Integration of Surgical Navigation to a Spherical Parallel Manipulator Utilized for Robotic Brain Biopsy

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ABSTRACT
By the help of technological advances, robotic systems supported by surgical navigation procedures are becoming an integral part of the medical field. Due to the fact that getting high quality visual feedback from target workspace is one of the most important factors affecting surgeons' operation precision, current computer and imaging technologies in the medical field has started to focus on the possible ways of implementing virtual navigation methodologies to surgical robotics. Thus, surgical navigation systems have started to take place in many surgical operations in order to track surgical tools inside the operation volume. In light of this, current study tries to implement surgical navigation methodologies into a spherical manipulator that was previously designed by the same group for robotic brain biopsy operations. Throughout the study OptiTrack V100R2 motion capture cameras were utilized to track manipulator motions. Once the structural model of related robot manipulator was transferred to the virtual environment, least squares point based registration methodology was utilized in order to relate virtual and real workspaces together. At the end of the study, performance evaluation of the system was carried out by giving tumor locations from the virtual environment and letting robot manipulator to target related location in the real environment. In order to demonstrate hardware verification procedure, a mockup model with specific landmark points as tumor locations were utilized as surgical targets. As the brain biopsy operations are carried out in a closed environment with limited visual capabilities, acquired results promisingly point out the effectiveness of the mentioned integration.

Keywords
Medical Robotics, Surgical Navigation, Brain Biopsy Manipulator

1. INTRODUCTION
As a positive result of developing technology, the quality of the visual feedback which the surgeon receives from the operation volume became an effective impact for most of the surgical procedures. Although the usage of the tools such as special lamps and surgical glasses minimize errors that may occur by a naked eye under natural lighting conditions, these types of traditional solutions are insufficient in a closed workspace. On account of this, surgical navigation methodologies have been started to implement for the visualization of the target surgical volume. During surgical navigation, operations are visualized in a 3D virtual environment using medical imaging techniques and the poses of the surgical instruments are tracked in real time utilizing optical tracking systems.

In order to utilize surgical navigation procedures efficiently during the surgeries, relationships between various reference systems inside the surgical workspace (patient, cameras, surgical tool references etc.) should be clearly and precisely described. In light of this many approaches were proposed inside the ongoing literature. Arun, Huang and Bolstein [1], introduced the calculation of transformation matrix that is required to determine the relationship between two distinct reference systems by using least squares methodology. In their works authors used the coordinates of known point sets with respect to both references. Hong and friends [2], introduced an effective point based registration by using landmark points taken from the patient's body in order to determine the transformation matrix between the virtual and real environment. Also, in their later studies [3] they improved their methodology by the addition of landmark points inside the surgical workspace that were measured by the help of ultrasonic systems. This way they reduced the overall registration error. By using proposed algorithms, the same authors demonstrated successful results of surgical navigation in inner ear surgery [4], breast conserving surgery [5] and bone tumor resection [6]. Chen and friends [7] created a surgical navigation system utilizing see-through head-mounted display to create an effective AR assisted surgical navigation system.

Related literature on the field shows that navigation methodologies bring many benefits to the medical operations in terms of safety, enhanced accuracy and shorter operation times.

Taking this into consideration, current study focuses on the implementation of virtual navigation to the robotic brain biopsy.

2. STRUCTURAL DESIGN

Due to brain's complex structure, neurosurgery is one of the most important disciplines in which robotic systems are quickly adopted and used. Highly operational precision, enhanced dexterity, reduced complication risks and operation durations are just some of the numerous advantages of robot assisted surgeries. For this reason, previous study [8] focused on the conceptual design of a surgical robot manipulator system that can ensure the precise positioning of the biopsy needle to the tumor area during brain biopsy operations. Following the study, considering workspace constraints inside the brain, proposed mechanism was improved (Figure 1) to have larger workspace and ease of manufacturability without changing its kinematic structure [9].

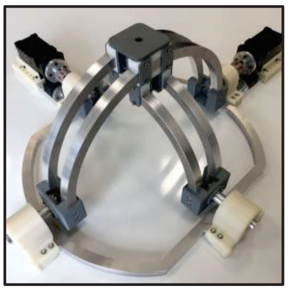

Figure 1. Prototype of the proposed surgical manipulator

3. NAVIGATION SETUP

In order to form navigation setup, dual motion capture cameras were deployed for real-time acquisition of tracking data of any arbitrary rigid bodies in space. Motion tracking cameras were connected to the system via their official software Motive Tracker that runs on a PC. Along with the official tracking software, 3D Slicer [10], SlicerIGT [11] extension, Plus ToolKit [12] software and Robot Operating System (ROS) were utilized for both visualization, communication and programming purposes.

4. REGISTRATION&METHODOLOGY

Utilized motion tracking cameras should be individually positioned inside the application workspace and calibration procedure provided by the manufacturer needs to be performed manually prior to the operation in order to acquire meaningful tracking data. In light of this, motion capture cameras were calibrated by using system specific calibration wand provided by the manufacturer. Existing mockup model (Figure 2a) was placed into the application workspace to simulate tumor locations. In order to match virtual (Figure 2b) and real model of the mockup in virtual environment inside 3D Slicer software, registration of the mockup was performed utilizing least squares registration methodology.

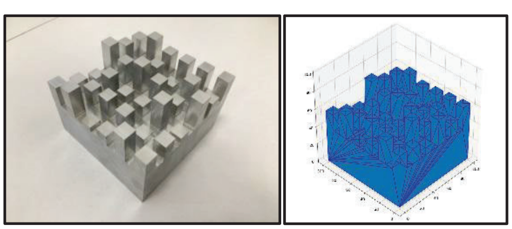

Figure 2. Real and Virtual Mockup

Apparatuses with distinct landmark points were also manufactured with rapid prototyping and assembled to the brain biopsy manipulator (Figure 3).

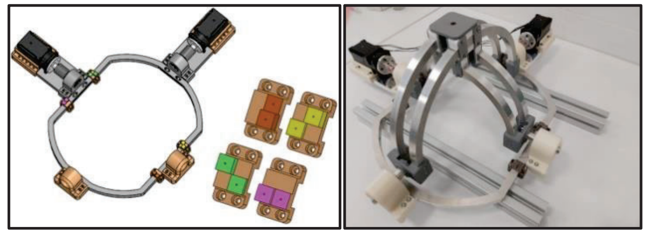

Figure 3. Designed apparatus for manipulator registration

Utilizing registration methodologies on landmark points, transformation between manipulator base frame and virtual environment global frame was acquired. At this point, both mockup model and manipulator base frames were easily visualized in virtual environment (Figure 4).

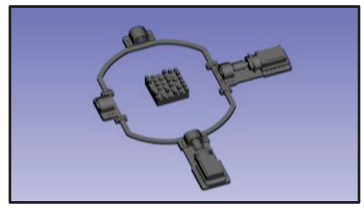

Figure 4. Mockup model and manipulator adjustment part in virtual environment

5. VERIFICATION & RESULTS

During hardware verification procedure, two arbitrary points (Point A and Point B) were selected on the mockup model to represent different tumor locations (Figure 5).

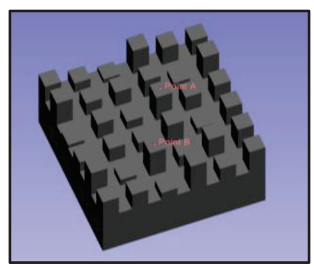

Figure 5. Two target points selected on mockup model

These target points were transformed to the manipulator base frame via 3D Slicer. These selected target points on the mockup model were projected to the spherical workspace of the manipulator's upper platform by using equation 1.

$$P'_{ix} = P_{ix}\frac{|\mathbf{r}_u|}{|\mathbf{r}_{\mathrm{Pi}}|},\ P'_{iy} = P_{iy}\frac{|\mathbf{r}_u|}{|\mathbf{r}_{\mathrm{Pi}}|},\ P'_{iz} = P_{iz}\frac{|\mathbf{r}_u|}{|\mathbf{r}_{\mathrm{Pi}}|} \quad i \to 1,2$$
$$\theta_{1i} = \tan^{-1}\frac{-P'_{iy}}{P'_{iz}},\quad \theta_{2i} = \tan^{-1}\frac{P'_{ix}}{P'_{iz}} \quad i \to 1,2 \qquad (1)$$

where P_{ix}, P_{iy}, P_{iz}, are the x, y, z coordinates of points (points A and B), r_{pi} is the distance between these points and isocenter of the manipulator, P'_{ix}, P'_{iy} *and* P'_{iz} are the x, y, z coordinates of the end-effector and r_u is the radius of spherical workspace of the manipulator platform (measured from the geometric center of the platform to the manipulator isocenter).

Required joint angles (θ_1 and θ_2) were calculated via inverse kinematics of the manipulator (Table 1) so that the end effector of the system can be oriented to the tumor location.

Table 1. The correlation between target points and platform position

Tumour Position (mm)			Manipulator End-Effector Position (mm)		Actuator Angular Position θ (deg)	
A	**x**	13.7955	**x**	73.6022	θ_1	θ_2
	y	-12.5115	**y**	-66.7518	25.5543	27.7986
	z	26.167	**z**	139.609		
B	**x**	-22.3917	**x**	-109.99	θ_1	θ_2
	y	5.09495	**y**	25.0269	-10.9802	-40.4538
	z	26.2602	**z**	128.992		

After the manipulator reaches desired orientation, a needle tool representing biopsy needle was guided from the manipulator platform to the target tumor location. Acquired target was visually verified (Figure 6).

Figure 6. Visual verification

6. CONCLUSION

Throughout the study, surgical navigation procedures were tried to be implemented on a brain biopsy manipulator. Arbitrarily selected dual landmark points on virtual mockup model were designated as target points and their positions were transformed to the manipulator base frame utilizing transformation matrix calculated via least squares point registration. As a last step required actuator values were calculated and the manipulator was posed to an orientation where it can focus on real tumor location. Visual verification revealed promising correspondence between desired virtual tumor location and real target.

7. ACKNOWLEDGMENTS

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