Guidance for Skullbase Surgery

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Project Statement

Our Goal:

Improve accuracy using **intra-operative sensing/imaging** to **protect critical structures** during drilling, particularly in **children**

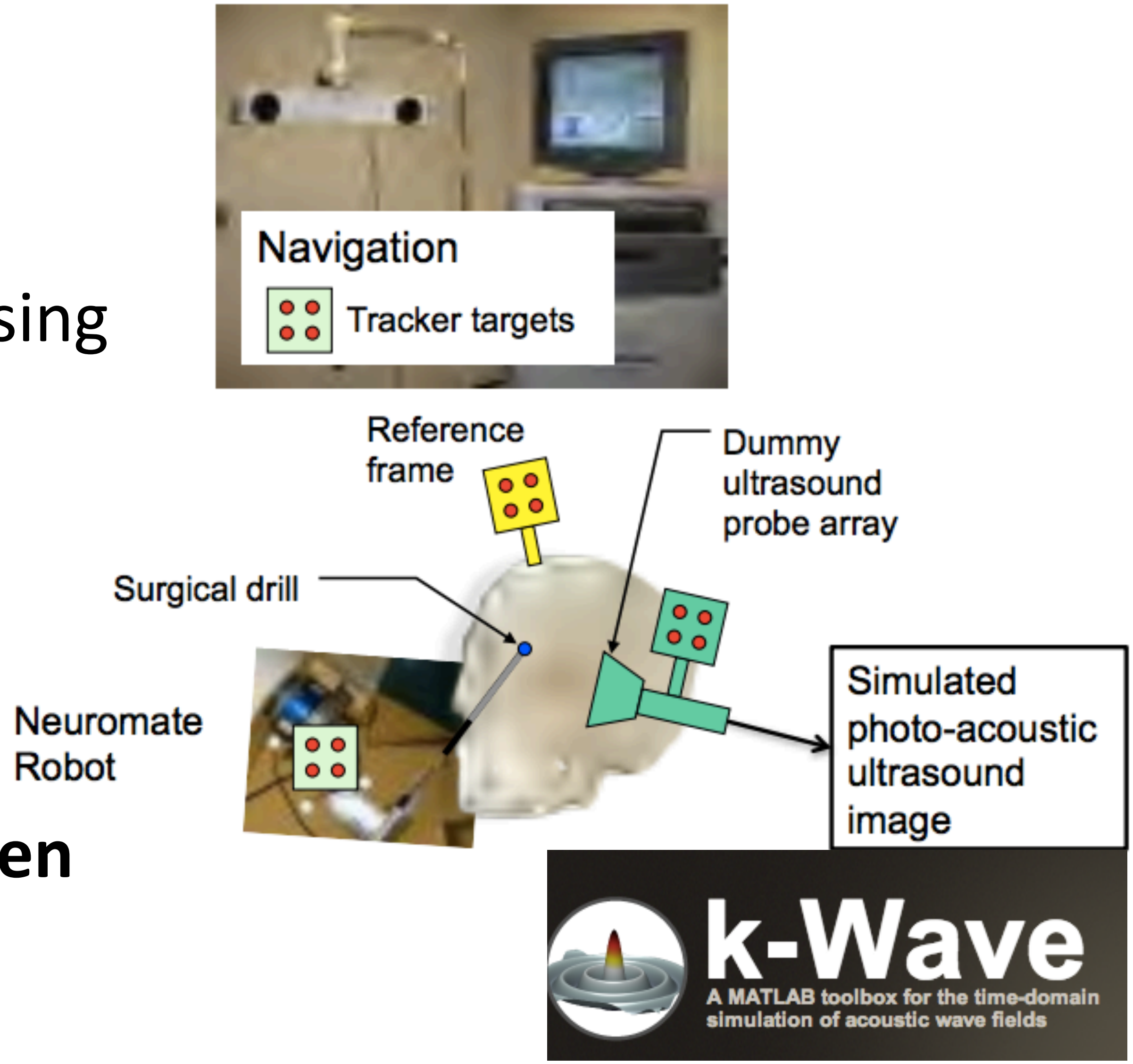

Image source: Dr. Kazanzides

Seminar Topic:
An integrated system for planning, navigation and robotic assistance for skull base surgery

Xia, T., Baird, C., Jallo, G., Hayes, K., Nakajima, N., Hata, N. and Kazanzides, P. (2008), An integrated system for planning, navigation and robotic assistance for skull base surgery. Int. J. Med. Robotics Comput. Assist. Surg., 4: 321–330. doi: 10.1002/rcs.213

Problem Statement

- Neurosurgery **is limited** by human dexterity and performance
- A **very high level of surgical skill** is required in skull base surgeries
- **Vascular and neurological structures** deep within the skull must be avoided
- Need an robotic assisted system **to increase the safety and efficiency** of these procedures

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Goal

Examine the **feasibility and accuracy** of an integrated robotic system for navigation, assistance, and control in skull base surgery

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Key Results

- Accuracy of individual robot and navigational subsystems are accurate to **less than 1mm**
- Phantom studies of the integrated system demonstrate accuracies **of roughly 1mm**
- However, cadaver studies show that overcut outside of virtual fixture region can be **up to 3mm**

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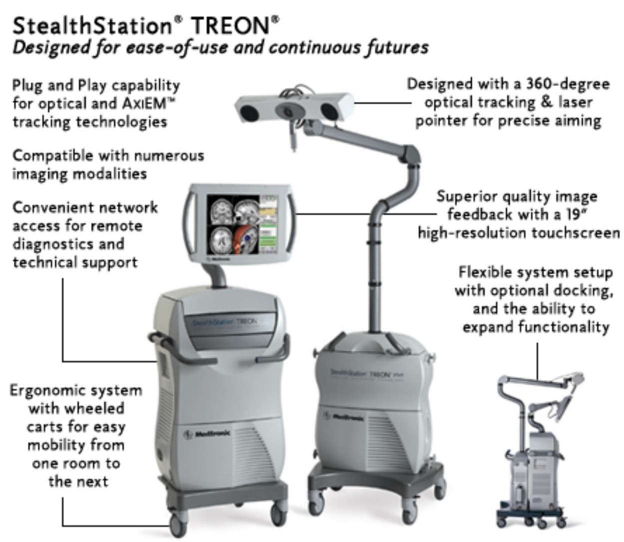
Background: Components

- Modified NeuroMate robot with force sensor
- StealthStation Navigation System
- 3D Slicer open-source software



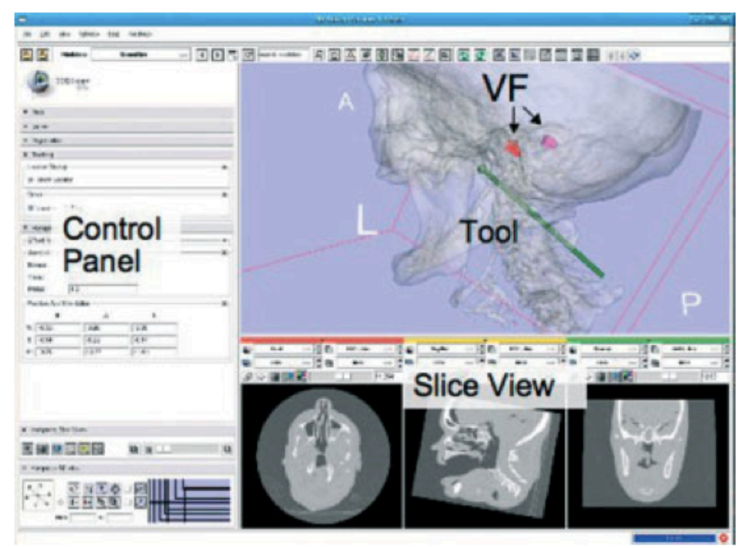


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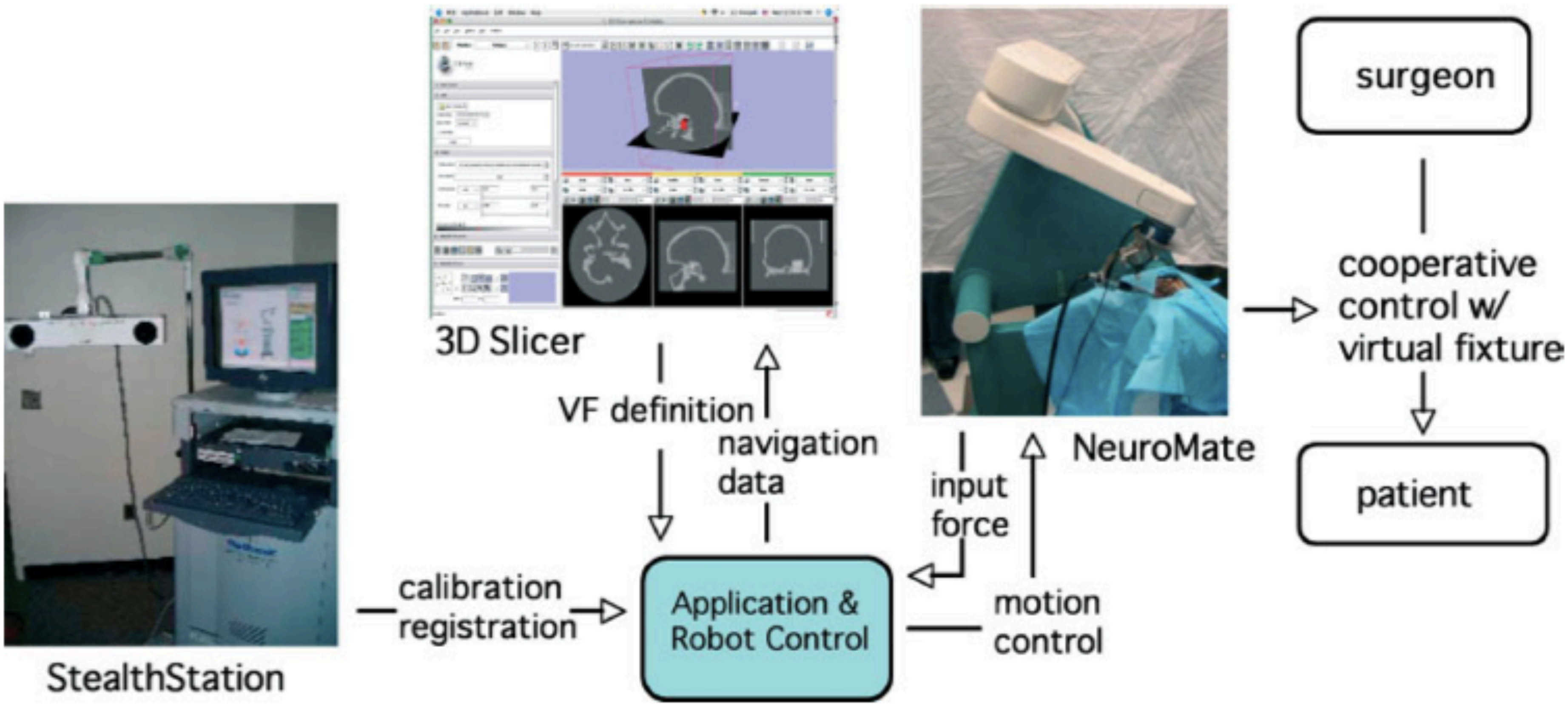
Image sources:
renishaw.com
medtronic.com

Background: System Overview



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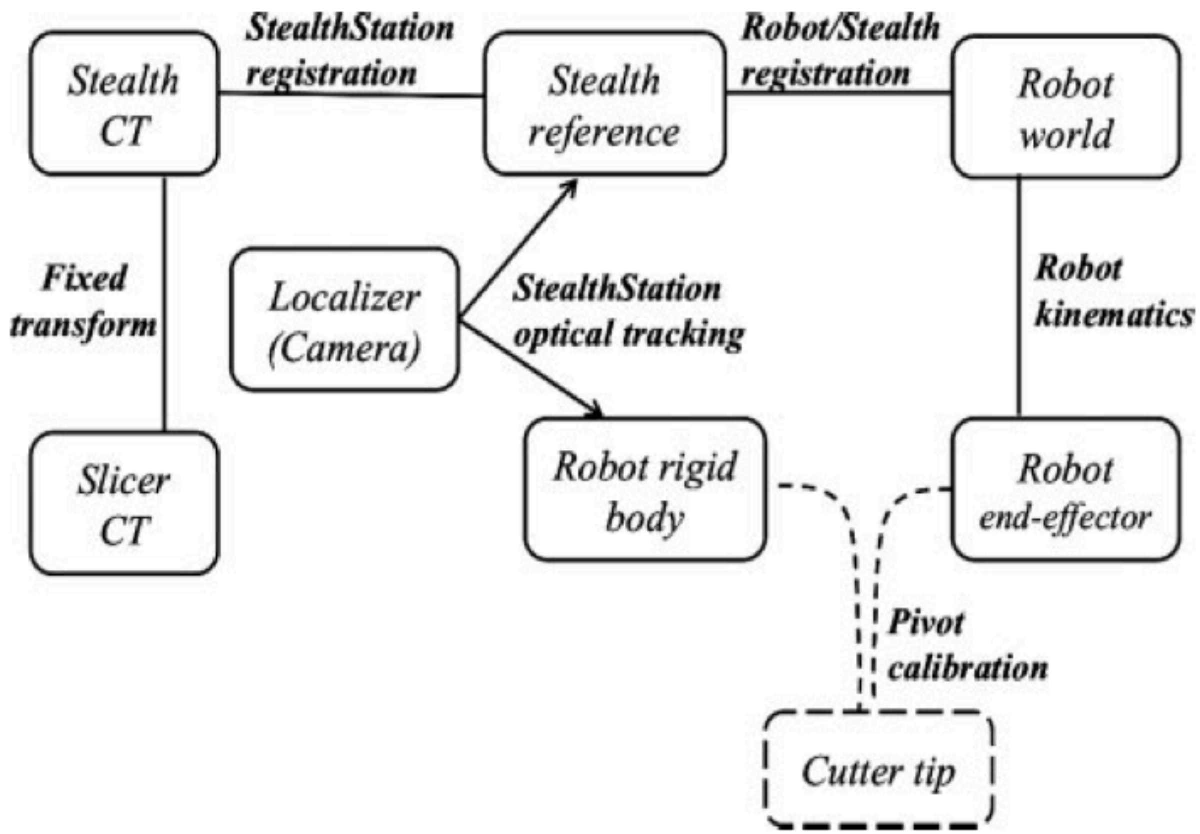
Methods: Registration and Calibration

- CT image data read by Slicer and StealthStation
- Different coordinate system for both
- Fixed transformation using registration methods from StealthStation



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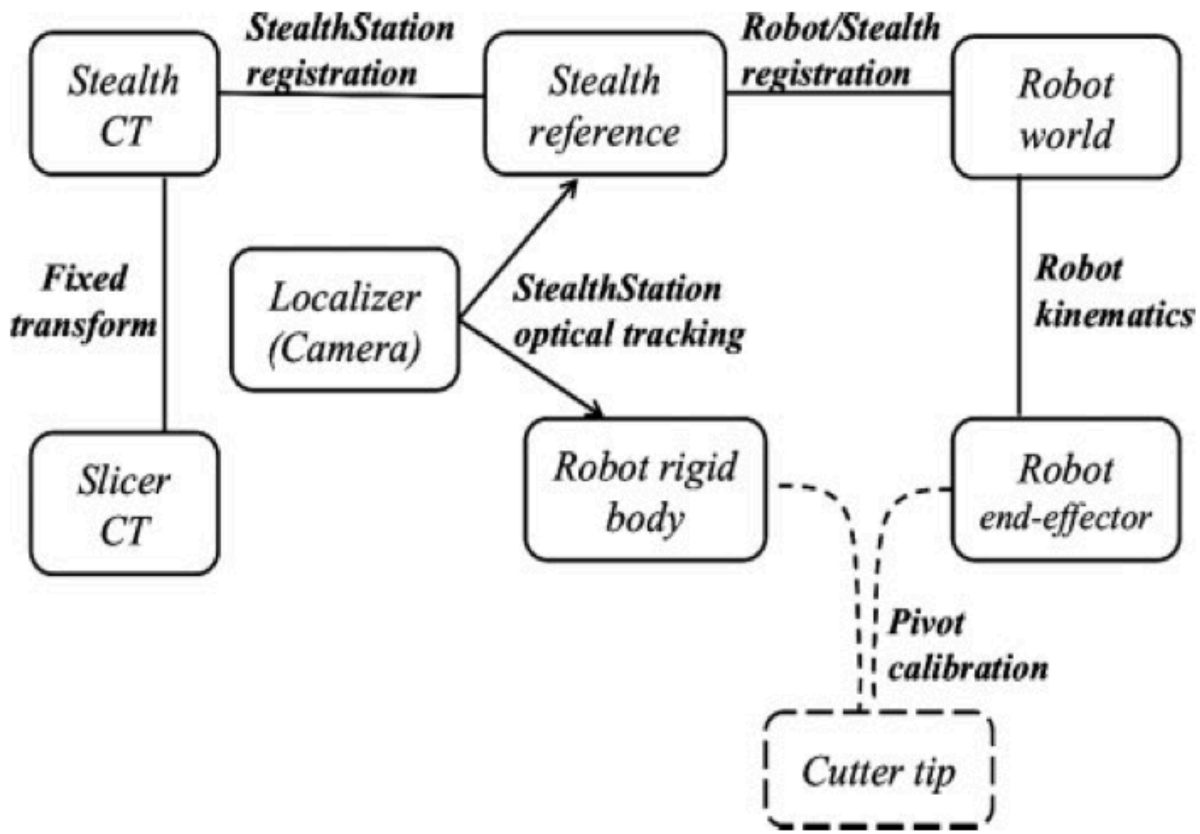
Methods: Registration and Calibration

- Fiducials placed before CT scan
- Tracked tool to touch each fiducial
- Registration calculated from two sets of points



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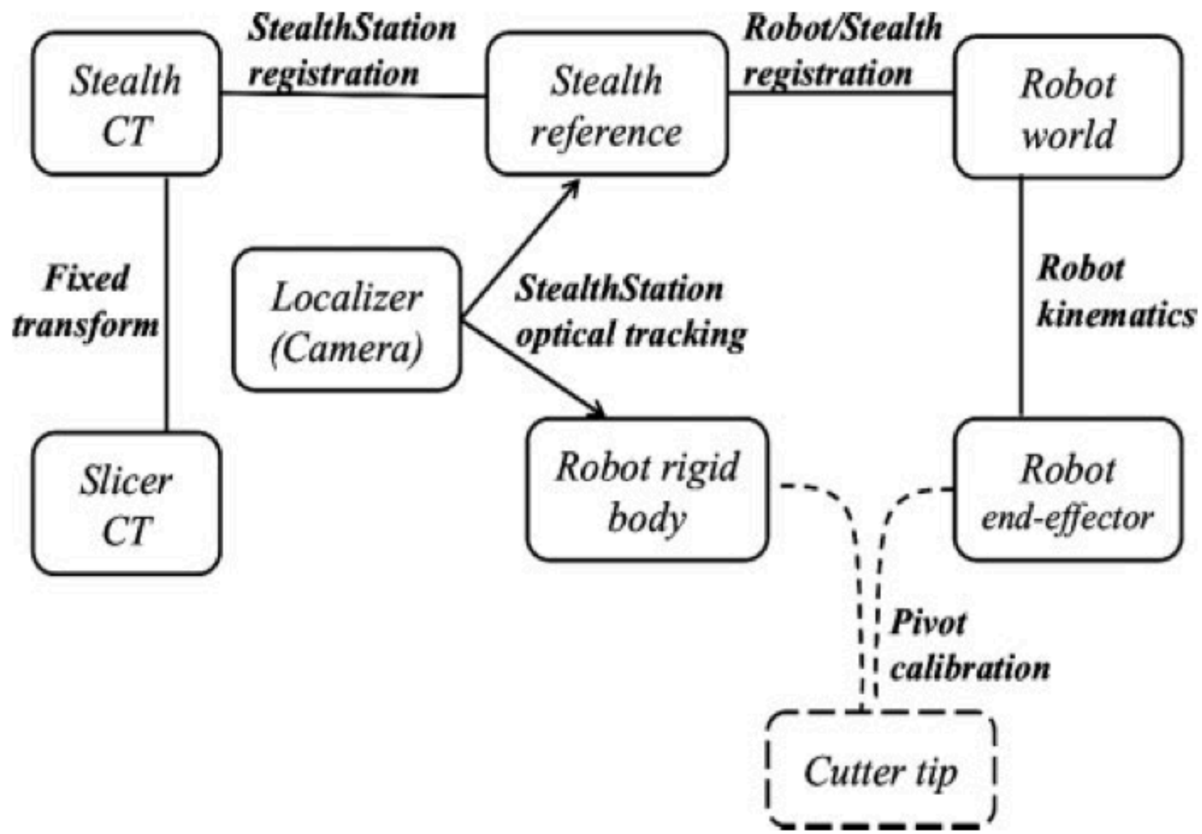
Methods: Registration and Calibration

- Cutter tip position unknown
- Simple translation from known robot end-effector and robot rigid body
- Simultaneous pivot calibration on tip



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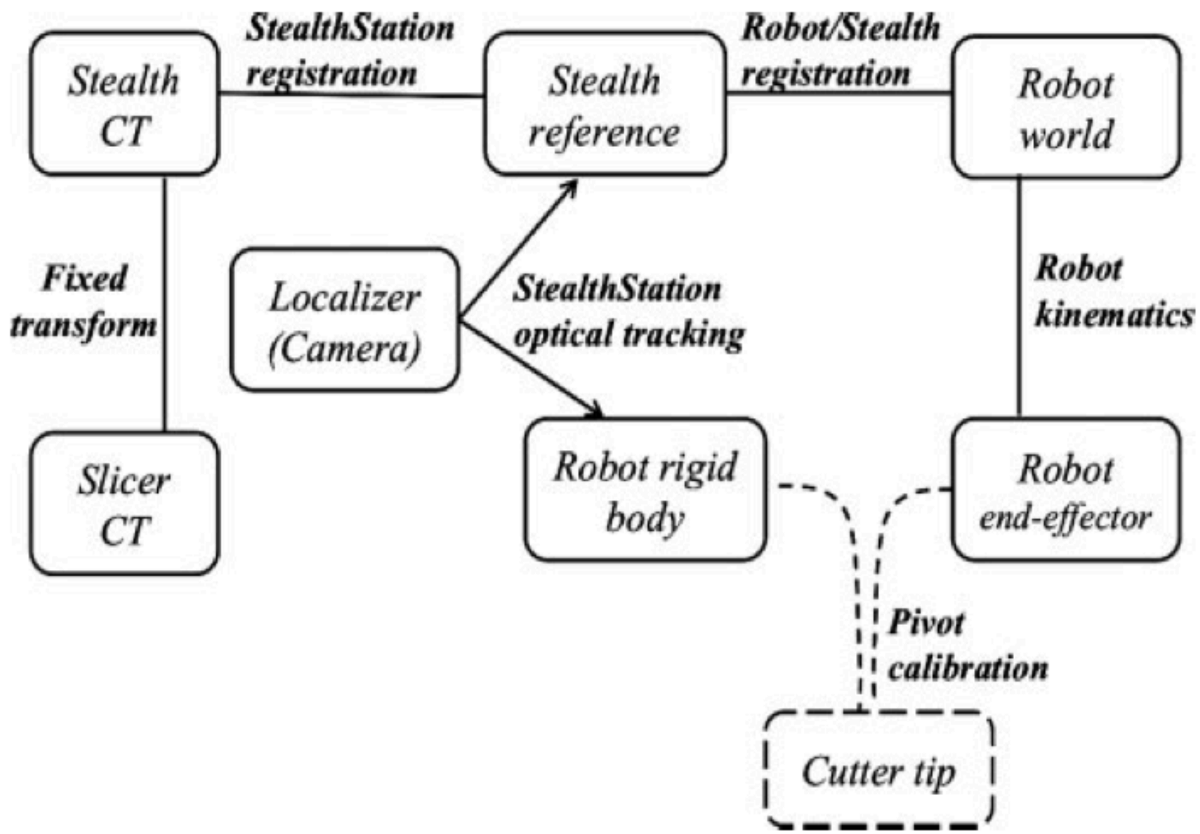
Methods: Registration and Calibration

- Cutter tip is moved to six different locations
- Points taken in robot world frame and Stealth frame
- Registration of two point sets



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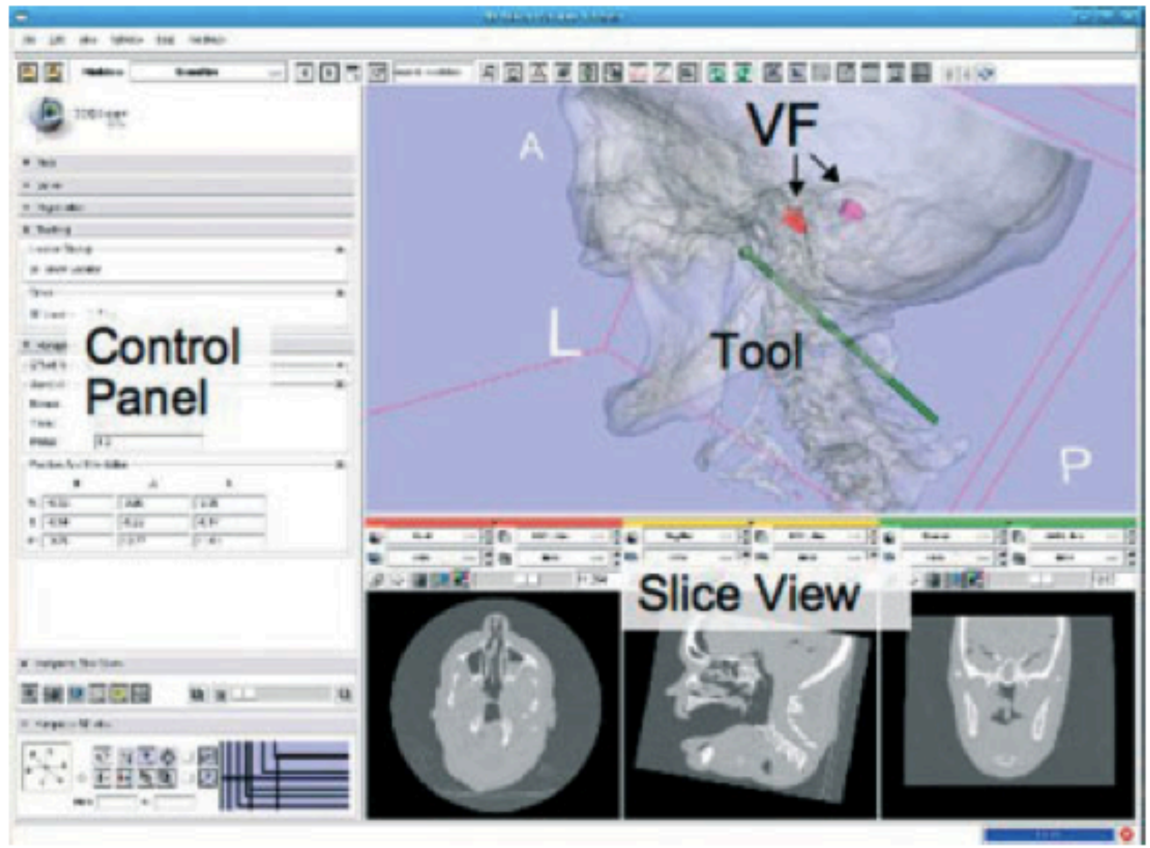
Methods: Virtual Fixture Definition

- Virtual fixture is defined in 3D slicer
- Can be implemented in robot frame **(does not keep track of head movement)**
- Can be implemented in navigational frame **(requires line of sight to camera)**



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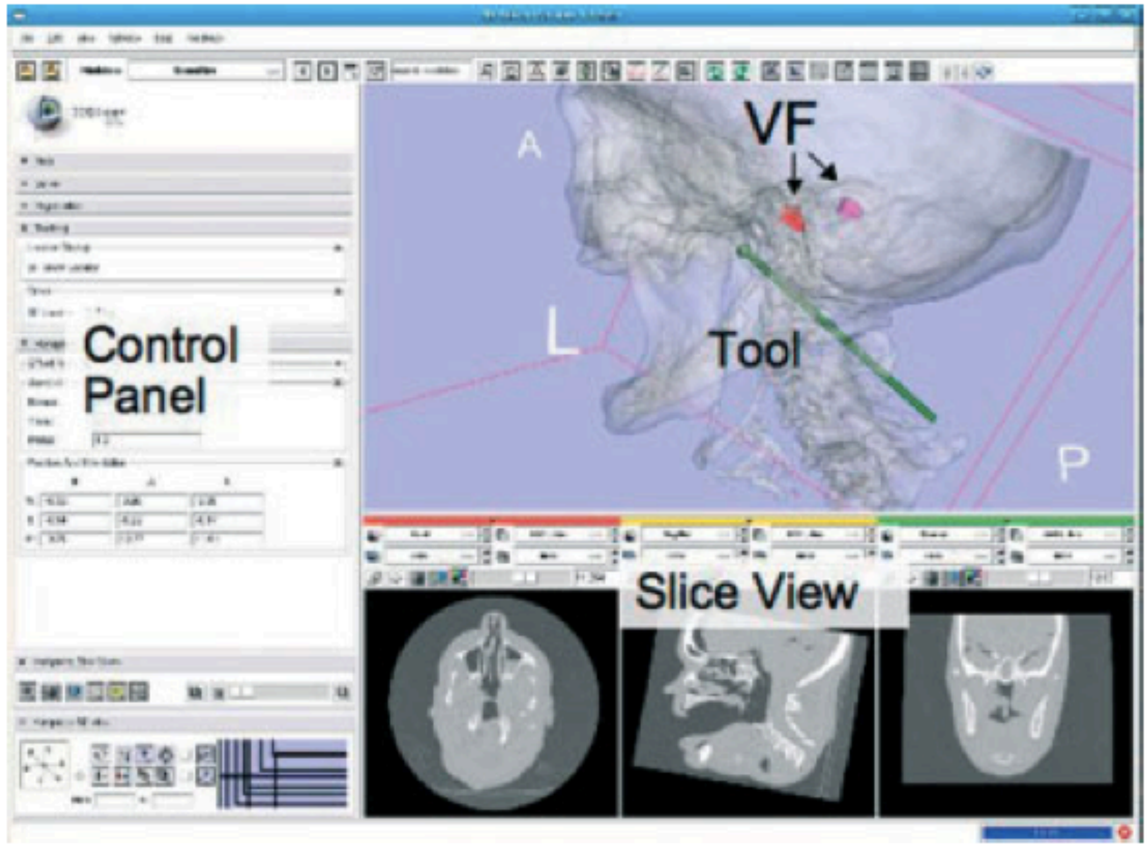
Methods: Virtual Fixture Definition

- Virtual fixture has three regions:
- Safe zone
- Boundary zone (with distance D)
- Forbidden zone



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Methods: Virtual Fixture Definition

$$\dot{q} = J^{-1}(q) \times K(d) \times G(f) \times \begin{bmatrix} F_w \\ T_w \end{bmatrix}$$

- Admittance control law (determines goal velocity)
- Jacobian inverse resolved at cutter tip converts Cartesian velocities to joint velocities
- F_w and T_w are measured force and torque in robot frame
- G is admittance gain as nonlinear function of force
- K is scaling factor dependent on distance from forbidden zone

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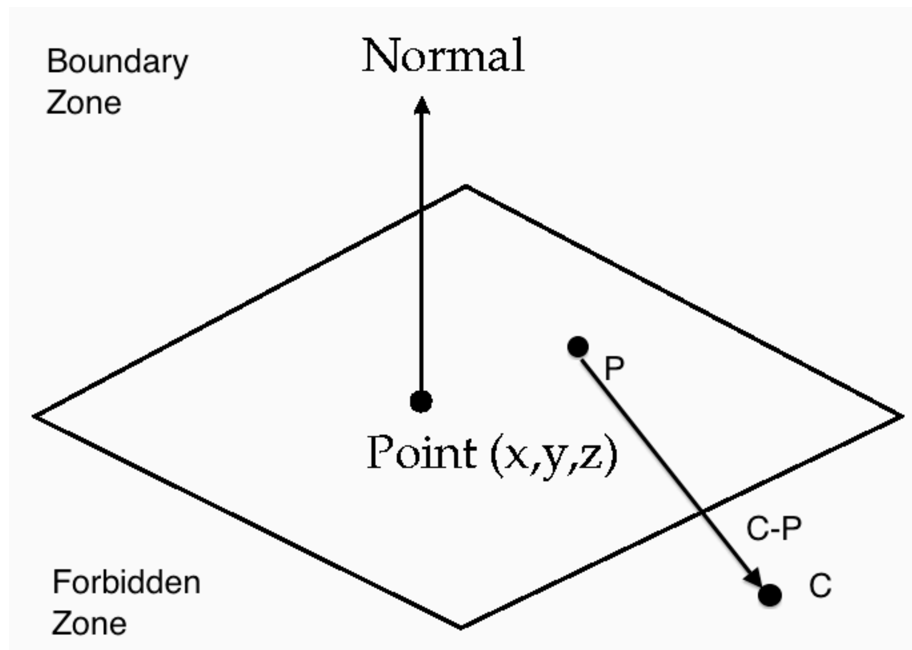
Methods: Virtual Fixture Definition

- C is coordinates of the cutter tip
- P is a point on a virtual fixture plane
- N is the unit normal to the plane
- If d_i is negative, cutter tip is in forbidden zone

$$d_i = \frac{(C - P) \cdot N}{|N_i|}$$



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Methods: Virtual Fixture Definition

$$\dot{q} = J^{-1}(q) \times K(d) \times G(f) \times \begin{bmatrix} F_w \\ T_w \end{bmatrix}$$

- If in safe zone K(d) = 1
- If in boundary zone scale by $K(d) = d_i/D$ for smallest d_i if heading toward the forbidden zone, otherwise K(d) = 1
- If in forbidden zone, only movement toward the safe zone is allowed

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Results: Subsystem Accuracies

- Test accuracy of robot and navigation systems
- Precisely machined aluminum plate with 13 divots (known accuracy 0.0127mm)
- Cutter tip guided into each divot
- Points recorded in robot and navigation frame
- Positions registered to known machined positions
- Fiducial registration error was **0.64mm for the robot** and **0.74mm for the navigation system**

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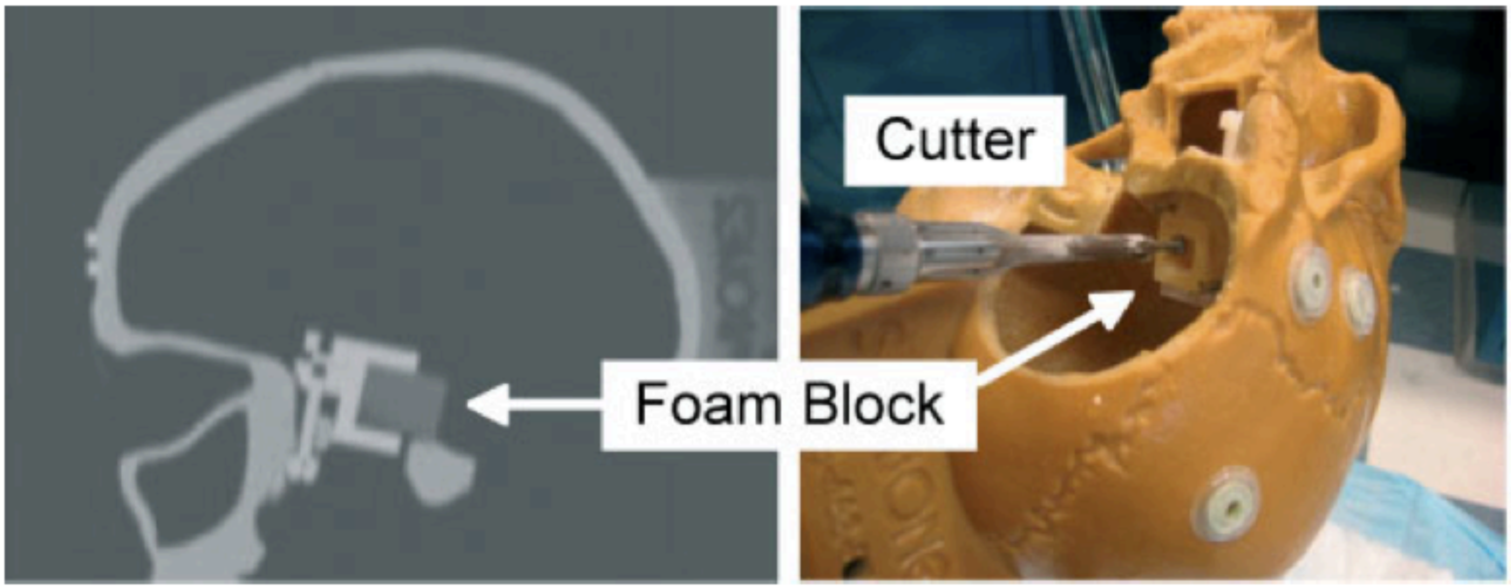
Results: Phantom Experiments



- Plastic skull with embedded fixture for foam blocks
- After registration, box-shaped virtual fixture was defined with known distance between cut edges and block edges

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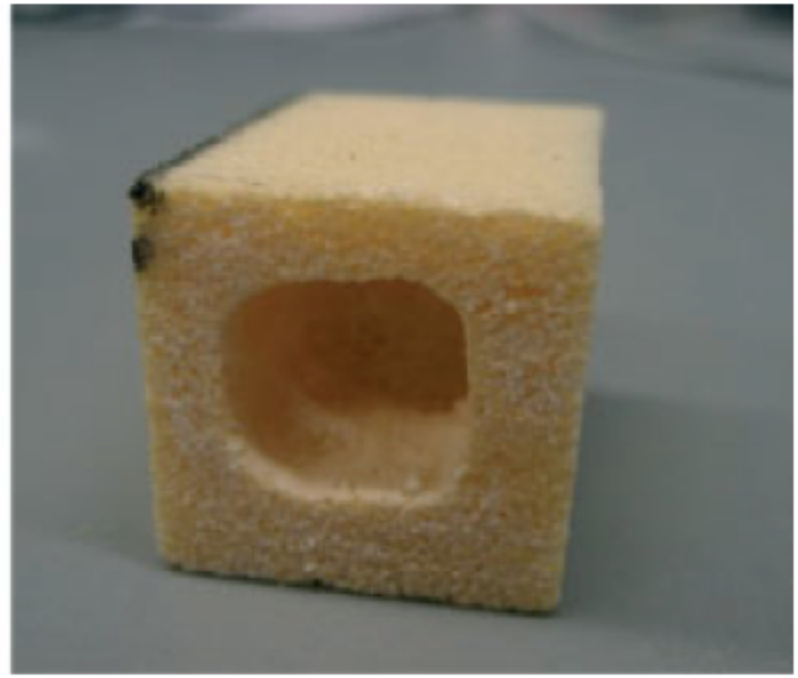
Results: Phantom Experiments

- Used cutter tip to drill out box in foam block
- Calipers used to measured distance between edges
- Placement error: difference between expected center and cut center
- Dimensional error: difference between actual and planned cut dimensions



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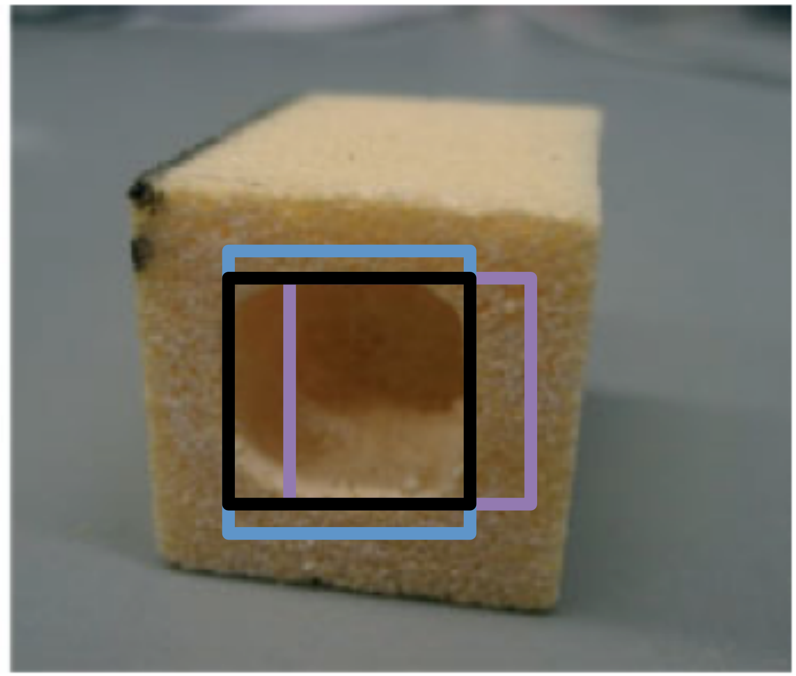
Results: Phantom Experiments

- Black is desired cut
- Purple represents placement error in x-axis
- Blue represents dimensional error in y-axis
- Total overcut = abs(positional error) + (dimensional error)/2



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Results: Phantom Experiments

	Placement		Dimensional		Depth
Foam	*X*	*Y*	*X*	*Y*	*Z*
1	0.17	1.12	0.54	0.25	1.16
2	0.04	1.08	0.50	0.20	1.06
3	0.49	0.96	0.25	0.05	1.19
Mean1	0.23	1.05	0.43	0.17	1.14
SD1	0.23	0.09	0.16	0.10	0.07
3	0.49	0.96	0.25	0.05	1.19
4	1.28	1.11	0.70	0.33	0.51
5	−0.44	0.79	0.99	0.35	1.39
6	1.04	−0.62	0.54	0.10	1.85
Mean2	0.59	0.56	0.62	0.21	1.23
SD2	0.76	0.80	0.31	0.15	0.56

- Mean placement error = 0.6mm
- Mean dimensional error = 0.6mm
- Total overcut error = 0.9mm

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Results: Cadaver Experiments

- Suboccpital approach, such as for resection of acoustic neuroma on left/right sides of three cadavers
- Virtual fixtures created from CT scan with 0.5mm slice spacing
- Registrations only accepted if less than 1mm for CT to Stealth and less than 0.5mm for Stealth to robot
- Post and preoperative images taken to examine over and undercut

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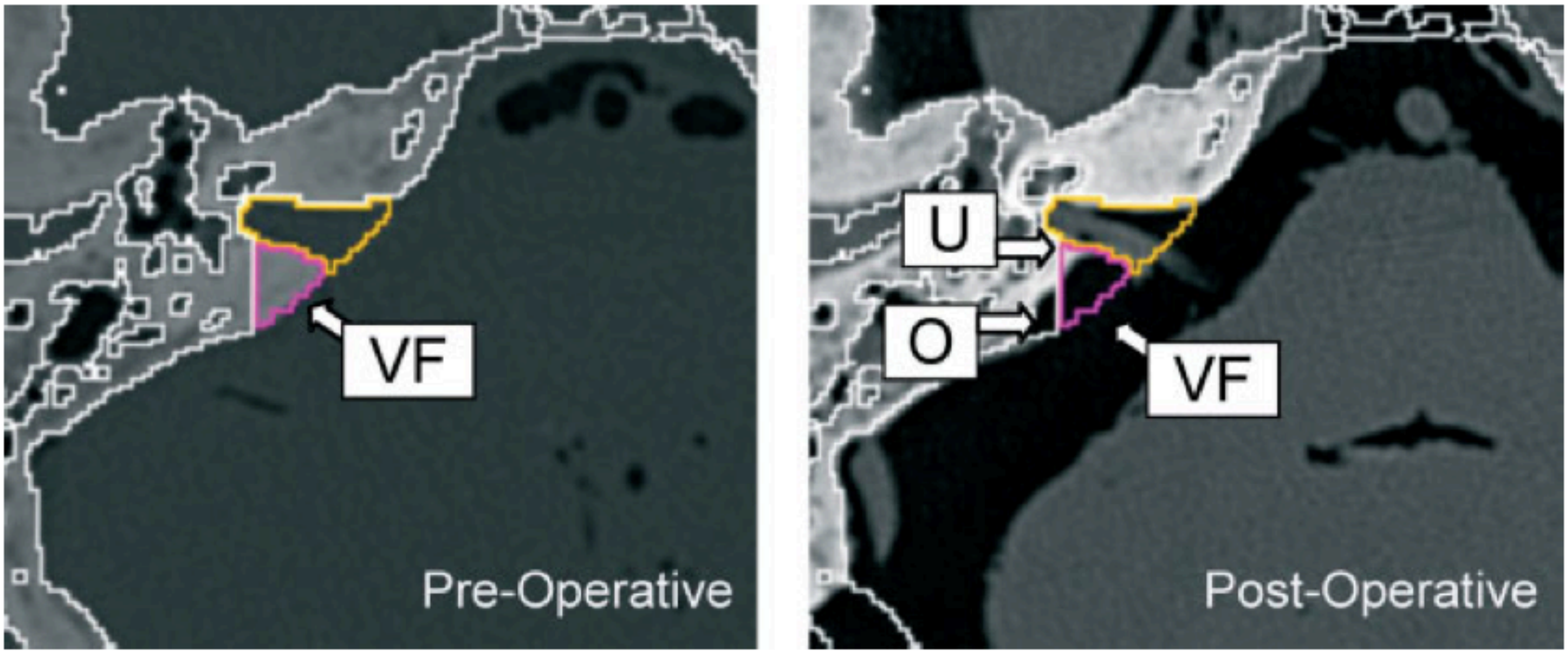
Results: Cadaver Experiments



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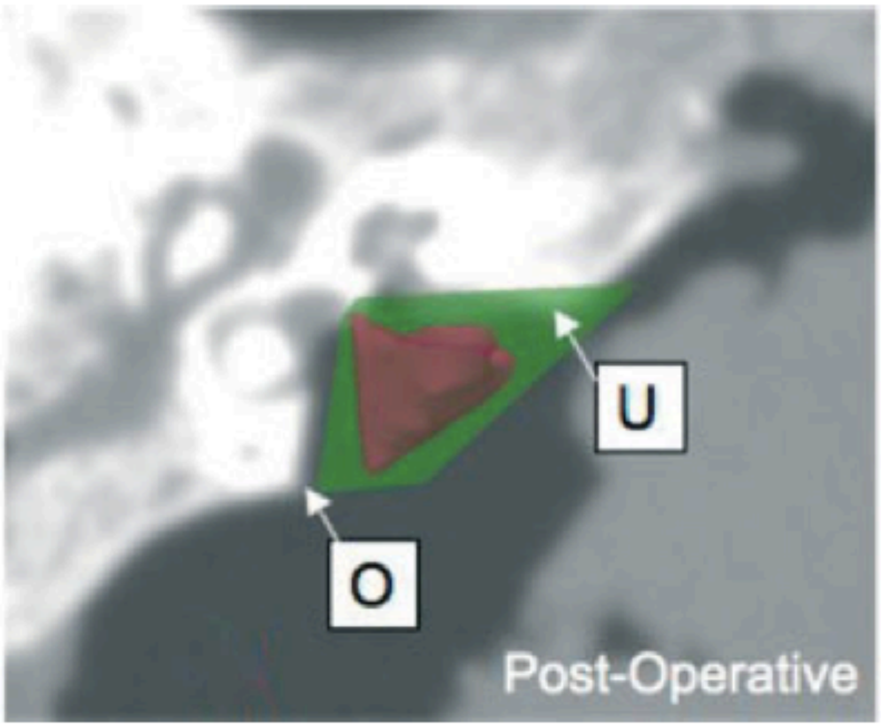
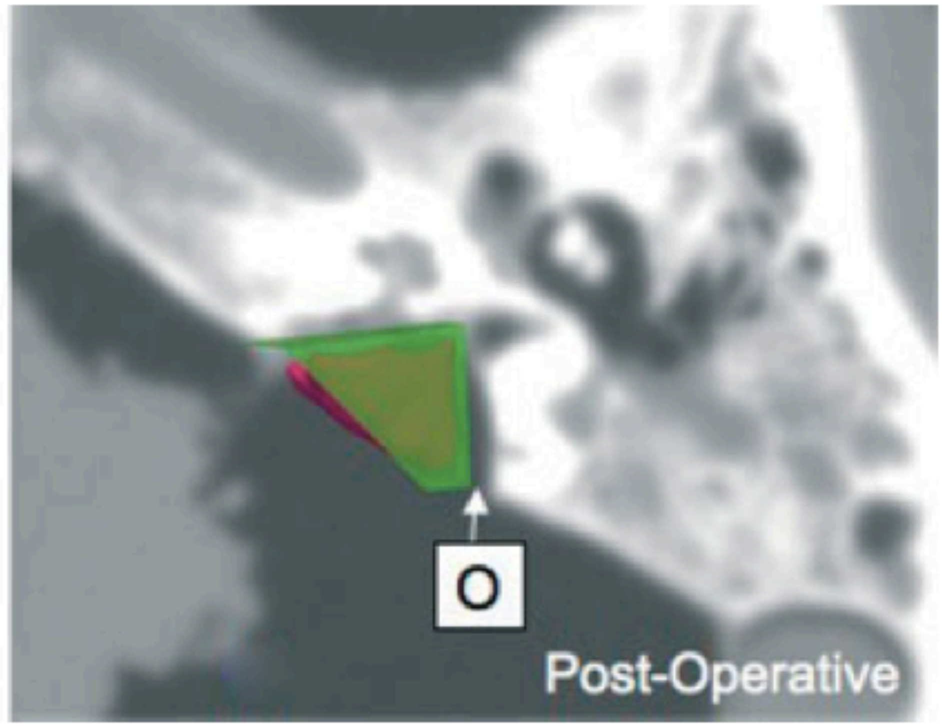
Results: Cadaver Experiments





- Average **1-2mm overcut**, with some regions of up to **3mm overcut**

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Discussion

- Many benefits **but low accuracy**
- Errors may results **from many places**
  - Registration error
  - Calibration error of cutter tip
  - Robot kinematics
  - Undetected head movement
- Has high ergonomic benefits to the surgeon

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Relevance

- Hope to address inaccuracies with **photoacoustic ultrasound imaging**
- Need to **understand current system** to successfully build upon it
- Results show that the system is feasible, **methods are more important** for our implementation

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The Positives

- Developed a system that **incorporated cooperative control with image-guidance**
- Well-written paper and clearly explained methods
- Results show a **very feasible system** through a couple of different experiments

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Limitations

- **Not enough trials**
- **Quantitative analysis** for cadaver experiments are not strong
- Virtual fixture boundary movement (problems with algorithm)
- Overcut error analysis in phantom experiments **assumption**

Future Work

- Increase accuracy of the system through **intraoperative photoacoustic ultrasound** imaging
- More experiments under **non-ideal** conditions
- Update virtual fixture definition
- Incorporate telemanipulation **(long-term)**
- **Reduce error!!!**

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Conclusion

- There is a high feasibility of an integrated system for use in skull base surgeries
- Virtual fixture definition allows for increased safety and efficiency in procedures
- However, the errors seen are too large for clinical implementation
- Next steps are to use an intraoperative imaging system to improve accuracy

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Questions?

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