Motion Planning for a Stereotactic Neurosurgery Robot

RBE 580 Group Project Proposal

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***Abstract*— With the advancement of MRI compatible robots, surgical procedures like stereotactic neurosurgery, which were previously carried out based on pre-operative MRI images, can now be performed with high-resolution live MRI imaging guided feedback. This increases the accuracy and reduces the damage to surrounding healthy tissues. This project is aimed at developing motion planning software to provide surgeons with possible entry points on the surface of the brain, given a target point - most likely a tumor that is to be treated with thermal ablation. In order to reach the desired target point with minimal impact, our program executes path planning for the robot while considering white matter in the MRI brain image as an obstacle. In addition, the program accounts for the kinematic constraints of the robot so that it may generate a few entry points that can have minimal insertion depths. This could help the surgeon with recommendations in deciding the best location for creating the burr hole and use the same software to command the robot to autonomously place itself in the required pose after the burr hole is created to deliver the treatment.**

***Index Terms*—motion planning, slicer3D, vtk, neurosurgical robot**

I. Introduction

Surgery planning provides surgeons with useful information regarding feasible tool paths and robot trajectories, selection of the optimal entry and target points, segmentation and reconstruction of various anatomical structures, and the ability to define virtual fixtures that act like no-fly zones to avoid collision of the robot with crucial anatomy. It is the preoperative method of pre-visualising a surgical intervention, in order to predefine the surgical steps. Surgery planning plays a vital role in stereotactic brain surgery. Stereotactic brain surgery is a type of minimally invasive surgical procedure where lesion, frequently a brain tumor is treated with the assistance of image guidance in real time.

Conventionally, stereotactic brain surgeries were done using a high precision frame as shown in Fig. 1a. Here, the neurosurgeon is provided with several preoperative MRI scans of brain to guide the surgeon to the exact location of the lesion. This facilitates accurate pathway planning through the brain. This combination makes possible treatment for abnormal tissue while leaving normal healthy tissue realitively intact. However, using a static MRI image during the procedure to estimate the position of the tumor introduces inaccuracy and may require multiple insertion attempts. This may cause unnecessary harm to healthy tissues around the tumor as well.

Currently, due to the advancement of technology in medical imaging and MRI compatible robots, new avenues have opened in the field of image-guided therapy (IGT) procedures. One such advancement is using imaging modality to capture images of desired anatomy and surgical tool and provides them as feedback to the surgeon to help with the navigation of the tool to a desired target region within the anatomy. Robots have been proposed for use in medical applications almost around the same time of their first introduction to industry. The positional accuracy of robots along with ease of control integration with other systems made them suitable candidates for incorporation into stereotactic brain surgery as shown in Fig. 1b. This neuro robot is a custom made robot by the AIM Lab at WPI. The details about the early stage developments of the neuro robot is mentioned in the [1].

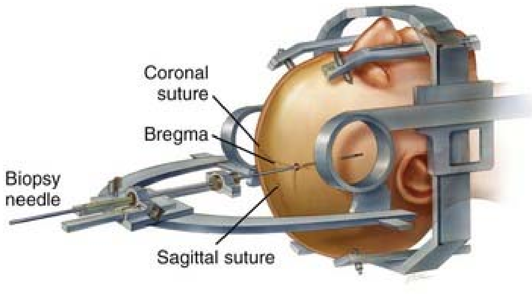
A. Problem Statement

In this project, we aim to work on motion planning software for pre-operative planning, which will provide the surgeon with burr hole positional recommendations so the procedure may reach the target point with minimal impact to the surrounding tissues, nerve tracts and blood vessels. To do so, three primary challenges and contribution needs to be made as enlisted here.

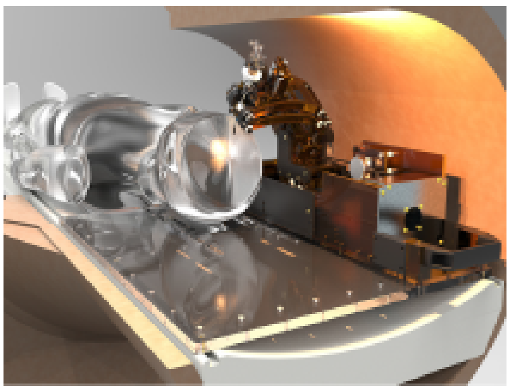
- Establish simplified kinematics model of stereotactic neurosurgery robot
- Identify and segment the set of given obstacles
- Provide a series of recommended valid burr hole positions with least insertion depth from brain surface to the tumor, as well as a collision free, straight line path for the robot to deliver treatment

II. Background

Previously, Nycz et. al [2] developed an MRI compatible stereotactic neurosurgery robot (NeuroRobot) for in-bore closed-loop conformal ablation of brain tumors using an interstitial ultrasound probe to deliver needle-based therapeutic ultrasound (NBTU). This robot, shown in Fig. 2, provides the positioning and alignment of the ablation probe given Desired Entry and Target Points (EP and TP respectively), as well as the probe rotation to enable conformal ablation of tumors using directional probes. This robot is designed to have 7 DOF of movements. 3 DOF are to move the robot on the Cartesian plane. Additionally, 2 DOF provide the pitch and



(a) Traditional frame for brain stereotactic surgery



(b) Modern neuro robot in closed-bore MRI scanner

Fig. 1: Setup for traditional vs modern brain stereostatic surgical procedure

yaw movements to mimic the traditional sterotactic surgical frame. Finally, another 2 DOF provide the ability to insert and rotate the tip of the probe. For this project, the probe rotation is not considered since the problem statement focuses on determining the path generation to reach the TP from set of recommended burr holes.

Typically, surgical workflow using the NeuroRobot [3] follows a systemic pre-operative planning approach which starts with a registration scan taken to register the robot with respect to the imager's frame. Following this, the patient is placed and secured on the MRI bed. Then, a series of pre-operative scans are acquired and visualized on the 3D slicer software. The physician locates the burr hole on the MRI image and selects the desired EP and TP using fiducial markups. EP and TP are sent to the robot's inverse kinematics solver through OpenIGTLink to evaluate the reachability of those points. The software returns the desired joint values if the EP and TP are validated. In case the points are kinematically invalid, the physician is asked to select another EP and TP. The robot is moved into the targeting configuration and the probe is inserted into the brain. MRI intervention is required to monitor the applied thermal dosage and are followed by post-ablation scans to validate the accuracy and procedure results.

For pre-operative surgical planning of NeuroRobot, a toolkit called the Neuro Plan was developed by Farid et. al [4]. This toolkit is developed as a 3D Slicer extension module,

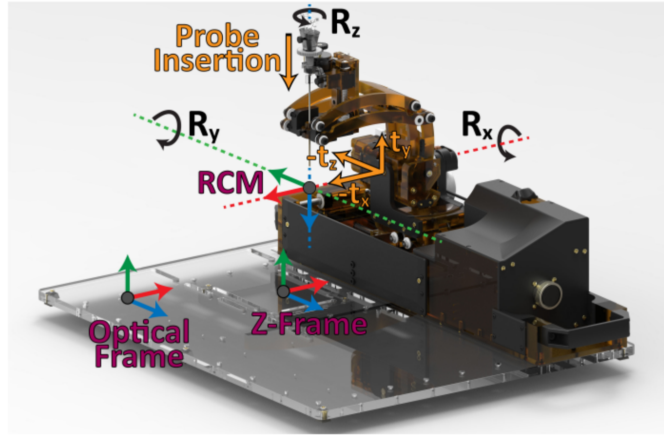


Fig. 2: The registration frames and motions of the robot developed by Nycz et. al [2]. A fiducial z-frame placed under the robot's base is used for MRI registration and an optical frame is used for accuracy assessment registration.

taking advantage of the superior medical image analysis and visualization capabilities of this open-source platform. This toolkit addresses challenges regarding the lack of workspace visualization and accurate burr hole identification in the surgical planning of the NeuroRobot. It does this, by overlaying the robot's reachable workspace as well as its constrained sub-workspace based on the desired EP, on top of the MRI image within the 3D-Slicer software. We plan to determine valid burr holes in the reachable workspace given by the Neuro Plan toolkit. Using the segmented obstacles (important blood vessels and nerve tracts), we aim to find a series of burr holes through which the TP can be reached without impacting the obstacles.

III. Project Goals

We propose a series of goals which we hope to achieve with this project. These goals have been broken down into three subsections: minimum, expected, and extended goals. The first subsection consists of the minimum goals that we strongly expect to accomplish within the duration of the project. Secondly, the expected goals section consists of those goals which we anticipate accomplishing during the time frame of this project. Lastly, the extended goals are expected to be outside of the time constraints and project scope, however, if the project runs ahead of schedule we would like to continue in their direction. In addition, the extended goals may provide direction for future research.

Below are the goals this project aims to achieve:

A. *Minimum goals*

- We hope to establish a simplified kinematics model of our stereotactic neurosurgery robot such that the robot is able to move to a directed pose
- Given a set of obstacles to avoid in the brain, either manually or automatically identified, we hope our system would be capable of identifying a series of collision free,

straight-line pathways from the target area (tumor) to the surrounding skull
- Given a set of obstacles to avoid in the brain, either manually or automatically identified, we hope our system would be capable of providing a series of recommended valid Entry Points (EP)

B. Expected Goals

- Once the operator has selected one of these options, we hope to extend the software to generate a sequence of motions for every joint (i.e. trajectory planning) such that the robot doesn't hit the patient or the obstacles around while moving to the desired pose to deliver the treatment.

C. Extended Goals

- Using DTI (diffusion tensor imaging) and software packages to automatically identify nerve tracts that must be avoided by the robot during surgery
- Similarly, using image parsing packages to automatically identify blood vessels that must be avoided by the robot during surgery
- Working within the framework of a premade burr hole, this is rare but possible during surgery procedures
- Integrating path comparison into the recommendations returned by the system to the operator. This may include predictive analysis into the affects each recommended path might have on the patient

IV. Methodology

In this section we propose our workflow to be divided into four sub-tasks. The first two sub-tasks can be categorized as the pre-processing of MRI images. Firstly, it is required to segment crucial anatomy like nerve tracts and blood vessels in the brain MRI image. Then, we plan to generate a mesh object of the resultant image from the previous step that would immensely help in implementing collision detection of the needle with the anatomy of interest. Further, the kinematics of the robot developed by the previous team needs to be understood and incorporated into our work so that we may know the workspace limits of the robot. Finally, the fourth sub task would be to develop a motion planning software that can generate multiple entry points on the brain surface that provide a collision-free path the robot can take to reach the tumor with minimal insertion distances to minimize the harm to other healthy tissues. The finer details of each of these sub-tasks are further elaborated in this section.

A. Segmentation of Crucial Anatomy

For any motion planning software to be beneficial, the most rudimentary requirement is to have maximum information about the obstacles in the workspace under consideration. In our context, the crucial anatomy that needs to be avoided while the probe is inserted into the brain is defined as the obstacles. The segmented nerve tracts identified in the brain MRI image is expected to look like the figure (B) as shown in Fig. 3. For instance, it could be some important nerve tracts

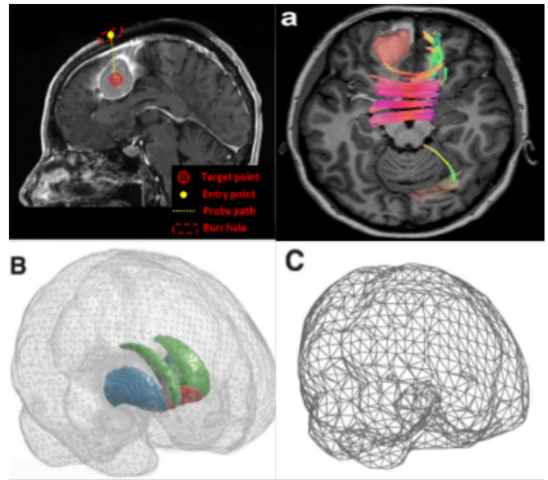


Fig. 3: The expected outputs from each sub-task of the proposed methodology [4], [**?**].

or blood vessels in the brain. As a first step, it is our plan to obtain some samples of brain MRI images from a medical imaging repository commonly used for research such as [5]. Further, we plan to use the Diffusion Tensor Imaging (DTI) Tractography plugin in the Slicer 3D software to segment the nerve tracts from the brain MRI images. Slicer 3D is a software platform for the analysis (including registration and interactive segmentation) and visualization (including volume rendering) of medical images and for research in image guided therapy with powerful plug-in capabilities for adding algorithms and applications. This software provides support for multi-modality imaging including MRI which satisfies our requirement for this project.

B. Creating Mesh Objects

As the second step of pre-processing the MRI image, we plan to generate the mesh object from the resultant image in the previous step. This step cannot be skipped because implementing collision-detection of the probe with the nerve tracts of the brain in 3D space becomes relatively easier with the mesh objects compared to working with the DICOM images directly. The meshed objects identified in the brain MRI image could like (C) or (D) as shown in Fig. 3, the latter having fewer meshes to increase the computational speed. This task can be achieved using the C++ based Visualization Toolkit (VTK) library, which also has extensive documentation for the wrapper APIs for other interpreted programming languages like Python, Java, TCL as well. The Visualization Toolkit (VTK) is open source software for manipulating and displaying scientific data and includes state-of-the-art tools for 3D rendering, a suite of widgets for 3D interaction, and extensive 2D plotting capability. To make things easier for this short-term project, it is our plan to apply a bounding box to the probe that will be inserted into the brain as well as to the region with highly sensitive nerve tracts to aid in the implementation of collision detection that will be used by the motion planning routine.

C. Kinematic Modelling

It is also important for the motion planning software to consider the kinematic constraints of the robot during the planning phase. For instance, the constraints could be reachability limits of the joints to validate if the entry points generated by the planning software. As mentioned in I, the robot we are using for this project has 6 DOF and has a relatively complex scissor mechanism to provide the translation in the z direction. It is our plan to understand the forward and inverse kinematics of this robot from the previous work done [4] and incorporate it into our software.

D. Motion Planning Approach

This is the heart of the project, and we will have to develop an algorithm or modify an existing one to suit our needs. The primary heuristic for this algorithm is to generate paths which has the least distance to the tumor from the brain surface to minimize the damage to the healthy tissues as much as possible. We would like to discuss three different approaches that would plan a set of optimum paths.

In the first approach, we could plan to create a configuration space of all 6 joints of the robot considering their maximum limits. Then, sample one configuration from each joint space, i.e. one possible pose of the robot. Further, we can validate if a collision-free straight path from the brain surface to the tumor exists. This process can be continued in every iteration until a pre-defined set of entry points are generated or a maximum iteration count is reached. Furthermore, an acceptable pre-defined insertion depth can be provided which could be used to filter out un-optimized paths and continue the search till the above stop conditions are reached.

Another approach could be to generate a conical volume of space that opens up from the tumor to the brain surface that could limit our search region. This conical volume can be chosen based on the region through which the distance from tumor to brain surface is minimal, thereby including the heuristic defined earlier. Then, the robot's ability to reach this area of the brain would be validated using the inverse kinematics of the robot incorporated into our software in the previous sub-task. From here, we can take 2 different approaches as explained further.

As a second alternative approach, we could check for a collision-free straight path at equidistant points on this surface area of the brain. The advantage of this approach is that we are limiting our sample space in the robot's configuration space based on the heuristic of our algorithm rather than blindly checking for a viable path randomly anywhere on the brain surface. The downside to this approach is that it is a kind of brute-force approach and since the robot has a precision in the order of milli-meters, the possible points could be significantly higher and the algorithm can exit without finding a path if the region it starts exploring has too many obstacles.

As a third alternative approach, we plan to generate samples within the above discussed conical volume such that the sample points in the narrow spaces and the free space are explored and the samples on the obstacles could be rejected. To achieve this, a hybrid of bridge sampling [6] and uniform sampling could be used. Then a collision-free straight line passing through each of these samples with brain surface and tumor on either ends of the line could be fitted to generate the viable entry points on the brain surface. This approach seems to be a more informed way to search for optimal paths, i.e. the kinematic constraints as well as the heuristic defined are considered in the first step of generating the conical volume from the tumor itself. This is computationally efficient to generate new set of paths on-the-fly if the surgeon likes the conical region considered but not the entry points generated.

It is our primary plan to use the third alternative discussed above for this project purposes. However, it seems to be more time-consuming to implement compared to the former one. Therefore, it is advantageous to have multiple approaches available at hand, as we will have the option to resort to the first approach in the worst-case scenario. We believe this plan will allow us to reach our goal even with tight deadlines.

V. Results

For the purposes of this project, our motion planning algorithm will be using the segmented image output from the Slicer 3D software. This segmented imagery will be given to the VTK module which will then find the collision-free paths. Each of the generated collision-free paths will have an entry-point pose and target-point pose. As the final step, the motion planning software validates if these generated collision-free paths are reachable by the robot using the kinematics library. The unreachable paths are discarded and the final output of this project would be a set of possible entry poses and their associated robot joint values.

A. Brain Segmentation

3D Slicer has proven itself to be a straightforward and effective program for brain segmentation. The program has a number of pre-compiled MRI image libraries that include scans of a typical brain, brains with a tumor, as well as DWI (Diffusion Weighted Imaging) and DTI (Diffusion Tensor Imaging) scans.

Using these libraries, we have been able to return both 2D and 3D images that can be configured to identify different target regions.

Primarily, we targeted the identification of white matter, a given abnormality (tumor), and the outer skull. In addition to this, we were successful in identifying nerve tracts, however we did not get a chance to test these as an obstacle. We chose to overlay the tumor, skull, and white matter as 3D objects. In this way, slicer 3D could directly output .vtk files with a target object, starting point, and obstacles to avoid, respectively. This .vtk file was used for further visualization and collision detection discussed in the following section.

B. Visualization and Collision

Getting the Visualization Toolkit (VTK) to run required significant debugging. Initially there were issues with generating executable files and determining the correct file path to use.

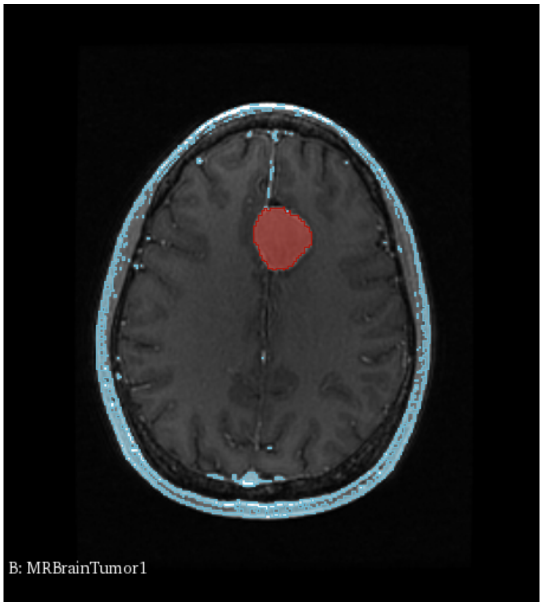


Fig. 4: Axial identification of outer skull and tumor

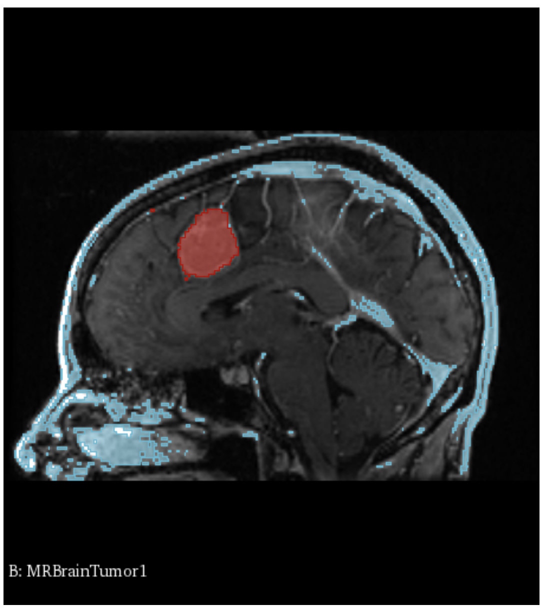


Fig. 5: Sagittal identification of outer skull and tumor

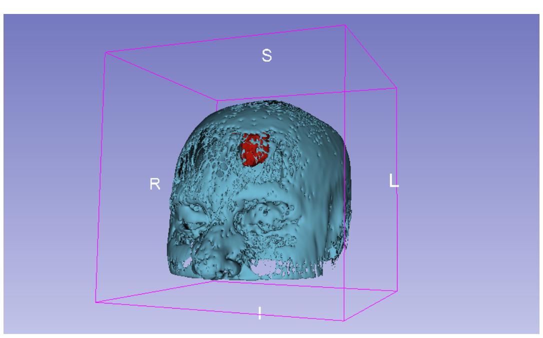


Fig. 6: A 3D image of the identified outer skull and tumor

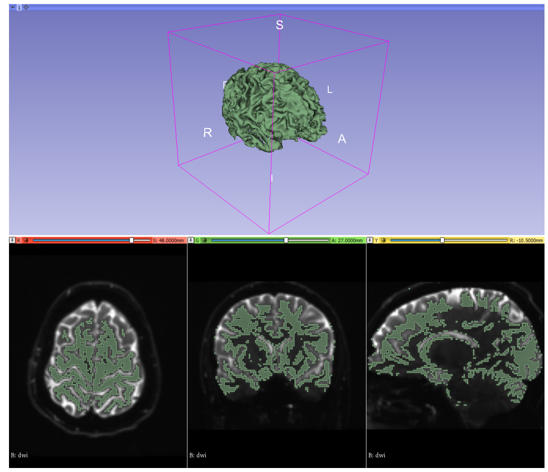


Fig. 7: 3D modeling of white matter using DWI, DTI, and filters

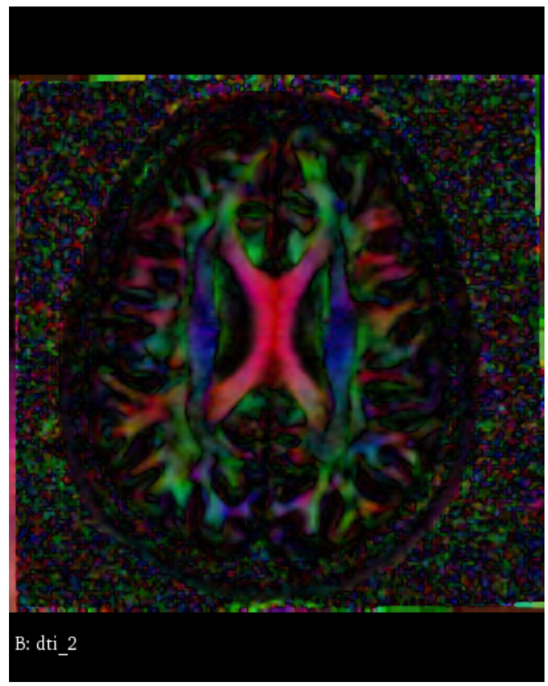


Fig. 8: Axial image of brain using DTI Imaging

Once those issues were resolved we were able to generate some basic forms and manipulate them as well as detecting collision between them. Fig. 10 shows the initial work done on creating colliding models.

Collision is straightforward in VTK and requires each object to be put through a collision filter which checks for overlapping sections of cells. There are three collision modes in VTK, but for this application's purposes the best option is the "All Contacts" collision detection which returns a list of all colliding cells. When this return value is 0 that means that there is no collision between our needle and the essential brain geometry. The toolkit allows for logic checks to trigger events which can then determine the pose whenever the

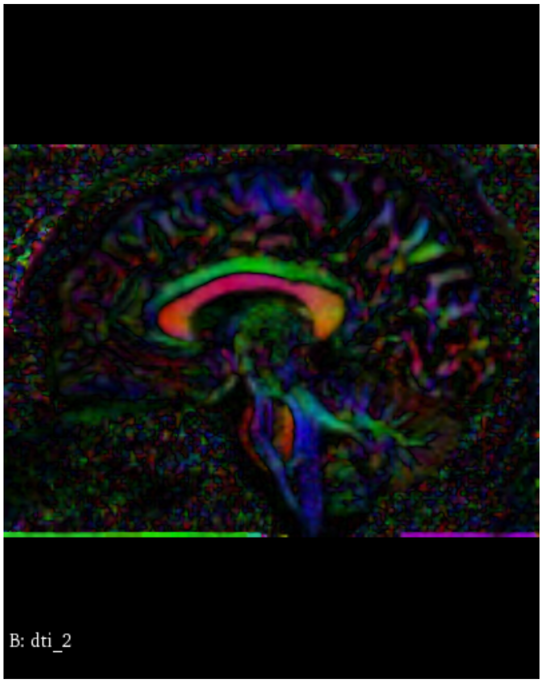


Fig. 9: Sagittal image of brain using DTI Imaging

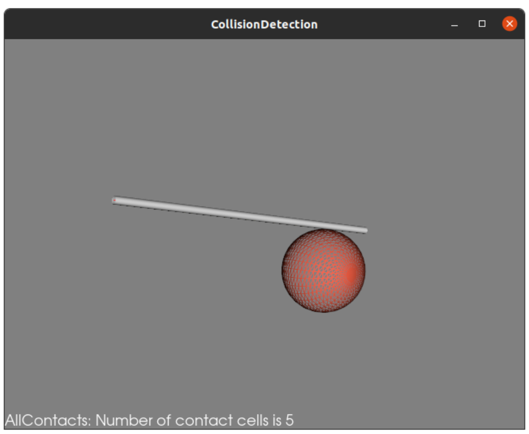


Fig. 10: A collision test generated in VTK

environment meets certain criteria. Namely, this means that all non-colliding poses can be recorded. This threshold can also be variable and if it is found that all paths have some element of collision than the least damaging points can be chosen.

As far as actually generating the model, we expect the brain object can be directly output from Slicer3D into VTK. Since Slicer3d was initially designed using VTK it can provide .vtk or .vtp files which allow for direct brain generation without having to convert or modify the segmentation. The needle generation can be done using a line object with a tube filter. That will allow the needle to be created along straight line paths that start at viable poses outside of the head and end in the tumor. The tube filter then creates a radius around the path to check for collision of whatever radius needle is desired. By changing the start point (the point outside the head) the Cartesian coordinates of the needle insertion will be known as set values, and the angular values can be computed from the vector.

C. Neuro Robot Kinematics

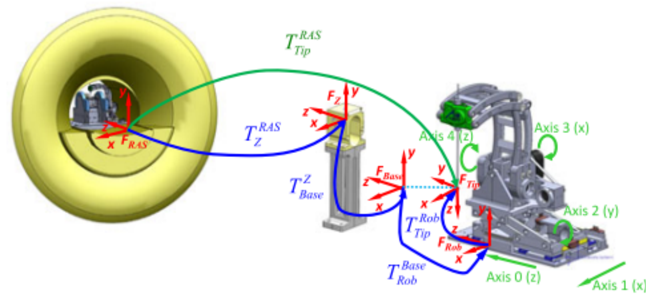


Fig. 11: Registration of Imager RAS Frame to Z frame [2]

As noted above, the MRI brain images used for our work were imported from a repository online. The first road block was to move these sample images in the reachable workspace of our robot. This problem was solved by the registration process. In order to generate the transformation matrix T ^{RAS} zframe, we need the point cloud of the image as well as the point cloud of the workspace of our robot. The Forward Kinematics of the robot was used to generate the robot's workspace. Now, we find the centroids of either point clouds and compute the transformation T^{RAS} zframe using the Arun's method. This transformation is denoted as the T RAS zframe in the Fig. 12.

Axis	Motion	Min Value	Max Value	Units
1	tx	-37.5	0	mm
2	ty	0	44.23	mm
3	tz	-86	0	mm
3	tz2	-143	57	mm
4	Rx	-90	0	deg
5	Ry	-37.2	30.6	deg
6	Rz	-	Continuous	deg
7	Pi	-40	0	mm

Fig. 12: Minimum and maximum joint position specifications of the robot [2]

As the next step, the target pose was computed using the entry points and target point from the VTK software. This list of entry points are those that allow collision-free paths from the surface of the head to the tumor. The Inverse Kinematics of the robot was used to compute the robot joints positions for the required target pose and the entry points. However, any value of the robot joints computed are not feasible because of the constraints of the robot dimensions and motor encoder limits. The joint limits of the robot is shown in the Fig. **??**. As the last step, the robot joint positions obtained from the Inverse Kinematics were validated to ensure that the entry point considered is reachable by the robot. At this point,

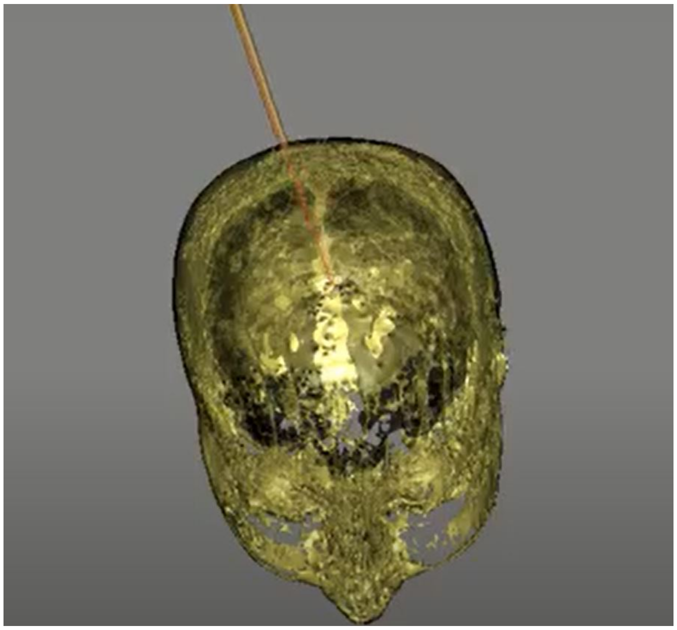


Fig. 13: Visualization of brain and needle collision generated in VTK.

we would like to mention that the Inverse Kinematics code was not working as expected for many target points. This is considered as part of future work to enhance the Inverse Kinematics code to work more reliably for any given inputs.

VI. Conclusion and Future Work

A. Visualization Toolkit

Using VTK we were able to generate potential burr holes as well as the path from the entry to the tumor using information from the collision detection. This information includes XYZ information as well as spherical angles for both sides of the needle. The developed techniques are general and could work for any supplied obstacles although our results were generated simply from the white matter. Additionally the collision check currently only records completely collision free poses, but could be updated to check for any threshold or collisions or record the best performing positions by minimum amount.

As seen in Fig. 13 VTK also allows the operator to see the potential entry angle as well as generating the numeric values. Overall VTK proved to be exceptionally successful at performing collision analysis and the procedure we developed allows for future work to be done using any potential obstacles generated so long as they accomodate the given file format (.vtk or .stl).

As mentioned above future expansions on this work would be primarily focused on broadening the scope of the collision and creating more sophisticated metrics for the best path. Since the program is built in C++ any logical operator can be used and should allow for potentially scaling the importance of certain brain elements or including other considerations like path length or even checking kinematic workspace considerations in VTK. The other major area for growth would be the include more than a singular obstacle and having tighter margins on obstacle collision. For this work as a prototype the white matter was only a singular condensed test object that wasn't designed to really find exceptionally collision free paths. Actual applications would need research to study what elements should be avoided to best promote patient recovery.

VII. Timeline

Project Timeline			
Slicer	***Status***	***Start***	***End***
Generate 2D & 3D images identifying tumor, skull	Completed	April 1	April 8
Generate 2D & 3D images identifying white matter, DTI nerve tracts & other potential obstacles	Completed	April 8	April 17
Export various 2D and 3D files for testing in VTK	Completed	April 17	April 21
VTK			
Debuggin & compilation of VTK library	Completed	March 28	April 14
Understanding example codes	Completed	April 14	April 19
Take outputs from Slicer3D as input to VTK	Completed	April 20	April 22
Create needle model of fixed length	Completed	April 25	April 27
Get pose output on collision	Completed	April 21	April 25
Put poses into list for later reference	Completed	April 27	April 29
Transform needle through possible poses	Completed	April 25	April 29
Kinematics			
Kinematics Library setup and testing	Completed	April 1	April 10
Determining the T_RAS_tip transformation	Completed	April 19	April 22
Integrating with VTK and Slicer	Completed	April 22	April 25
Full System Testing	Not completed	April 25	May 1
Documentation			
Project Proposal	Completed	March 20	March 24
Midterm Report	Completed	April 15	April 19
Final Report	Completed	April 28	May 3

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