Mission

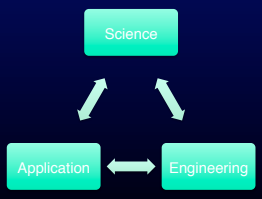
The Surgical Navigation and Robotics (SNR) Laboratory enables more effective and less invasive treatment in image-guided therapy.

SNR Mission

- We fulfill our mission through a commitment to:
  - Inventing disruptive computer and engineering methods
  - Applying the developed technologies in actual clinical cases and delivering unique feedback to the scientific research community
  - Sharing the research data, software, and device design with industry and academic peers
  - Applying synergistic coupling to scientific disciplines unaware of or presently disconnected from image-guided therapy

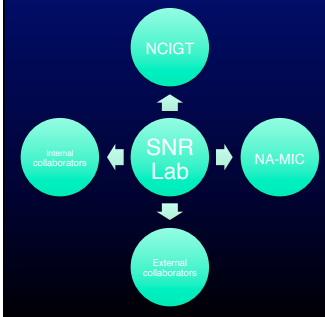
SNR Value

Quick cycle



Engineers in OR

Team Science



Acknowledgements

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- Dr. Fichtinger (Queens Univ.), Dr. Morikawa (Shiga Univ., Japan)
- Slicer (www.slicer.org)
- NIH U41 U41RR019703 (PI: Jolesz, BWH)
  National Center for Image Guided Therapy
- NIH 5U54EB005149
  National Alliance for Medical Image Computing (PI: Kikinis, BWH)
- **NIH** 5P01CA067165 (PI: Jolesz, BWH)
  MRI-guided therapy
- **NIH BRP R01-CA111288** (PI: Tempany, BWH)
  Enabling Technologies for MRI-Guided Prostate Interventions
- **NSF EEC 9731748** (PI: Taylor, JHU) ERC Center for Integrated Surgical Systems Technology
- CIMIT, Boston, MA
- Swimming Capsule Endoscope
- Intelligent Surgical Instruments Project of METI. Japan

Outline of talk

- Part 1: MRI Guided Therapy
- Part 2: Robot as precision targeting device
- Part 3: Future: Robot as enabling tool for new therapy options (moving organ, molecular image-guided therapy, etc.)
- Part 4: Engineering and resource sharing

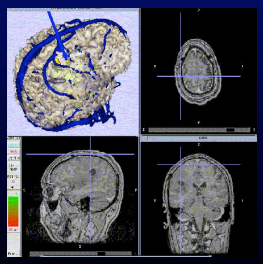
MRI-guided therapy

State of art

Unmet needs

Image Guided Therapy

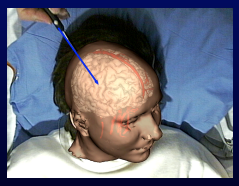
- Guides procedures with re-sectioning of pre-operative images (MRI, CT, ….)
- Aims at
  - Fast and accurate Surgery wit minimized intervention
  - Better clinical outcome



Slide courtesy of Dr. Jolesz

Navigation

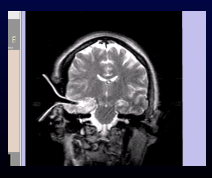
- To see beyond skin
- Computer-assisted stereotactic neurosurgery [Kelly86]
- Frameless stereotaxy [Watanabe87]
  - With free-hand tracking device
- An interactive tool to correlate "pre-operative images" and "therapeutic action"

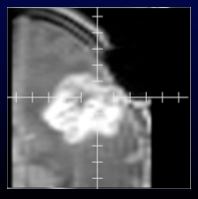


Subject for demonstration purpose only

Issues in pre-operative image-based surgical navigation

- Deformation (breaks accurate correlation between image to intra-operative anatomy)
- Cannot capture the "effect" of the therapy





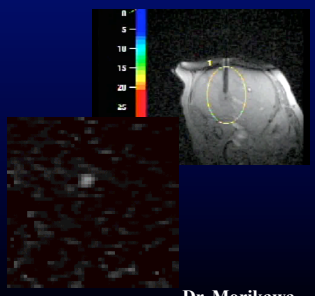
Intra-operative MRI

Imaging modality to navigate, monitor, control surgery

Slide courtesy of Dr. Jolesz Brigham and Women's Hospital, Boston, MA

Intra-operative MRI

- MRI for
  - Planning
  - Targeting
  - Navigation
  - Monitoring



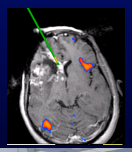
Dr. Morikawa

Intra-operative MRI

pictures from the vendors' web site

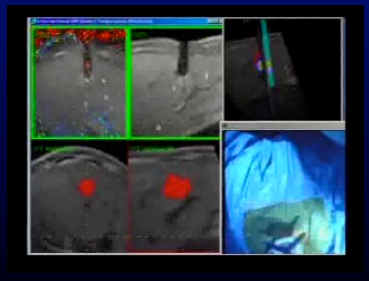
Navigation in MRI-guided therapy

- "Updated navigation"
  - Requires patient-to-image registration after each patient transport
- [Nimsky04] Philips open-bore 0.2 and close-bore 3T and Stealth Station
- BrainSUITE iMRI (Brain Lab/ Siemens)



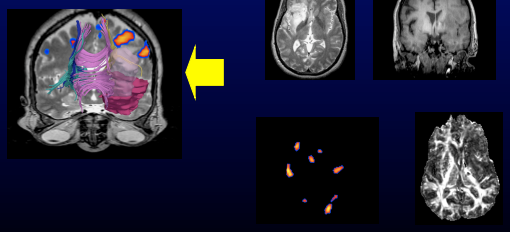
Philips

MR-guided Liver ablation Therapy



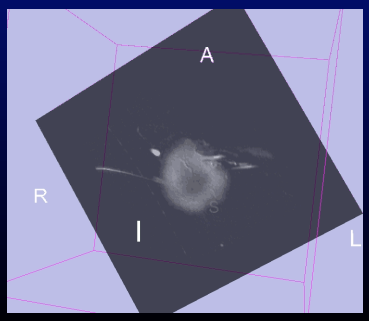
Morikawa S, Hata et. Al.. Acad Radiol. 2003;10(2):180-8
Morikawa S, Hata et. Al., Acad Radiol. 2003;10(12):1442-9.

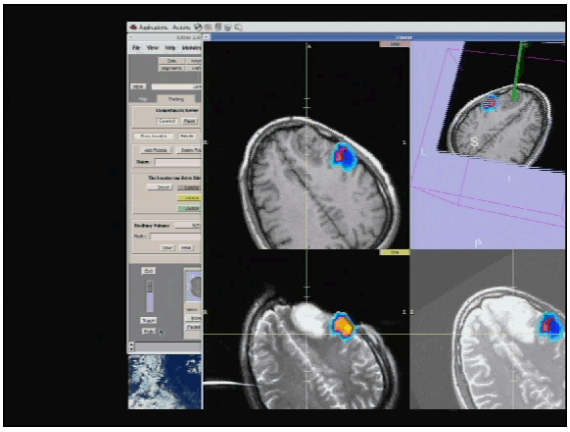
MRI-guided Neurosurgery



Dimaio SP, Hata N, et al. IEEE Eng Med Biol Mag. 2006;25(5):67-73.

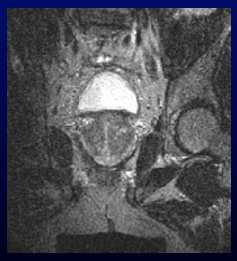
fMRI and intraoperative MRI





MR-guided Prostate Biopsy

Intra-procedural 0.5T FGR for needle control

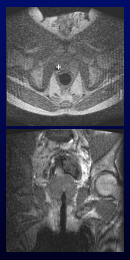


Registered Pre-procedural 0.5T T2w

Hata N et al, Radiology. 2001;220(1):263-8.

Needle Placement Accuracy in Prostate Therapies

- Improved cancer detection in targeted MRI-guided biopsy [So 2005]
- Retrospective clinical analysis (N=10) showed 6.5mm error [Blumenfeld 2007]
- Need for better needle placement control
  - Understanding of needle-tissue interaction for trajectory planning, optimization and control

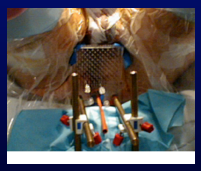


Blumenfeld P, Hata N, et al. J Magn Reson Imaging. 2007 Sep;26(3):688-94.

MRI-compatible robot

Autonomous approach
Precision Targeting

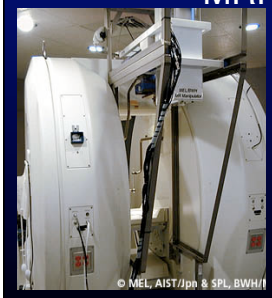
Precision needle placement



- Prostate needle placement up to 6 mm inaccuracy
  - fixed needle guide template with holes spaced at least 5mm apart
  - limits needle trajectory position and orientation
- Robot as dynamic needle guide for accurate needle placement [Chinizei MICCAI 1999]

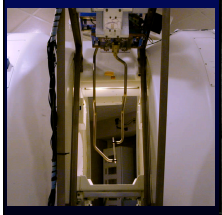
•AIST-Japan and Brigham and Women's Hospital

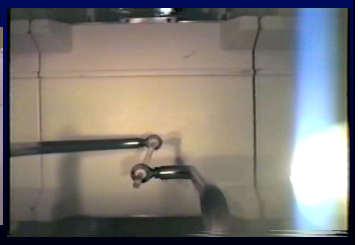
MRI Robot



- 5DOF translational stage
- Maneuvering two arms
- Accurate needle placement

DiMaio SP, Hata N, et. al. Comput Aided Surg. 2007;12(1):15-24.



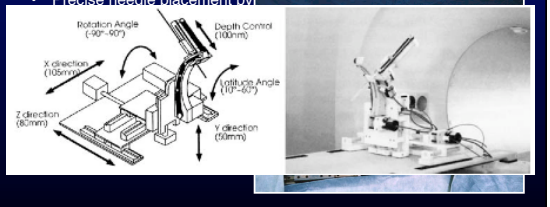


MRI compatible robot

- Comprehensieve review by Elhawary et al. 2006
- Open bore robot
  - Prototype for prostate biopsy [Chinzei 1999] [DiMaio 2006]
  - Heart [Tajima 2003]
  - Liver ablation therapy [Hata 2008]
- Close bore robot
  - Brain [Masamune 1995]
  - Breast [Larson2004]
  - Prostate biopsy and brachytherapy [Fischer 2008]

MRI compatible robot

- Precise needle placement by



•Dohi T, Hata N, et. al. Robotics in Computer Aided Surgery. Journal of Computer Aided Surgery. 1995;1(1):4-10

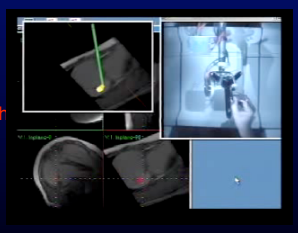
MR Compatibility

- Actuators: **Ultrasonic**, Pneumatic, Hydraulic motors
- Ceramics bearing
- Aluminum and Stainless
- Optical encoder: MRI compatible or custom made with detached optical pickup and circuit

Our Proposal
Needle-guiding robot

Steps
1. Volume imaging
2. Target definition
3. Remote Center of Motion (RCM) set on th target
4. Optimal path search

•Synergistic robots [Troccaz, Robotics Workshop CARS 03]
•Cooperative robots
•[Kumar, Taylor ICRA 2000, MICCAI03]

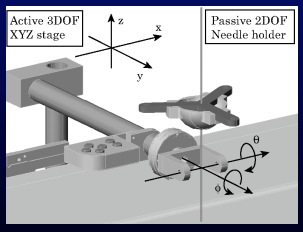


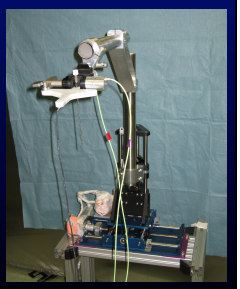
•Proof of concept by the robot and a retrospective liver case

Synergistic Robot in MRI

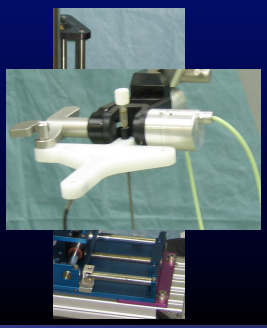
- hands-on
  - Physician takes initiative
  - Robot assists targeting by keeping motion tip at the target
- Conceptually, integration of
  - Stereotactic device
  - Master-is-slave

Configuration





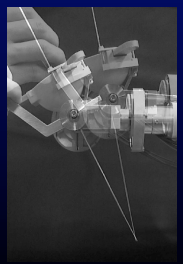
MRI Safe/Compatible



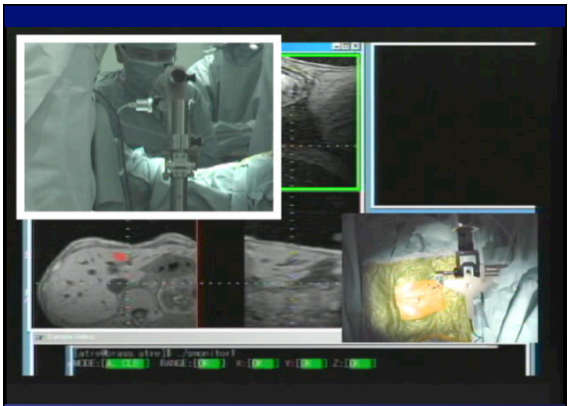
- Actuators
  - Ultrasonic motors
- Motion parts
  - Rigidity!
  - Stainless (SUS304) for screw rod and linear guide
  - Ceramics bearing
- Frame
  - Aluminum, Stainless
- Optical rotary and linear encoders
  - With counter circuit
  - Extension fiber and separated circuit

Clinical applications!

- Concept Needle guiding robot [Hata et al. ICRA 2005] [Hata et al. JMRI 2008]
- Three generation (in-lab machining -> professional robot re-design/ assembly)
- August 2007: First clinical case in liver ablation therapy
- N=4 as of today



J Magn Reson Imaging. 2008 Apr 11;27(5):1130-1138.



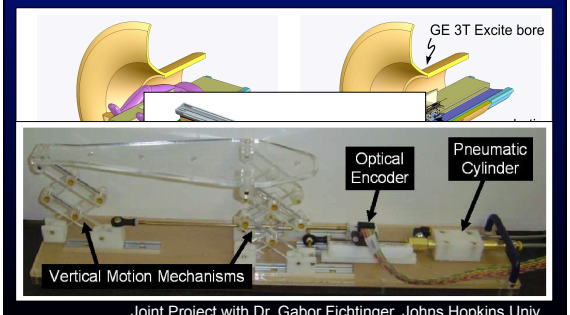
0.5T Closed-bore Precision targeting → 0.5 T Open-bore Precision targeting →

Long-term Clinical Goal at BWH

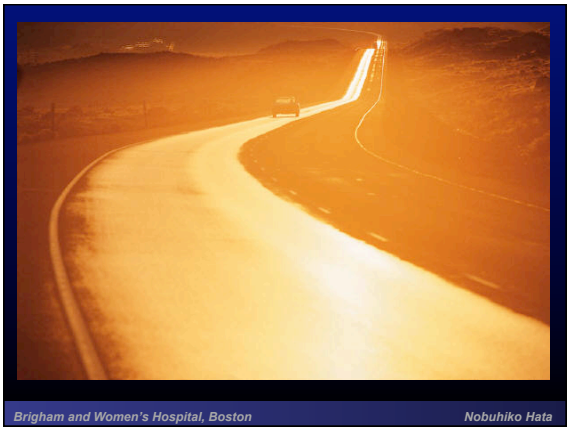
- Diagnosis and therapy in multi-modality image setting, incl. high-field closed-bore scanner (3T)
  - High-quality imaging,
  - More prevalent in clinics and hospitals.
- Challenges
  - Access to lesions
  - Motion compensation
  - Device-tissue interaction

0.5T Closed-bore Precision targeting → 0.5 T Open-bore Precision targeting → 3T Targeting & Enabling tool

In-bore Needle Placement



Joint Project with Dr. Gabor Fichtinger, Johns Hopkins Univ.



Vision
Image Driven Robotics

Evolution

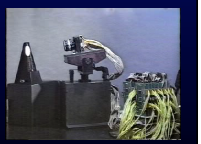
Neuro/Orthopedic/ENT surgery

Semi rigid organs: Prostate, Brest

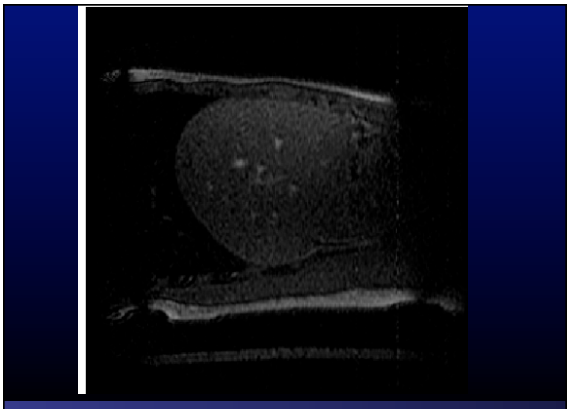
Moving organ

Moving organ: rationale

- Combining MRI and Robot
- Value
  - MRI can track motion of moving organ
  - Robot can synchronize its motion to the moving organ
- IGT of moving organ
  - Liver, Lung, Heart



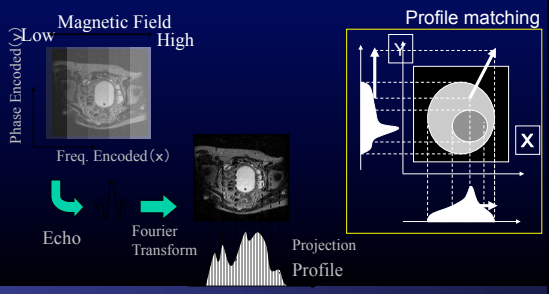
•Ishikawa, Univ. Tokyo



Synergistic robot with motion compensation in MRI

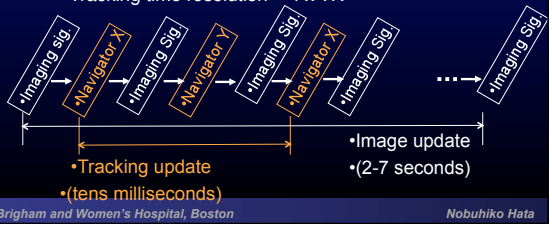
Navigator echo and projection profile matching

Tokuda, Hata, et.al. Acad Rad 2005



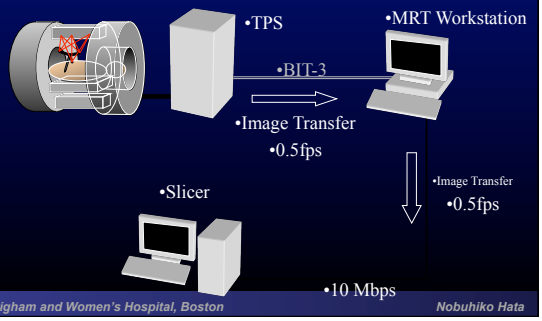
Pulse Sequence

- FGRE + Navigator
  - Projections along two axes
  - 128 navigators / image
  - Matrix: 256x128 TR: 27ms~
  - Tracking time resolution = 4 x TR

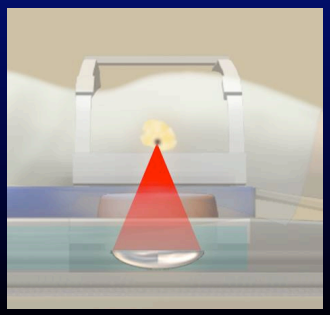


System Integration to Signa/SP

- Off-the-shelf system + 3D Slicer



Tumor Treatment of moving organ with FUS



InSightec

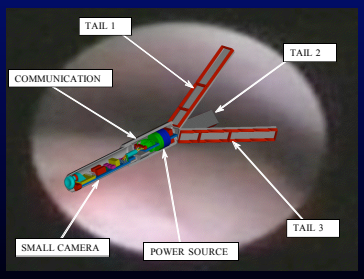
Actively swimming capsule endoscope using MRI for energy delivery, imaging, and navigation

- Goal of CIMIT project
  - Novel swimming mechanism to effectively steer and position the capsule inside the small intestine
  - using MRI's magnetic field to wirelessly send energy and generate propulsion force
- Our multi-year clinical goal
  - To mount a miniature endoscope camera and treatment device onto our swimming capsule to aid in diagnosis and treatment of the small intestine.

Benefit

- The capsule endoscope today is purely diagnostic
  - Cannot be used to take biopsies, apply therapy, or mark abnormalities for surgery.
  - Cannot be controlled once it has been ingested
  - Once it has passed a suspicious abnormality, its progress cannot be slowed to better visualize the area

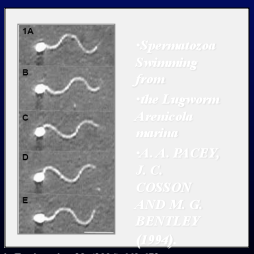
- *The propos* •Given Imaging swallow the capsule, and the gastroenterologist maneuvers it using MRI along with guidance and monitoring mapping



Background

Flagellar movement of microorganisms in low Reynolds number hydrodynamic field [Colgate et al)

the oscillating beam can create approximated sinusoidal traveling wave in viscous flow and produces propulsion force effectively (Kosa et al)

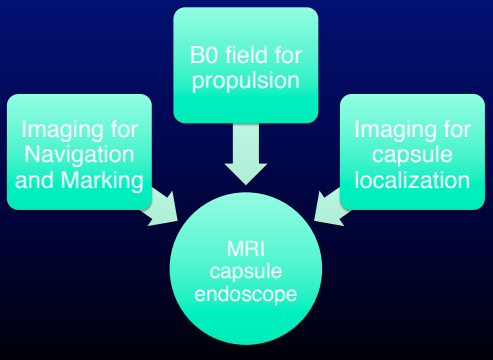


Spermatozoa Swimming from the Lugworm Arenicola marina A. A. PACEY, J. C. COSSON AND M. G. BENTLEY (2004)

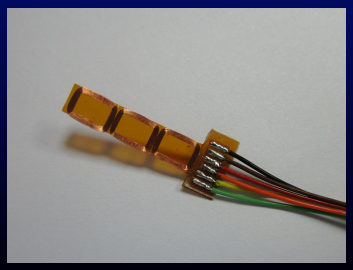
•Colgate, J.E. and Lynch, K.M., IEEE Journal of Oceanic Engineering 29, (2004) 660-673.
•Kósa, G., Shoham, M. and Zaaroor M., IEEE Conference on Robotics and Automation (ICRA05), (2005) 1339-1343.

Our approach

- To combine a magnetic coil and swimming tails and convert the force-couple created by the magnetic coil into a propulsive force in the direction of the static magnetic field
- We will design and develop an optimal waving pattern for the tails and try to achieve advancing speed of 5 mm/sec with a magnetic force of 5 mN.
- The capsule will be 3 mm in diameter and 20 mm long including the three swimming tails.



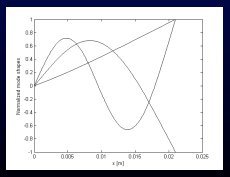
Prototype

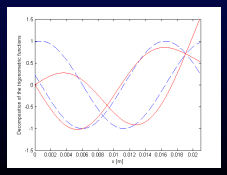


Simulation

- Length of swimming tail 10 [mm]
- Width 5 [mm]
- Total thickness 0.15 [mm]
- Current 3.7 [mA] in the MRI's magnetic field 3 [T].

- Traveling wave
- Amplitude 14 [μm]
- Frequency of 12.836 [kHz]

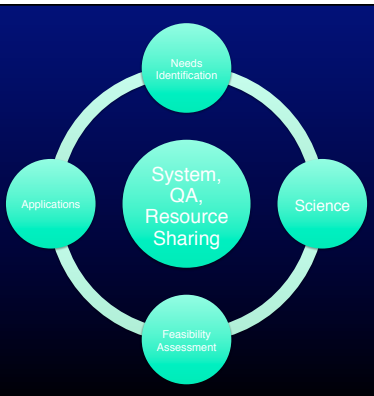




Future direction

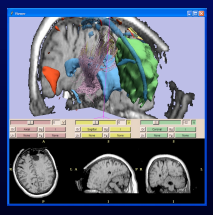
- Miniaturization by MEMS
- Treatment
- Molecular imaging

Engineering



What is 3D Slicer?

- 3D Slicer is…
  - An end-user application for 3D medical image computing research and Image Guided Therapy
  - A platform for research where new techniques can be plugged into a useful framework
  - A freely-downloadable program with source and binaries for Windows, Linux, Solaris and (increasingly) Mac OS



Slide courtesy of Drs. Kikinis and Pieper

Slicer Background

- SPL Image Guided Surgery and Visualization (Kikinis, Westin, Hata, Halle, others)
- Slicer Application Pulled Together by Dave Gering 1997-1999 with VTK and Tcl
- Further Development and Architecture by Lauren O'Donnell 1999-2001
- Ongoing Development of Slicer's Base Primarily by Steve Pieper and Nicole Aucoin
- Many Modules and Contributions by Various Authors
  - BWH, MIT, MGH, Georgia Tech, UCSD, JHU…
- Now being used as a reference application platform for NA-MIC

•Slide courtesy of Drs. Kikinis and Pieper

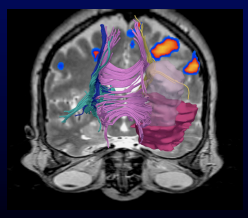
Features

- **Load Medical Image Data: MR, CT in DICOM, GE, Analyze…**
- **XML-based File Format: MRML (Medical Reality Markup Language)**
- **Interactive Editor: Draw, Threshold, Math Morphology…**
- **Automated Segmenters: EM Segmentation, Fast Marching, Level Sets…**
- **Visualization: Model Building, Stereo Rendering, Animation…**
- **Registration: Manual, ITK, CNI**
- **Measurement: Fiducial-Based, Volumetric, Polyhedral Intersection, Vessel Cross-Section, Osteotomy Planning**
- **IGT: Tracked Probes, Real-Time Images, Robot Control**
- **OPEN SOURCE**

•Slide courtesy of Drs. Kikinis and Pieper

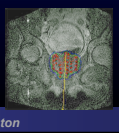
Slicer in IGT

- To facilitate application of state-of-art medical image processing in IGT
- IGT specific extension to support this translation
  - Tracker (IGSTK, Cleary RO1)
  - GE MRI scanner
  - Endoscope support
  - (3D US)
  - (Siemens, Philips)



IGT Software Design

- Software design to maximize function commonalities among applications
  - Brain (biopsy, craniotomy, NdYAG laser ablation)
  - Prostate (brachytherapy, biopsy)
  - Liver and kidney (Microwave, Cryo, laser ablation)
  - Endoscopy (broncho-, neuro-, feto-scopy)


Open-source software: why?

- Resource Sharing
  - Lower development cost
  - Dissemination and training
  - Facilitates communication and collaboration
- Open architecture
  - Access to proprietary hardware
- BSD-style license for potential commercialization

Conclusion

- Robot, as positioning tool, enhances the precision of the MRI-guided therapy
  - Autonomous -> Interactive
- Robot can be an enabling tool to perform therapies in close-bore scanner
- Added value - organ motion compensation will enable IGT of moving organ
- Capsule endoscope, with an addition of image guidance, can be extended to treatment

- Slides:
  - www.snrlab.org -> events