Patient Specific Steerable Concentric Needle-Based Robot Design with Neurosurgery Robot Workspace - Team 1

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***Abstract*— In needle-based surgical interventions, accurate alignment and insertion of the tool is paramount for providing proper treatment at a target site while minimizing healthy tissue damage. Conducting interventions in an MRI scanner can provide real-time, closed-loop feedback for a robotics platform, improving its accuracy, yet the tight environment potentially impairs motion, and perceiving this limitation when planning a procedure can be challenging [1]. Concentric tubing robots are a type of continuum robot that are comprised of nested combinations of Pre-curved super-elastic tubes, which is widely used in Cardiac Surgery (CV) in medical usage [2]. This project developed a surgical workflow and software system for evaluating the workspace and planning the motions of a robotics platform within the confines of an MRI scanner. Combining with concentric tubing robot technilogy, this system enables MRI-guided deployment of a precurved and steerable concentric tube continuum mechanism, and is suitable for clinical applications where a curved trajectory is needed [3]. For this study, a 7 DOF robot arm designed for ultrasonic ablation of brain tumors was the targeted platform, and a designed cannula genetrating system is design to application.**

I. INTRODUCTION

One of the goals during surgical procedures is to minimize healthy tissue damage while remaining effective at performing the procedure. Minimally invasive surgical techniques can mitigate the risk of infection, blood loss, tissue damage, cosmetic scarring, and improve recovery time by reducing the size of the incision made in the skin and exposure to the environment. However, this usually comes at the cost of diminished perception, manipulative ability, and surgeon comfort, and the associated cost increases that can come with these issues. While the quality of the surgery is better than traditional procedures, this raises questions as to the broader societal implications of minimally invasive surgical techniques. [4]. MRI is an ideal guidance tool for IGS due to its ability to perform "real-time", high quality, volumetric imaging. The ability to redirect the path of a needle once it has entered the body enables minimally invasive access to challenging surgical sites, as well as the ability to compensate for intraoperative tissue motion. [3]. A number of different approaches have been investigated to steer flexible needles, including: (1) needle base manipulation of symmetric-tip needles [5], (2) asymmetric tip-based needle steering [6], (3) pre-curved tip needles [7], and (4) concentric tube continuum robots (also referred to as active cannulas) [8][9][10]. MRI-guided robotic surgery systems have been investigated with considerable efforts for neurosurgery, prostate biopsy and brachytherapy, breast biopsy and cardiac interventions.

This project entails developing a research-grade software system which integrates existing medical platforms, provides a mechanism for evaluating the neurobot's reachable workspace, and generates collision-free trajectories to enable faster, less tiresome, and more intuitive surgical procedures using the neurobot in ultrasonic ablation with exibility to be adapted on similar platforms. Also it describes the design and evaluation of an MRI-guided concentric tube continuum robotic system, combining our recently developed framework for MR-conditional piezoelectric actuation with a concentric tube robot deployed as a steerable needle.

*This work was supported AIM Lab and Professor Gregory S. Fischer
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II. PROJECT GOALS

This project is a combination of previous projects from AIM lab. While we are rebuild the project, we are trying to find the balance of combining the two project to one application and used it for neurosurgery (Fig. 1).

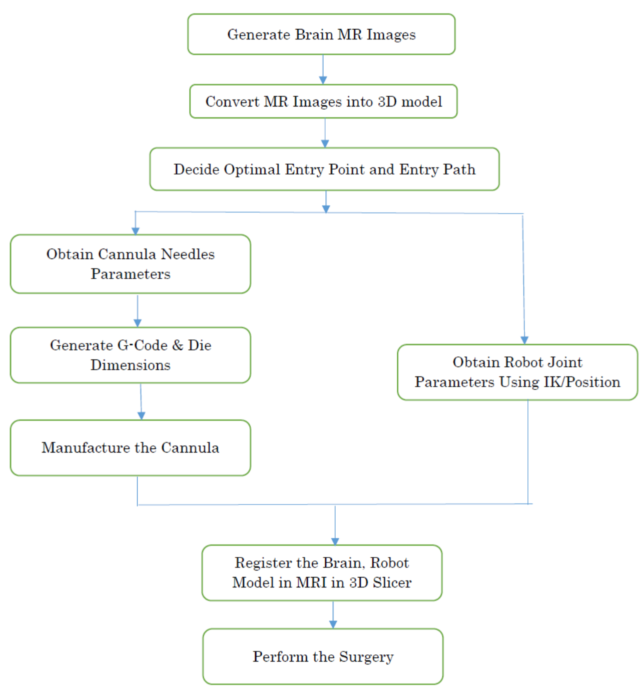

Fig. 1. Work flow of the project. It contains goals and work we need to reach. This can also be understood as a flow chart, which means we just an brain scan image as single input, then we can have all the details we need to build the system for neurosurgery procedure.

A. Get 3D Model of Brain and Identify Tumor

We will take the DICOM images of brain from MR scanner and integrate it into a 3D model using 3D slicer software tool. Then Visualize the 3D model of the brain in 3D slicer and identify the Tumor location. After finding the tumor location we will create a fiducial point on the center of it by approximation and name it as tumor point/target point.

B. Decide the Optimal Entry Point and Optimal Entry Path

After identifying the tumor we will take an expert advice and identify all the possible entry points to approach the tumor. Among all the possible entry points we will identify the optimal Entry point where there is minimal damage to the brain tissues. After identifying the Optimal entry point we create a fiducial and name it as entry point and look at all the possible paths to approach the tumor from the entry point. Fig.6 shows all the possible paths from entry point to tumor point. Among all the paths shown in the image we will take expert advice to decide the optimal path in which there is minimum damage to the healthy tissues. But for the course project we have assumed entry point and entry path as randomly. In studying all the paths we have found out the curves which are on the upper side of the straight path cannot be carried using cannula needles because we cannot insert the cannula needles with 45 degree angle at the entry point at all parts of the head.

C. Obtain Robot Joint Parameters and Position of Robot Base on Surgery bed

After finding the Optimal Entry point and Optimal Entry Path we will register both the fiducial points of the Entry point and target point with respect to the Patients Skull frame and MR machine Frame. This entry point will be the target for the End-effectors. Fig.3 shows the control User Interface of the Neurobot joints. We will target each and every joint and move the robot to reach the target point. So, After getting the End-Effectors frame to the target point we will not move the joints and keep the pose of the robot same through out the surgical procedure is completed. Controlling each joint one by one and executing the joints in a sequence so that the arm will not collide with any machine parts is a very time consuming and repetitive task. We are planning to automate it by integrating it with ROS-Moveit motion planning tools using ROS-IGT APIs.

D. Obtain Cannula Needles Parameters and Create the CAD models

Using the Entry Point and Target point fiducials we will calculate the lateral and longitudinal distance of Tumorpoint and the Entry point and based on the decided optimal path we will design the cannulas. We have created a matlab function which will take inputs of two co-ordinates and give the output as parameters of cannula like the side of tumor point, number of cannulas required and the region in which the tumor point is placed. After getting this parameters we will design it in CAD software and design the dies for manufacturing the Cannulas. And then Generate the G-code for the CNC/VMC machines to manufacture the Dies. After we fabricate the cannulas we will assemble them to concentric system which will then fit on the end effector of the Neuro Robot.

TABLE I
PARAMETERS OF THE TUBES AND NEEDLES.

	Stanless Steel	NiTi Tube		NiTi Needle
OD (Inch)	0.095	0.065	0.0496	0.027
ID (Inch)	0.071	0.053	0.039	—-

E. Manufacture the Cannula

By using the oven from Washburn Lab, we are able to heat and quench the tubes.

F. Register the Brain and Robot Model in MRI in 3D Slicer

Getting the Robot model and Brain model simultaneously in the MRI and then practicing the Surgery.

III. METHODS

Our team is made by three talented individuals with different skills and experience. Chinmay has experience on ROS and coding, he will be in charge of setting up the robot and modify the motion capture. Zhanyue "Jimmy" Zhao has experience on medical device design and skilled in fabrication, also he has experience on animal surgeries so, he will be in charge of fabrication and the reach the goal of surgery. Ashley will be working with both areas, and she will be helping with Chinmay and Jimmy to optimize all the work.

A. Optimize Previous Work

First, we need to get MRI Scanned Images and create a 3D model of Brain and visualize it in software. Identify the tumor and decide the best entry point for surgery through the skull based on minimum damage to the brain tissues and nerves. The image will from previous papers and from Professor Fischer. Second, we need to convert the MR images to a 3D model based on previous work. (Fig. 2).

Next step, based on the entry point and tumor location we will identify the optimal approach direction to reach the tumor. Based on the approach direction we will consider the end-effector orientation. By using the slicer and the designed GUI system (Fig. 3), we are very easy to confirm the entry point for the given image of human brain tumor. Based on the manipulability of the robot arm we will calculate the position of the robot platform on the surgery bed (Fig. 4).

B. Cannula Parameters Generation Analysis

Based on the lateral and longitudinal distance between end-effector frame and tumor frame we will calculate the cannulas' parameters. The tubes we have now is two sizes of NITI tube which concentric with each other, one size of stainless steel tube and one size of NITI needle. The parameters of the tubes and needle is shown in Table I.

We have finished a generating system to generate the parameter, which consisted by 2 steps: simulation analysis and generation system.

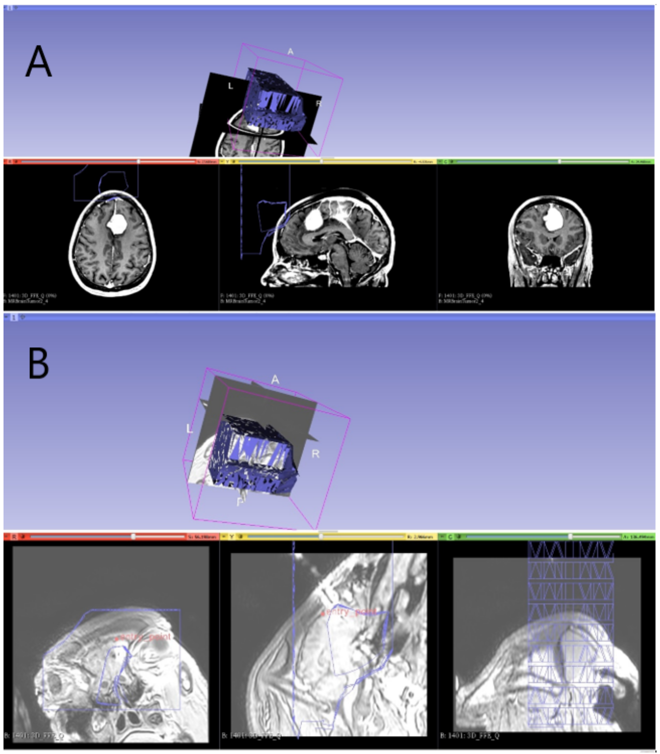

Fig. 2. 3D model from slicer. (**A**.) This is a human brain MRI scan with a tumor in the upper position of the brain. The tumor is very big and in the main part of brain location, under this circumstance the entry point and the surgery path is very important. We will find the entry point and design the path without touching any tissue of the brain by using steerable concentric needle-based robot to reach the targets. (**B**.) This is a pig head scan by our previous work. The slicer software well defined the dimensions of head, also there is fiducial point shown on the image. With the help of the 3D imaging system, it will help with the surgeons to find the target point directly with visible image.

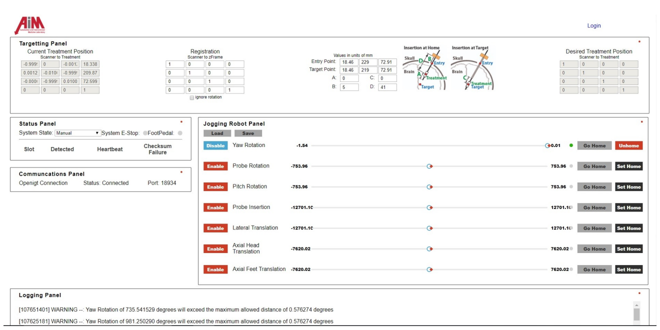

Fig. 3. From previous work we are able to control the robot arm to a series of registration point. The GUI is very easy to operate and clear, just need to put into the registration and the target point, then move the points to the expected range, then step onto the position trigger, the arm will move to the designed target.

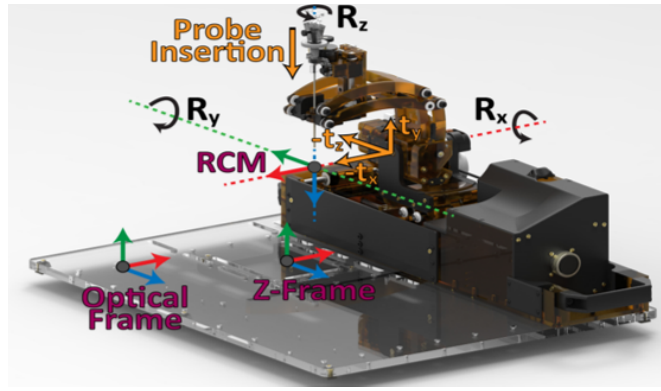

Fig. 4. The system will generate the position of the robot platform. By knowing the entry point we just need to input the registration points and the target point from the slicer, then the arm will move to the target position by stepping onto the trigger switch.

1) CAD Simulation Analysis: To better design the insert path, We have designed a MATLAB function which takes input as two co-ordinates one as entry point and other as tumor point (See Appendix A). And gives the output as the point lies in left side or right side of the entry point and also gives the region in which the tumor point lies. It also gives outputs the cannula parameters like number of cannulas required to reach the target point and few dimensions of the cannulas and template.

The cannula can reach the tumor point from the entry point till a certain extent. In this project we have assumed the area between the farthest tumor point and entry point as 1414 mm. And we have considered the work area as 100 x 100 mm square. There are two cases the tumor point is on the right side or left side of the entry point. Considering the work area of the tumor and entry point, we have divided the whole area into four regions.

Region 1: If the tumor point lies in these region there is no need for using cannula needles to reach the target point. The target can be reached directly by inserting a straight tube tilted with some angle. **Region 2:** If the tumor lies in these region there is a need for cannula. And the tumor can be reached by using only two concentric cannula needles. **Region 3:** If the tumor lies in these region then we require three concentric cannulas to reach the target point. **Region 4:** If the tumor lies in these region then there will be some complexity for designing the cannula to reach the target point. (Fig. 5) So we avoided considering the target points in these region.

With the path plantation finished, we are able to fabricate the customized concentric tubing system needles. By using Catia and MATLAB, we are able to generate the Parameters of tubes and build the CAD file of the tubes, including the number of tubes, curve parameter of each tube, length and diameter of tubes, we are able to fabricate the template.

2) Working Volume Simulation: We also designed MATLAB code to generate the work volume by the concentric cannula system (Fig. 6). In this project we are using two curved tube as main steerable function part. This code can

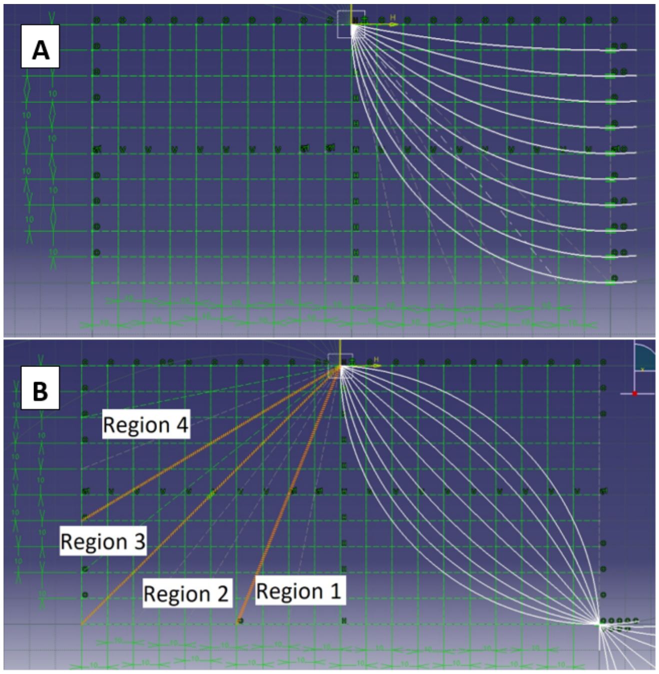

Fig. 5. Simulation from Catia. (**A**.) Cannula parameter consideration, shows possible path of the procedure. (**B**.) cannula possible paths region distribution. From the result we should avoid region 4, or change the entry angle.

be used to generate more complex concentric robot system even up to 4 tubes cannula system.

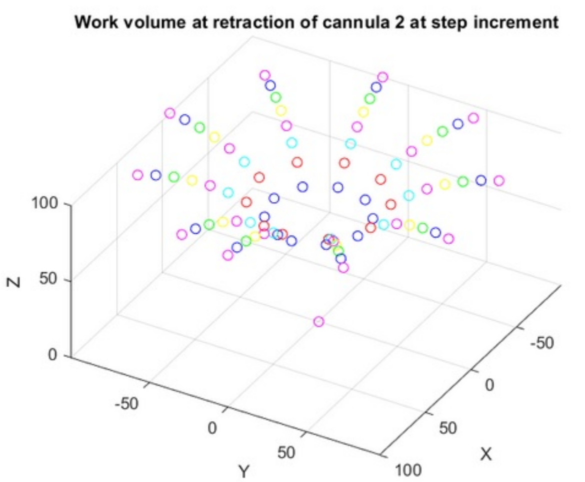

Fig. 6. MATLAB simulation of cannula with two tubes work volume.

C. Manufacture and Fabrication

The tube parameter is generated by Caita and MATLAB, then we have the template for the tube to do heat treatment (Fig. 7).

The template is made by T6061 aluminum bar. By using the G-code generated from the last step, we are able to get the notch for the NITI tubes to fit into. We use the template to fix tube's shape and put into furnace to heat treat under 525°C

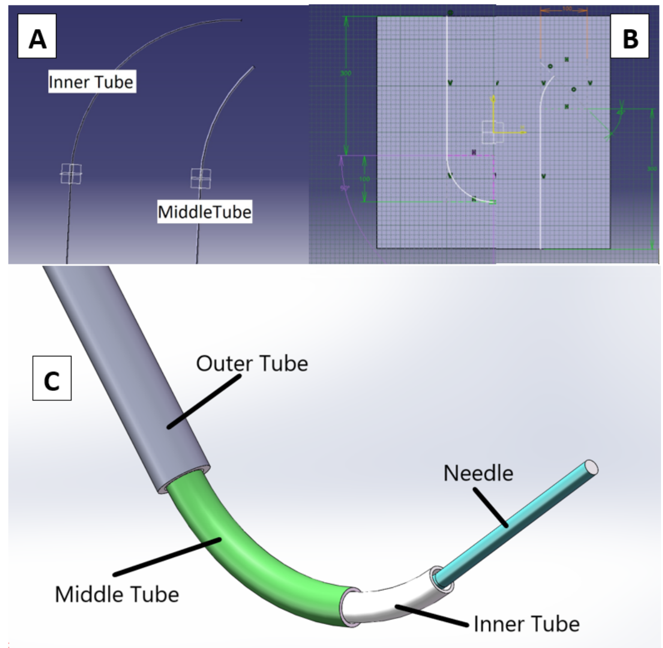

Fig. 7. CAD file generate from Catia. (**A**.) The tube file generated from Catia and MATLAB, which is consisted from inner tube and middle tube, they are all NITI tubes. (**B**.) The template file generated from Catia by the tube parameter. (**C**.) The assemble CAD file. The cannula system is consisted by 4 part, stainless outer tube, middle and inner NITI tube and the NITI needle.

for over 45 minutes, then quench the tubes into cold water, then the tubes will stay its curved shape. (Fig. 8) Before assemble the tubes, put them into cold water or environment to straight them back, insert them together and ready to use.

D. Assembling and Testing

The outer tube is fixed into the robot arm, the middle and inner tubes and needle are connected to aluminum rod as connector. Concentric the system and we can have the cannula system. The cannula has 5-DOF, which are 3-DOF translation by middle, inner tubes and needle, and another 2-DOF rotation by middle and inner tubes (Fig. 9). Then we can install the system onto the neurobot and finish the integrated neurosurgery-cannula system (Fig. 10).

E. Preliminary Manually Evaluation Experiment

After we confirm the entry point, we can plan the cannula system and process the path procedure. The tumor is a sphere shape tissue which grow inside the brain. Considering the tumor is connected to the brain tissue randomly, we are not sure where we should insert the needle to proceed the procedure, so in theory when the tumor image is acquired, we need to set the needle to reach every point on the inner surface. We print out the section cut brain tumor paper model as the same size in the slicer software, and define 7 points as the target points. Consider the other point locates in sphere shape tumor, we can rotate the connector in order to rotate the middle and inner tube to reach other points (Fig. 11). The point locates in different area inside the tumor inner surface. The red point locates in the bottom of the tumor, which is in

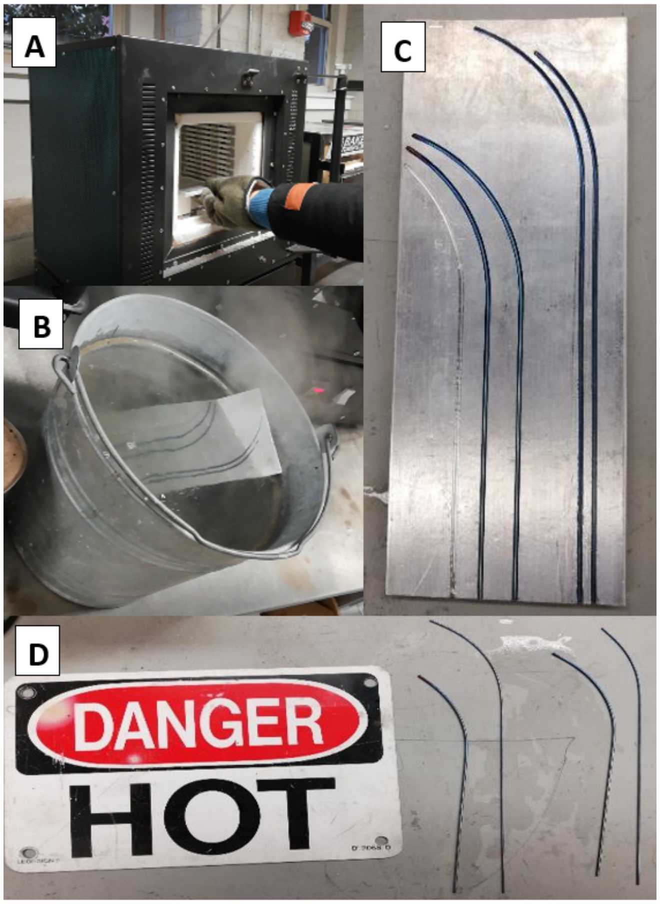

Fig. 8. Fabrication of cannula parts. (**A**.) Use furnace to do heat treatment, keep curing under 525°C for 45 minutes. (**B**.) Quenching into cold water. (**C**.) After heat treatment the NITI tube will change color to blue. All body blue mean the heat treatment is perfect and the shape is fixed. (**D**.) We got 2 series of concentric tubes. The left system is 80° curve angle, and the right system is 40°.

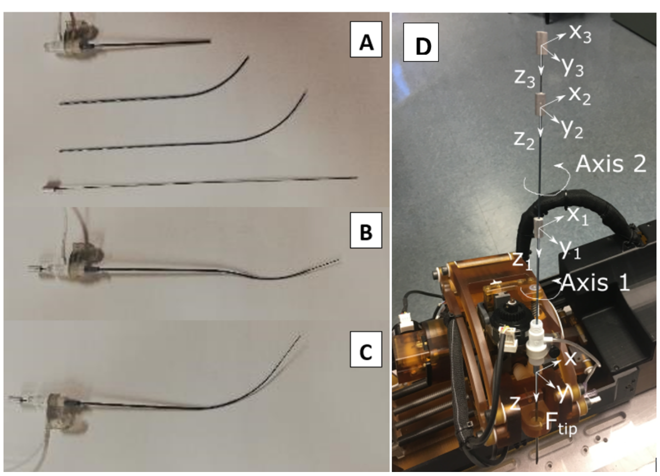

Fig. 9. Cannula system assembly. (**A**.) The system is consisted by outer tube, which fixed in the arm part, the middle and inner tubes and needle. (**B**.) The natural concentric tubing system insertion with same direction. (**C**.) The middle and inner tube are 180° opposite with each other. (**D**.) The cannula system coordinate. The cannula has 5-DOF, which are 3x DOFs translation by middle, inner tubes and needle, and another 2x rotation DOFs by middle and inner tubes.

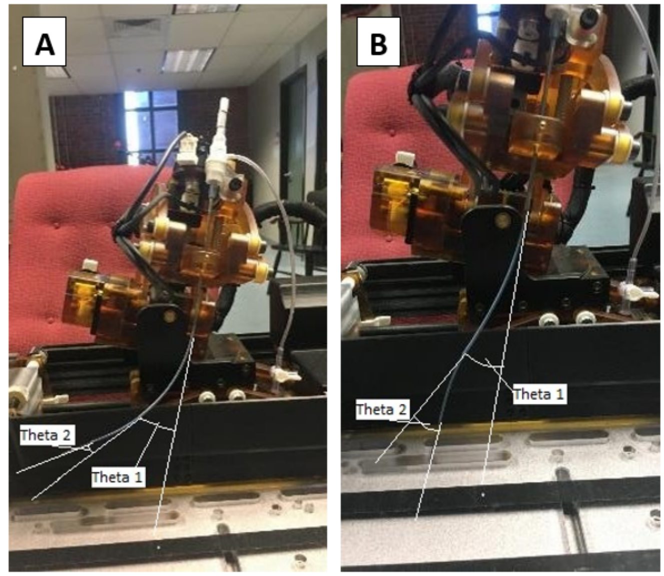

Fig. 10. Integrated system assembly. (**A**.) The natural concentric tubing system insertion with same direction, we can get middle tube curved with $\theta 1$ and inner tube curved with $\theta 2$, the needle is curved with $\theta 1 + \theta 2$. (**B**.) The middle and inner tube are 180° opposite with each other, we can get middle tube curved with $\theta 1$ and inner tube curved with $\theta 2$, the needle is curved with $\theta 1 - \theta 2$.

region 1 as we discussed in the path generate section, so this point doesn't need cannula system, just insert into and insert the needle to the red point.The two black points locate in region 2, so we need at least 2 cannulas (including the outer tube.), while the 2 blue points locate in region 2, and we need at least 3 cannulas. For the 2 green points, they locate in region 4, from the result of previous section, then there will be some complexity for designing the cannula to reach the target point. So we need to change the initial insert angle, which we need to control the neurobot arm to change its trajectory, then we can reach the green point without redesign the entry point. With the help of the neurobot control system, we can reach all 7 points, from the entry point by using 1-3 tubes to approach them. We can now manually coordinate the neurobot with the cannula system to reach all the points (Fig. 12).

IV. FUTURE WORK AND DISCUSSION

The Neurosurgery is very precise procedure, with less than $1mm$ tolerance for the knife. Also we will encounter the shrinkage effect during the surgery. The goal of this project is to show the concepts and build a working prototype with simple situation, however in the future we will continue working on the general situation and try to give universal solution to the neurosurgery. For now the neurobot system is consisted of two part of box and the operation is still need manually input the position data. In the future we will integrate the system by all automatic controlling, which will make it easy to operate. The Tube/wire connectors need to redesign and improve robustness, which need inserting and rotating smoothly and stably. Special rotation need large friction between the tolerance, it may need experiment on different concentric tubes combination to achieve best tolerance to remain special rotation degree. Heat treatment process is an experience result, Limited research is focusing on the time requirement, we will try to find the equation to calculate the time requirements of heating with variable parameters of template volume, shape, furnace volume, air fluid, temperature etc. For now the cannula system is operated manually after the robot automatically reach entry point. We are planning to design a new 5-DOF MRI compatible (plastic or polymer based) concentric control robot to control the tubes insertion/rotation automatically, master-slave concentric tubing system with phantom omni worked on our existing neurosurgery robot platform.

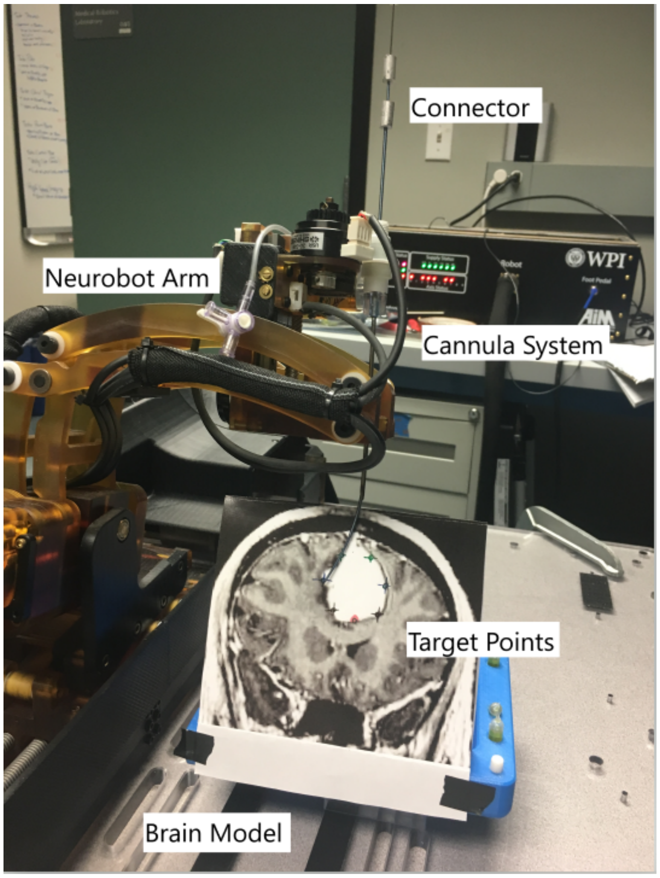

Fig. 11. The integrated system of the device. The outer tube is fixed on to the arm, middle and inner tubes are connected with connectors, and a section cut brain tumor paper model as the same size in the slicer software is printed out. In the inner surface there are 7 point locates in different area of the tumor.

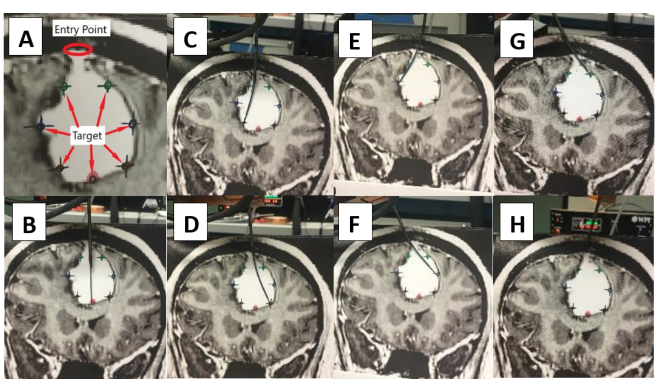

Fig. 12. Cannula system assembly. (**A**.) The system is consisted by outer tube, which fixed in the arm part, the middle and inner tubes and needle. (**B**.) The natural concentric tubing system insertion with same direction. (**C**.) The middle and inner tube are 180° opposite with each other.

APPENDIX

Please check the google drive link https://drive.google.com/file/d/1ayW2oLHu-C7gP4vFJJqWlOmXdemtjlED/view?usp=sharing for all the MATLAB code and the Catia files. Also see Cannula model and Workspace analysis PDF files within the folder.

ACKNOWLEDGMENT

This work is a brand new project by Professor Fischer, and will be collaborate with Brigham Women's Hospital (BWH) and Boston Children's Hospital (BCH) for further study.

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