Smooth Path Planning for a Biologically-Inspired Neurosurgical Probe

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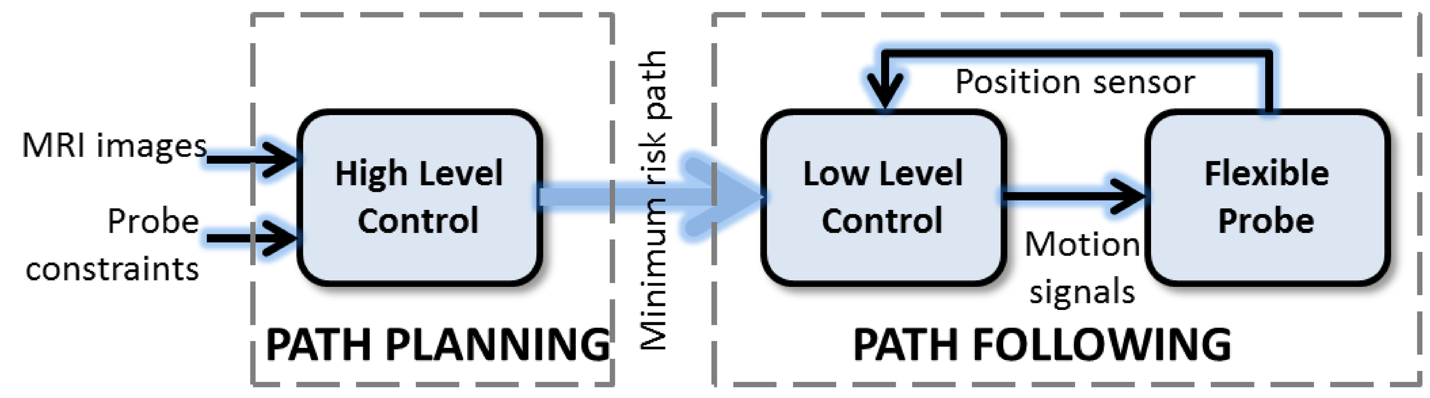
1. Introduction

In recent years, percutaneous interventions have become the preferred choice of many neurosurgeons, due to several benefits over open neurosurgery. They require the insertion of probes or needles inside the brain, precisely targeting lesions, based on CT/MRI images. A bio-inspired neurosurgical flexible probe named ***STING (Soft-Tissue Intervention and Neurosurgical Guide)*** [1, 2] is currently being developed at Imperial College London, the aim of which is to access deep brain lesions, with reduced risk to the patient.

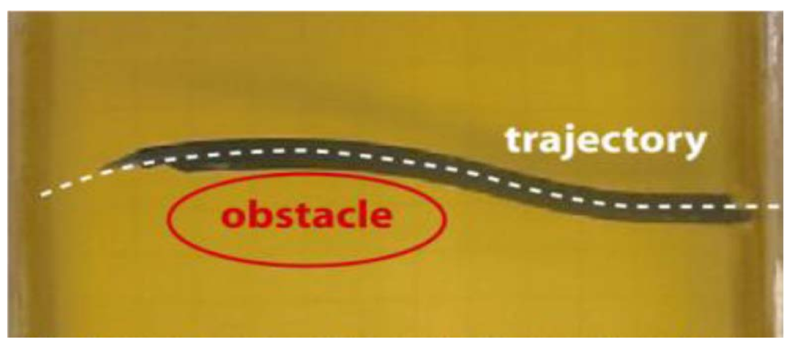
The bio-inspired neurosurgical flexible probe is capable of steering in 2D space and is modelled as a nonholonomic system. ***Mechanical constraints*** of the flexible probe impose a minimum radius of curvature bound on the path. Further, for the probe's closed loop control, the curvature must be continuous and smooth.

2. Objective

The aim of this work is to find an optimal path for the neurosurgical flexible probe, from a given start point to a lesion on a 2D risk-map of the brain, while respecting its mechanical constraints.



System architecture of the flexible probe



Flexible probe in gelatine

3. Continuous Curvature Path Planner

A path planning algorithm for generating pre-operative paths for the neurosurgical flexible probe (STING) is developed using a gradient-based method [3]. The approach is deterministic and generates a bounded and continuous path by means of an optimization of the curvature (cubic polynomial) model.

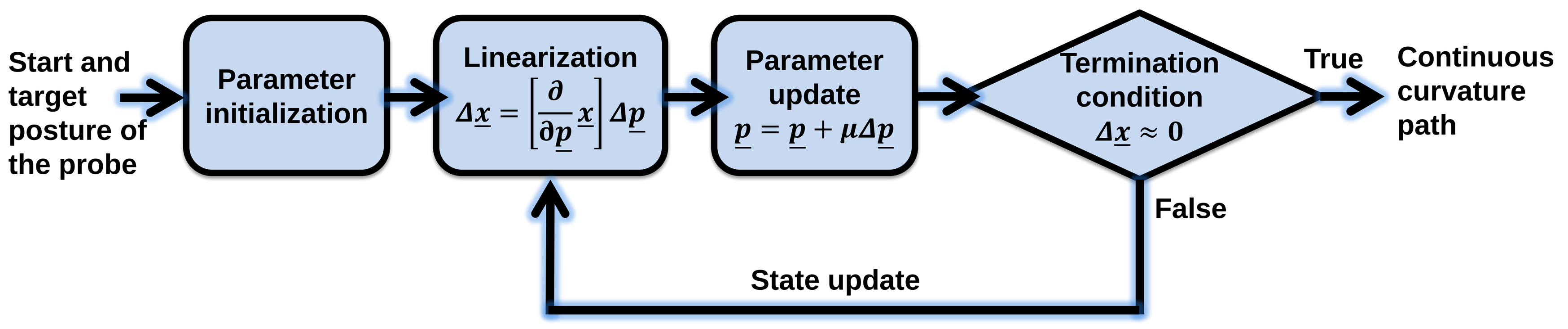
$$\underline{x} = \begin{bmatrix} x(s) \\ y(s) \\ \theta(s) \\ \kappa(s) \end{bmatrix} = \begin{bmatrix} x_0 + \int_0^s \cos(\theta(\tau))d\tau \\ y_0 + \int_0^s \sin(\theta(\tau))d\tau \\ \theta_0 + \int_0^s \kappa(\tau)d\tau \\ \kappa_0 + as + bs^2 + cs^3 \end{bmatrix}$$

$\underline{x}$ - State vector

$\underline{p}$ - [a, b, c, s]^T (Parameter vector)

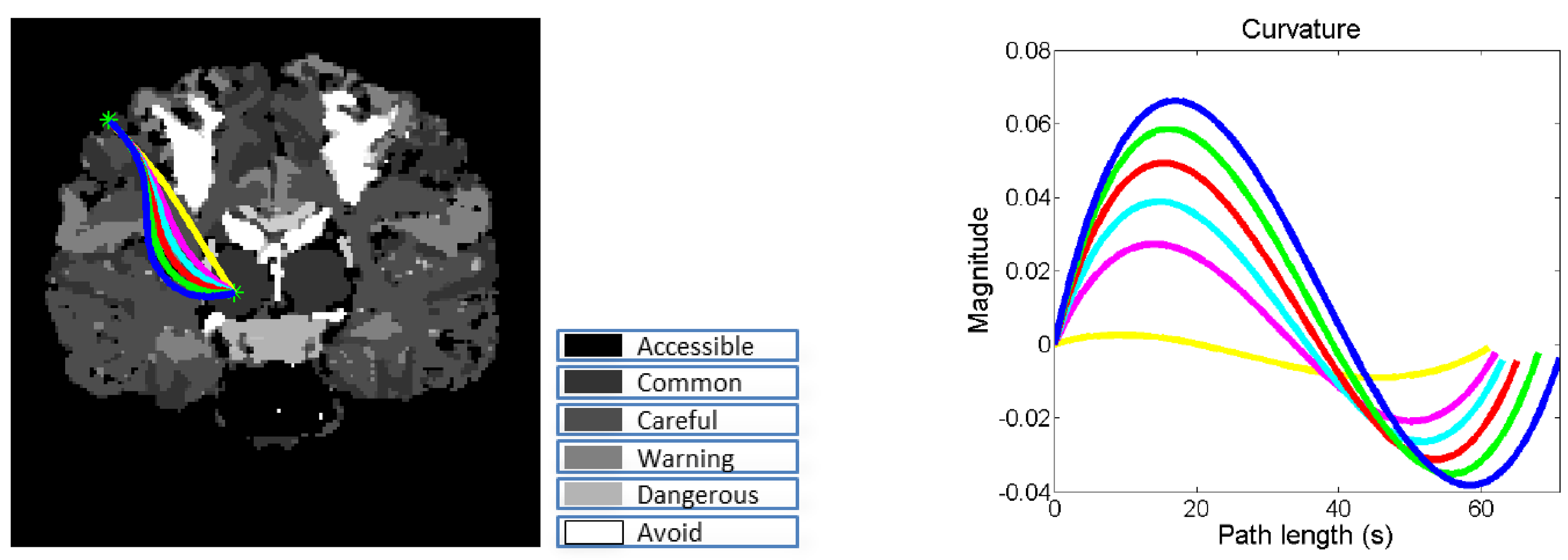
State equation solution

Curvature polynomial



Gradient-based method for optimization of the curvature

4. Simulation Results



Gradient-based path planner showing the effect of varying target orientation (left) and curvature (right) on the optimal path

Configuration space

A risk-map divides the segmented brain structure into six different regions. The configuration space is formed by dilating the highest risk-value (AVOID) by the thickness of the flexible probe.

5. Path Optimization

The optimal path is the one having the minimum value for the following cost function [4]:

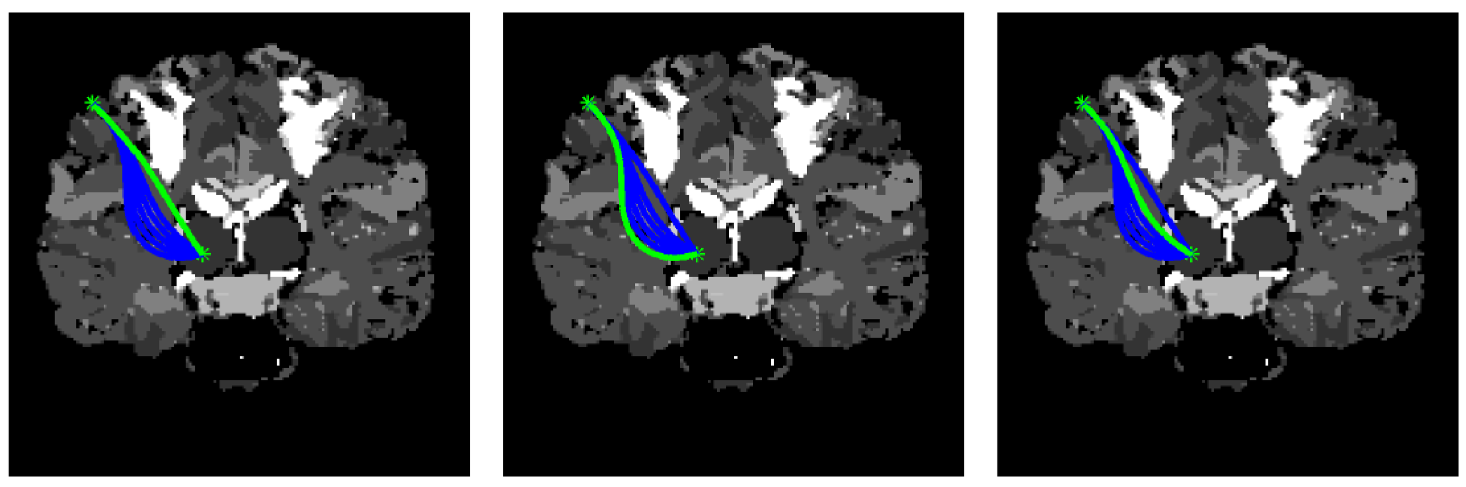
$$C_i = \alpha \frac{\phi_i}{\max(\phi)} + \beta\left(1 - \frac{\psi_i}{\max(\psi)}\right) + \gamma \frac{\eta_i}{\max(\eta)}$$

C_i - ith path's cost

ϕ_i - length of path

ψ_i - minimum distance from an obstacle

η_i - accumulated risk along the path



the shortest path (α, β, γ) = (1, 0, 0) | path with maximum clearance from the obstacle (α, β, γ) = (0, 1, 0) | path with minimum risk (α, β, γ) = (0, 0, 1)

6. Conclusions and Future Work

A gradient-based method for the continuous and smooth path planning of a steerable probe has been successfully developed, satisfying its specific mechanical constraints. A path optimization scheme is also reported, which computes an optimum path based on predefined criteria.

Future work involves incorporation of soft tissue deformation during insertion to reduce placement error and extension of the path planner to 3D, since the neurosurgical flexible probe design will allow it to steer in 3D space.

7. References

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[4] C. Caborni, S. Ko, E. Momi, G. Ferrigno, and F. Rodriguez y Baena, "Optimization of rapidly-exploring random trees (rrt)-based path planning for a neurosurgical steerable probe," in Proceedings of The Hamlyn Symposium on Medical Robotics, 2011.

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