Path Planning for a Conentric needle Robot: MRI-Safe Brain Tumor Ablation

Nicholas Novak   
*University of Maryland Engineering*  
*Master’s of Engineering in Robotics*College park, MD, USA  
nnovak@umd.edu  
  
Thomas Birney  
*University of Maryland Engineering*  
*Master’s of Engineering in Robotics*College Park, MD, USA  
tbirney@umd.edu

*Abstract*—This project explores the application of traditional pathfinding techniques when applied to brain tumor ablation via a concentric needle robot operating in an MRI environment. It was found that simplifying a scan to a 2D image and utilizing random-sampling methods allowed a consistently safe path to the tumor, when possible. This work can be developed into a full 3D model that will be implemented into robots in future applications.

Keywords—Robotics, Neurosurgery, Path Planning, Tumor

# Background

Brain tumor ablation is a time-consuming process that spans multiple days and requires a significant amount of professional time. Currently, this procedure can be done in a minimally invasive manner where a needle is inserted into the brain to facilitate the tumor removal process. To enable such a procedure, a Magnetic Resonance Image (MRI) must be taken, and a neuroscience specialist must plan a path through the brain using a map constricted from the MRI. This usually takes a full day to complete. Recently, there has been a push for robots constructed from ceramics or aluminum which are safe to operate in the MRI environment to facilitate surgical procedures without the need for a separate operating theatre. As a result, a need has arisen for a planning algorithm that can take the images from an MRI and perform the basic planning actions for use by a neurosurgeon. Not only would this remove the full day of planning needed for brain surgeries, but it would also allow the surgery to take place in the same environment where the MRI is performed.

# Project Propsal

## Robot Definition

To enhance the pathfinding performed, this project used the recently developed concentric needle robot [1],[2]. This way, a plan can be checked for a traditional straight needle as well as the concentric curved needles if a straight path cannot be found.

## Path Planning

To perform the path planning, the search was separated into two parts. First, a search would be performed for just the straight needle. This would use the Rapidly-exploring Random Tree (RRT) method to see if a straight needle could reach the goal (tumor) from the start (skin). If this method was not successful, a second modified approach would be taken that would search along potential curves from the previous needle’s endpoint. To do so, an x-coordinate would be sampled locally, and a y-coordinate generated along possible curves. This project utilized three total needles, two of which were curved, though it could be expanded to any number of curved needles.

# Implementation

First, the map was built out with the obstacles implemented. To represent this, the 2D map was simplified to a matrix which represented the x and y coordinates of the space. Then, the obstacle space was updated within the map matrix.

Chart, box and whisker chart

Description automatically generatedNext, the RRT search was performed. Points were sampled within the range of the straight needle and categorize based on their intersection with the object space and closeness to the goal. If the needle was able to intersect the goal, the program was completed. An example of this can be seen in Fig. 1.

Fig. 1: RRT search performed with a single needle instance that reached the goal without curving.

Chart

Description automatically generatedIf one needle could not connect to the goal, the first curved needle would then extend from the initial straight needle. During this stage, a modified search would be performed along the curve of the needle in each direction. First, x-coordinates were generated in a local space, and then y-coordinates were generated that matched the curves of the needle. This provided a continuous sampling function. If this search resulted in the curved needle intersecting the goal, the program was ended. One such result can be seen in Fig. 2.

Fig. 2: First needle results combined with the modified search for the second needle

Finally, a second action-based search was performed if the first curved needle could not reach the goal. This was done in a similar method where the action-based search was performed from the end of the prior needle. This would provide a result that could effectively curve around obstacles, as seem in Fig. 3.

Chart

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Fig. 3: Combined search for a three-needle case, joining the three needles.

# Results Discussion

Fig. 1, Fig. 2, and Fig. 3 all show potential results for reachable goals within the three-needle range. Since the search time for the second and third needle was dependent on the sample size, the full program’s time complexity was greatly variable.

I addition to searching for successful solutions, an equally important component of this project was determining if a goal could not be reached. An example of an unreachable goal can be seen in Fig. 4.

# Difficulties

This project required some rescaling from its initial conception. The initial obstacle space was going to be a 3D section of a brain, represented by a rectangular prism. However, it was found that a 2D implementation would allow for the development of a similar search method without spending as much time designing an implementation for a 3D environment. As such, it was decided to maintain the 2D implementation.

A further difficulty arose in trying to accurately represent obstacle spaces that would be present in the brain such as blood vessels or nerve tissue. To simplify the program and allow for ease of future implementation, a series of rectangles was used. This way, future implementations can either create a bounding rectangle around an obstacle or just directly plot the obstacle into the workspace.

# Future Development

Future development on this project could include a few different implementations.

First, the 2D implementation can be modified to allow for a 3D environment. Two methods could be used to do so. First, the entire program can be implemented over a series of 2D rectangular zones. These could then be layered to create a 3D section. While this would be easiest to implement, it would only allow each needle to extend one way or another. Instead, a more effective implementation would be to design a rectangular prism workspace and utilize the code or 2D searching but rotate it by a set angle over a full circle. This would represent each needle’s ability to rotate a through a full circle from the prior needle. For such an implementation, we recommend utilizing voxels to group multiple points together and thus modulate search time. Another aspect of this implementation would be to modify the first needle search to take place over the first edge of the rectangular prism.

Secondary to a 3D implementation, a full-brain implementation can then be developed. Instead of using a rectangular prism, the search would take place over a full brain shape. This would require modifying the first needle search to allow searching over a curved surface, but the interior needles could maintain their searches from a prior-developed 3D implementation.

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