

Integration of CBCT and a Skull Base Drilling Robot

Summary

The performance of a Skull Base Drilling Robot is limited in cadaver studies mainly due to registration error in current system. In this project, a C-arm cone-beam CT will be used to provide guidance and "no-fly zones" to the robot that properly accounted for anatomical deformations imparted during the surgery. Hopefully, this integration will reduce registration error and improve the performance of the robot in cadaver studies.

- **Students:** Hao Dang, Zihan Chen
- **Mentor(s):** Prof. Jeff Siewerdsen, Prof. Peter Kazanzides
- **Course Mentor:** Prof. Russ Taylor

Background, Specific Aims, and Significance

Neurosurgeries such as skull base surgeries are often challenging due to the complex anatomy and the critical nature of adjacent neural and vascular structures. The use of image-guided robots in neurosurgeries can provide precise intra-operative guidance and mechanical assistance. Current skull base robot system developed in Prof. Kazanzides' lab integrated a Stealthstation navigation system, a NeuroMate robotic arm with a six degree-of-freedom force sensor, and 3D Slicer visualization software to allow the use of the robotic arm in a navigated, cooperatively-controlled fashion by the surgeon. Pre-defined virtual fixture has also been developed to constrain the motion of the robot-held cutting tool within safe zone. The system yielded high accuracy in phantom study--0.6 mm average placement error and 0.6 mm average dimensional error. But in cadaver study some bone outside virtual fixture was cut and the typical overcut was 1–2 mm, with maximum about 3 mm. This keeps the robot from being further tested in real clinical trial.

Considering that intra-operatively updating anatomical deformation and registration may be a possible way to increase cutting accuracy, an advanced intra-operative imaging device--C-arm cone-beam CT will be integrated into the robot system. This prototype CBCT imaging system based on a mobile isocentric C-arm has been developed in Prof. Jeff Siewerdsen's lab in collaboration with Siemens Healthcare (Siemens SP, Erlangen Germany). It has demonstrated sub-mm 3D spatial resolution and soft tissue visibility which are suitable for neurosurgery navigation. The typical acquisition and reconstruction time are ~60s and ~20s respectively which will not interrupt the surgical workflow.

Our specific aims are:

1. Fusion of intra-opera CBCT and pre-opera CT images by fiducial-based rigid registration.
2. Construct complete transformation flow including robot, skull, CBCT images with navigation system. Perform phantom experiments using CBCT-Guided skull base drilling Robot system ('CGR' system) with navigation.
3. Construct another transformation flow without navigation system. Perform parallel phantom experiments using the two CGR system above (with and without navigation) and previous non-CBCT system. Make comparison and analysis.

Deliverables

- **Minimum:**
 1. Fusion of intro-opera CBCT and pre-opera CT images by fiducial-based rigid registration.
 2. Complete transformation flow including robot, skull, CBCT images along with navigation system.
 3. Target-pointing experiment on phantom using CBCT-Guided skull base drilling Robot system ('CGR' system) along with navigation.
- **Expected:**
 1. Foam-drilling experiment on phantom using CGR system with navigation.
 2. Another transformation flow including robot, skull, CBCT images without navigation system.
 3. Parallel phantom experiments using the two CGR system above (with and without navigation) and previous non-CBCT system. A comparison report.
- **Maximum:**
 1. Image-based CBCT to CT registration framework.
 2. Cadaver experiment using CGR system and comparison of results with Phantom studies.

The deliverables listed above may be adjusted after each milestone has been achieved because this project largely deals with performance on phantom and cadaver experiments, which has uncertainty in itself. However, each adjustment will follow the ultimate goal of pushing the skull base robot technology into clinical use.

Technical Approach

1. Robot System with CBCT and Navigation System

- Pre-operation
 - Obtain CT Image of Skull Base
 - Create virtual fixture on CT image in TREK
 - Obtain CBCT Image of Skull Base
 - CBCT to CT registration
 - ◆ Pick up fiducials in both CBCT and CT images in TREK
 - ◆ Paired-point registration
 - CBCT to Skull (relative to tracker) registration
 - ◆ Use passive probe to point fiducials on skull
 - ◆ Paired-point registration
 - Robot to Dynamic Reference Base (relative to tracker) registration (Dynamic Reference Base is mounted on the head clamp)
 - ◆ Get tip position with reference to Robot World frame
 - Do pivot calibration to get cutter tip position with reference to Tool Center Point frame
 - Calculate tip position with reference to Robot World frame using forward kinematics
 - ◆ Get tip position with reference to DRB frame

- Attach rigid body to robot cutting tool
- Do pivot calibration to get cutter tip position with reference to robot rigid body frame
- Calculate tip position with reference to DRB frame using navigation system
- ◆ Paired-point registration
 - Register virtual fixture from CT image frame to Robot World frame using the transformation flow above, prevent tool from entering “no-fly-zone”
- Intra-operation
 - A neurosurgeon holds the robotic arm and drills in cooperatively controlled fashion guided by CBCT image and navigation system and protected by virtual fixture
 - Obtain CBCT images after achieving each milestone in surgery
 - Register new CBCT image to earlier ones, update deformation information and virtual fixture
- Post-operation
 - A CBCT image is taken to evaluate the operation process

2. Robot System with CBCT but without Navigation System

The only difference from the system above lies in:

- Pre-opera CBCT to Robot registration
 - ◆ Do pivot calibration to get cutter tip position with reference to Tool Center Point frame
 - ◆ Hold the robotic arm and point the tip to fiducials on skull to get positions with reference to Robot World frame
 - ◆ Pick up fiducials in CBCT images in TREK
 - ◆ Paired-point registration

Dependencies

1. Usage of NeuroMate Robot. Resolved. We have got access to mock room and will share the use of robot with another group in Peter’s lab.
2. Move robot to medical school. To be resolved by March. We have confirmed with Prof. Peter that we can move it during the project. We will negotiate with the other group and set a proper time to move it to MISTC in medical school.
3. Usage of C-arm Cone Beam CT and MISTC. Resolved. We have got approval from Prof. Jeff and will share the use of C-arm CT in MISTC with the image-guided surgery group in Jeff’s lab. For each experiment, we will contact the C-arm operator in advance to make arrangement.
4. Radiation training and radiation badge. To be resolved before the start of CBCT experiment section. The C-arm operator will help Zihan obtain a badge. Hao already has one.
5. Usage of phantom. Resolved. A suitable phantom for pointing experiment is the Red Skull in Jeff’s lab, and the skull phantom in Prof. Peter’s lab is ideal for drilling experiment. We will share their use with other groups.
6. Biohazard training. To be resolved before experiment. Online Training.
7. (Possibly) Usage of cadaver head and schedule of a neurosurgeon. If the result in phantom experiments shows good and we still have time this semester, we will move forward to cadaver studies. Prof. Jeff will help us order a cadaver head, contact a proper neurosurgeon and arrange a time for cadaver experiment.

Budget

Rental fee of a truck to move robot to medical school. ~\$50. Prof. Peter will support.

Management Plan

1. Weekly meet with Prof. Peter in Hackerman Hall and Prof. Jeff in Traylor Research Building separately.
2. Monthly meet with Prof. Peter and Prof. Jeff together. Place TBD.
3. Present plan, checkpoint and final results, receive feedback from Prof. Taylor and the class.
4. At least 15hrs for programming + experiments + discussion every week.
5. Assess the viability of Phase 2 when completing Phase 1.

Assigned Responsibilities

We share responsibilities mainly based on differences in our background (BME, ME) and locations (Medical, Homewood).

Phase 1	
CBCT to Navigation Registration	Hao Dang
CBCT/CT to Robot Direct Registration	Zihan Chen
CT to CBCT Registration	Hao Dang
Robot to Navigation Registration	Hao Dang, Zihan Chen
Virtual Fixture and Control	Zihan Chen

Phase 2	
System without Navigation	Zihan Chen
System Integration and Phantom Pointing	Hao Dang, Zihan Chen
Phantom Foam Drilling	Hao Dang, Zihan Chen
Cadaver (Optional)	Hao Dang

Phase 3	
Image based Registration (Optional)	Hao Dang, Zihan Chen
Further Analysis	Hao Dang, Zihan Chen
Final Report	Hao Dang, Zihan Chen
Documentation	Hao Dang, Zihan Chen

Milestone/key dates

02/22/2011: Plan Presentation

03/27/2011: Complete four registration process with navigation system included

04/15/2011: Get phantom foam drilling experiment data

05/19/2011: Poster Presentation

Project Bibliography

Robotic system

1. Accuracy Improvement of a Neurosurgical Robot System. Haidegger T., Tian Xia, Kazanzides, P. Biomedical Robotics and Biomechatronics, 2008. 2nd IEEE RAS & EMBS International Conference on, pages 836 – 841, 27 January 2009

2. An integrated system for planning, navigation and robotic assistance for skull base surgery. Tian Xia, Clint Baird, George Jallo, Kathryn Hayes, Nobuyuki Nakajima, Nobuhiko Hata, Peter Kazanzides*. *The International Journal of Medical Robotics and Computer Assisted Surgery*, Volume 4, Issue 4, pages 321–330, December 2008

C-Arm Cone Beam CT

1. Siewerdsen JH, Daly MJ, Chan H, Nithiananthan S, Hamming N, Brock KK, and Irish JC, “High-performance intraoperative cone-beam CT on a mobile C-arm: An integrated system for guidance of head and neck surgery,” *Proc. SPIE Visualization and Image-Guided Procedures* Vol. 7261: 72610J-1 – 72610J-8 (2009).
2. Nithiananthan S, Brock KK, Daly MJ, Chan H, Irish JC, and Siewerdsen JH, “Demons deformable registration for cone-beam CT guidance: Registration of pre- and intra-operative images,” *Proc. SPIE Visualization and Image-Guided Procedures*, Vol. 7265: 72650L-1:7 (2010).
3. Bachar G, Barker E, Chan H, Daly MJ, Nithiananthan S, Vescan A, Irish JC, and Siewerdsen JH, “Visualization of anterior skull base defects with intraoperative cone-beam CT,” *Head and Neck* 32(4): 504-512 (2010).
4. Daly MJ, Siewerdsen JH, Cho YB, Jaffray DA, and Irish JC, “Geometric calibration of a cone-beam CT-capable mobile C-arm,” *Med. Phys.* 35(5): 2124-2136 (2008).
5. Daly MJ, Siewerdsen JH, Moseley DJ, Jaffray DA, and Irish JC, “Cone-beam CT for image-guided head and neck surgery: Assessment of dose and image quality using a C-arm prototype,” *Med. Phys.* 33(10): 3767-3780 (2006).

Project Timeline: Integration of CBCT and a Skull Base Drilling Robot

Hao Dang, Zihan Chen

Tasks	February				March				April				May			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Background Reading	█															
Project Proposal & Presentation	█															
Phase 1: Registration and Robot Control																
CBCT to Navigation Registration			▨													
CBCT/CT to Robot Direct Registration			▨													
CT to CBCT Registration			▨													
Robot to Navigation Registration			▨													
Virtual Fixture and Control					▨											
Phase 2: Experiment																
System without Navigation								▩								
System Integration and Phantom Pointing									▩							
Phantom Foam Drilling									▩	▩						
Cadaver (Optional)											▩					
Phase 3: Analysis and Final Report																
Image Based Registration (Optional)													▭			
Further Analysis													▭			
Final Report													▭			
Documentation	▭															

█	Proposal
▨	Phase 1
▩	Phase 2
▭	Phase 3
▭	Documentation

Key Dates	
02/22/2011	Presentation
03/27/2011	Finish Phase 1
04/15/2011	Phantom Foam Drilling
05/19/2011	Final Poster