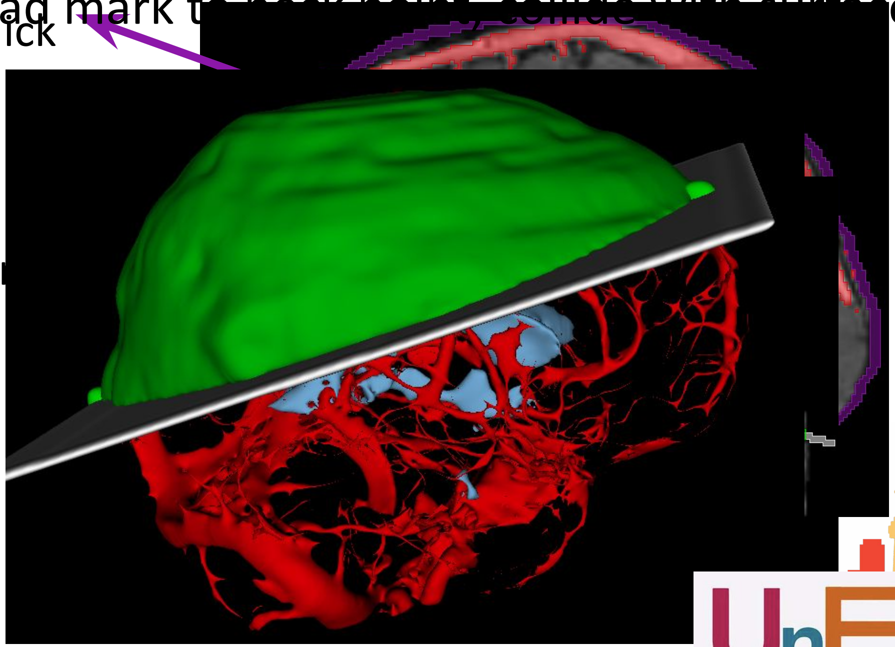
- Tumor Core (already segmented)
- Cluster separation (threshold= 20 voxels)
- Center coordination of cluster as target point



Surface, ROI Extraction

- Landmarks : 2 points manually selected by expert indicating Forehead and above neck
- Surface shell: by thresholding pixels above 0 value, expanding 1 voxel and subtracting the original brain mask
- Draw a ...ne, perpendicular t... ...tal plane from forehead mark t... ...collide with surface shell an... s... into : above and bellow ...er plane
  - Valid e...tr... points a... ...e above the p... indicat...g ... fast es... ...of hairline, avoiding e... eyes n... ...d jaw... ...edle entry
  - Avg ... entry points: 27,051
  - Man... ROI typical range: 500-...





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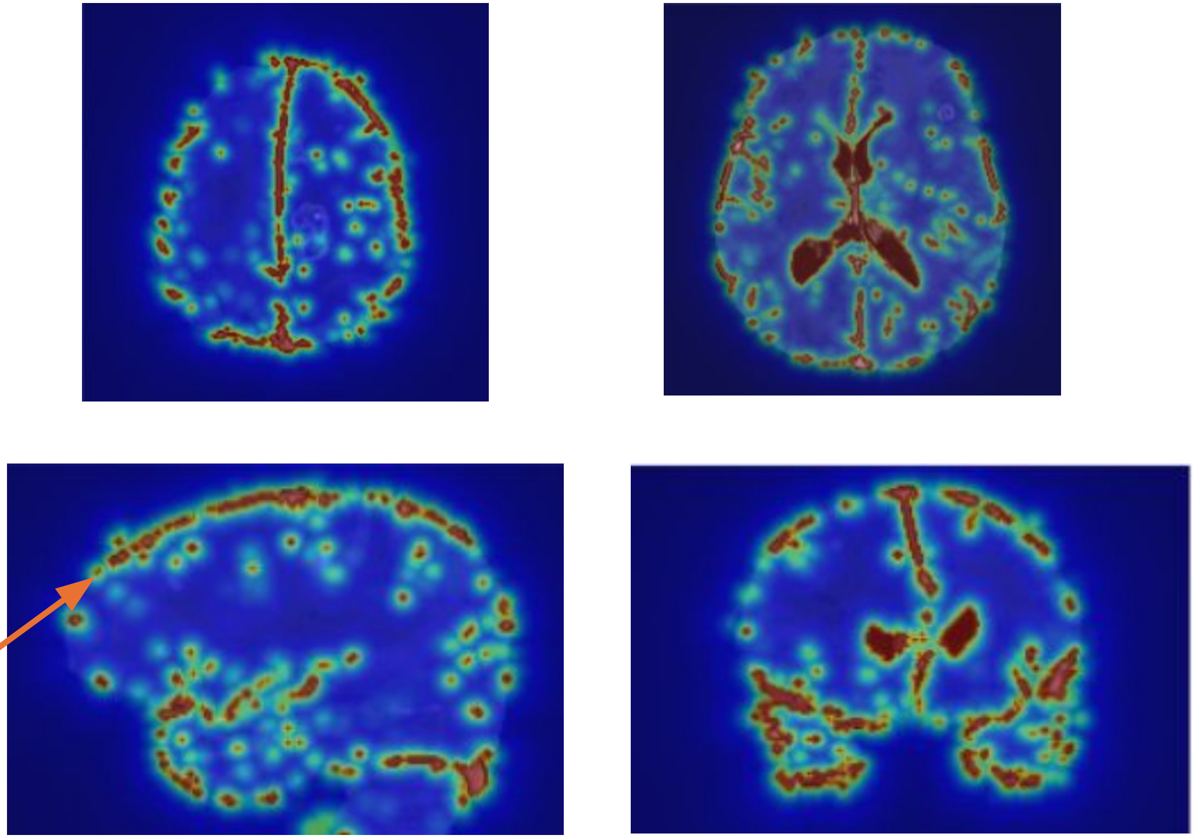
Deterministic Optimization

Risk map, exhaustive search & multi-path planning

Risk Map

- Probe-aware risk map construction
- Euclidean distance to ventricles and vessels separately computed -> not as needle-aware
- Euclidean distance to combined obstacles (ventricles + vessels) as global class -> main objective

Voxels closer to these structure have higher risk values! allows **complete** needle volume rather than just centreline.



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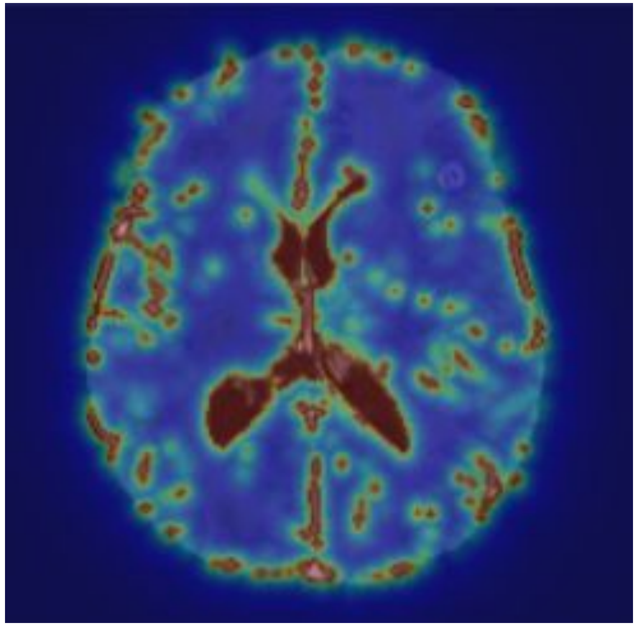
Cost



- Vessels + CSF are merged as hard obstacles (if interjected, game over)
- Euclidean Distance Transform gives clearance to nearest obstacle. Higher risk as you approach more critical structure.
- Probe radius is modeled along the trajectory

Distance

Extracted from [3]

$$\begin{cases} d_{k(v)} = \sqrt{(x_k - x_i)^2 + (y_k - y_i)^2 + (z_k - z_i)^2} \\ g(d_{k(v)}) = \dfrac{1}{d_{k(v)} + \epsilon}, \\ R_{\mathrm{sum}(v)} = \sum_k w_k g(d_{k(v)}) . \end{cases}$$

$$J = \sum_{v \in L} \frac{1}{(D_n(v) + \varepsilon)^2} + \lambda \| P_{\mathrm{entry}} - P_{\mathrm{target}} \|_2 \qquad \theta = arccos\left(\frac{n_{\mathrm{skull}} \cdot (P_{\mathrm{target}} - P_{\mathrm{entry}})}{\| P_{\mathrm{entry}} - P_{\mathrm{target}} \|_2} \right)$$

Cost = proximity penalty + path-length penalty

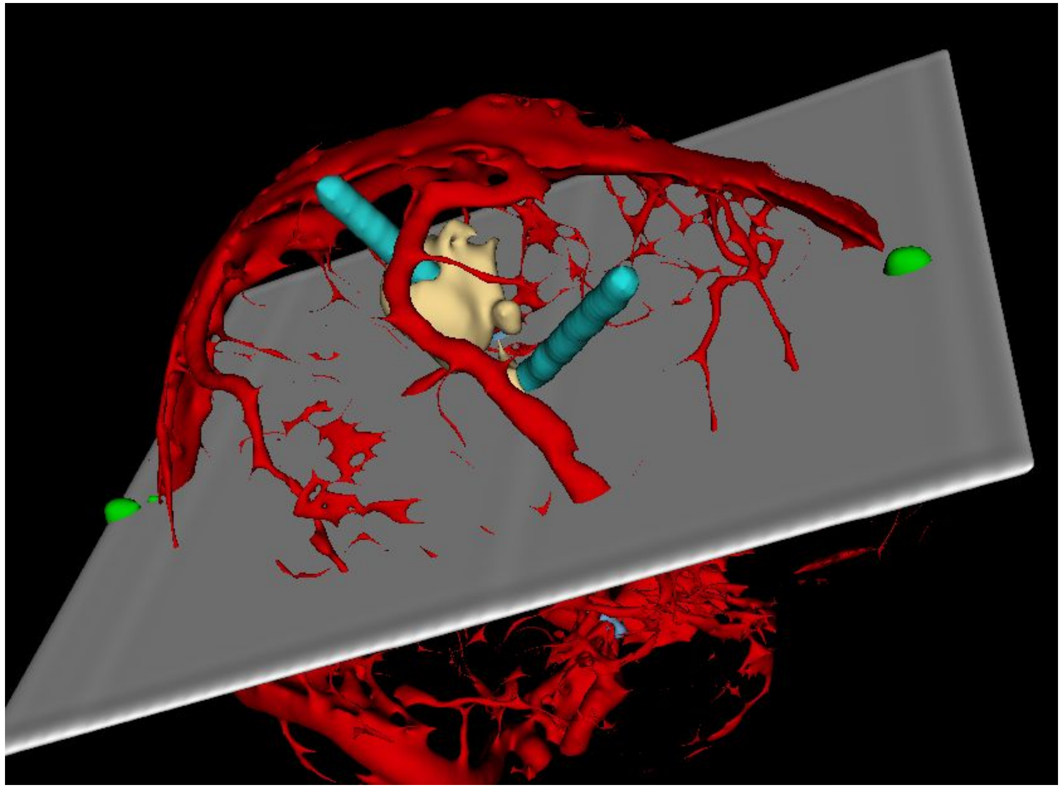
$$\tau^* = argmin_{P_{entry} \in H^+} J(P_{\mathrm{entry}}, P_{\mathrm{target}})$$

Trajectory cost = Σ obstacle proximity penalty + λ × path length

UnERD

Exhaustive Search

- Evaluate all valid entry points
- Rank feasible paths by cost
- Return global optimum + spatially distinct alternatives



Key constraints as small badges:

- **Length ≤ 90 mm**
- **Entry angle ≤ 15°**
- **Entry separation ≥ 10 mm for alternatives**
- Five trajectories reported (one optimal, 4 efficient)

05

Results

Results of path planning and extraction techniques

Main Quantitative Results

10.54 ± 1.15 s
Mean computation time per patient

99.3%
Patient-level success at 4–5 mm envelope

98.5%
Cluster-level success at 4–5 mm envelope

5
Spatially distinct alternative trajectories

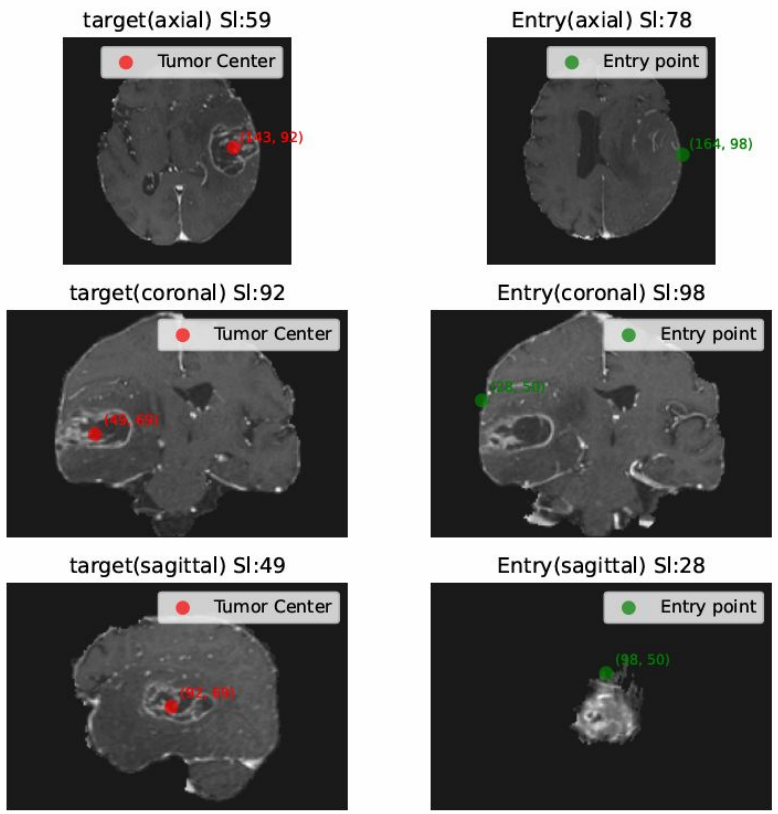
27,051
Average candidate entry points

Outputs

1. 1 Optimal path, 4 Efficient proposed paths

2. Can be implemented on multiple tumors (multiple path planning)

3. Time reduction



Outputs

Table.2 Results on 137 patients based on success/failure rate

Probe diameter	Patients with ≥ 1 feasible path	Patient-level success (%)	Tumor clusters (n)	Clusters successfully planned	Cluster-level success (%)
4 mm	136	99.3	402	396	98.5
5 mm	136	99.3	402	396	98.5
6 mm	127	92.7	402	284	70.6

As probe level increases, patient success rate and cluster success drops.

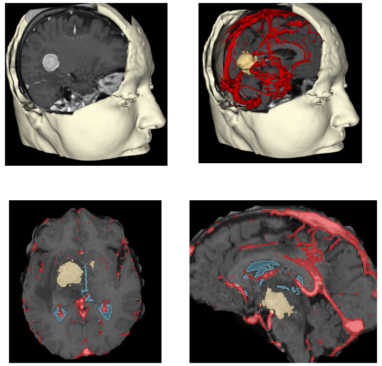
Outputs

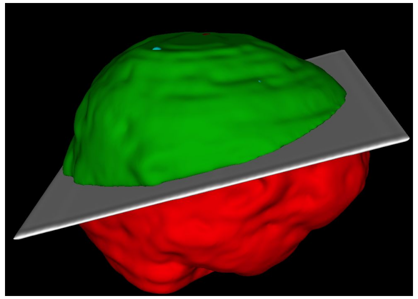
Table.3 Results on 137 patients based on Cost and Coordination's

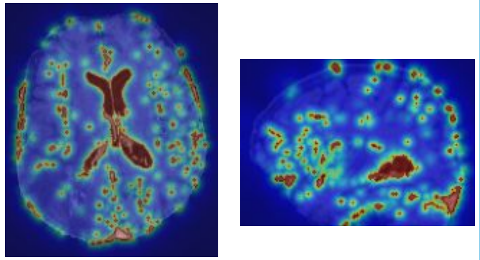
Patient	Tumor	Target (x, y, z)	|E|	Best entry (x, y, z)	Valid paths	Cost / Outcome
26	1	[115, 105, 52]	40866	[144, 91, 107]	962	4.6441 / Success
26	2	[128, 91, 86]	40866	[146, 68, 102]	1093	2.9192 / Success
67	1	[59, 62, 37]	28616	[92, 132, 118]	19	14.5604 / Success
67	2	[117, 99, 72]	28616	[150, 105, 103]	415	4.2234 / Success
67	3	[121, 83, 25]	28616	–	0	– / no valid path
76	1	[80, 75, 96]	22435	–	0	– / no valid path
76	2	[86, 74, 87]	22435	–	0	– / no valid path
76	3	[105, 75, 107]	22435	[121, 89, 124]	765	8.4382 / Success
79	1	[97, 76, 63]	21220	[154, 125, 83]	26	9.4672 / Success
79	2	[108, 74, 83]	21220	–	0	– / no valid path
103	1	[49, 123, 80]	36348	[120, 174, 20]	296	2.8700 / Success
103	2	[63, 92, 80]	36348	[71, 112, 118]	1151	3.1525 / Success

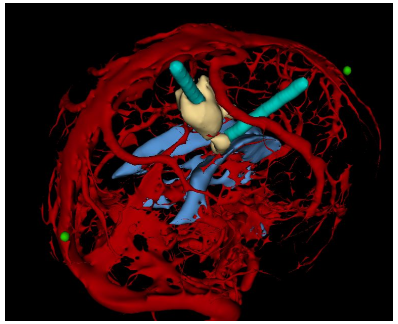
Note no valid path for some!

Outputs









01 **Patient-Specific Modeling**

T1CE MRI→ vessels, tumor, CSF

02 **Automatic entry-zone Generation**

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Limitations & Future Work

Current limitations

- Retrospective, single-center validation; expert review is not a substitute for prospective outcomes
- Rigid preoperative anatomy. Intraoperative brain shift is not explicitly modeled
- Uncertainty is not yet included in planning
- Straight-line trajectories and fixed cost-function weights may limit access to complex targets

Next steps

- Prospective study with blinded comparison against manual planning
- Multi-center external validation with diagnostic-yield and hemorrhage-outcome assessment
- Integrate deformable registration / intraoperative imaging for brain-shift compensation
- Develop uncertainty-aware risk maps & surgeon-adjustable weights

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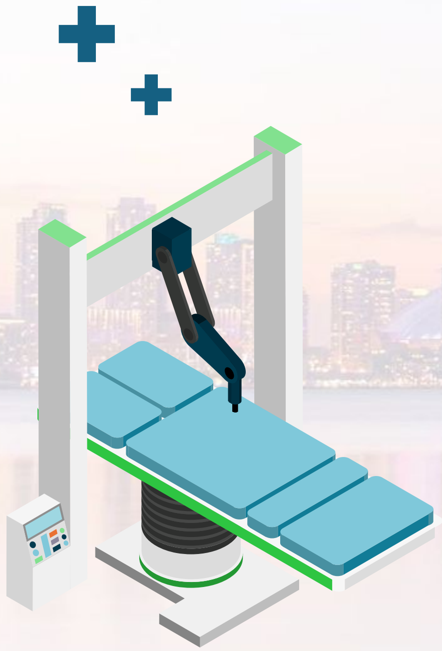

Thank you!

Please ask questions :))