Research Issues in Robot-Assisted Needle Interventions

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Engineering Research Center for Computer-Integrated Surgical Systems and Technology

- Multi-institution, multi-disciplinary center
  - **Johns Hopkins University** + Medical Institutions
  - MIT + Brigham & Women's Hospital (SPL)
  - Carnegie Mellon + Univ. of Western Pennsylvania
  - Others: Harvard, Penn, Georgetown, Morgan State
- Director/PI: Russell H. Taylor
- Core funding from NSF
- Supplemental funding from NIH via NCI, NIBIB
- ***Mission: Couple Information to Surgical Action***

Long (and incomplete) list of contributors…

ENGINEERS: **Russ Taylor, Allison Okamura, Greg Chirikjian, Louis Whitcomb, Dan Stoianovici, Alex Patriciu, Dumitru Mazilu, Greg Hager, Chad Schneider, Axel Krieger, Tabish Mustufa, Keenan Wyrobek, Sangyoon Lee, Yu Zhou, Randy Goldberg, Pat Jensen, Peter Berkelman, Punet Gupta, Greg Fischer, Robert Webster, Ken Masamune, Gernot Kronreif, Ron Kikinis, Steve Pieper, Nicole Aucoin, Clif Burdette, Attila Tanacs, Ergin Atalar, Rob Susil, Emese Balogh, Ameet Jain, Anand Viswanathan, Anton Deguet, Herve Mathieu, Rajesh Kumar, Emad Boctor, Peter Kazanzides, Emad Boctor, Kevin Cleary, Sheng Xu, Ameet Jain, Simon DiMaio, …**

CLINICIANS: **Cynthia Menard, Jonathan Coleman, Vincent Lerie, Ted DeWeese, Lee Myers, Scott Borzillary, Howard Francis, John Niparko, Dan Rothbaum, Gene DeJuan, Louis Kavoussi, Michael Choti, Clare Tempany, Ferenc Jolesz, …**

and surely several others to whom I apologize…

Financial support for GF

NSF EEC-9731478
NIH 1R01EB002963-01
NIH 1R41CA106152-01A1
NIH 5R44CA088139-04
NIH 1R43CA099374-01
NIH 1R41CA103468-01
NIH 1R41RR019159-01
NIH 2R42EB000374-02
AdMeTech
CMS Burdette Medical Systems
Siemens Corporate Research
… and more of my collaborators

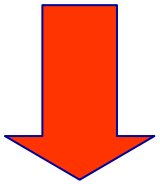
Overview

- CIS (a.k.a. CAS or IGS)
- Needle Based Surgery
- Microsurgical Assistants
- Point and Click Surgery
  - CT-guided systems
  - US-guided systems
  - MRI-guided systems
- Lessons Learned

Benefits of CIS

"Better" Technology

- Greater accuracy & precision
- Greater consistency
  - "equalizer" among physicians
  - "equalizer" among communities
- Eventually faster, less expensive

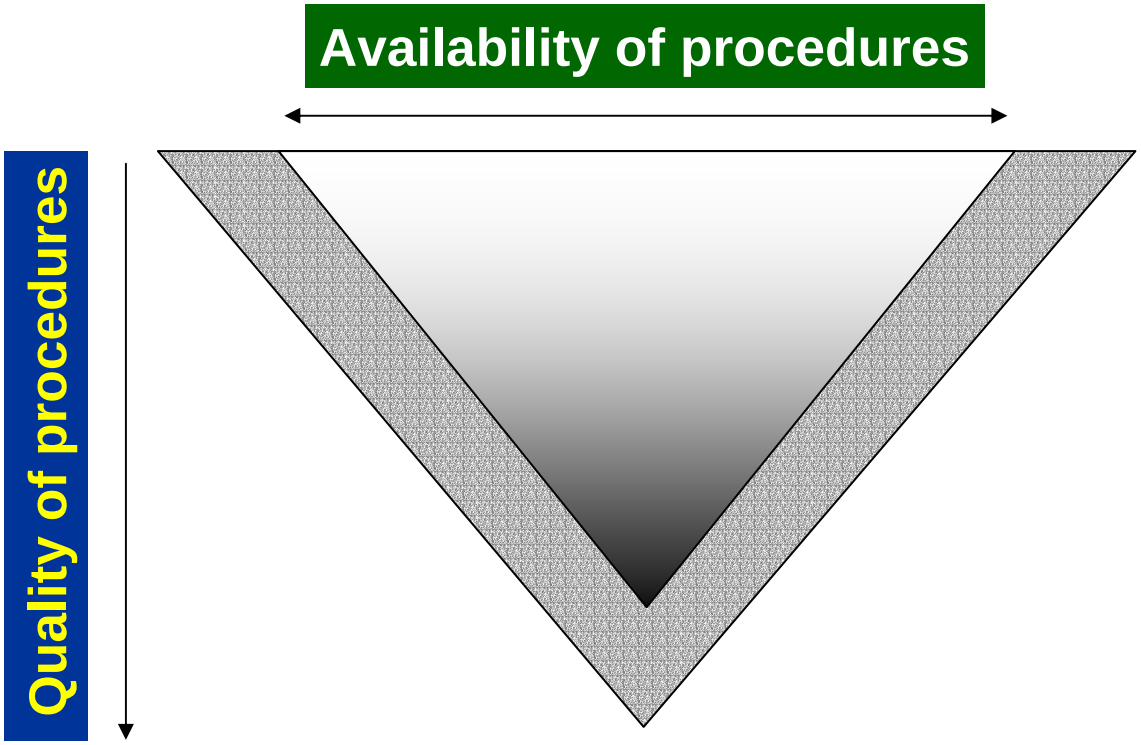


"Better" Medicine & Life

- Higher curative rate
- Less morbidity
- Fewer complications
- Better outcome

Impact

- Procedures performed “better”
- Availability increased



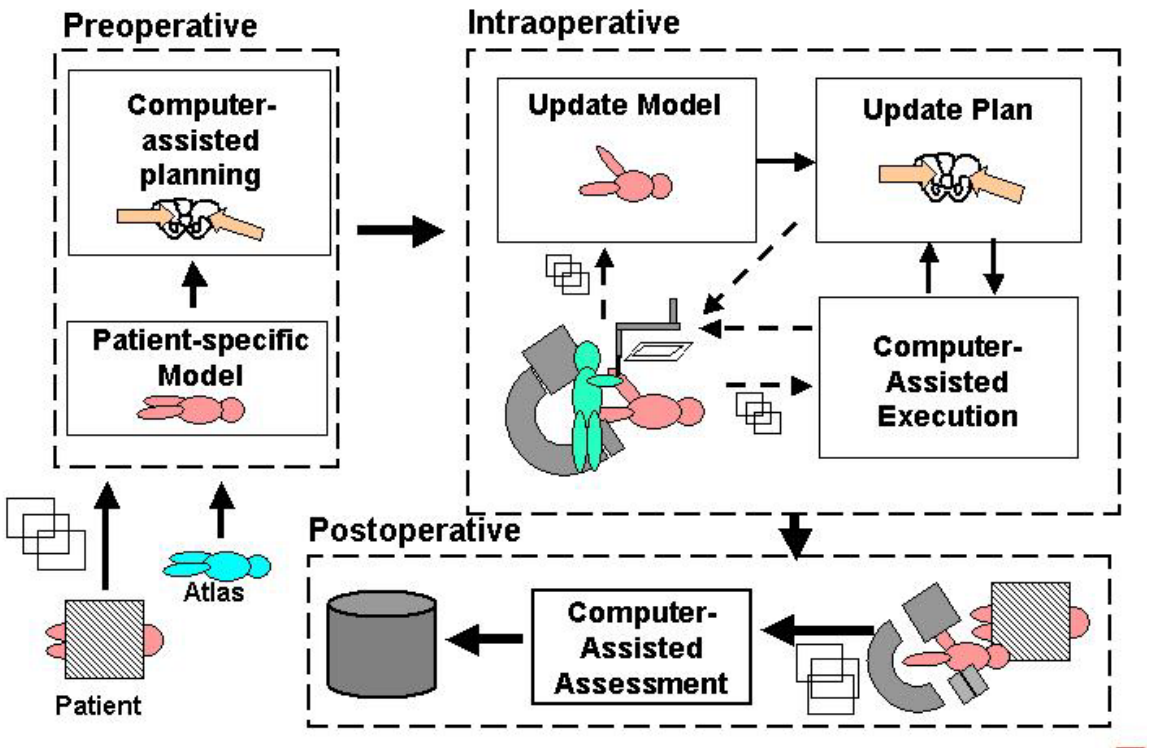
The Prime Directive

Usefulness

But how?

- **Read the clinician**
- **Simplicity**
- **Work incrementally**

Computer Integrated Surgery

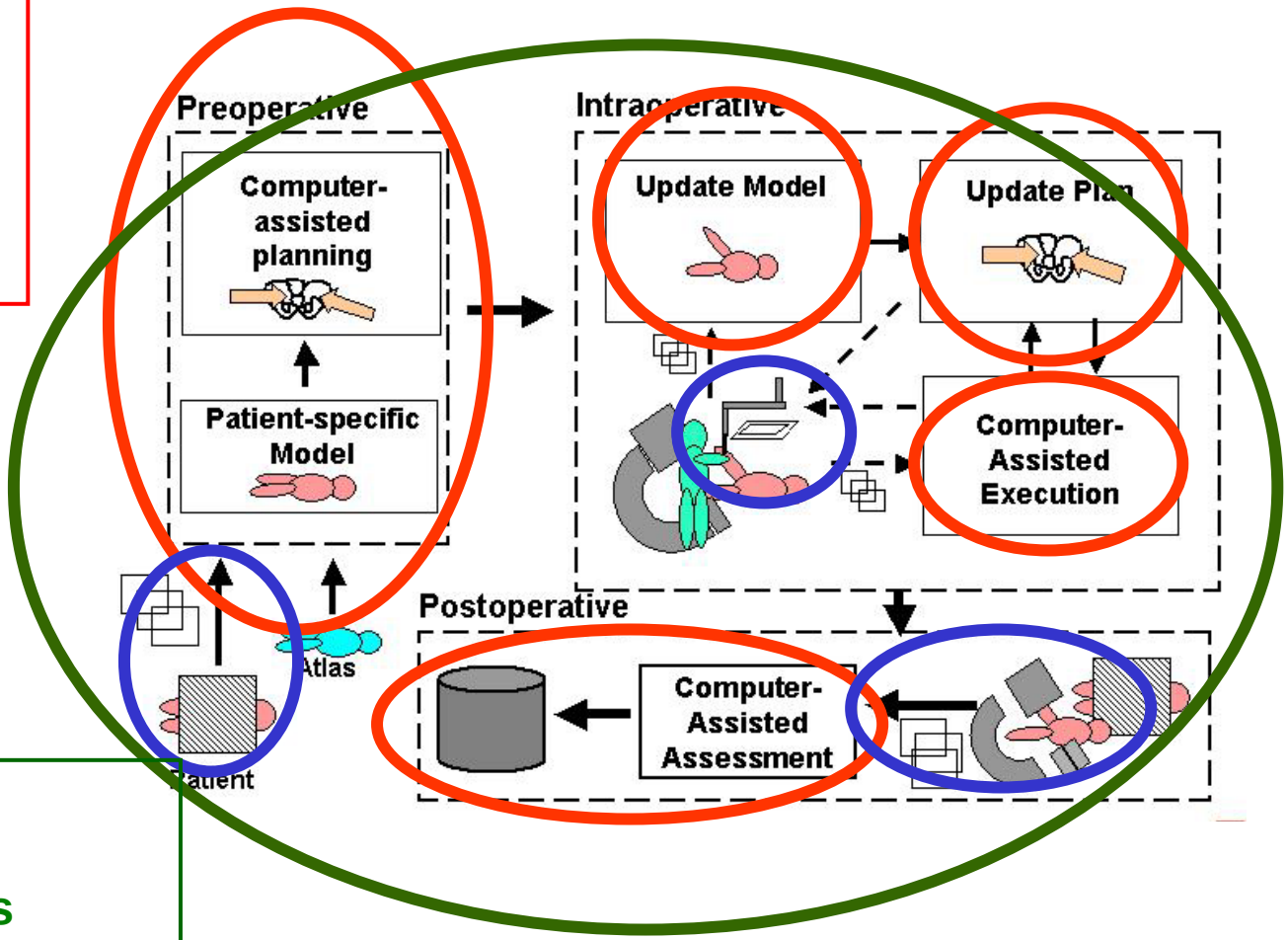


Fundamental research barriers

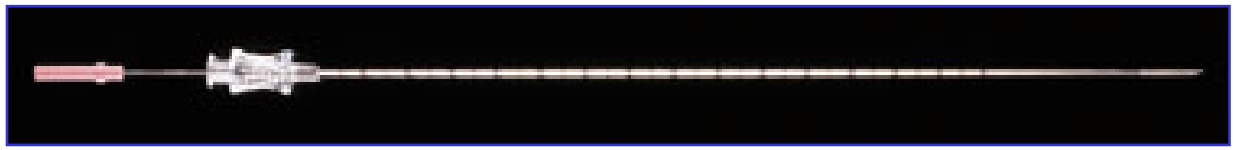
Modeling & Analysis
- Segmentation
- Anatomical Atlases
- Registration
- Reconstruction

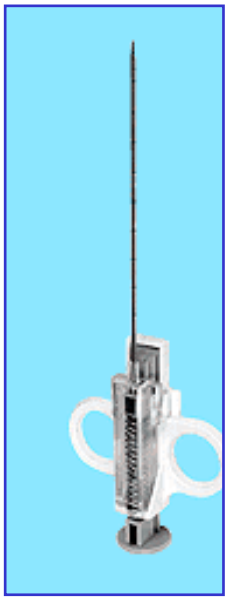
Physical Interfaces
- Sensing/Imaging
- Robotics
- Haptics

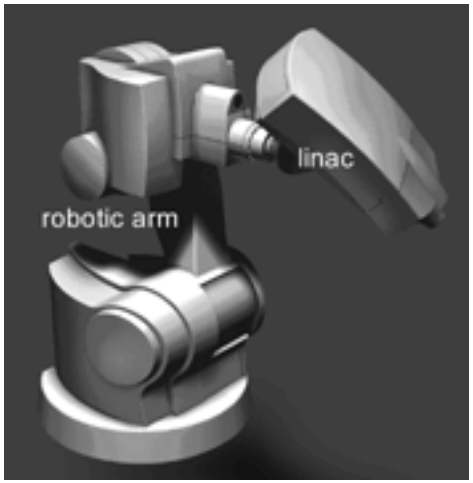
Systems Integration
- System Design
- Performance Analysis
- Architecture
- Clinical Applications

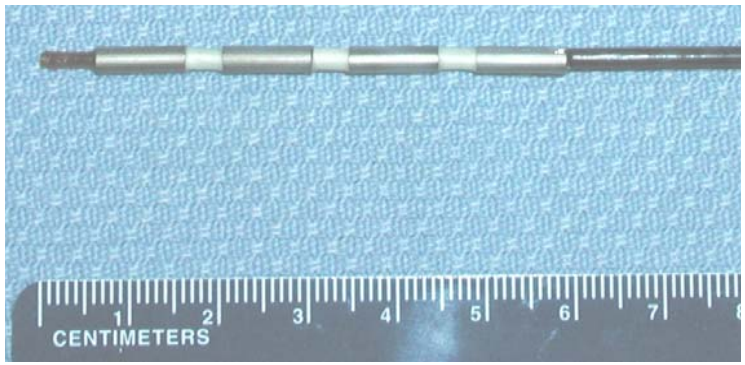


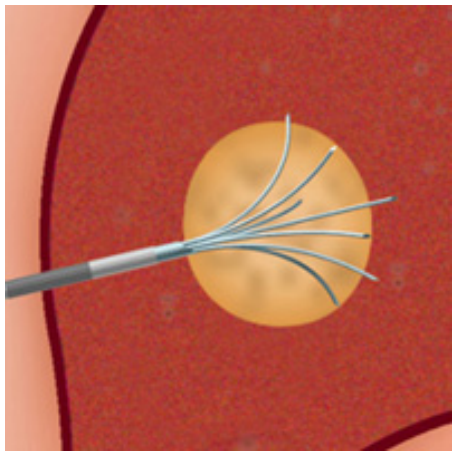
Sensible technical scope: needles











Why needles?

Potentially significant impact on medical practice

- **Minimally invasive (compared to open surgery)**
  - Faster recovery
  - Less morbidity
  - Fewer complications
  - Lower cost
  - Repeatable in many indications
- **Sharply increasing number of procedures**

Challenging but also doable

- ***Constrained process – formally describable***
- **Major challenges (in addition to open/lap surgery):**
  - **no visibility**
  - **no access**
  - **no room to maneuver**
  - **no room to recover**

Sensible clinical scope

MACRO SCALE			MICRO SCALE	
Prostate 200,000 cancers/year 1M biopsies /year 10M BPH currently 25% of men affected in lifetime	**Liver** Metastasis from colorectal cancer 130,000 new /year 60,000 death /year Hepatitis worldwide	**Spine/Bone** 70% of population affected in lifetime 400,000 metastatic cancer /year	**Eye** ~100k/y retinal occlusions, >100k/y age-related macular degeneration (AMD)	**Ear** Hearing loss of 30-35% of 65-75 yo 40-50% over 75 yo

United States numbers

Kidney	ENT	Brain

Why these?

- **Significant health problems**
- **Right mix of challenge and doability**
- **Clinical buy-in**
- **Experience of investigators**
- **Funding opportunities**

Why these organ systems?

Humanitarian reasons

- Significant health problems in US and worldwide

Opportunistic reasons

- Right mix of challenge and doability
- Clinical buy-in
- Funding opportunities
- Experience of investigators
- Publishing opportunities

Engineering Goals

1. **"One-Stop Shopping"**
   - **Plan, Do, and Verify – in one sitting**
2. **"Plug & Play Surgery"**
   - **Rapidly configure for target organ, imaging modality, and therapy**
   - **Predictable performance**
3. **Critical Mass of Components**

The War of Roses

Serial v.s. Decoupled

Serial Robots

Where all joints move in synch

Pros:

- **Can move virtually anywhere**
- **Lots of different motions**
- **Smooth motion**
- **Can work like human limbs**

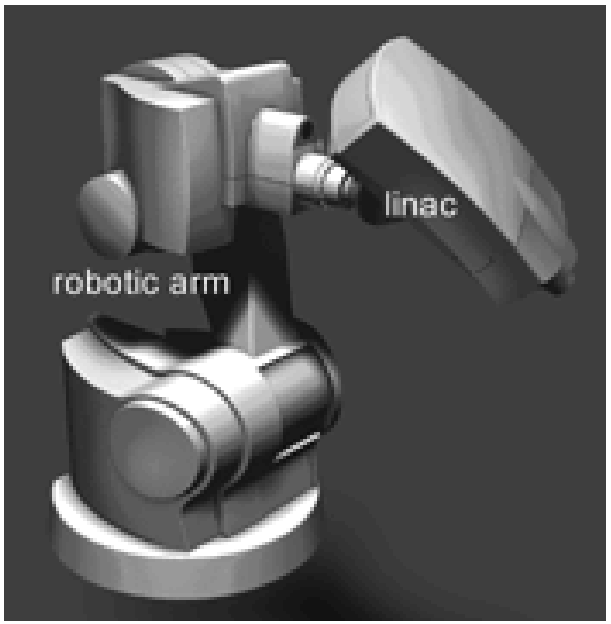
Cons:

- **Hard to constrain**
- **Safety concerns**
- **Complex control**
- **Ugly math**
- **Aggregating errors**

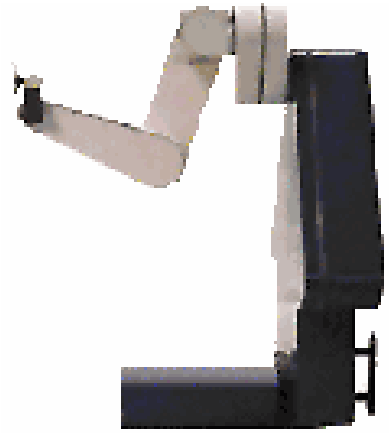
Serial Robots Examples

Where all joints move in synch

Most industry robots and derivatives (SCARA, PUMA, Kawasaki…



Custom-developed robots (Neuromate & see morning presentations…)



Decoupled Robots

Where joints can move selectively

Pros:

- **MAY BE INHERENTLY SAFE**
- **Separates steps of surgery**
- **Easy to constrain**
- **Simpler control**
- **Simpler Math**
- **Curbed error aggregation**

Cons:

- **Limited types of motions**
- **Limited trajectory**
- **Ragged motion**

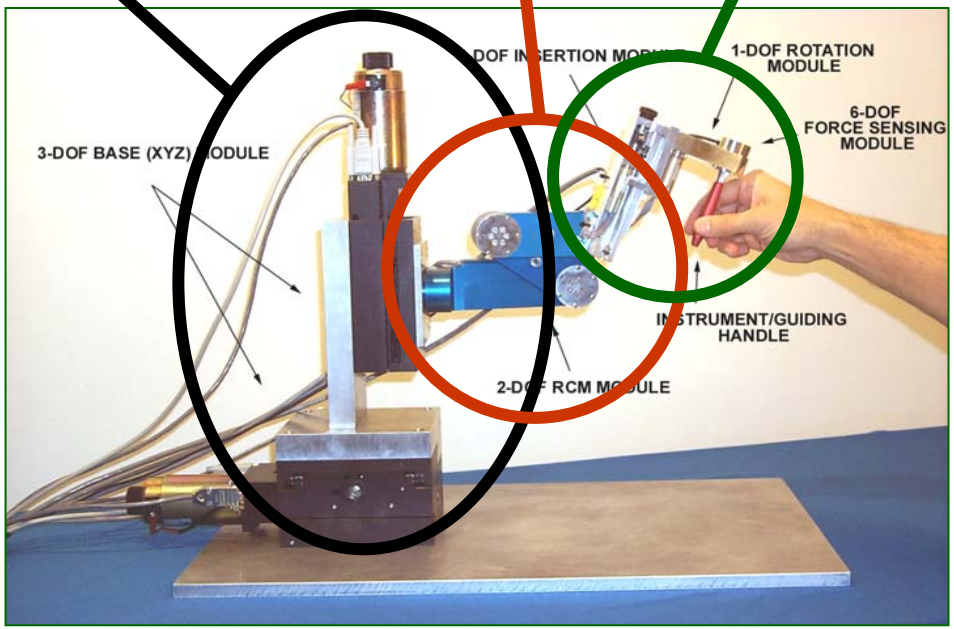
Hopkins approach : decoupled RCM robots

Rotation about stationary fulcrum point

1 3D translation "move needle to entry"

2 2D Rotation "orient needle"

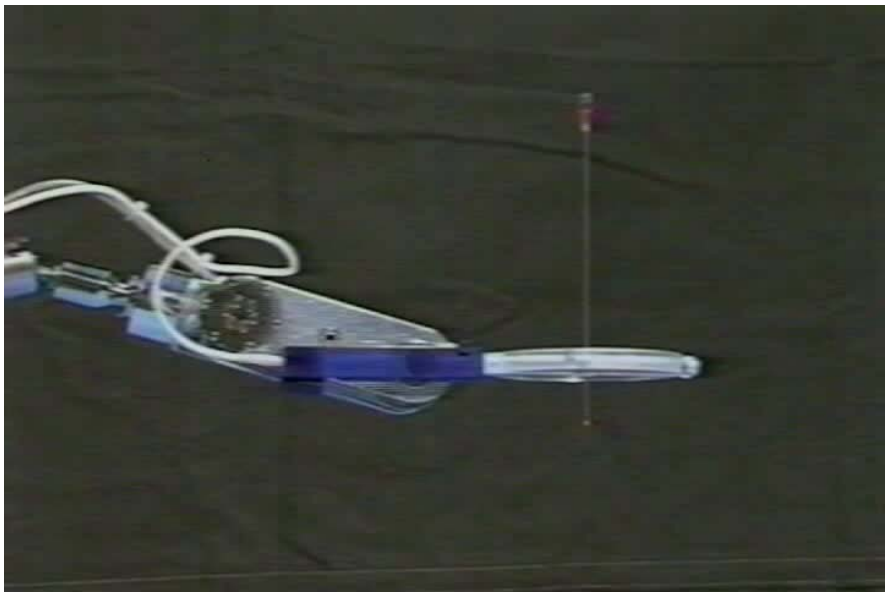
3 0D/1D/2D Insertion "drive needle"

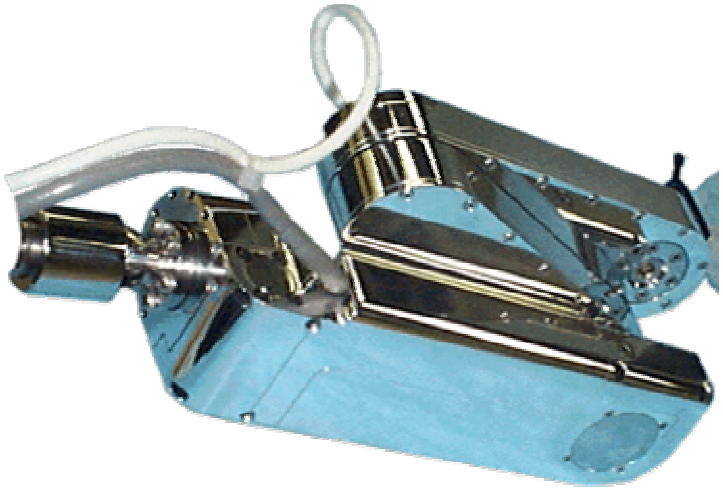


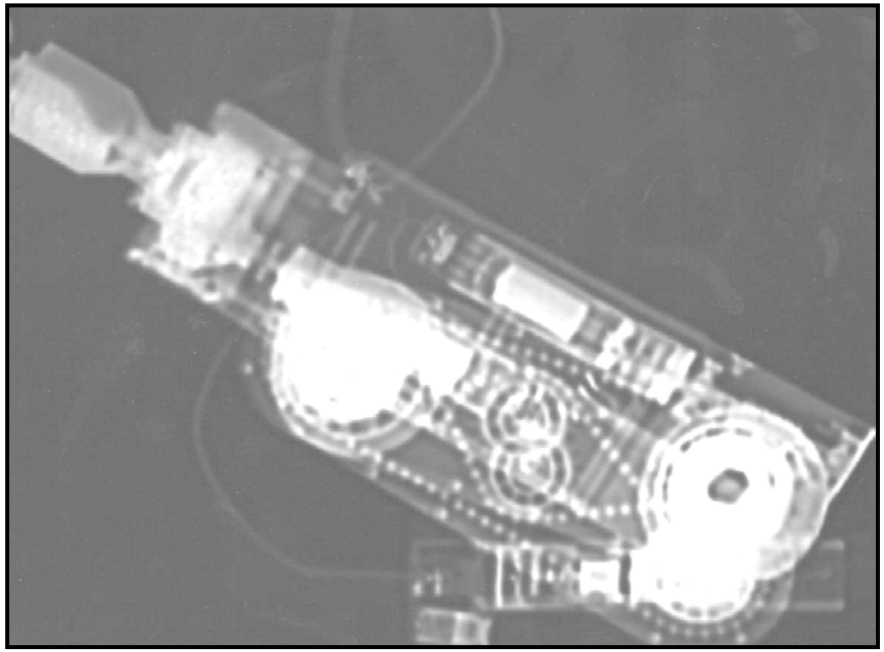
Main Benefits

- Feels natural
- Modular
- Safe

Chain drive & ball warm RCM robots



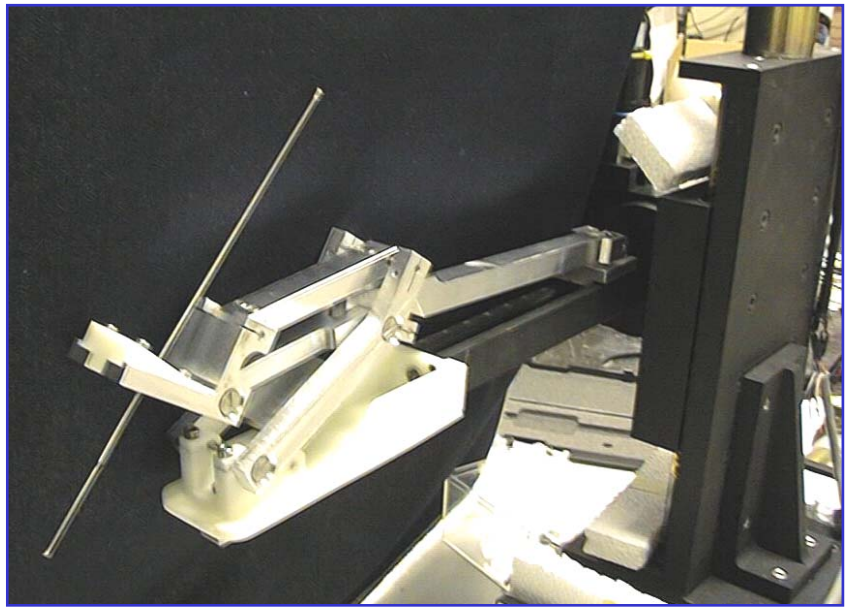


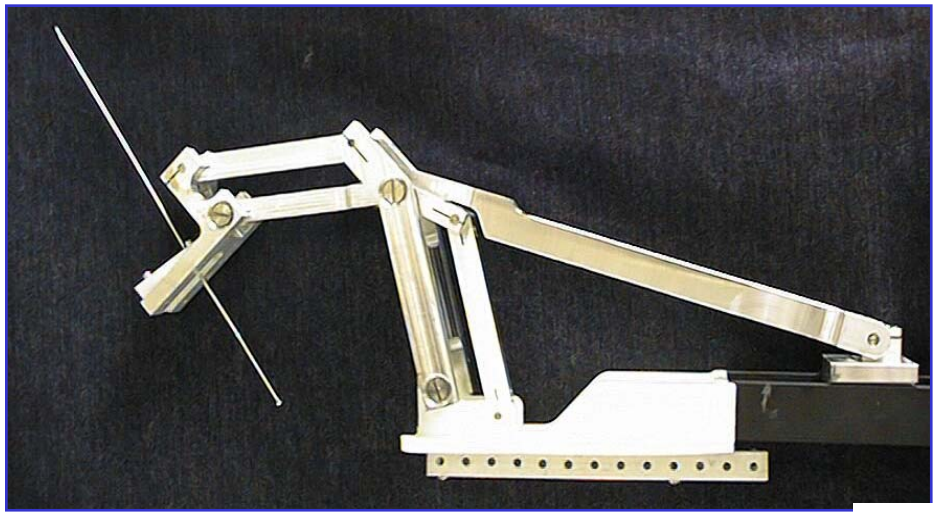


- No friction
- No backlash
- 2x360^{o} range
- 1.6 kg
- 20 cm

Credit: Stonovici, Taylor, Whitcomb al.

Econo-RCM a.k.a. “El Cheapo”

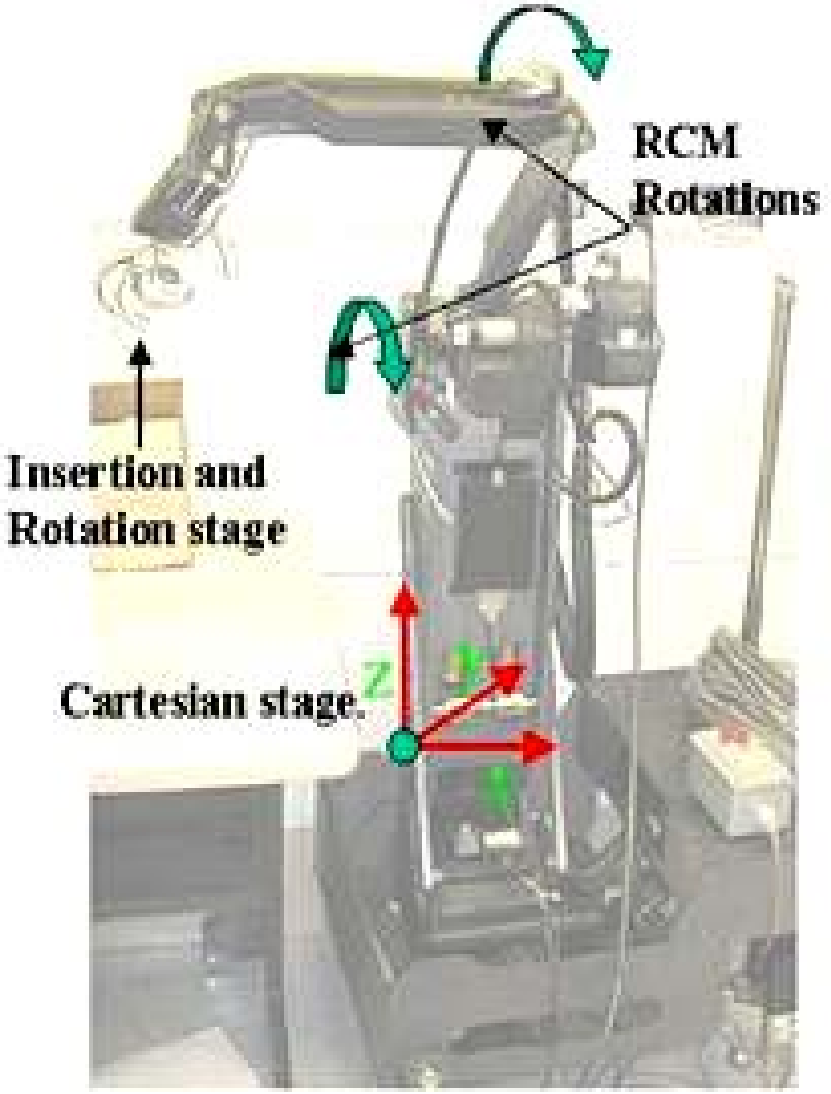




- Inexpensive
- Resizable
- Mass-Producible
- Possibly disposable

Credit: Lee, Webster, Kapur, Simaan, Taylor

LARS: RCM robot w/ parallel linkages



Credit: Taylor, Anderson, et al.

Davies: Goniometric arcs (for TURP)

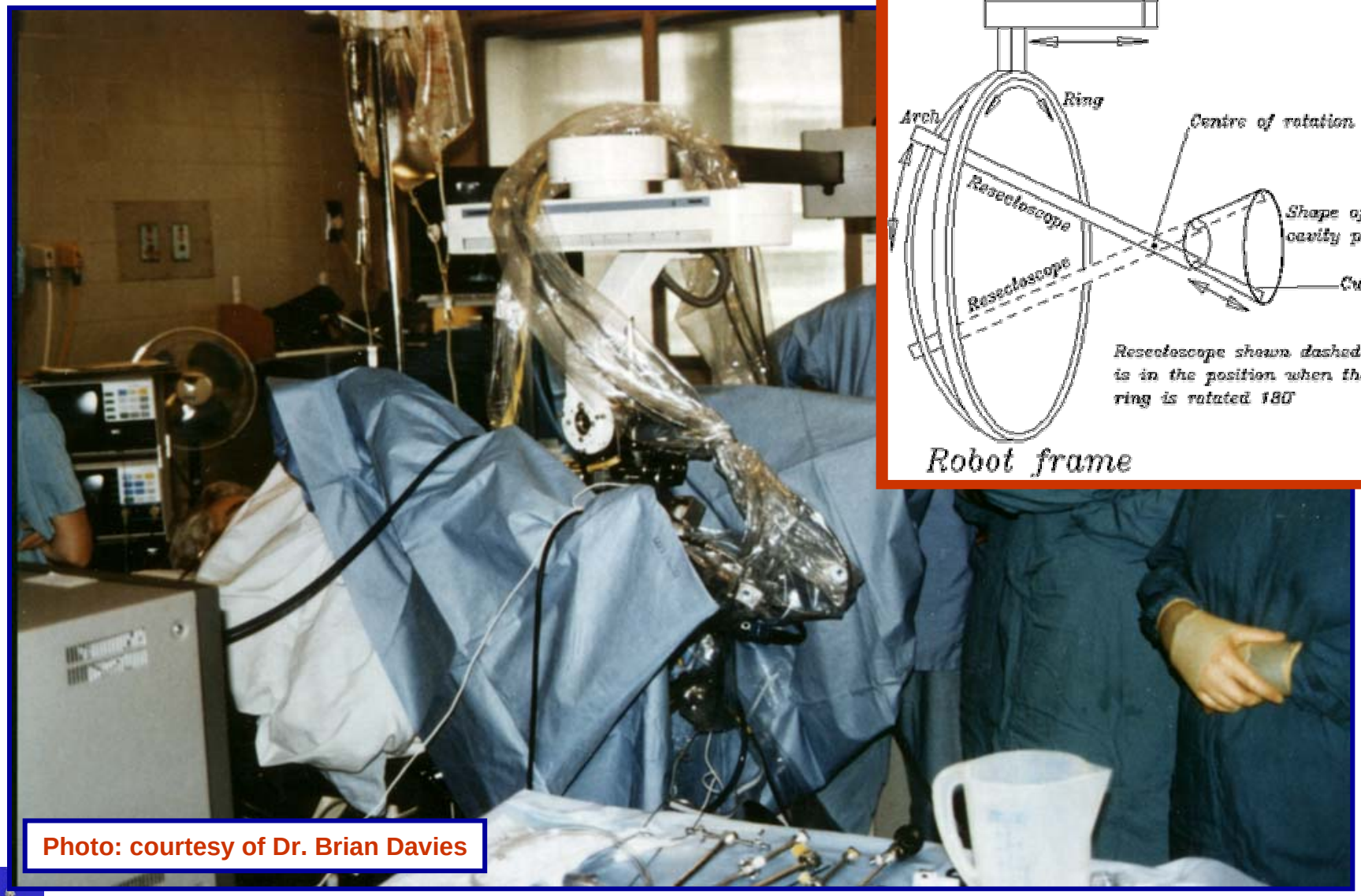


Photo: courtesy of Dr. Brian Davies

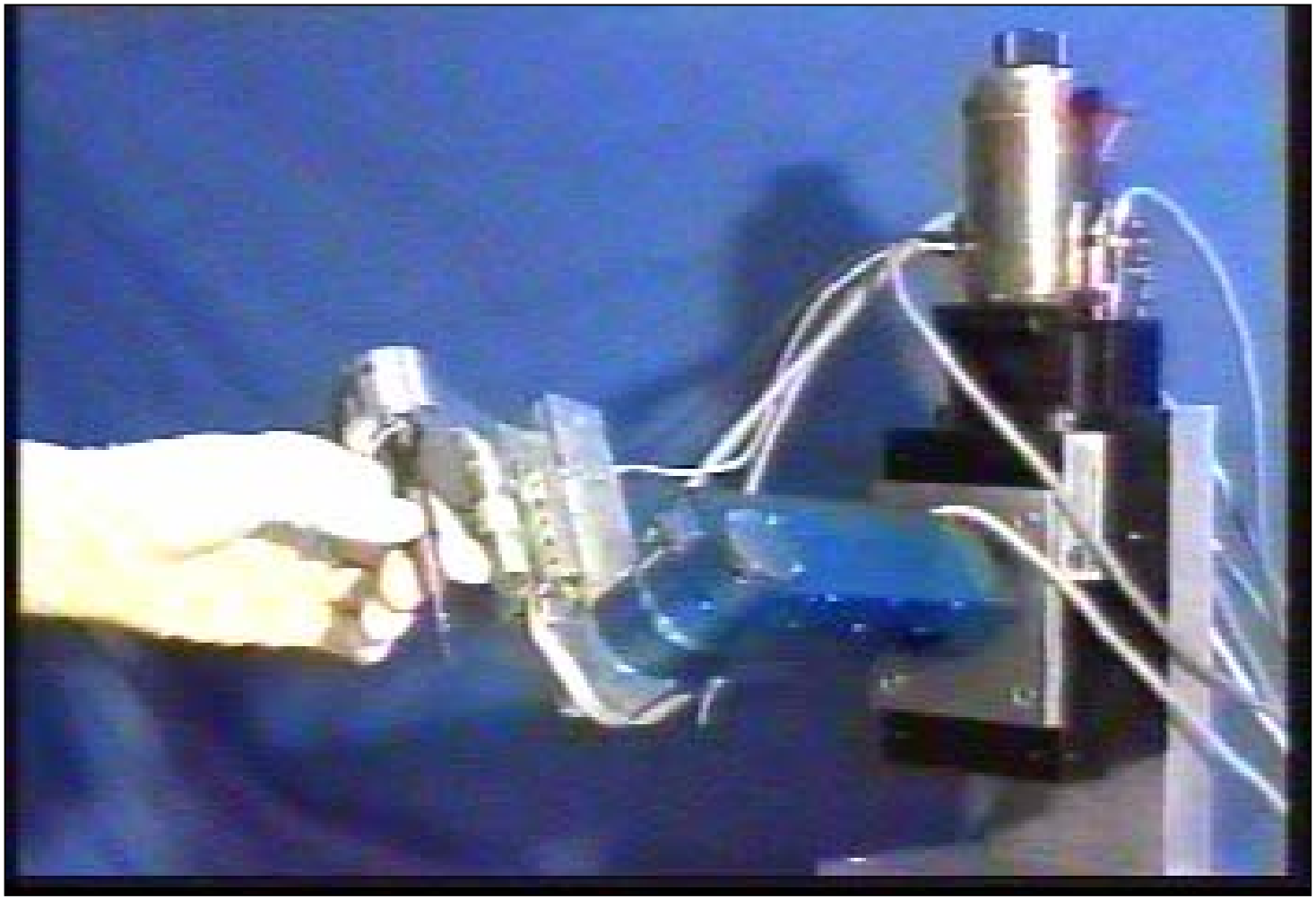
Credit: Brian Davies et al.

Overview

- Needles Everywhere
- Microsurgical Assistants
- Point and Click Surgery
  - CT-guided systems
  - US-guided systems
  - MRI-guided systems
- Lessons Learned

Microsurgical assistant systems

Backbone: SteadyHand robot



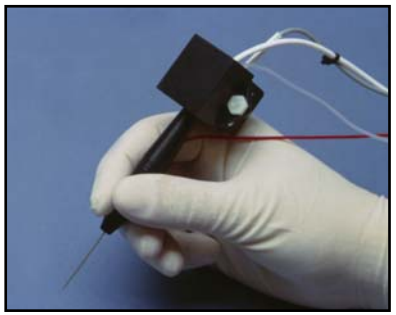
Credit: R. Taylor, D. Stoianovici, L. Whitcomb, A. Barnes

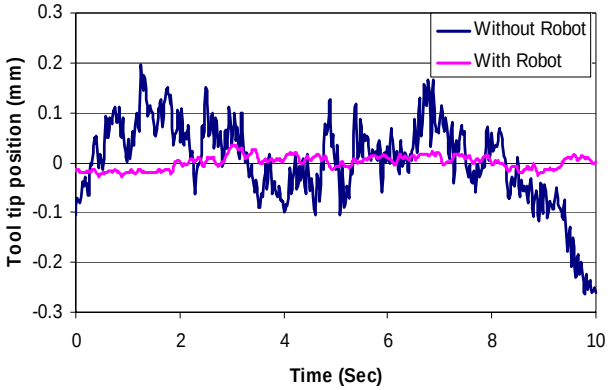
Freehand versus SteadyHand

Free Hand Motion:

~ 0.1 mm drift

~ 0.05 mm tremor

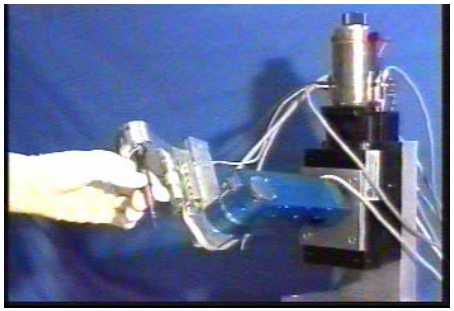


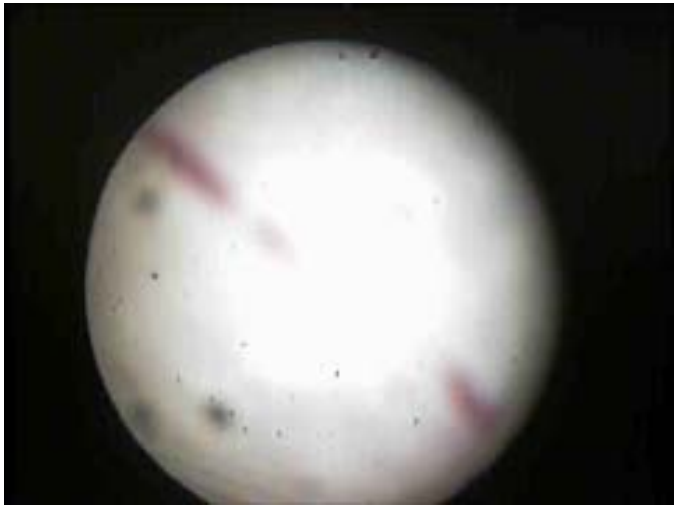


Steady Hand Motion:

~ 0.02 mm drift

~ 0.01 mm tremor



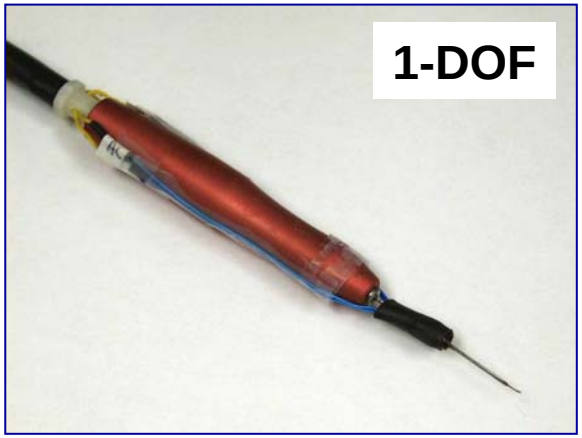


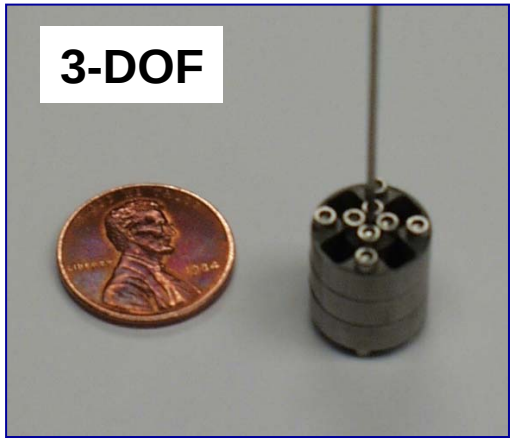
Movies: CISST ERC, MADLAB, JHU

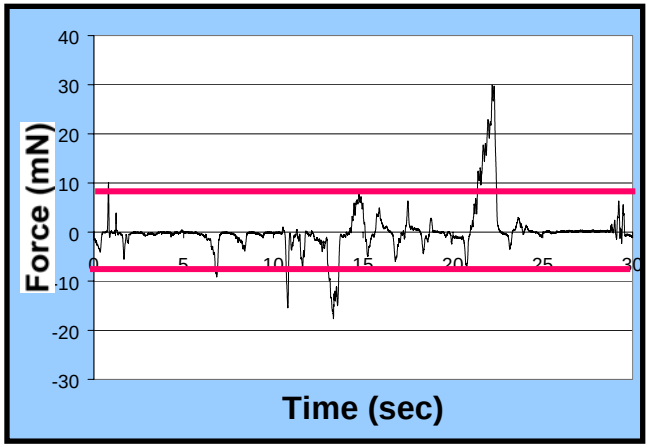
Credit: Kumar, Gupta, et al.

Forces in microsurgery

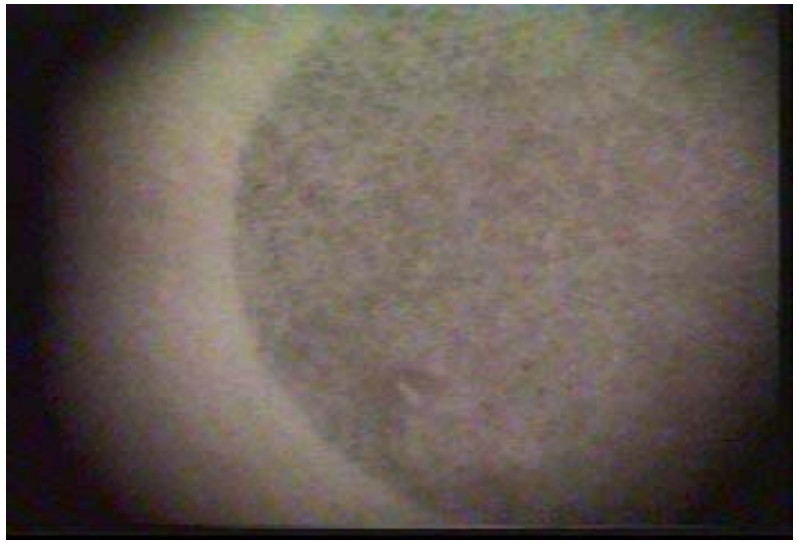
Instrument tip forces in retina surgery are mostly below +/- 7.5 mN human sensing threshold







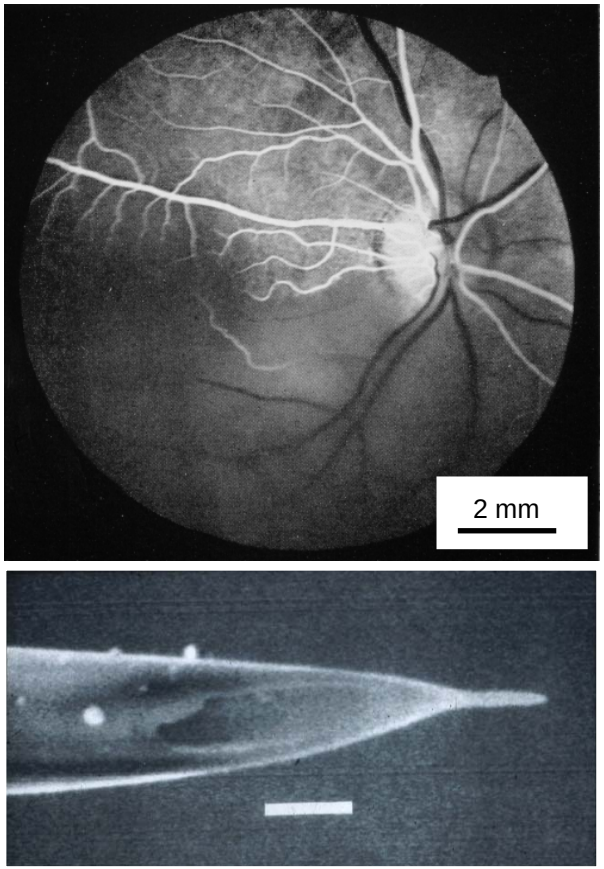
Force Scaling with SteadyHand robot →

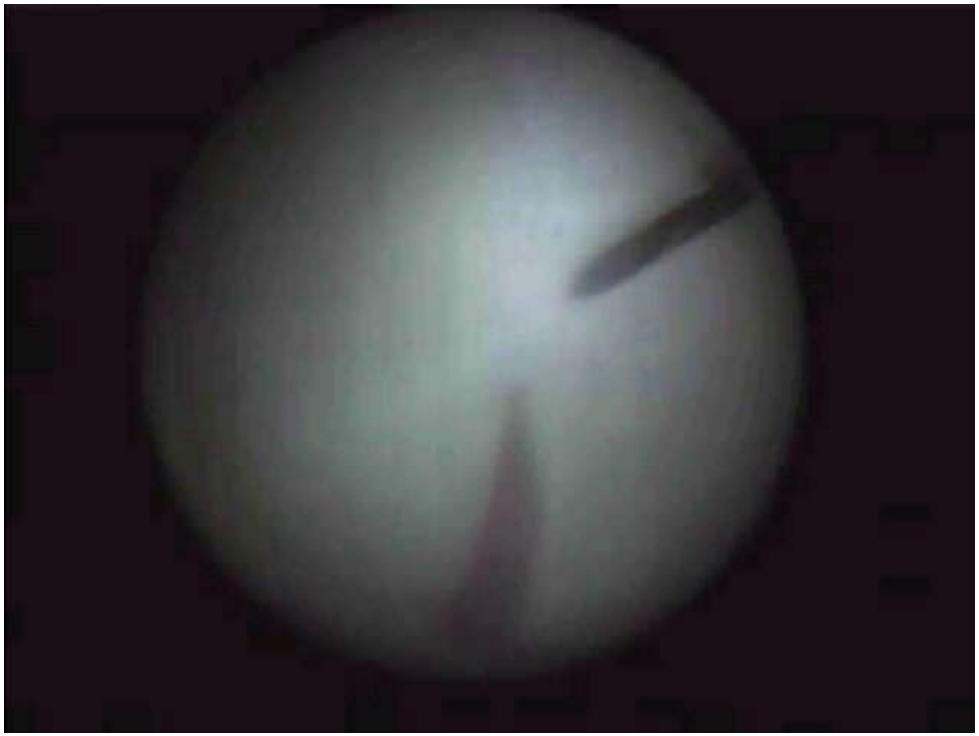


Credit: Gupta, Berkelman, Kumar et al.

Application: retinal vein cannulation

Insertion of a needle into the lumen (interior) of a retinal vein or artery in order to introduce theraputic drugs. May affect 200,000 patients per year in the US alone.



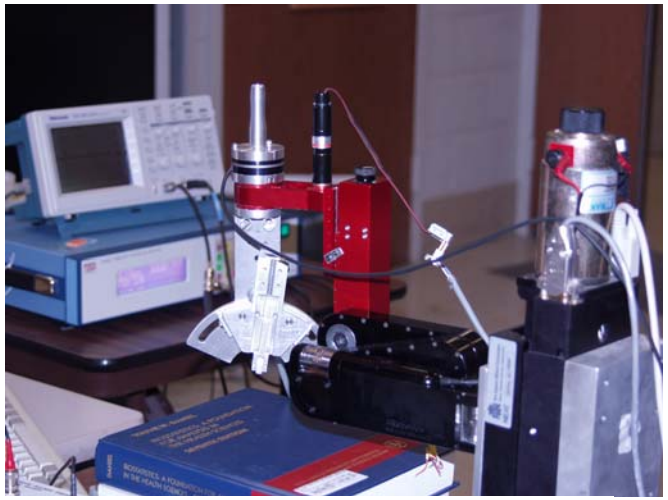


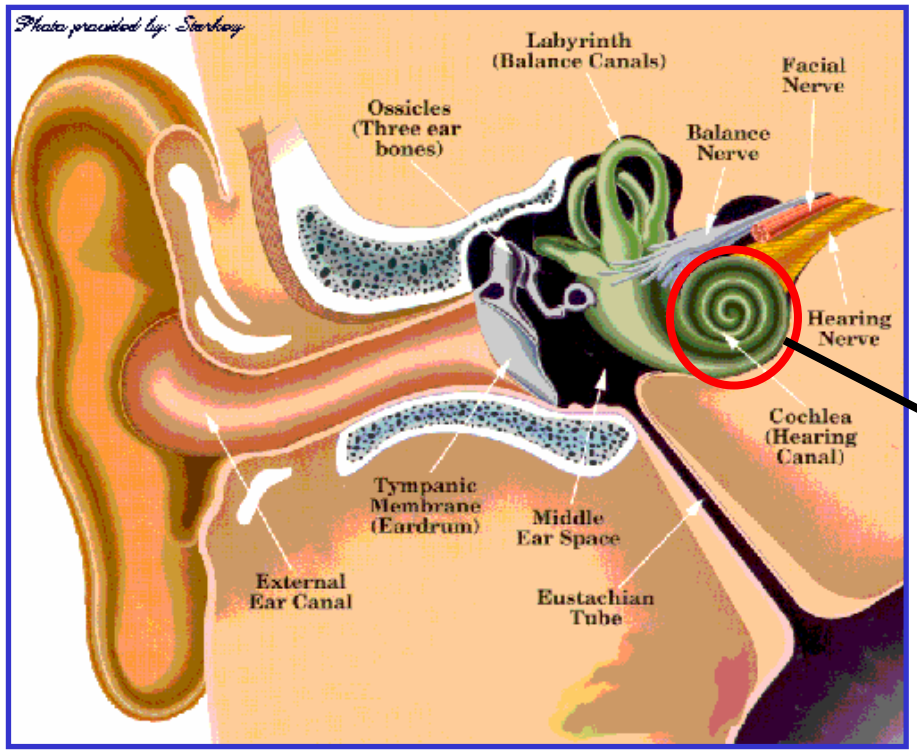
Cannulation of a 100 mm blood vessel w/ SteadyHand

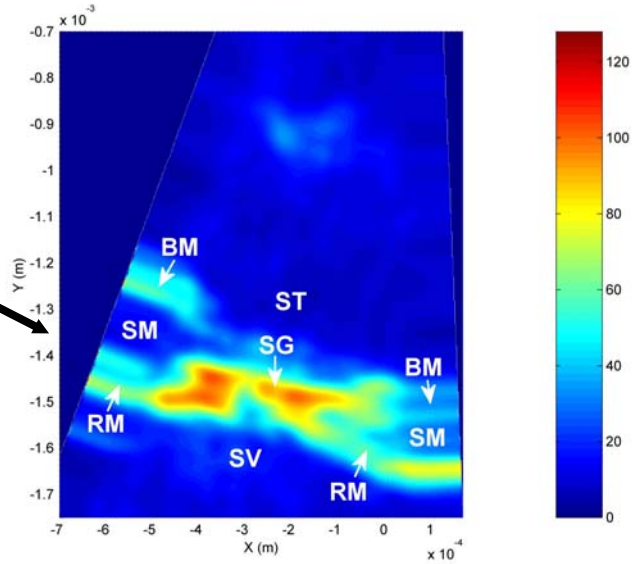
Credit: Kumar, Jensen, Hager, et al.

Application: mapping the scala media

- New high resolution US probe (collaboration with K. Shung, Biomedical Ultrasonics Laboratory at USC)
- 30 μm resolution
- Integrated US probe and needle





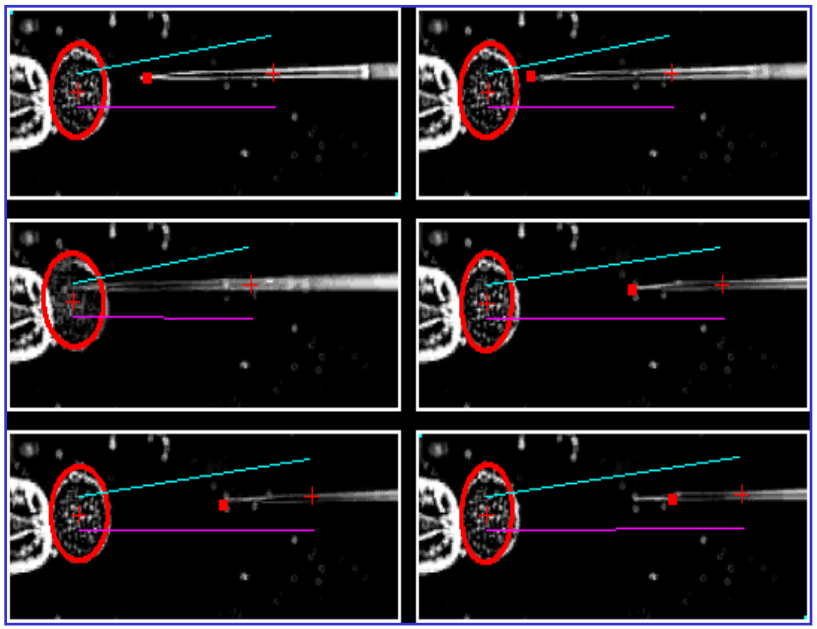


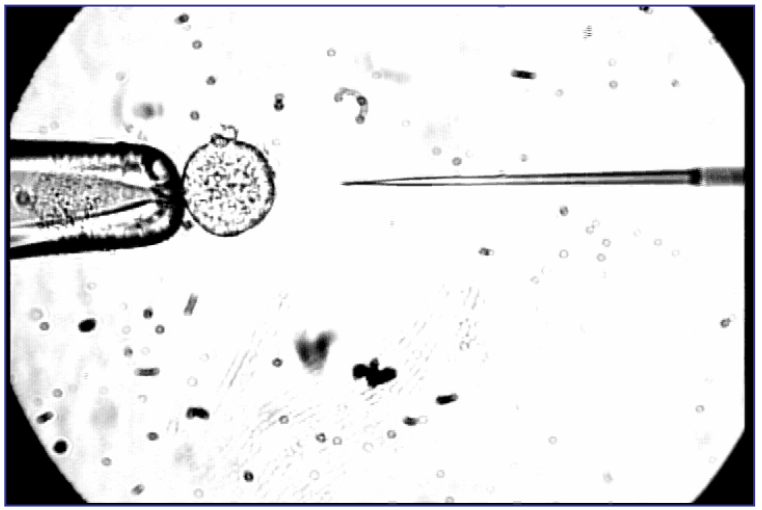
Credit: Rothbaum/Roy/Mustufa/Niparko/Francis/Whitcomb

Application: cell manipulation

SteadyHand robot assisted injections of nuclear material into mouse eggs and embryos

- "Freehand" guiding
- Visual virtual fixture assistance
- Semi-autonomous

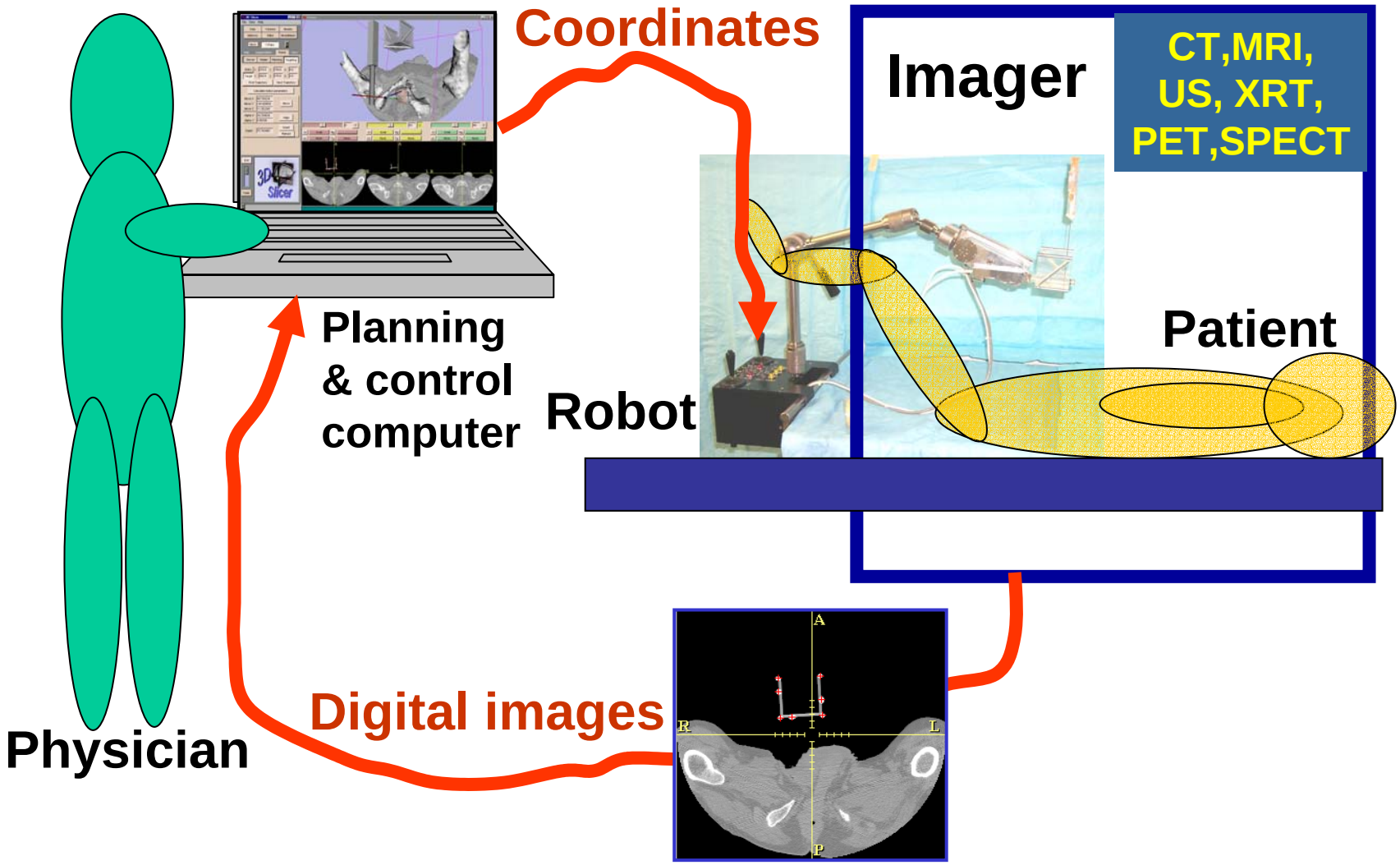




Industry partner: Foster-Miller, Inc

Credit: R. Kumar, A. Kapoor, R. Taylor

“Point & Click” needle surgery



Overview

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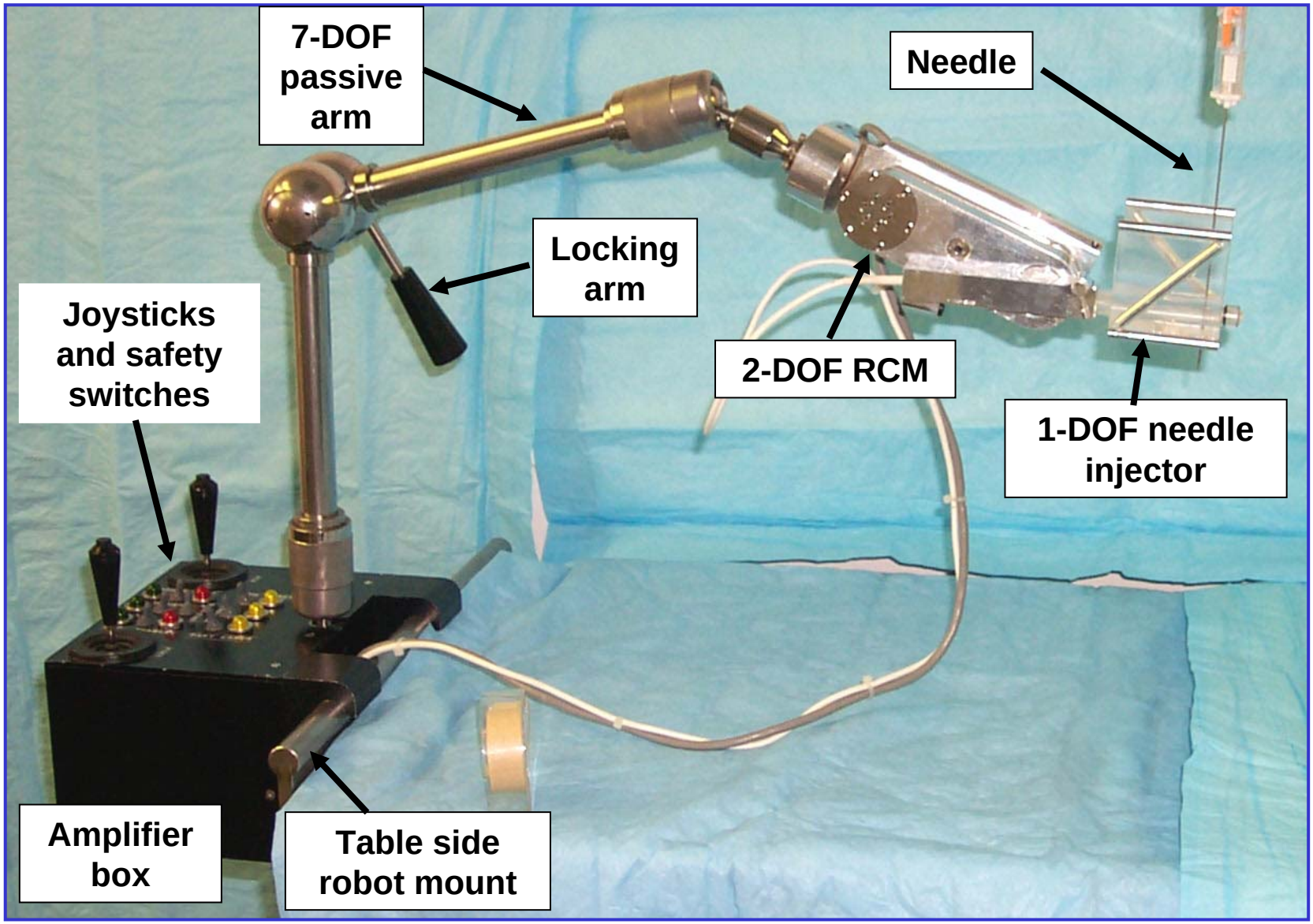
The problem in CT guidance

- Hand-eye coordination
- Image is shown off the surgical field
- Split attention (b/w display and patient)

CT-guided prostate biopsy

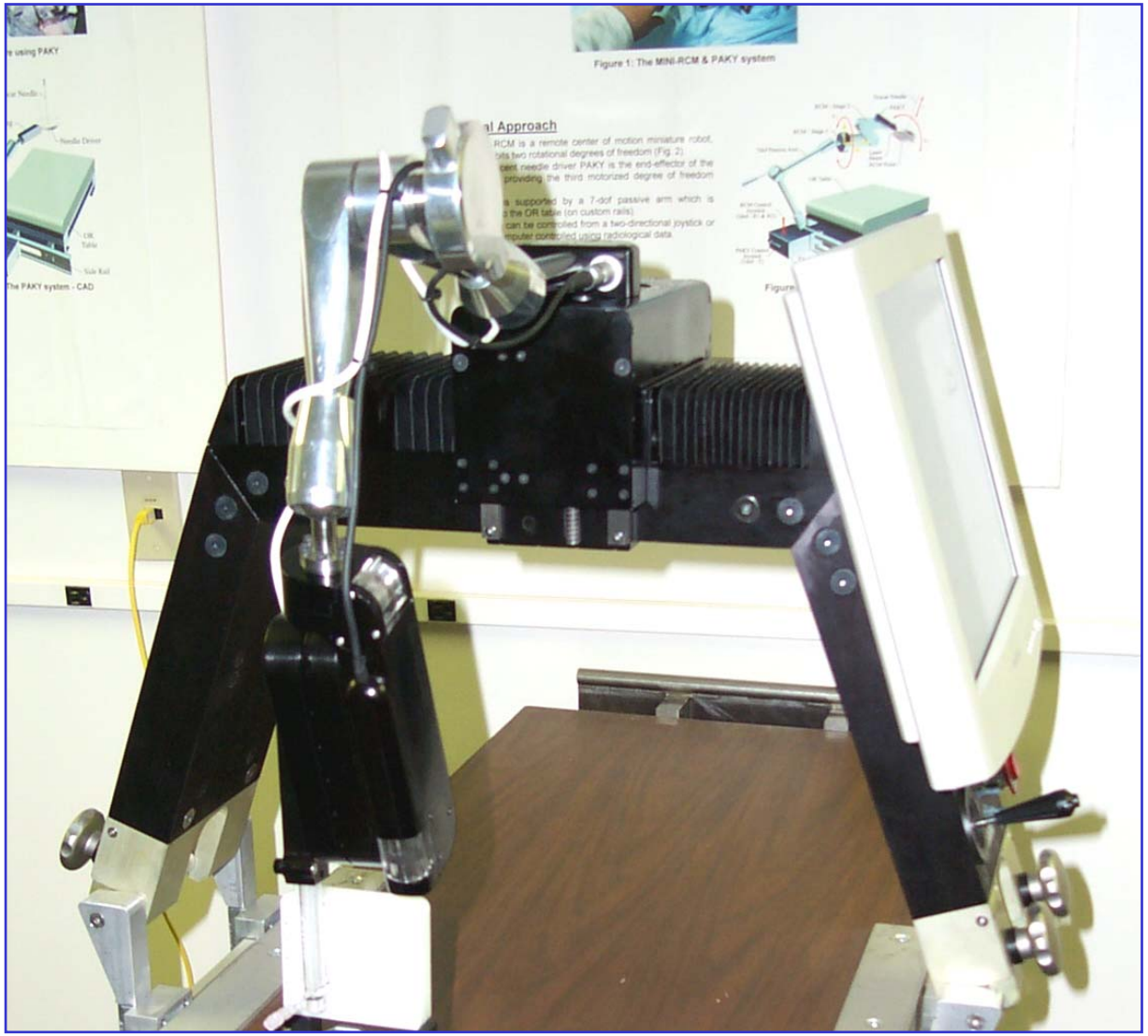
Credit: Stoianovici, Patriciu, Fichtinger, et al.

An embodiment: 3-DOF robot



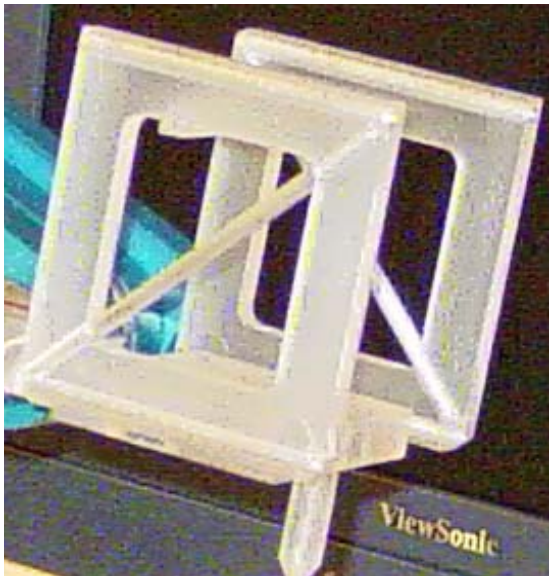
Credit: Stoianovici, Masamune

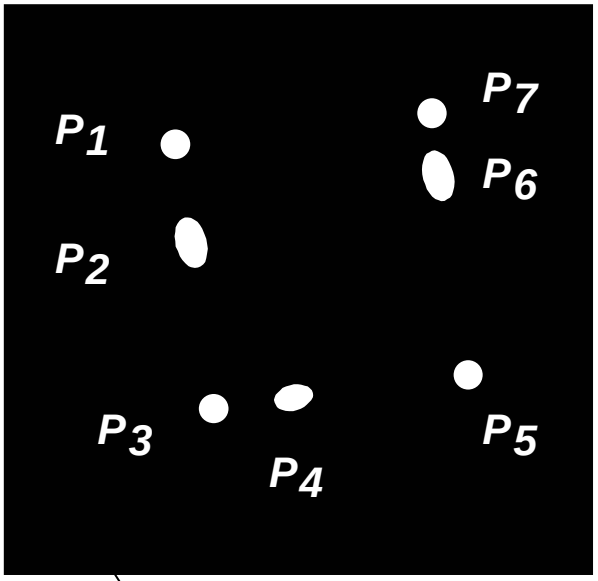
Another one: 5-DOF robot

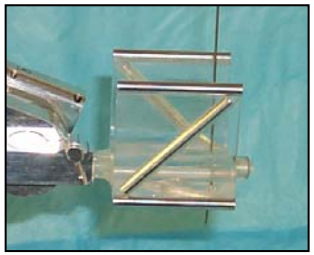


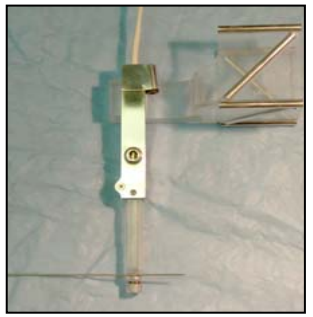
Credit: Stoianovici, Patriciu

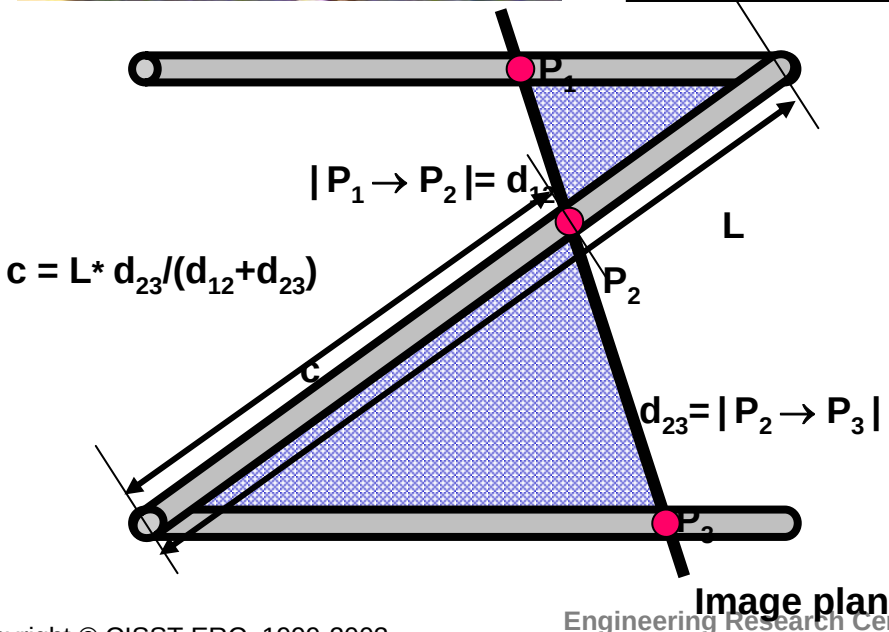
Single-Slice registration of robot to CT







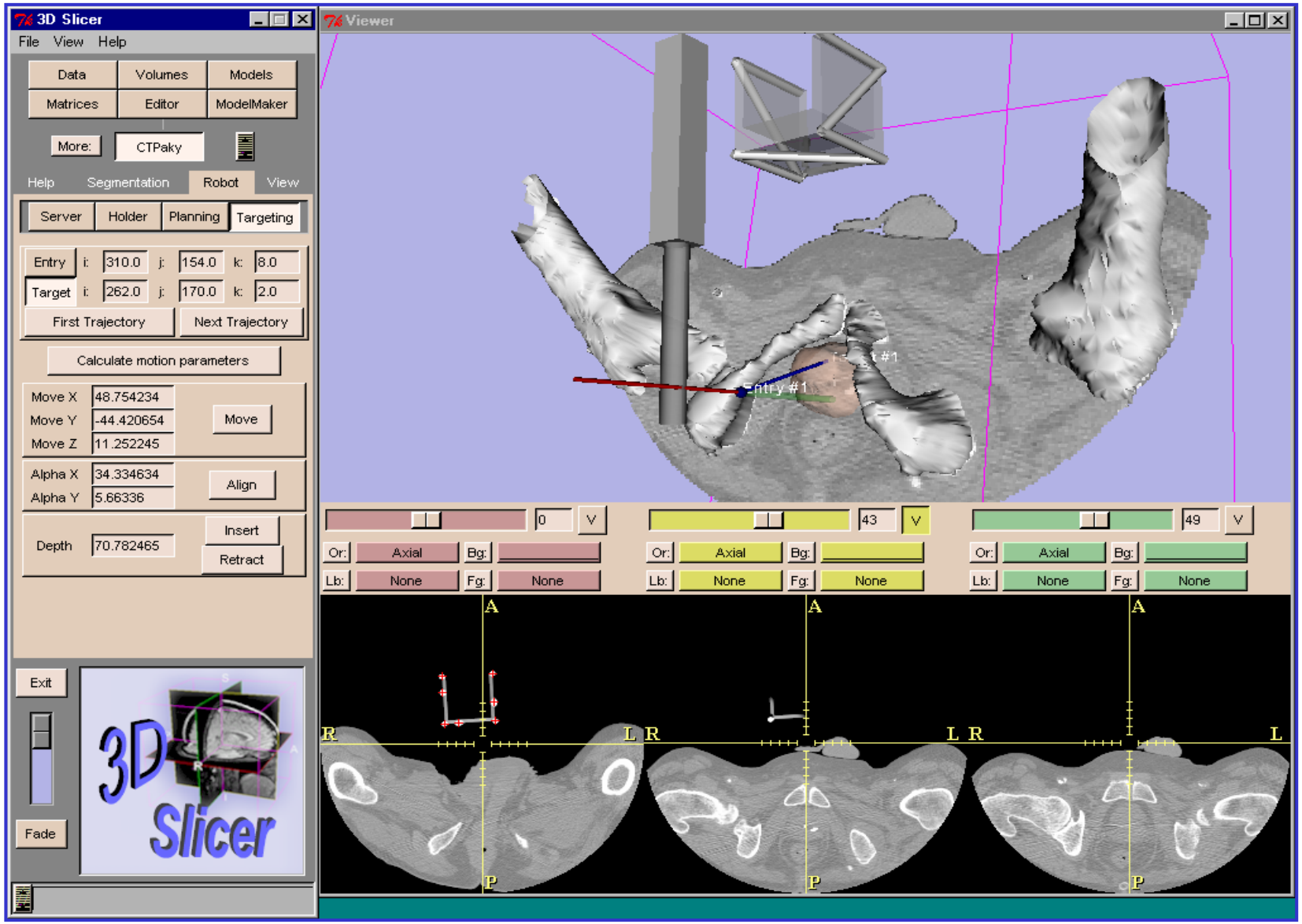




Closed form: fast and computationally robust

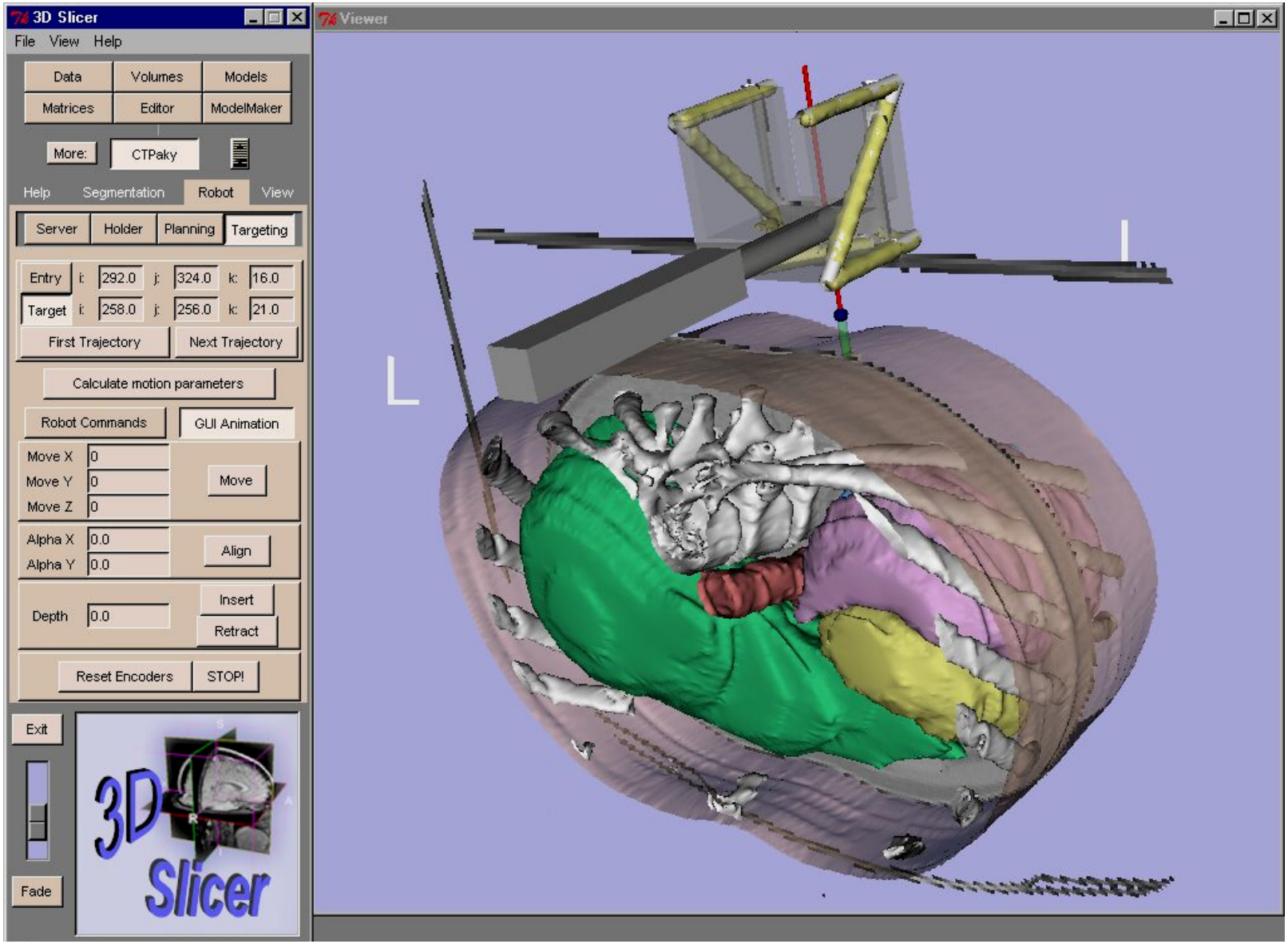
Credit: Susil, Taylor, Masamune et al.

Intra-op treatment planning



Credit: A. Tanacs

Similar for many organs…



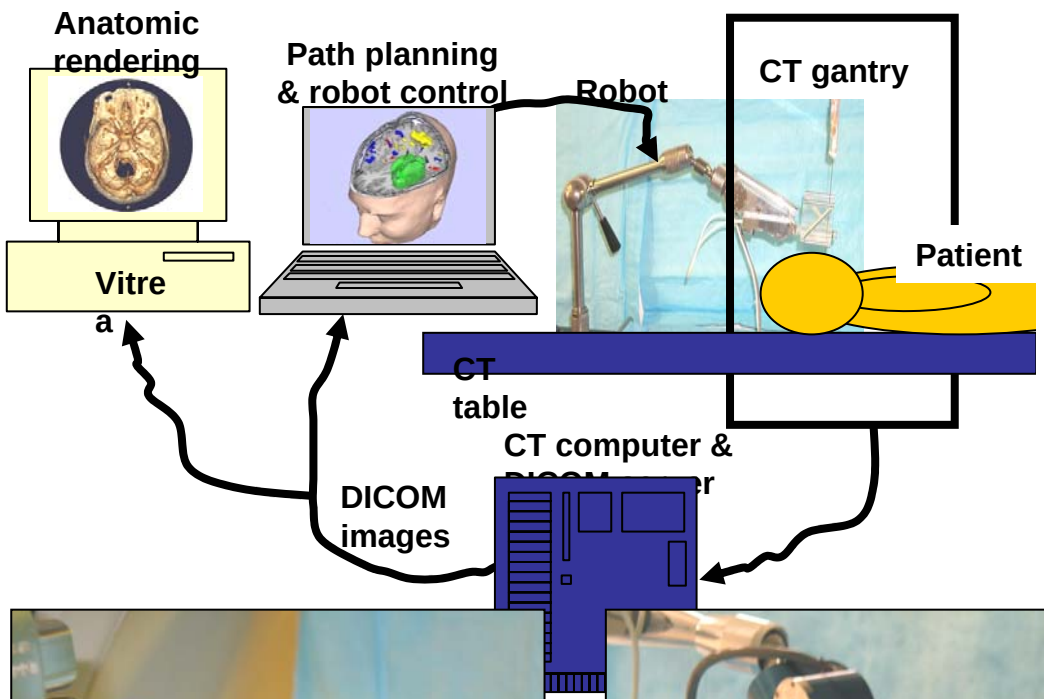
Credit: A. Tanacs

CT-guided kidney biopsy

Robot registered to CT from a single image using stereotactic frame on the end-effector

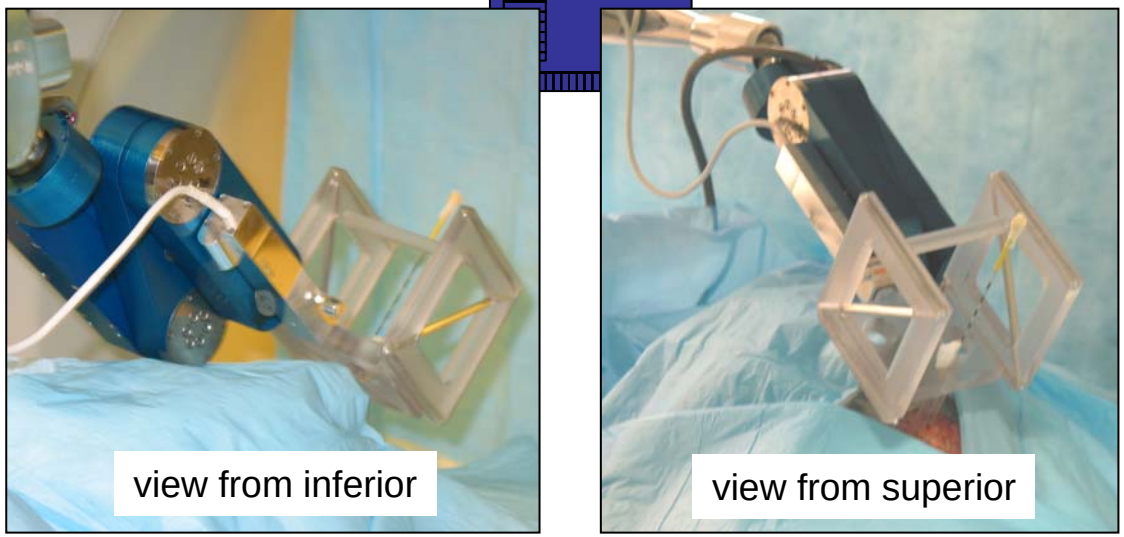
Credit: D. Stoianovici, L. Kavoussi, A. Patriciu, S. Solomon (JHU Bayview)

Intra-cranial hemorrhage removal



☹

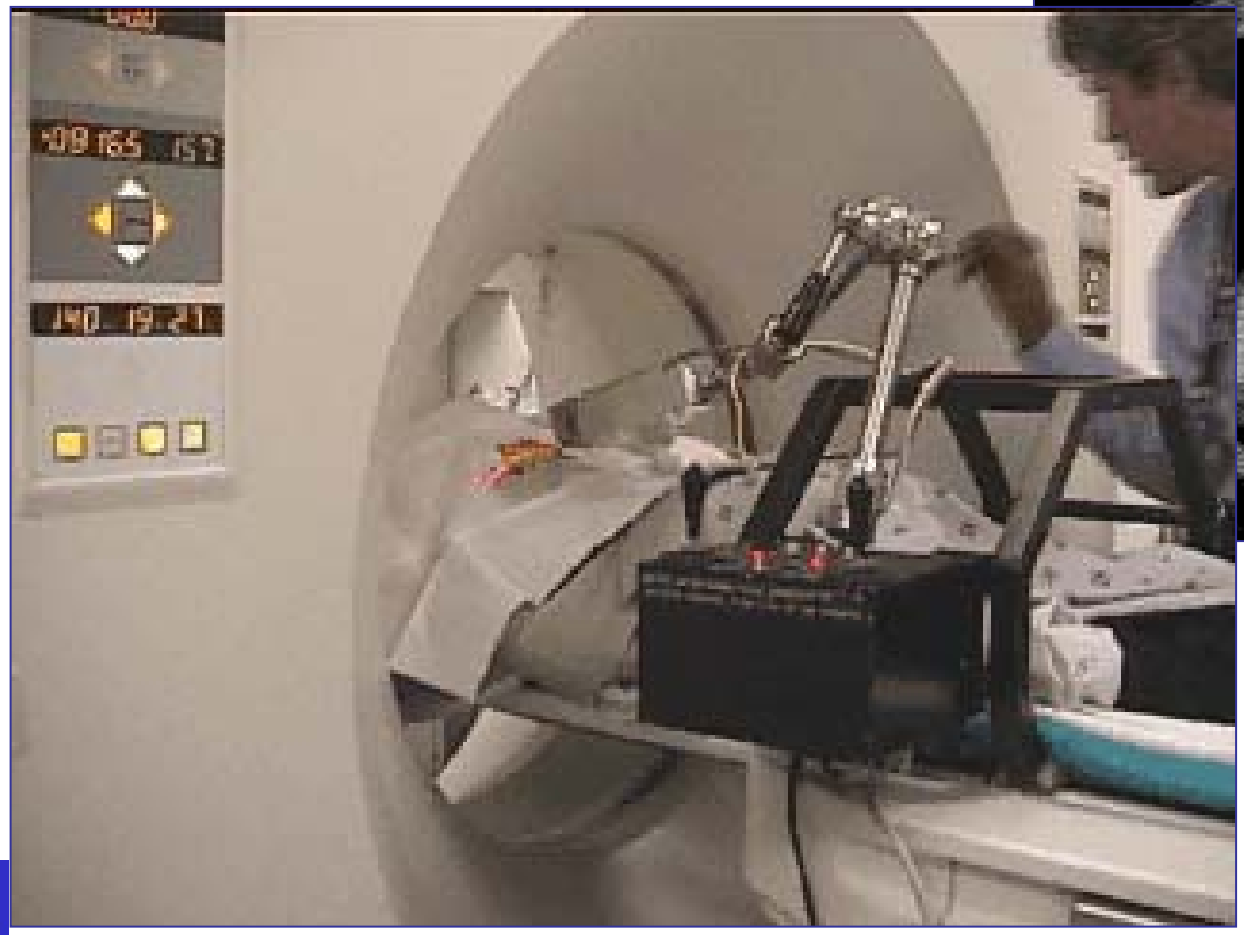
Blind spots
Collision
3DOF insufficient



Credit: Ellis, Fichtinger, et al.

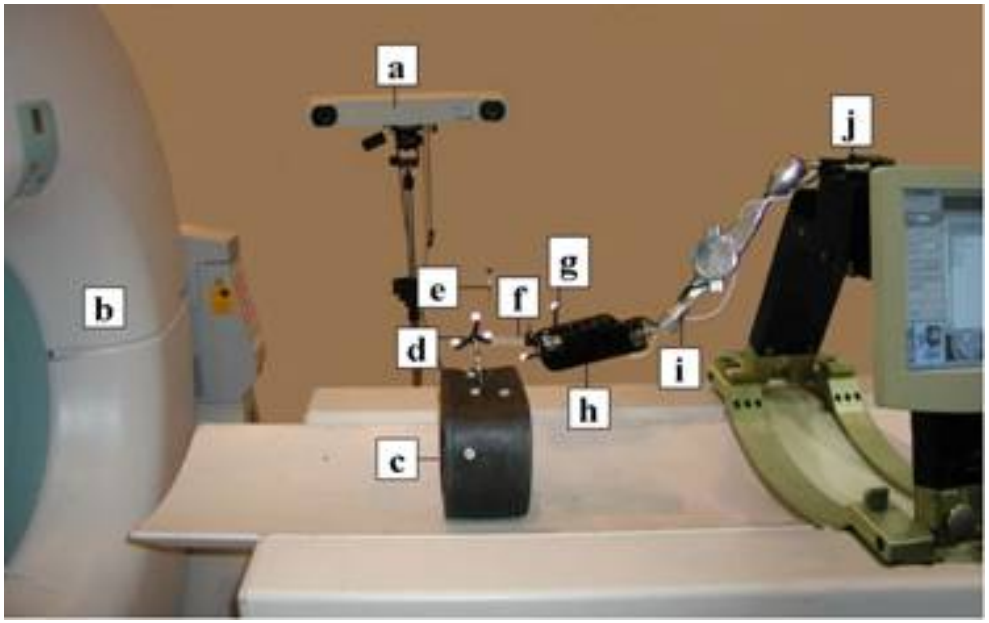
CT-guided to lung biopsy

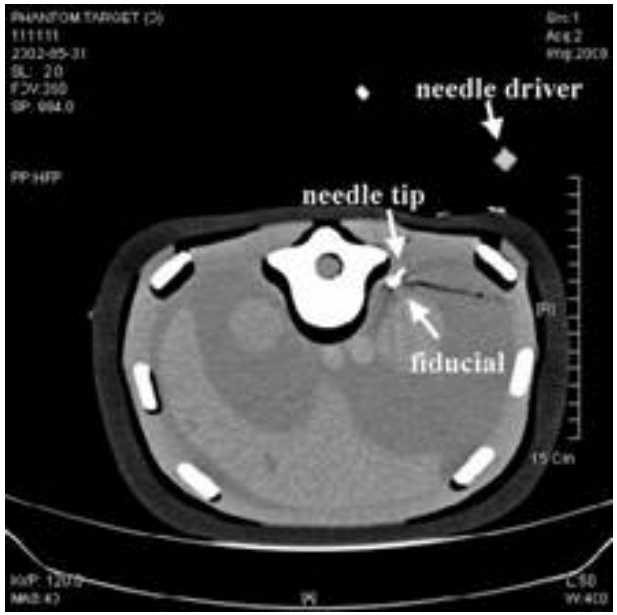
Robot registered to CT using the scanner's alignment laser

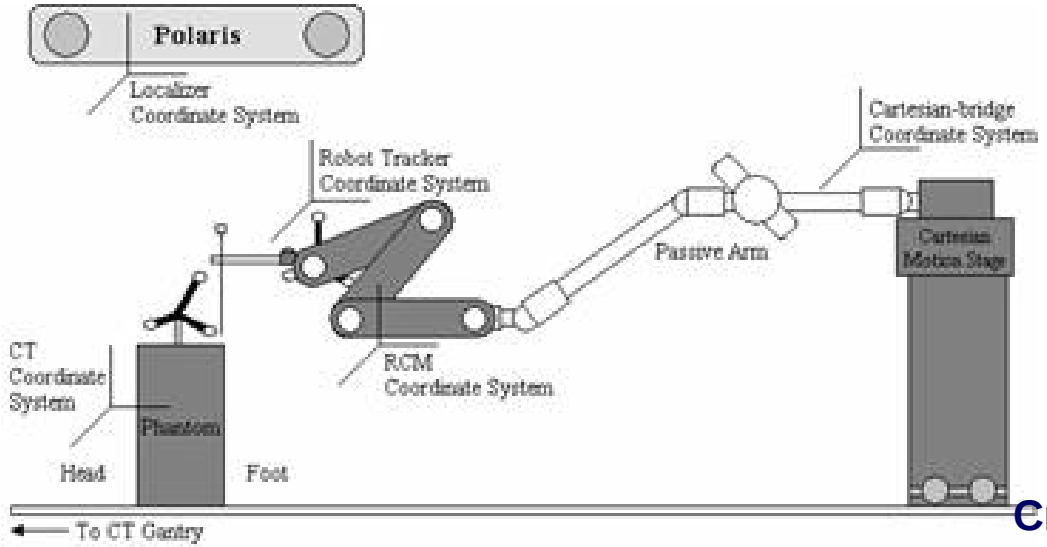


Credit: D. Stoianovici, L. Kavoussi, A. Patriciu, S. Solomon, JHU Bayview and G. Fichtinger, ERC

Motion tracking in spine biopsy



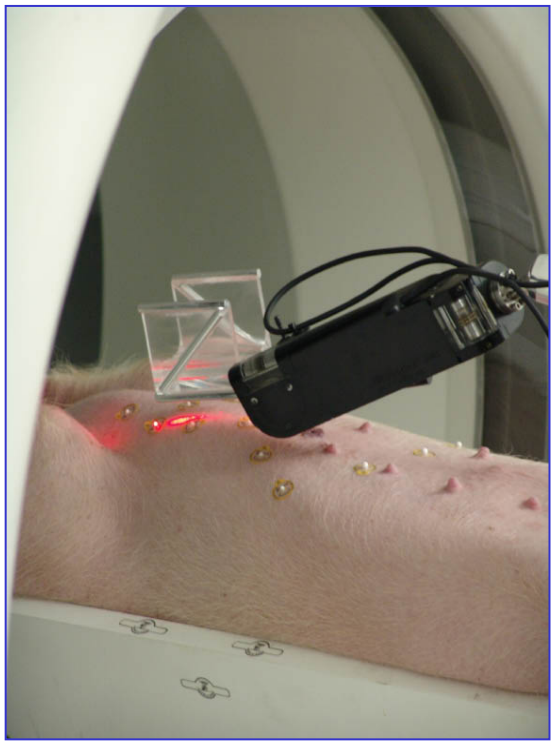


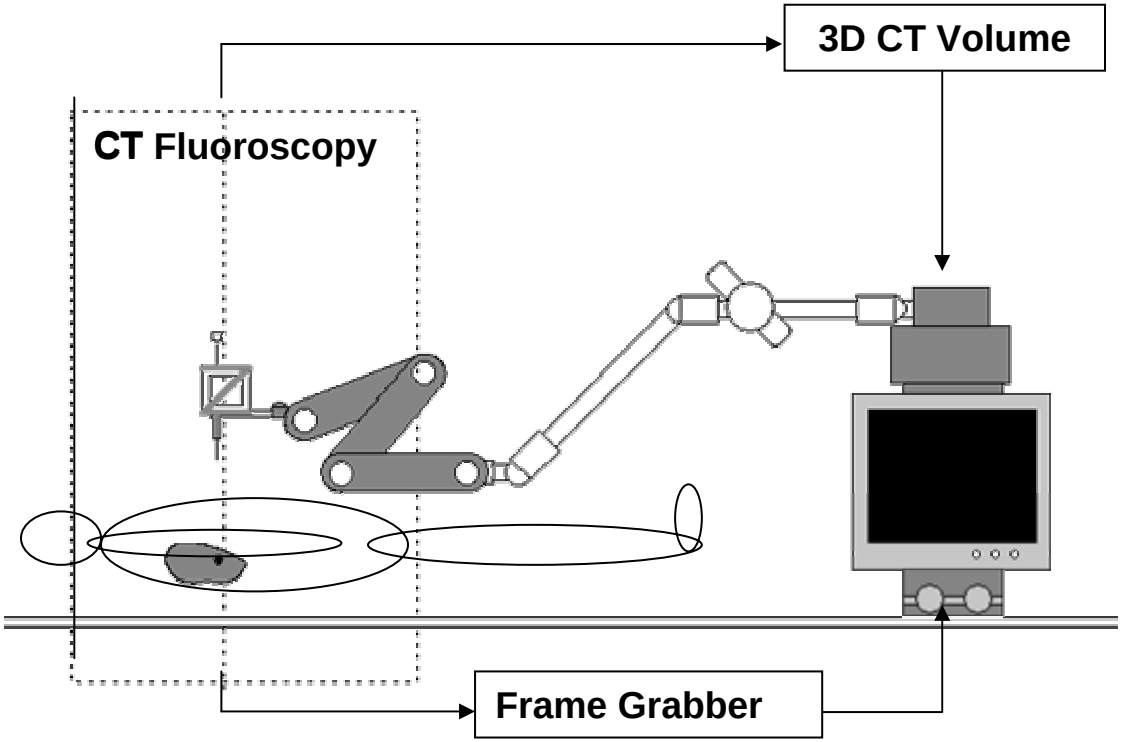


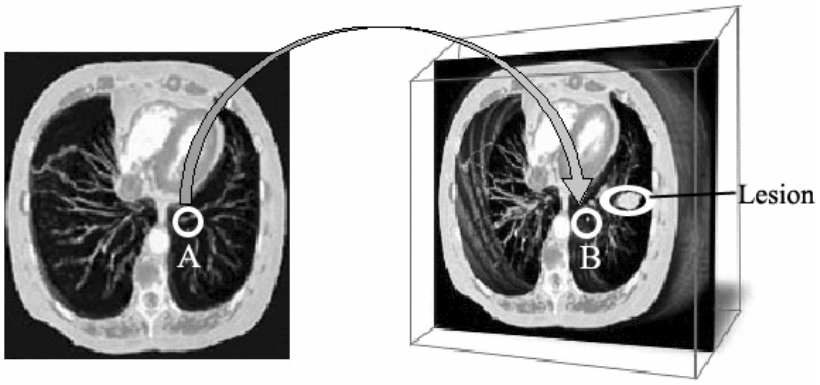
Tracker
Invasive

Credit: Xu, Cleary, Fichtinger et al.

CTF-Guided Lung Biopsy







CT Fluoroscopy Image *Pre-operative 3D CT Volume*

Register real-time CTF to CT
Then compensate with robot

Credit: Xu, Cleary, Fichtinger et al.

CTF-Guided Lung Biopsy

Preliminary Results

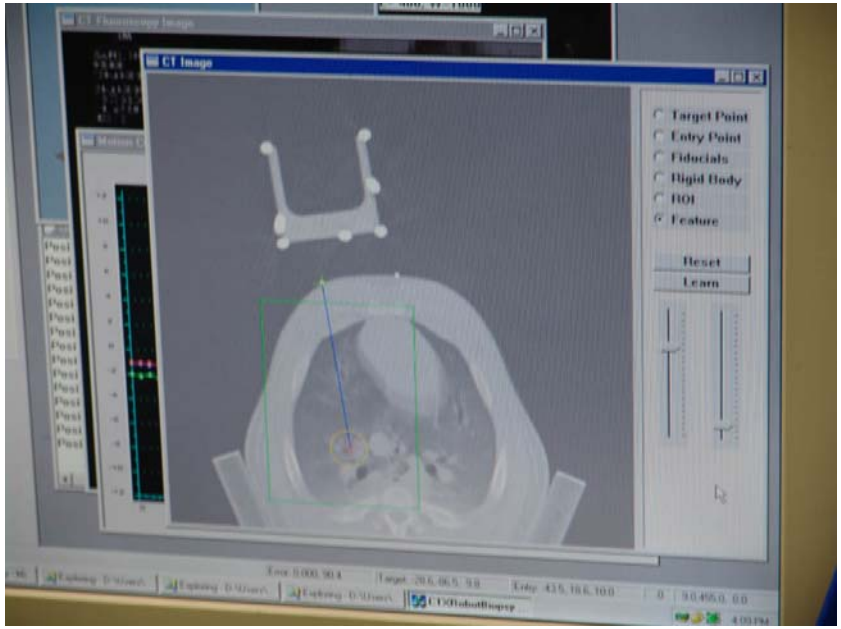
Tracking

On synthetic human image data, respiratory excursion: 0-20 mm:

- Average tracking error is 0.6 mm
- The standard deviation of the error is 0.4mm.

Overall Needle Placement

Visually correct, not yet quantified



Planned needle path

Actual needle path

Overview

- Needles Everywhere
- Microsurgical Assistants
- Point and Click Surgery
  - CT-guided systems
  - US-guided systems
  - MRI-guided systems
- Lessons Learned

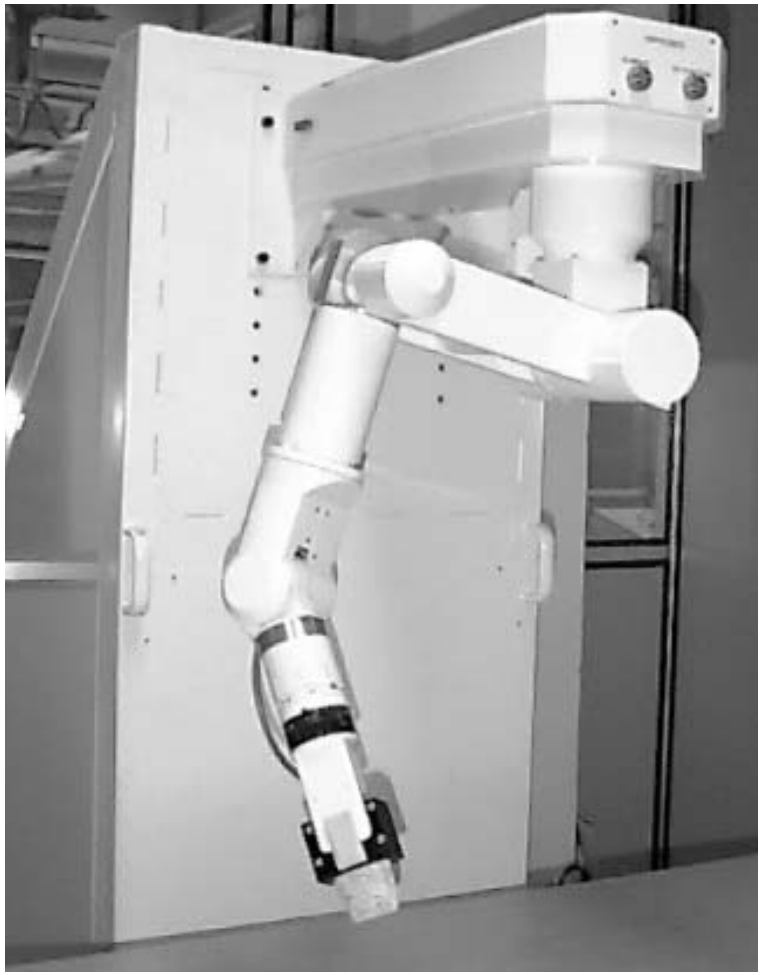
The challenge of US guidance

- **Operator dependent**
- **Invasive (deforms tissue)**
- **No image outside the body**

Salcudean et al.: 5-DOF tele-echograph

Credit: Tim Salcludean et al.

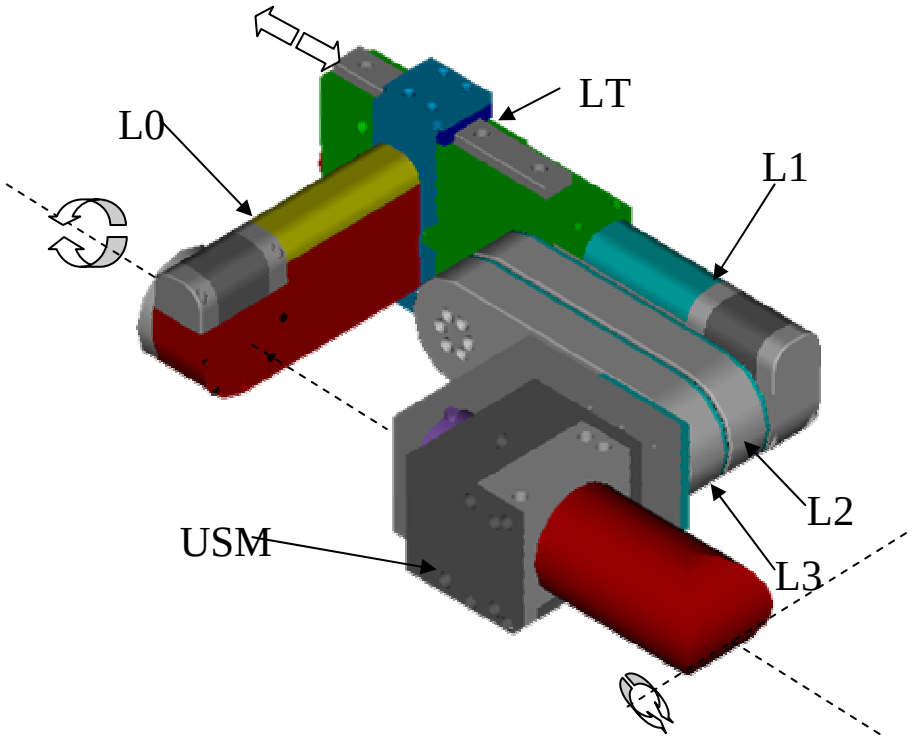
Degoulange te al.: Hippocrate tele-echograph



Troccaz et al.: 6-DOF tele-echograph

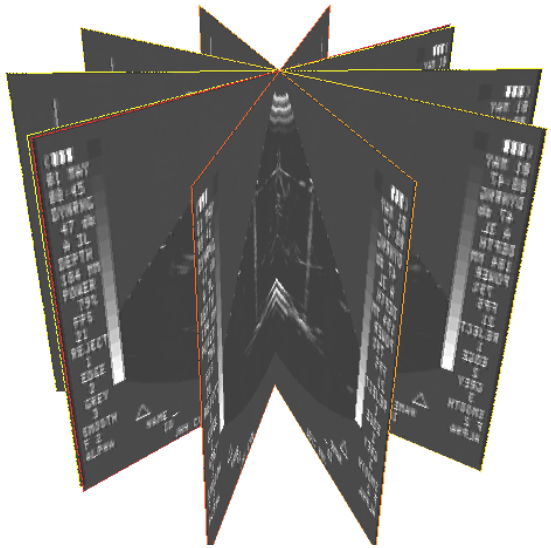
- Master-Slave system
- Remote exam by an expert
- With force feedback (Phantom)
- US probe moved by a light 6DOF robot
- Several communication media (RNIS, LAN, VTHD, etc.)
- Clinical validation (Brest/Grenoble – aortic abdominal aneurysms)

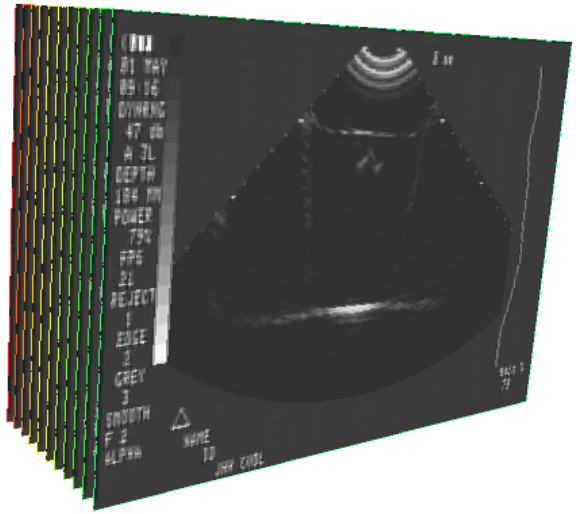
The Hopkins TRCM Robot

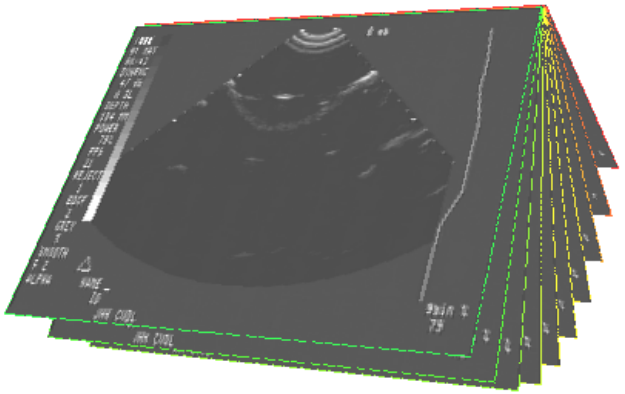


Credit: Randy Goldberg

TRCM in action

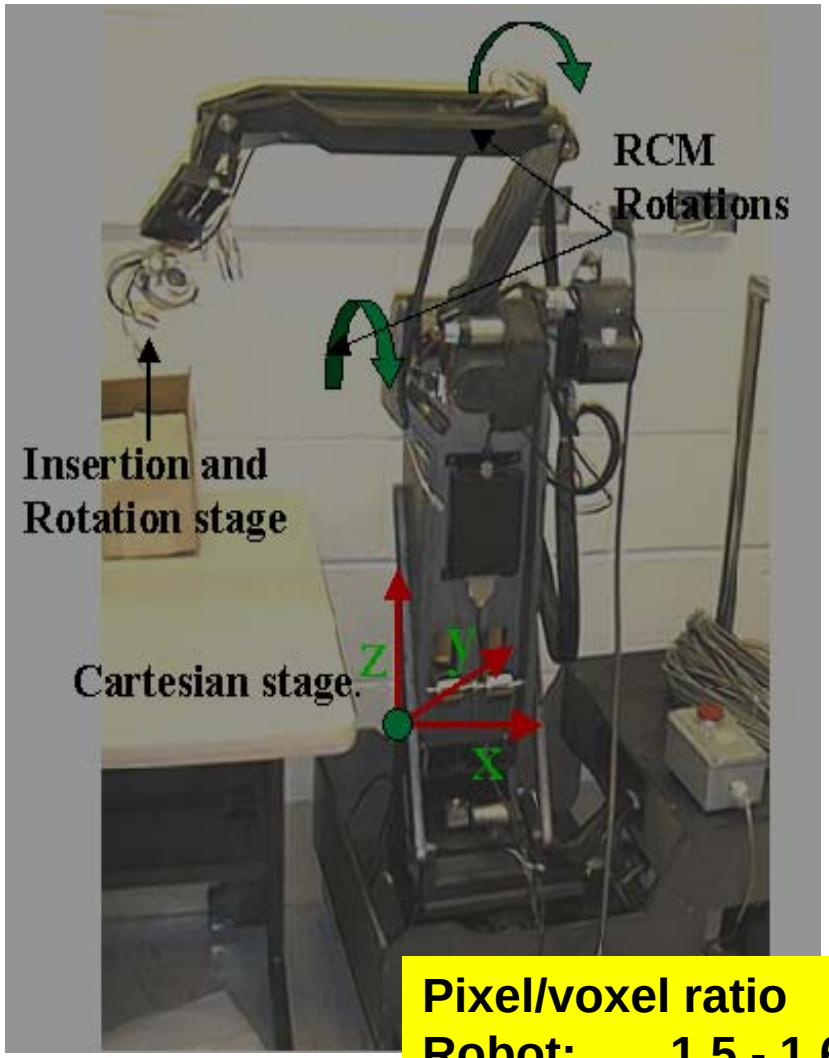






Credit: Randy Goldberg

Robotic 3D US w/ LARS robot



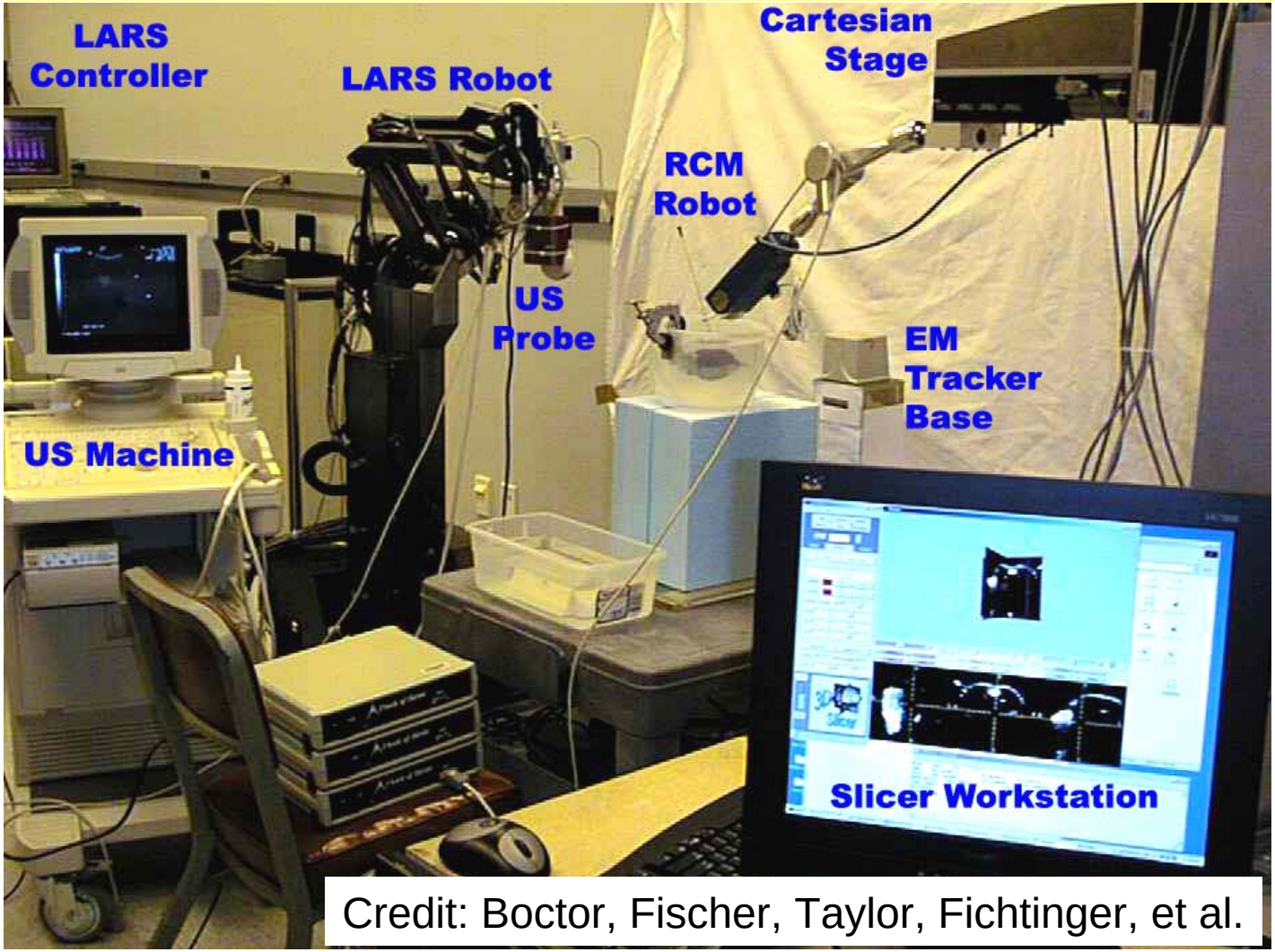
Both direct control and force compliant mode

Pixel/voxel ratio
Robot: 1.5 - 1.6
Freehand: 0.3 - 0.8

Credit: Boctor, Fischer, et al.

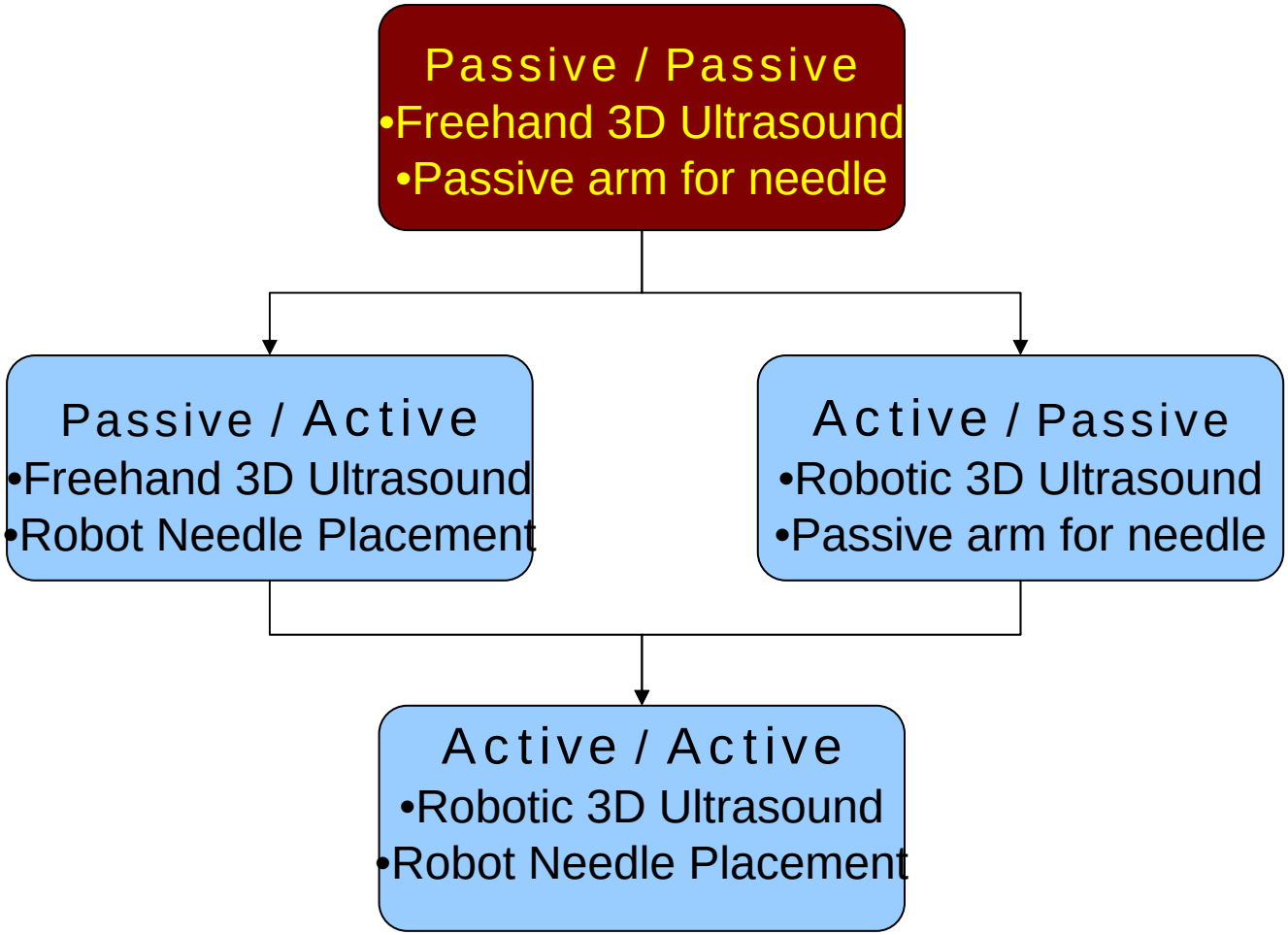
Hopkins dual arm testbed

Testbed for calibration, control, and interventions



Credit: Boctor, Fischer, Taylor, Fichtinger, et al.

Dual arm alternative configurations

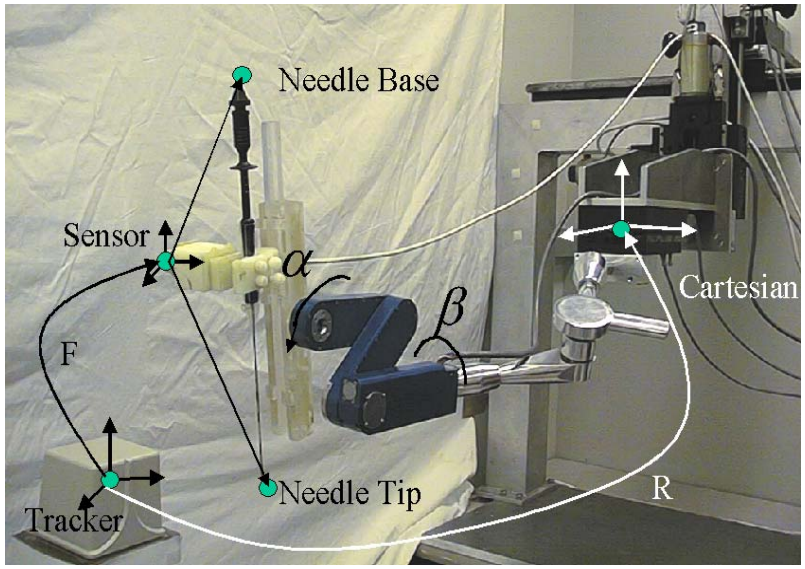


Credit: Boctor, Fischer, Taylor, Fichtinger, et al.

Virtual RCM needle placement

- Needle calibrated to tracker
- Pose from tracker

- 3-DOF Cartesian manipulator
- 2-DOF rotation module
- Unencoded passive arm
- EM tracker (FOB)

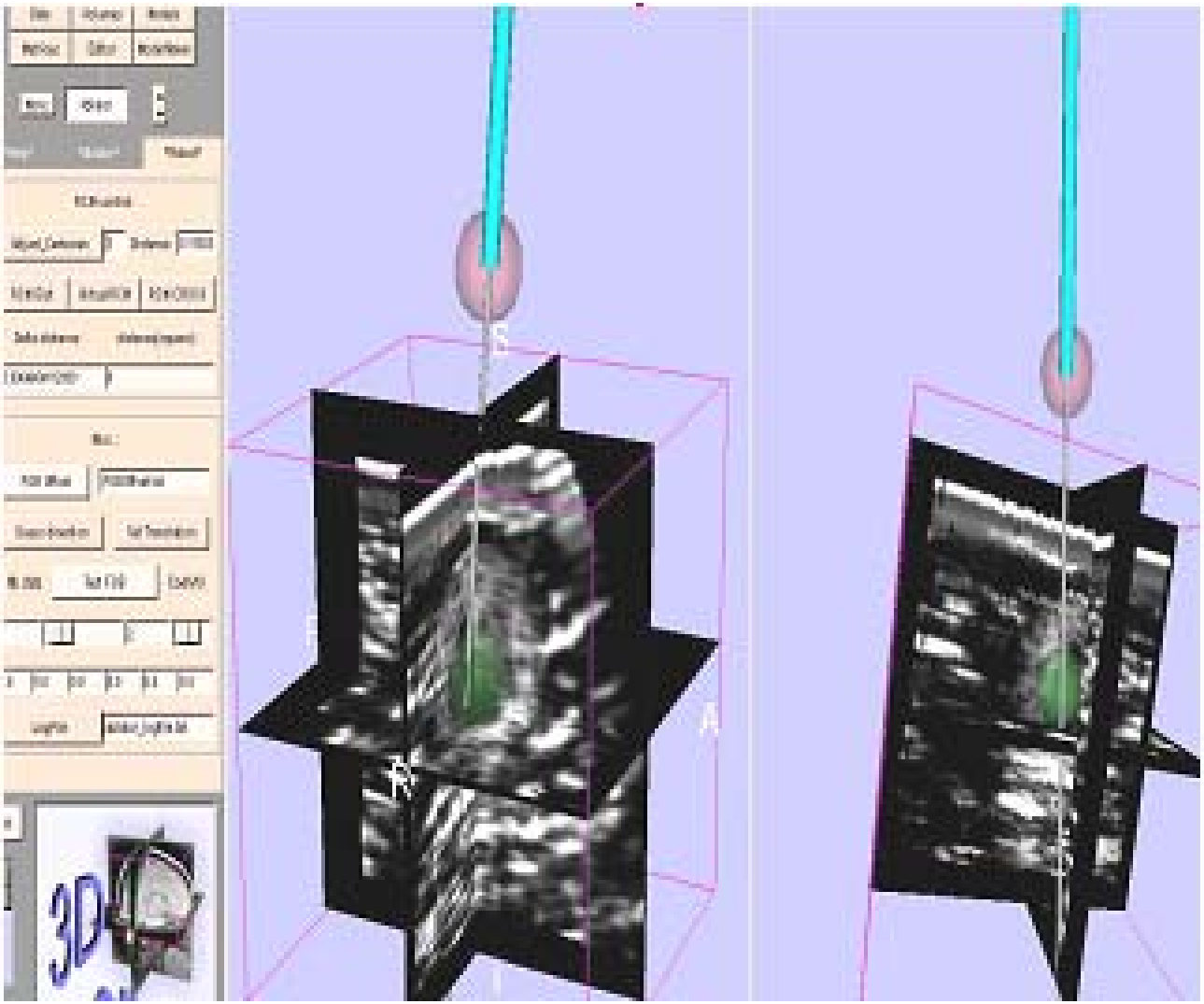


“Quasi-decoupled kinematics”

Un-calibrated kinematics

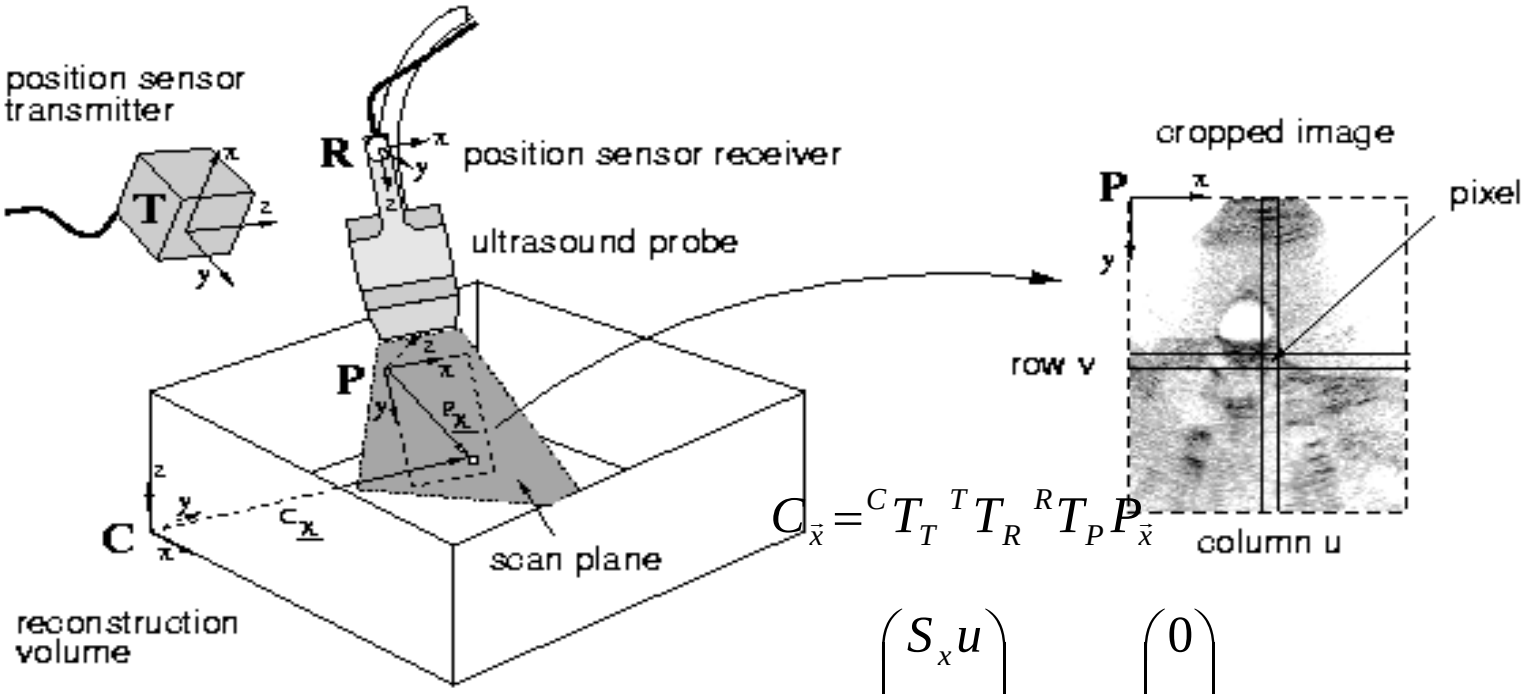
Credit: Boctor, Webster, Okamura, Fichtinger

CISUS – Slicer-based planning and control system



US probe calibration –a plethora of problems

The formulation of transformations in the cross-wire



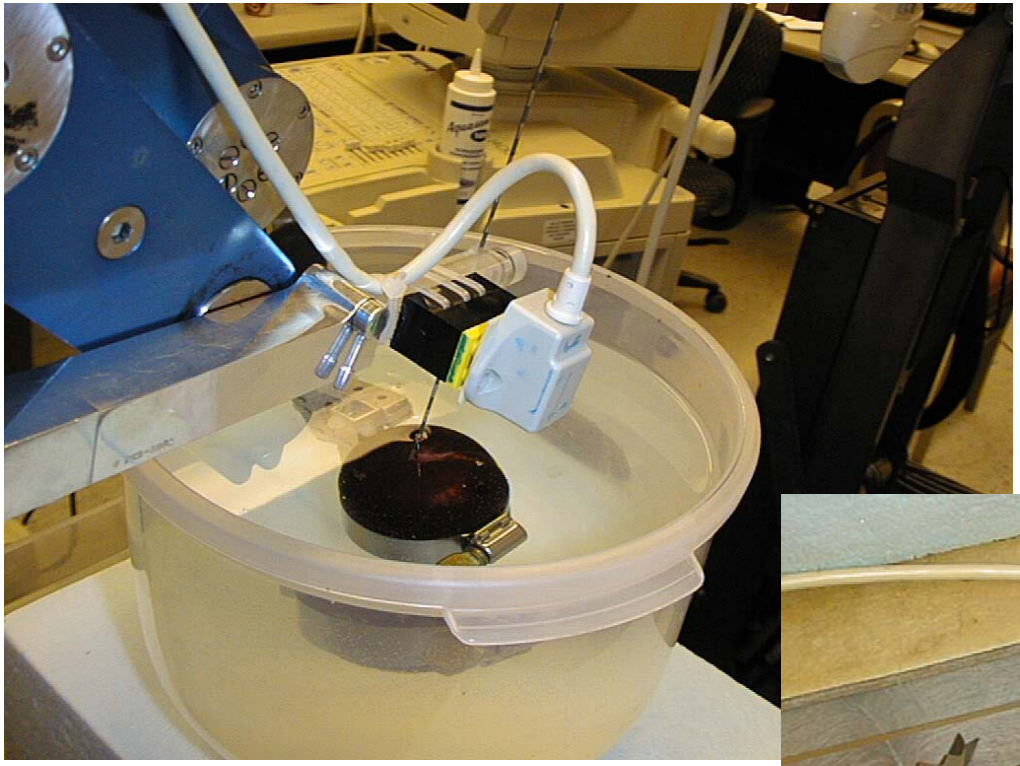
$$C_{\vec{x}} = {}^{C}T_{T}\,{}^{T}T_{R}\,{}^{R}T_{P}\,P_{\vec{x}}$$

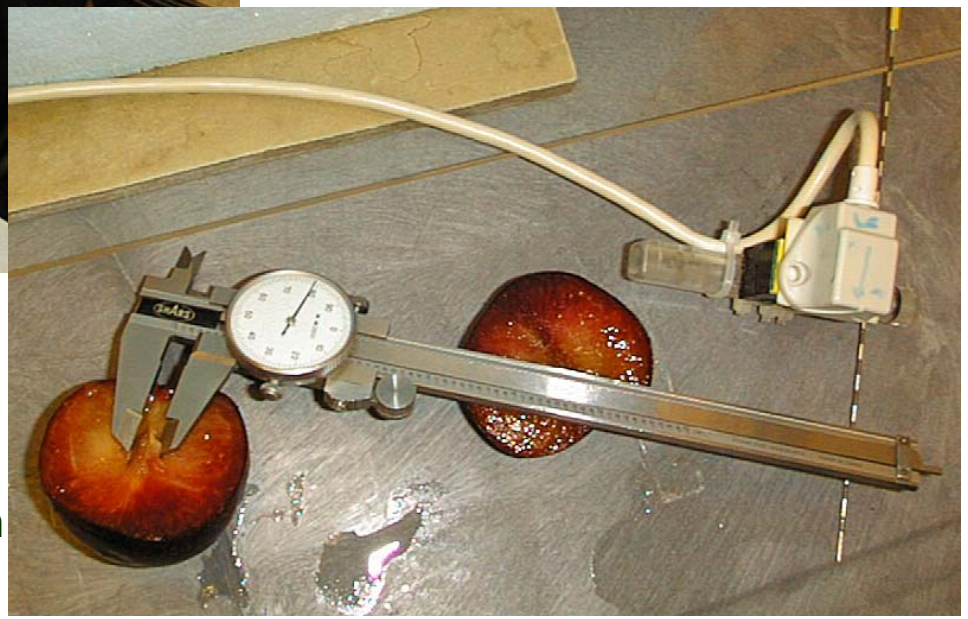
DO NOT UNDER ESTIMATE IT

$$P_{\vec{x}} = \begin{pmatrix} S_x u \\ S_y v \\ 0 \\ 1 \end{pmatrix}, C_{\vec{x}} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

(Courtesy of R. Prager)

Dual arm system: preliminary results

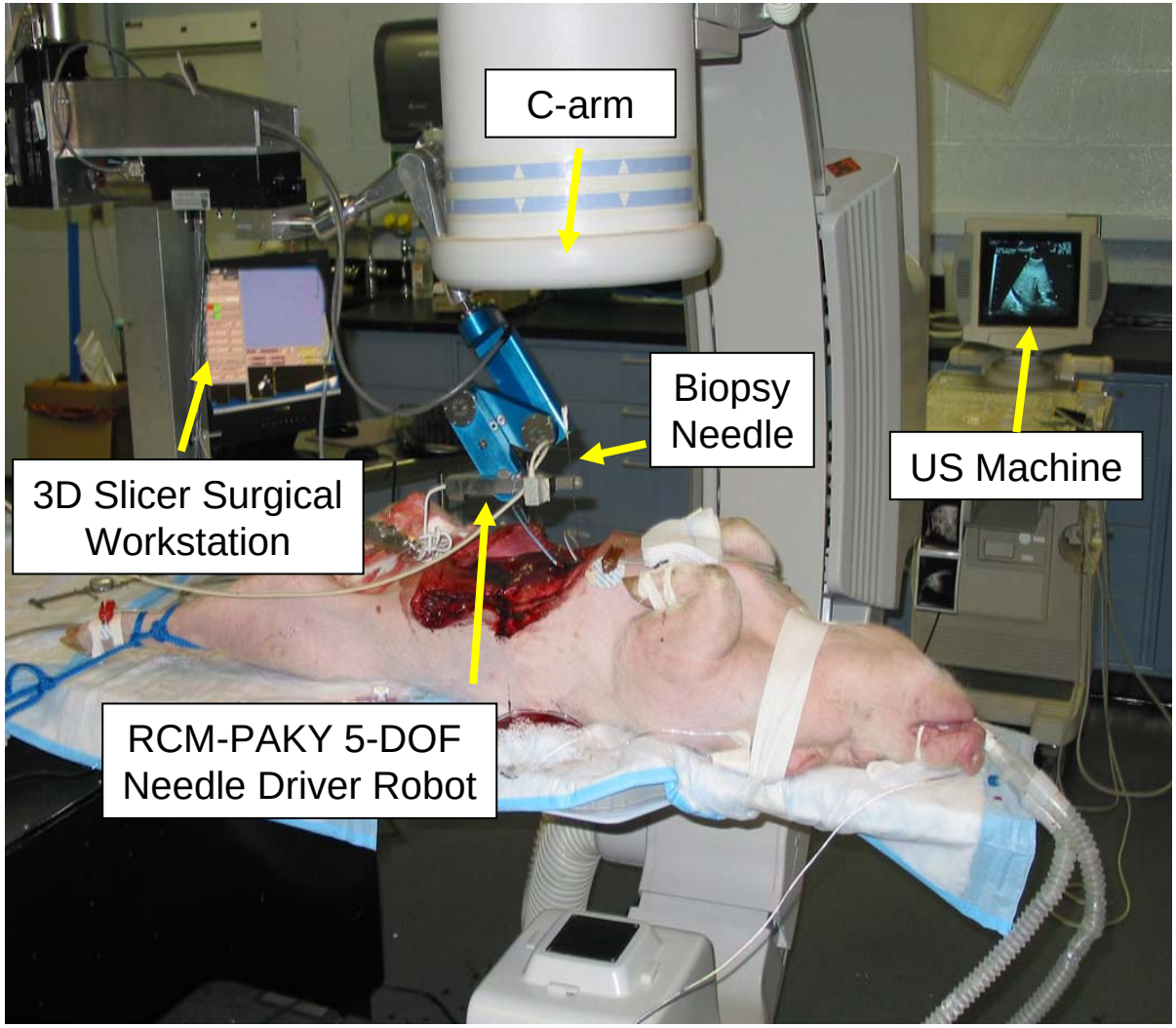




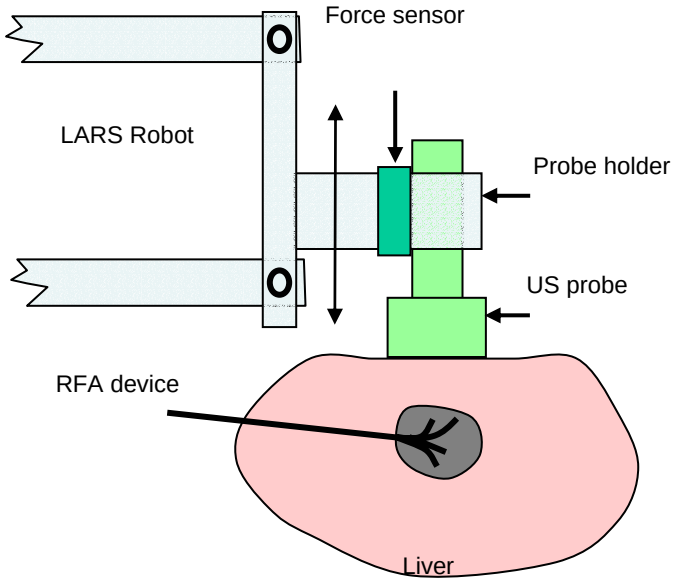
Average Error: ~3mm (from 10 trials)
Error Propagation:
- **US Calibration: 1.2 mm**
- **Floating point truncation: 1-2 pixels**
- **Needle tip calibration error: ~0.5 mm**
- **EM sensor uncertainty: 2.54mm**

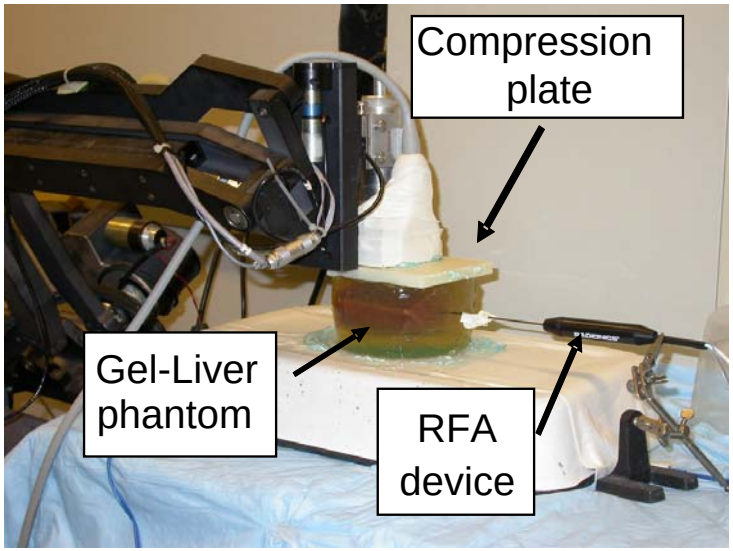
Credit: Boctor, Fischer, Fichtinger, et al.

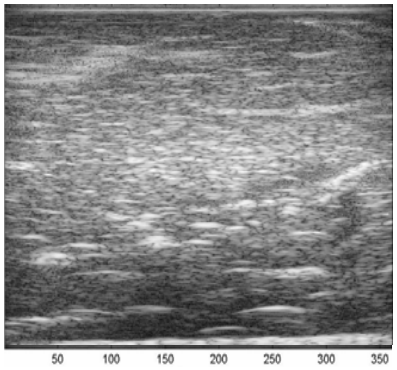
Active needle / passive US – live pig



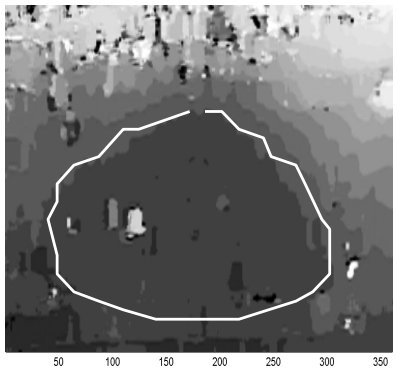
US Elastography in segmentation and monitoring



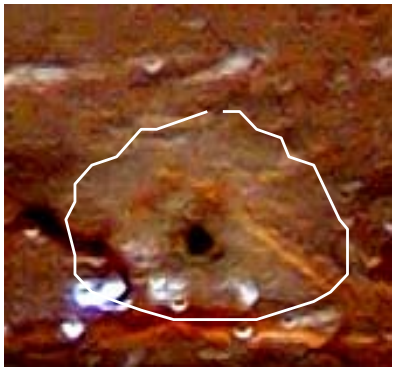




B-Mode image



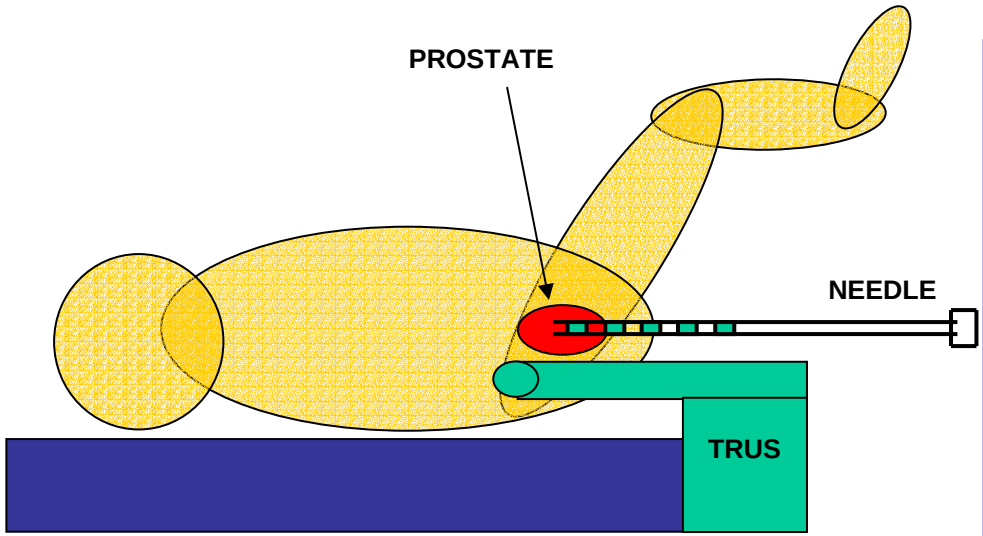
Strain image

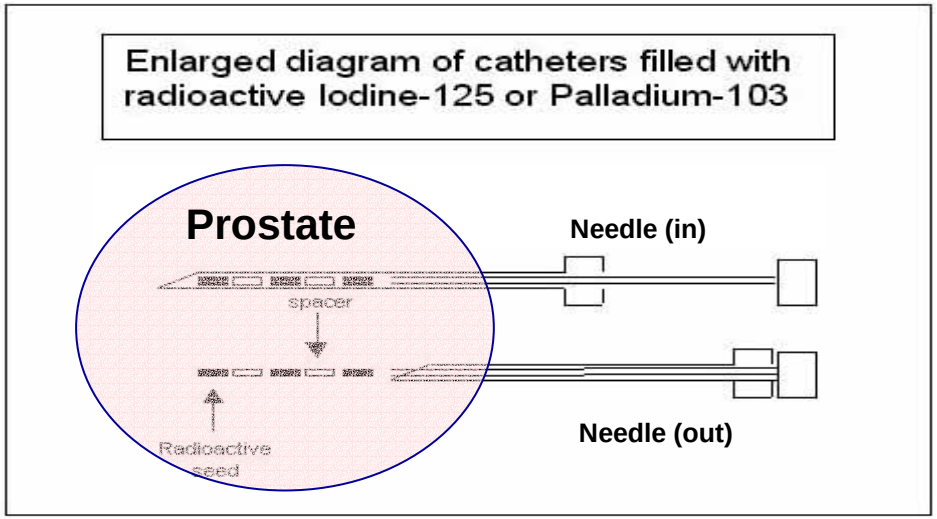


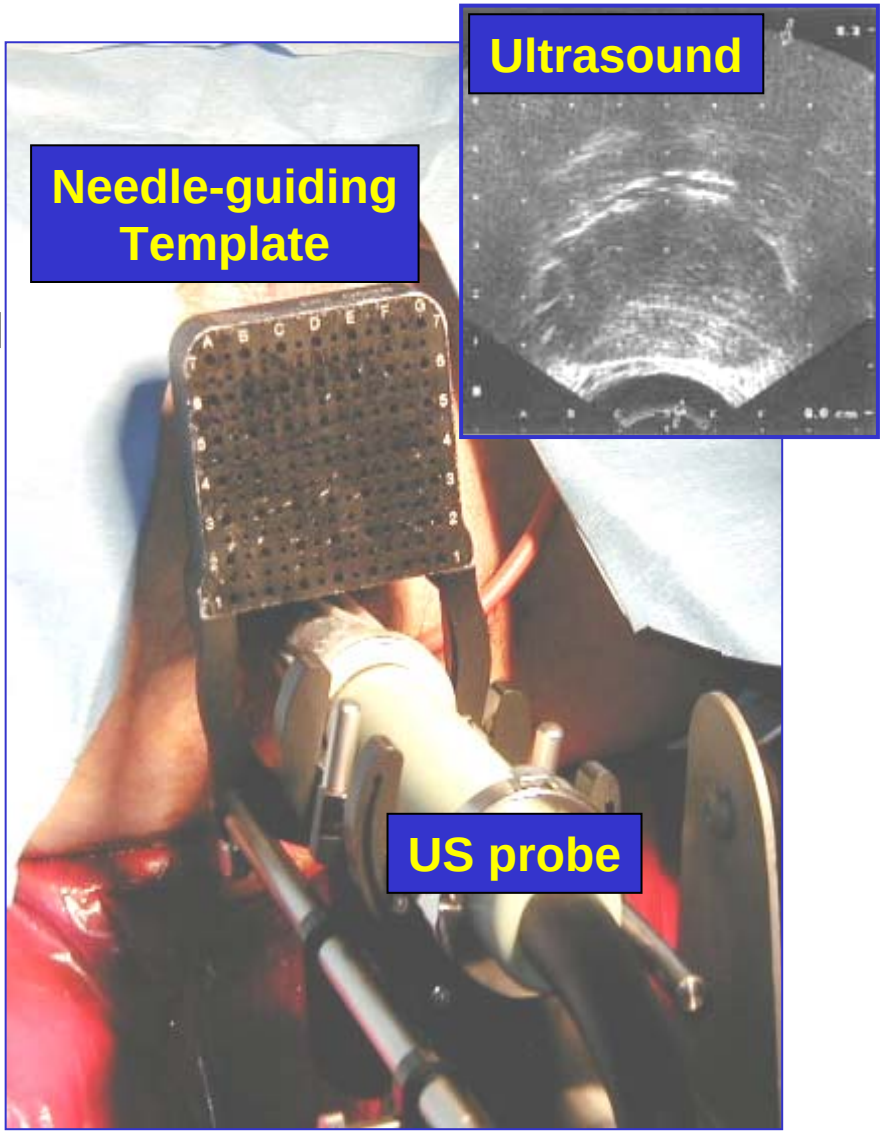
Pathology

Credit: Boctor, Fichtinger, Taylor, Choti et al.

TRUS-guided prostate brachytherapy



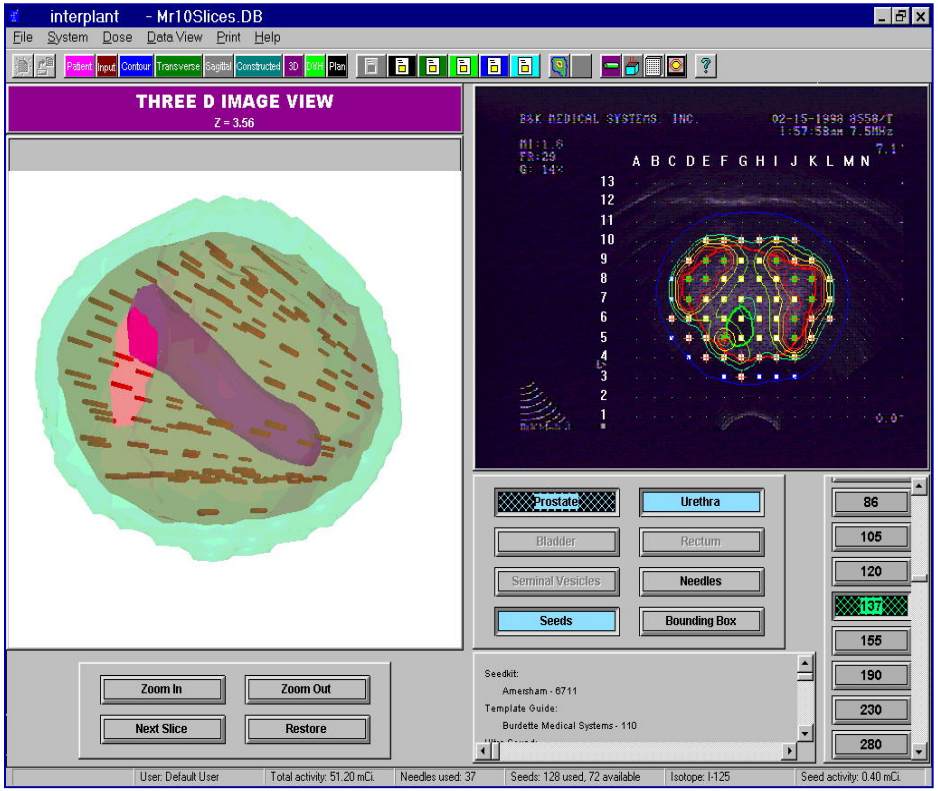




Courtesy of Paul Meskell, Beth Israel, Boston

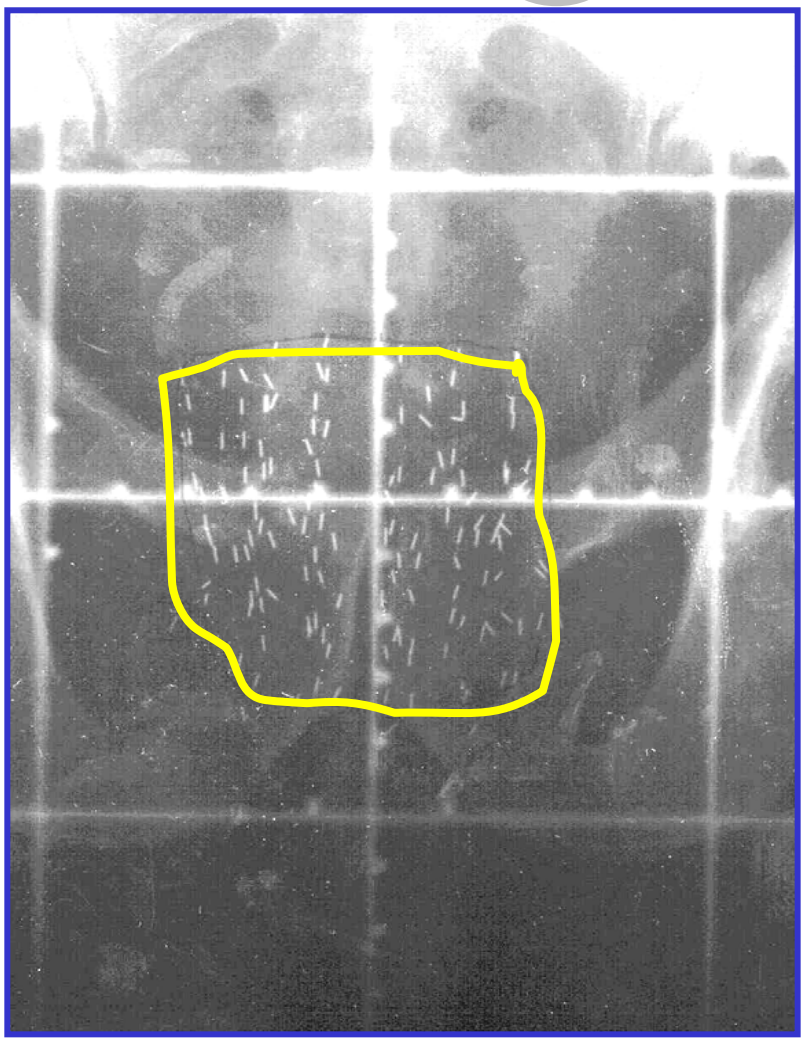
Plan versus result

PRE-OP PLAN



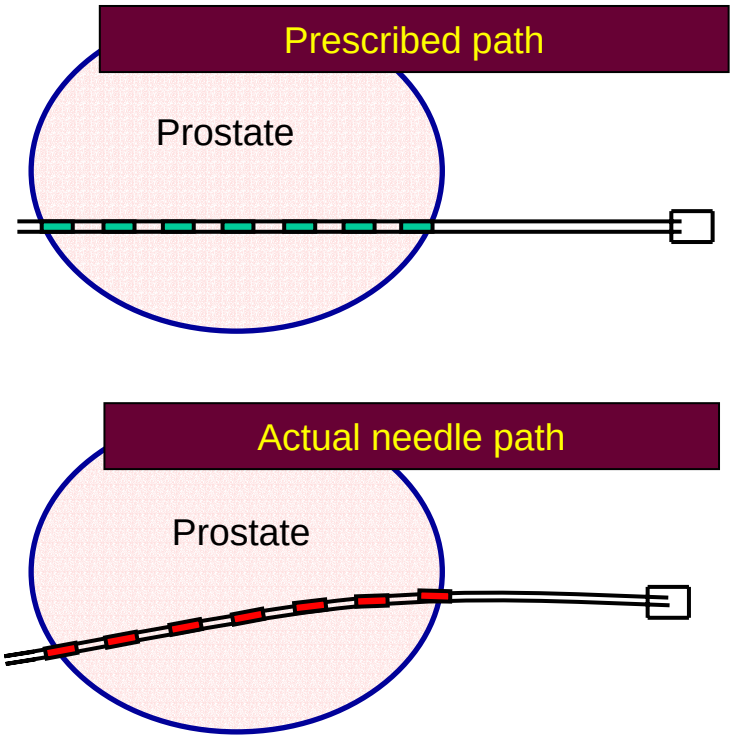
Courtesy of Burdette Medical Systems, Inc.

POST-OP RESULT

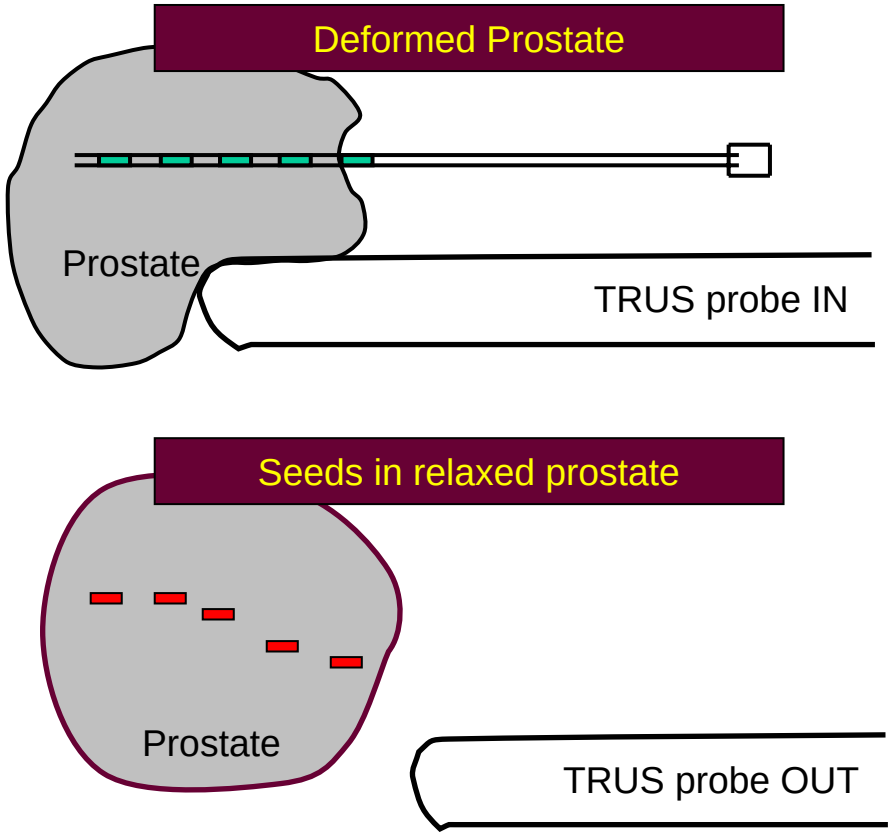


Why do implants go wrong?

(1) Needle Deflection

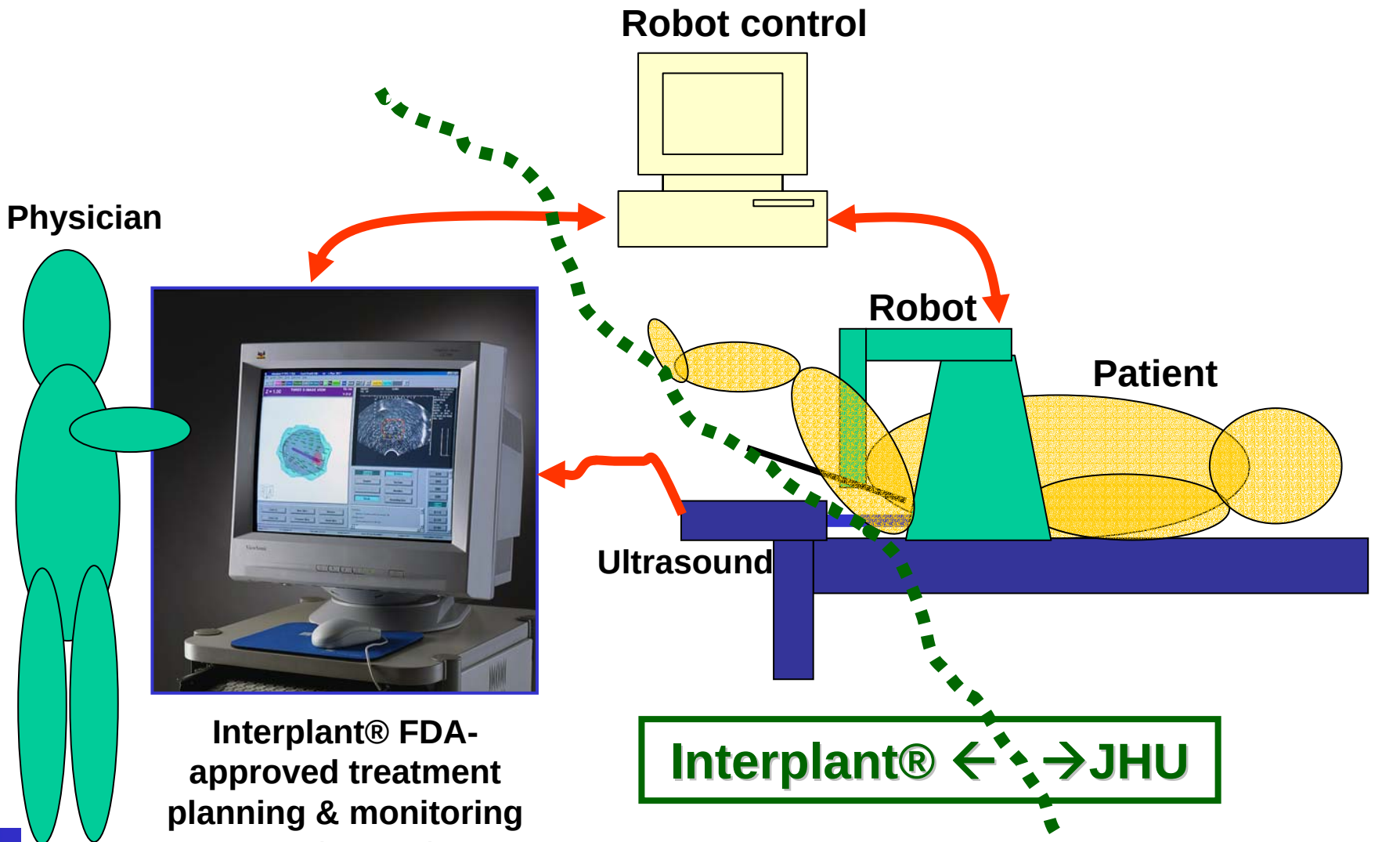


(2) Motion and Deformation Caused by Needle and Probe

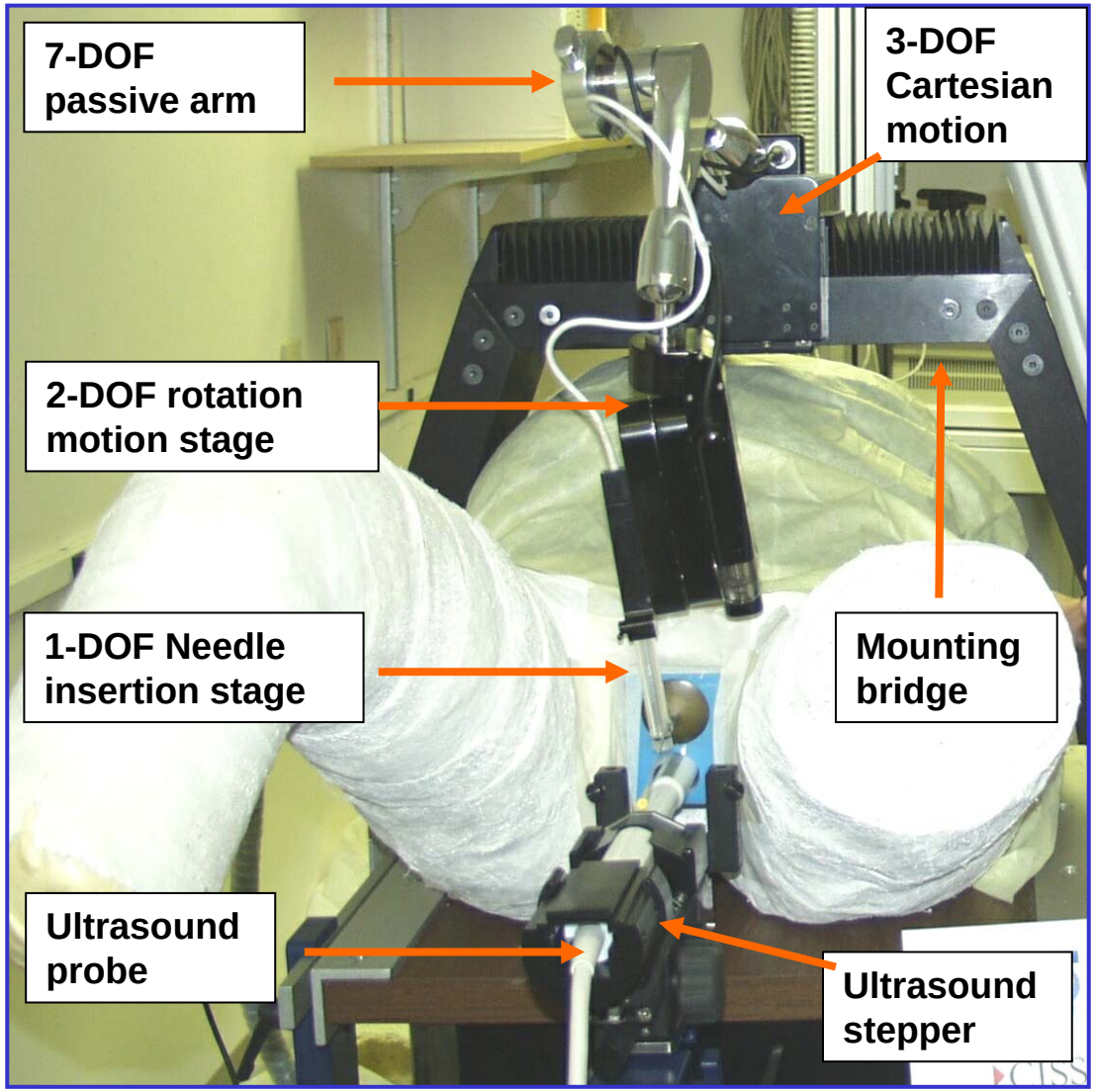


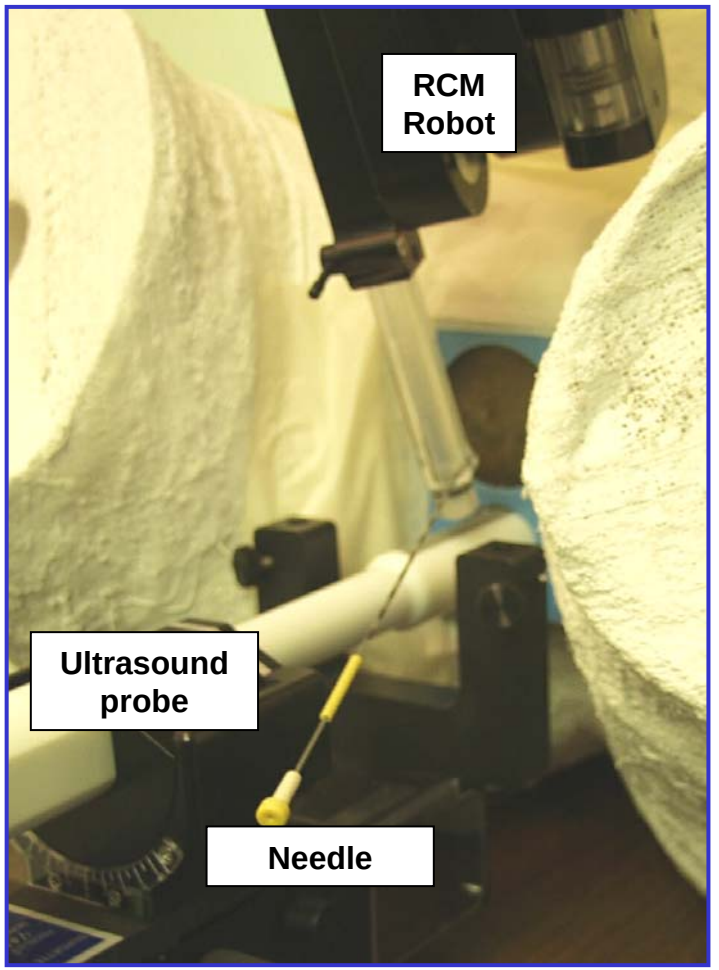
(3) Intra- and Post-Operative Edema

Our take: robotic assistance



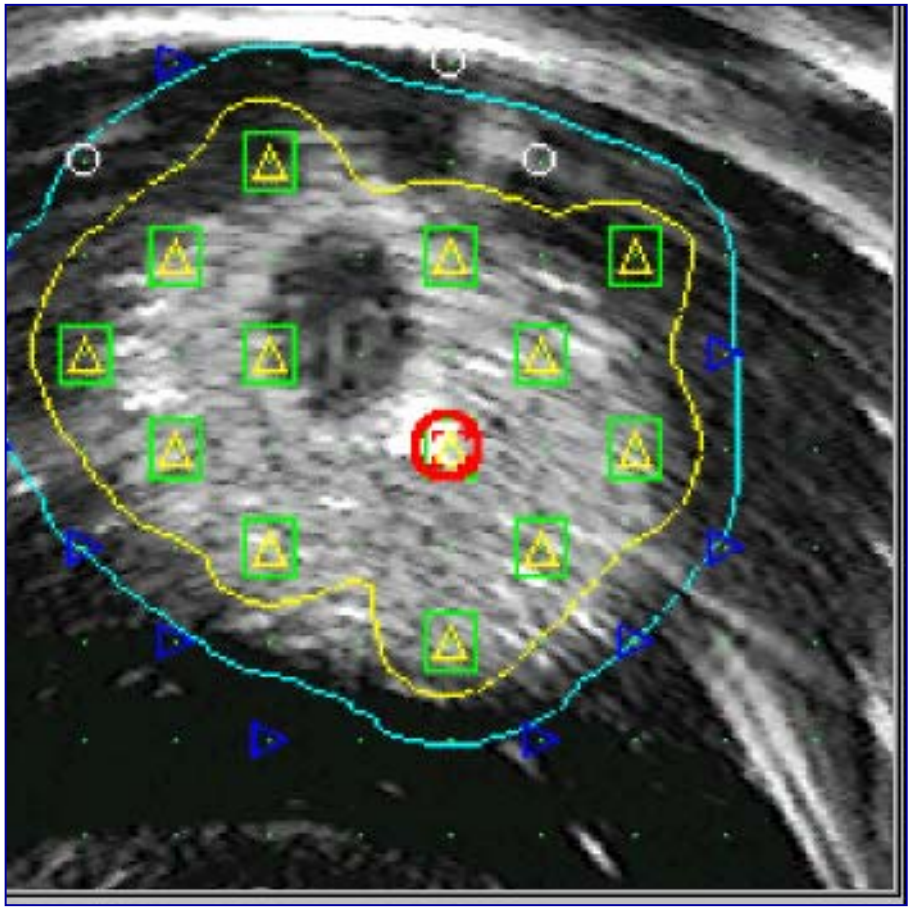
6-DOF decoupled Accubot™



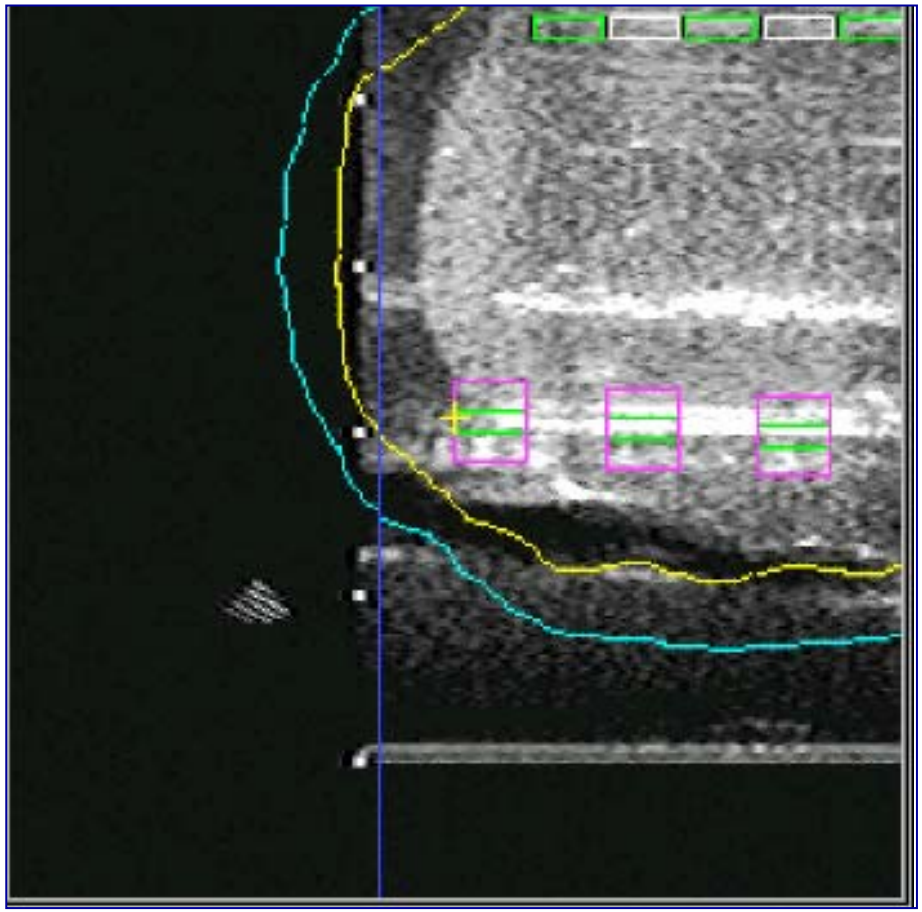


Credit: Stoianovici, Whitcomb, Burdette, Fichtinger

Needles and seeds tracked in TRUS



Needle captured in live transverse image



Seed captured in live sagittal image

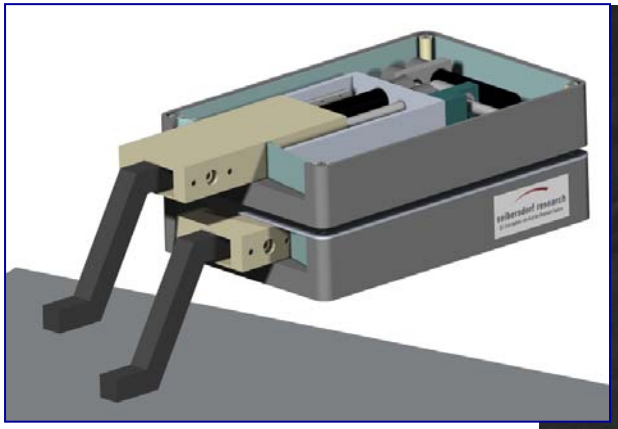
Credit: Stoianovici, Whitcomb, Burdette, Fichtinger

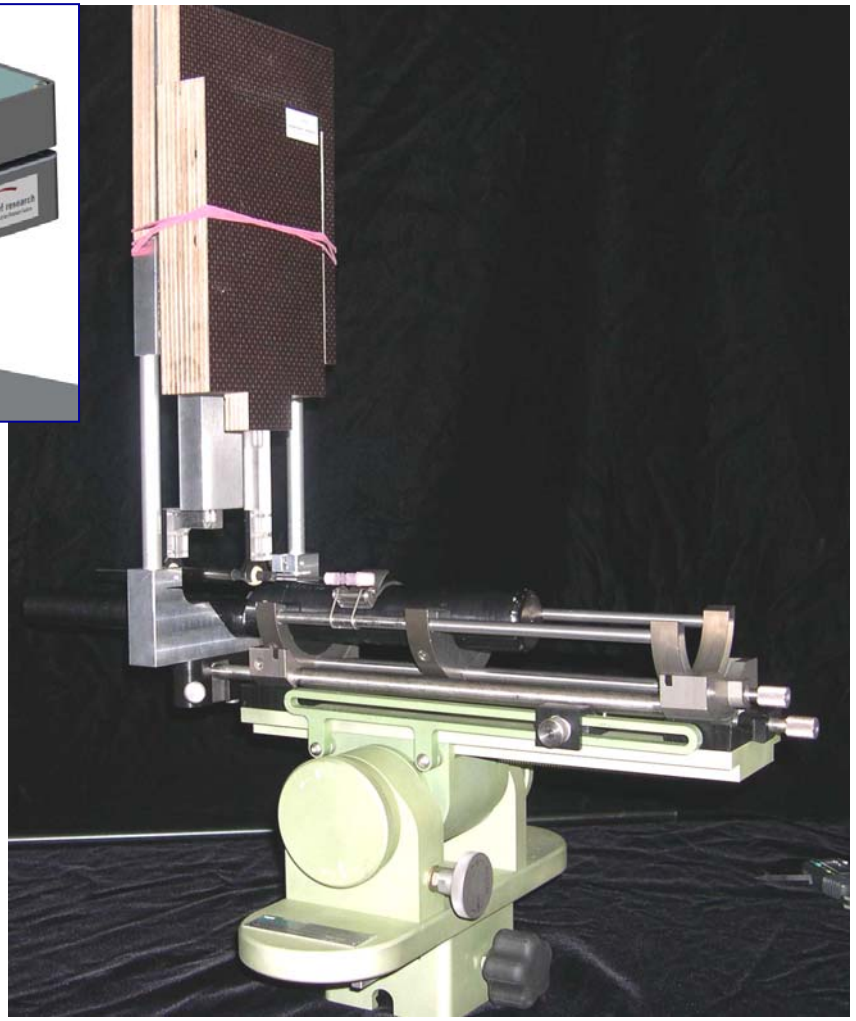
Phantom results

- Reached all relevant locations in prostate
- Demonstrated arbitrary entry and angle
- Aiming error:
  - ~ 2.0 mm
  - worst case 2.5 mm
  - 80% in 2 mm margin
- Depth error:
  - ~ 2.5 mm
  - worst case 5.0 mm
  - 70% in 2.5 mm margin
- Large size, cumbersome calibration
- Difficult to capture implants in TRUS

Credit: Stoianovici, Whitcomb, Burdette, Fichtinger

4-DOF decoupled brachytherapy robot

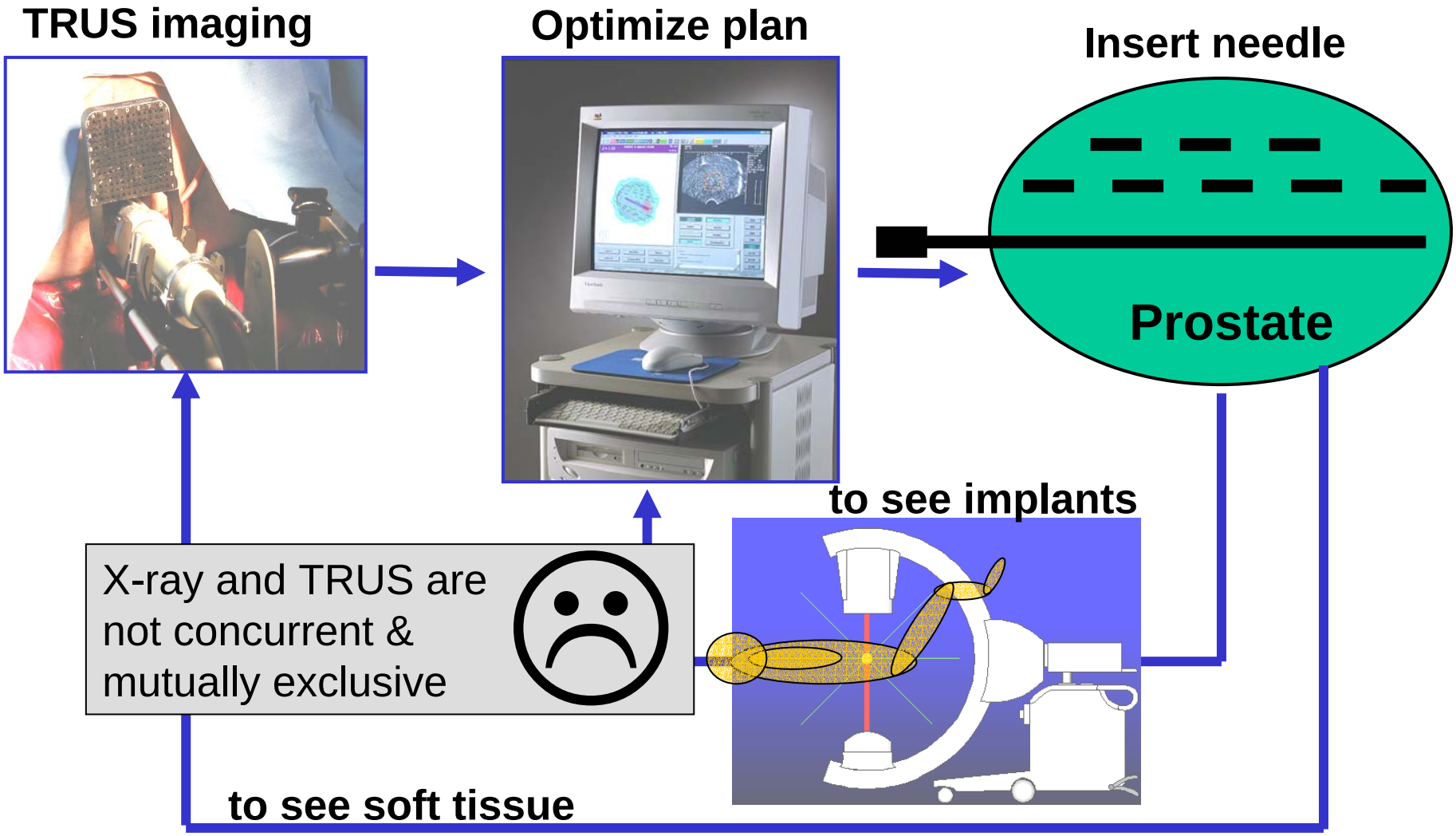




- **Integrated with TRUS**
- **Manual but encoded needle insertion**

Credit: Kronreif, Burdette, Iordachita, Kazanzides, Fichtinger

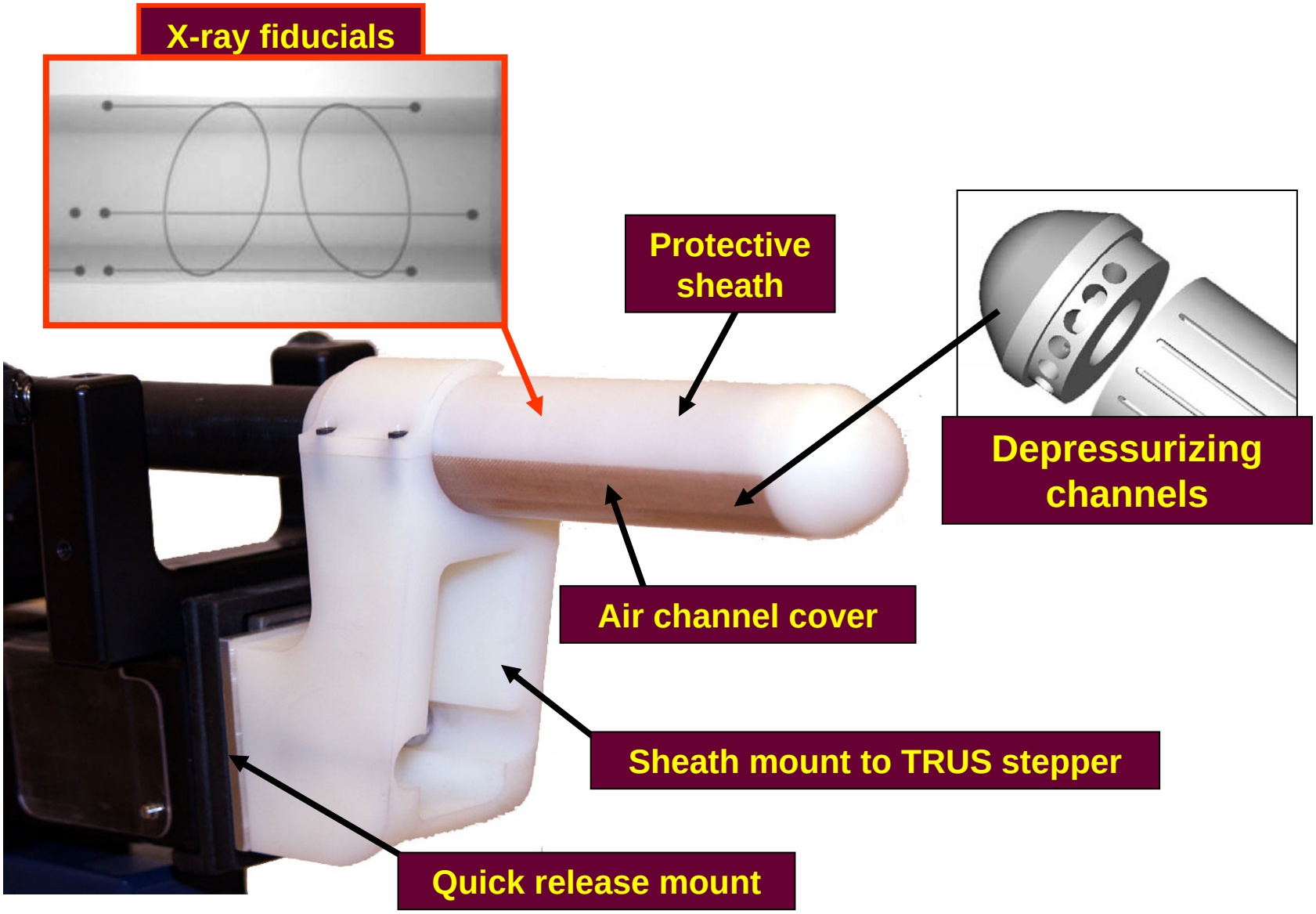
Fusion of TRUS and X-ray fluoroscopy



Industry partner: CMS Burdette Medical

Credit: Chirikjian, Burdette, Fichtinger

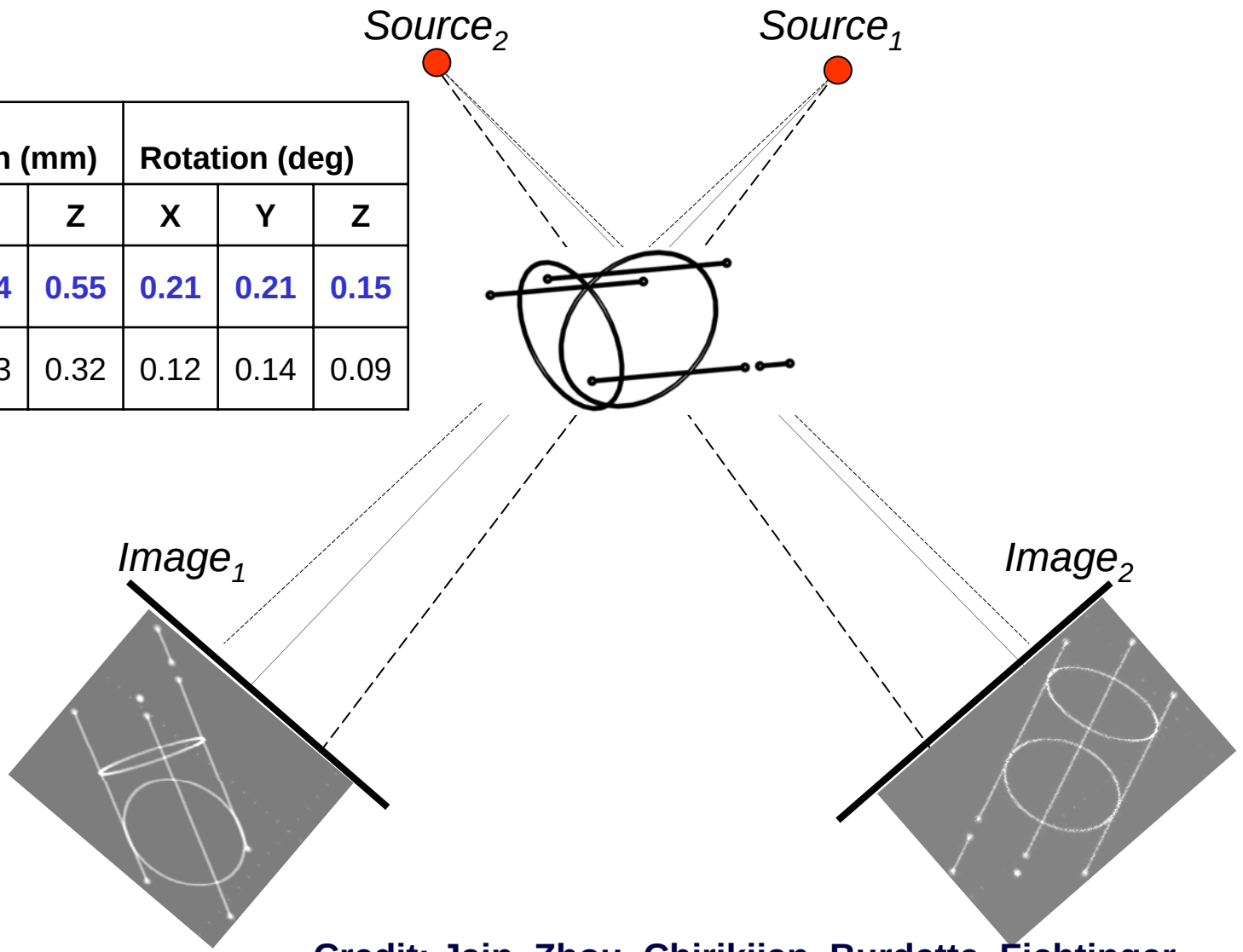
Protective rectal sheath w/ 6-DOF X-ray fiducials



Credit: Wyrobek, Mustufa, Jain, Burdette, Fichtinger

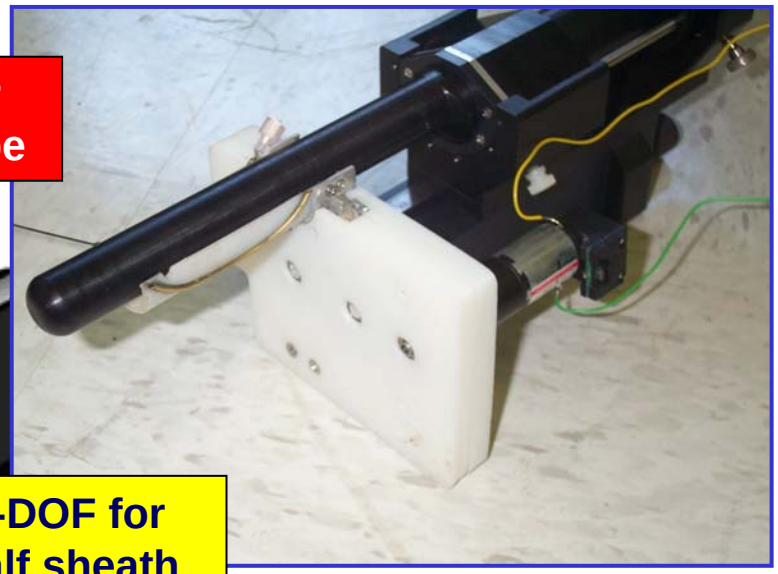
Register each image to the fiducial

	Translation (mm)			Rotation (deg)		
	X	Y	Z	X	Y	Z
Mean	**0.07**	**0.04**	**0.55**	**0.21**	**0.21**	**0.15**
STD	0.05	0.03	0.32	0.12	0.14	0.09



Credit: Jain, Zhou, Chirikjian, Burdette, Fichtinger

Intra-rectal robot around TRUS probe – decoupled 2+2+2 DOF



2-DOF for needle insertion (currently manual)

2-DOF for TRUS probe

Prostate

Prostate stabilizer

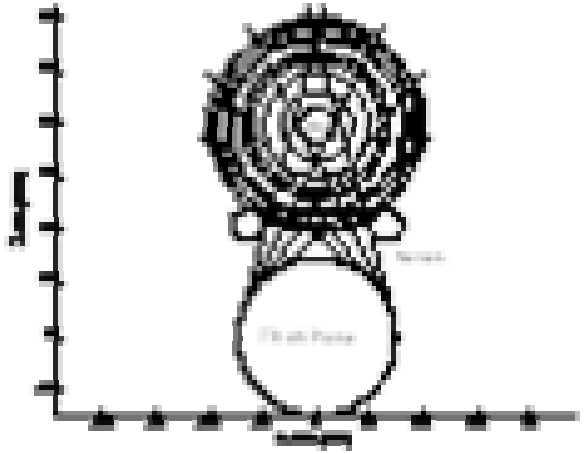
2-DOF for half sheath

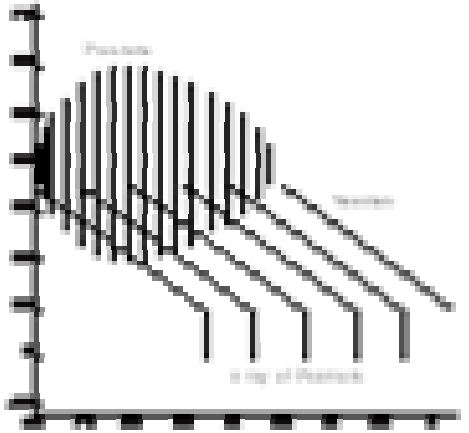
Needles bent inside curved guides

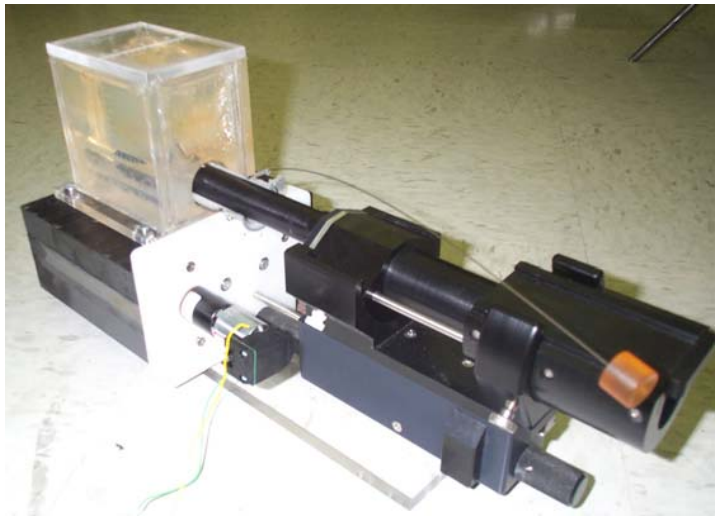
Industry partner: Acoustic MedSystem

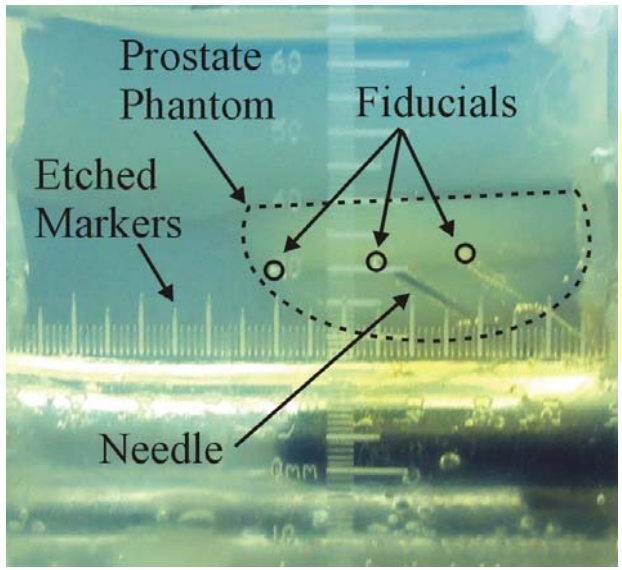
Credit: Okamura, Schneider, Fichtinger

First phantom experiments









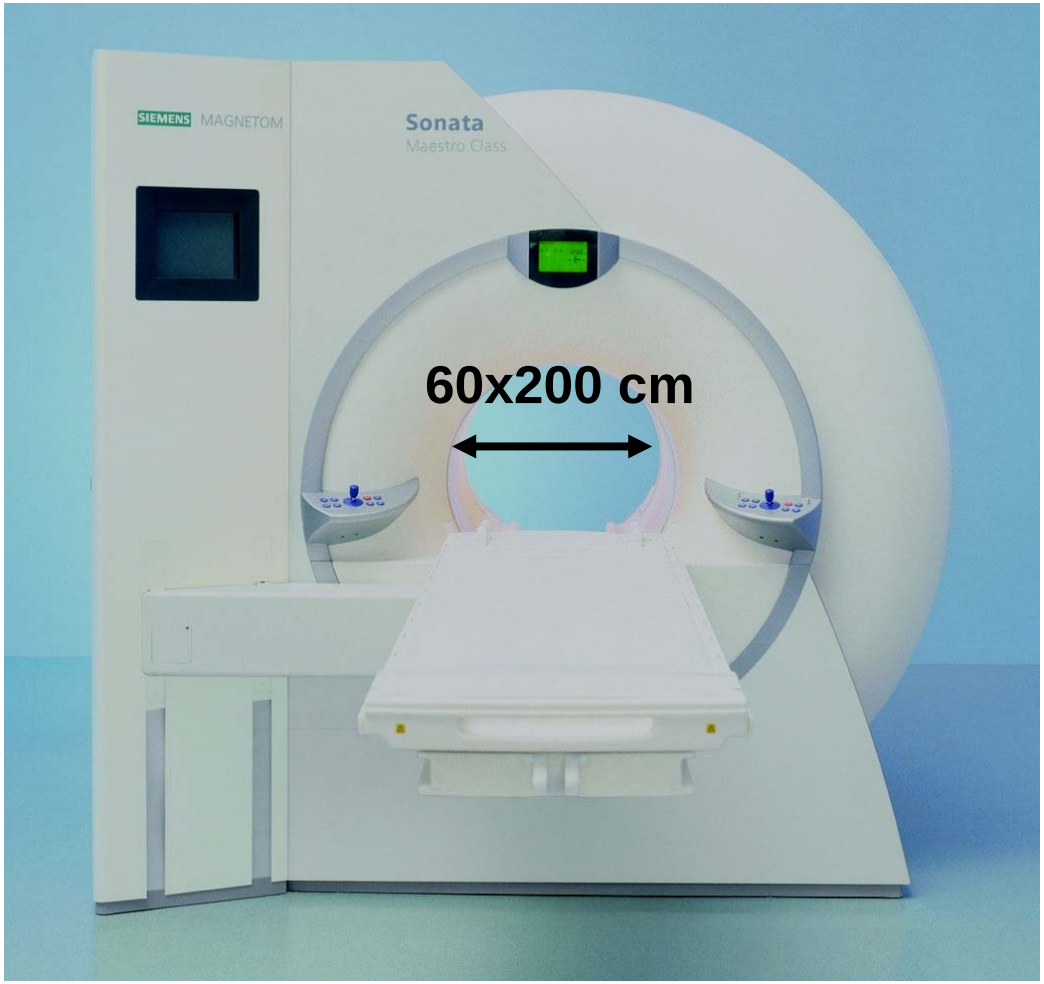
- Mean 2.5 mm (p=0.30)
- Reduced tissue deformation

Credit: Okamura, Schneider, Fichtinger

Overview

- Needles Everywhere
- Microsurgical Assistants
- Point and Click Surgery
  - CT-guided systems
  - US-guided systems
  - MRI-guided systems
- Lessons Learned

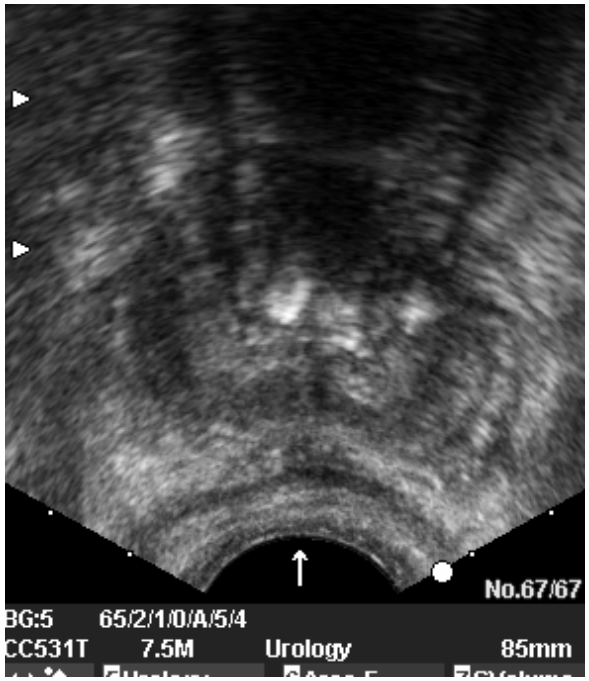
The MRI challenge



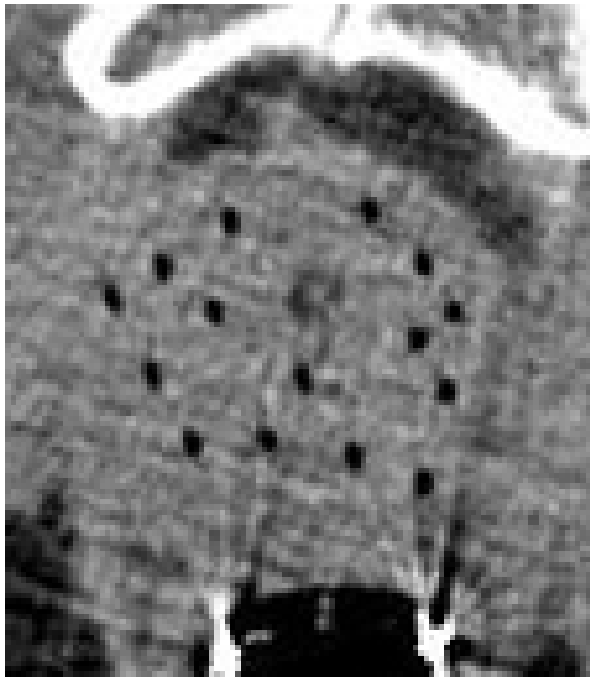
- No space
- B field

Why to bother?

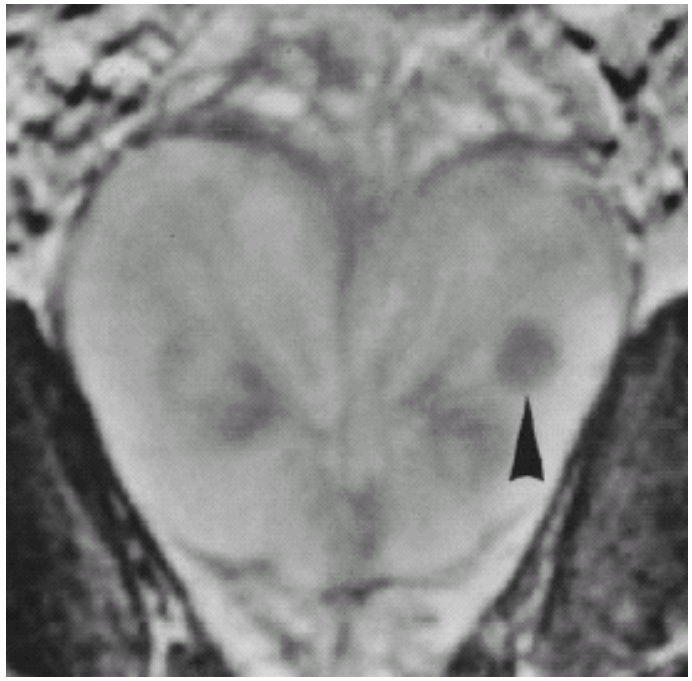
US



CT

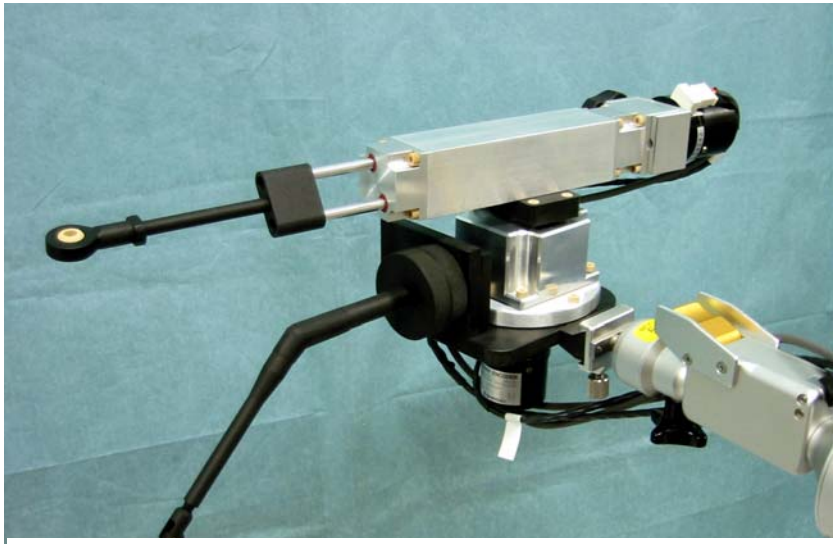


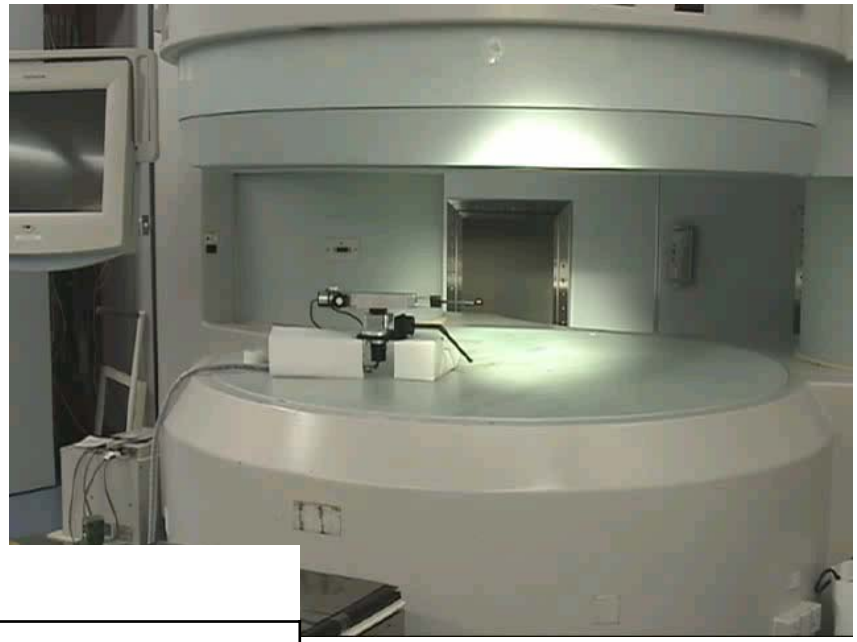
MRI



- 1M prostate biopsy, 200,000 new cancer
- TRUS imaging misses 20% cancer
- Freehand biopsy may miss <1 cc nodes

Masamune et al.: MRI compatible manipulator



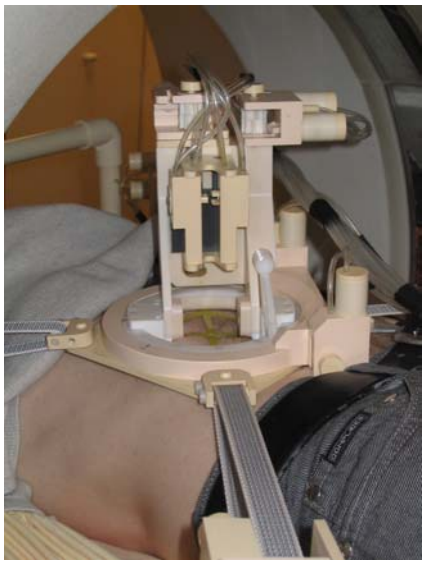


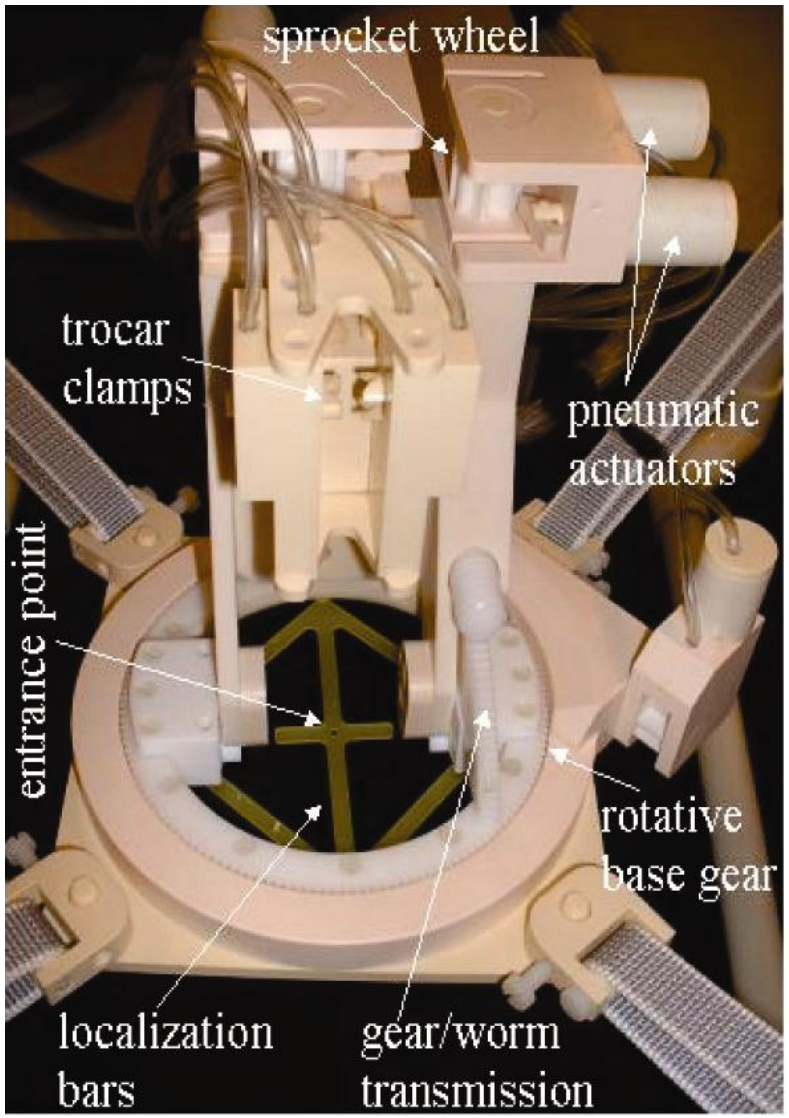
Materials

Parts	Material
Ultrasound motor	Piezo-electric device
Bearings	Plastics
Screw, Nuts	Plastics
Feed screw	SUS304、 fluoroplastic
Ball bearings	Ceramics

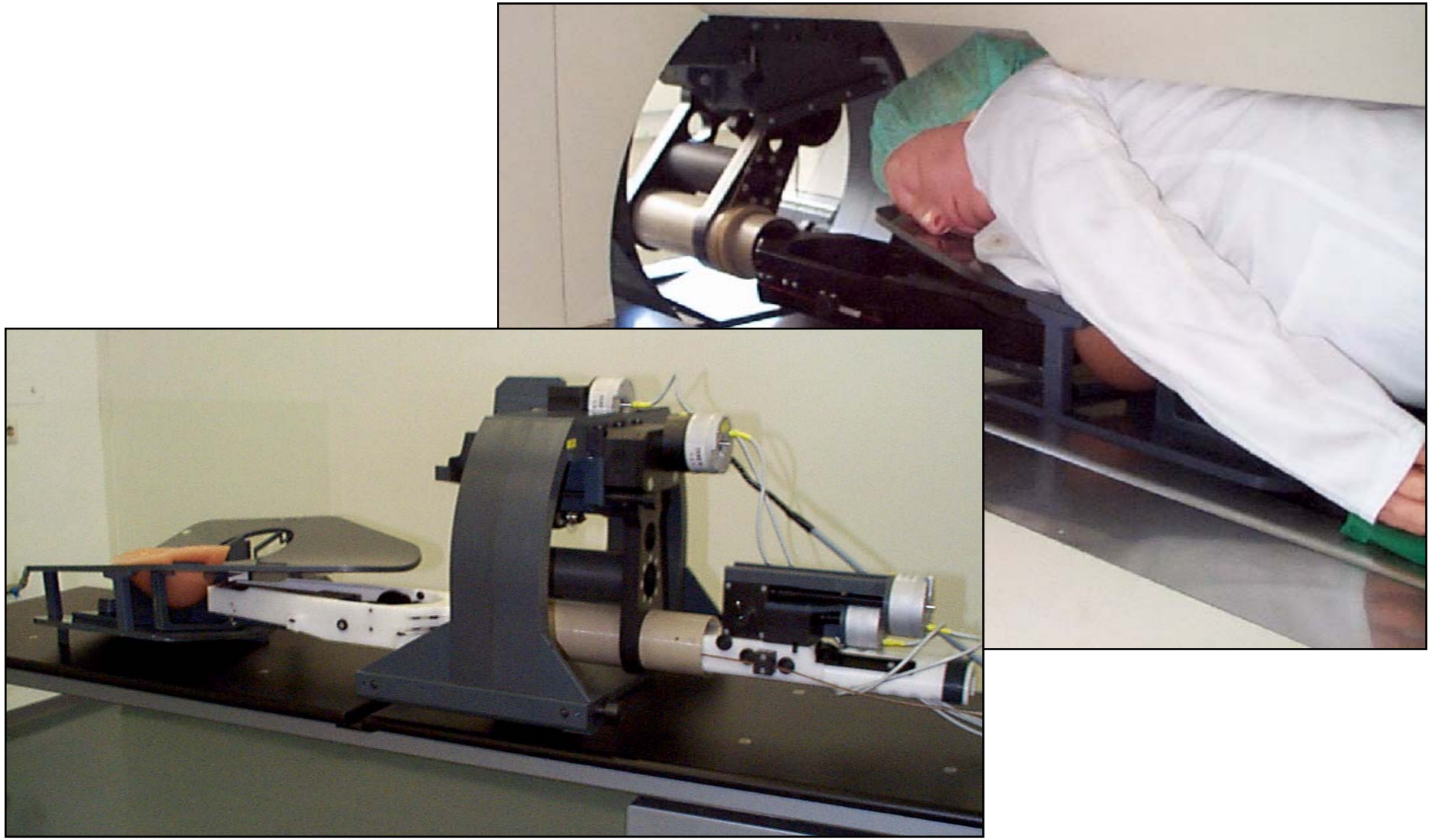
Troccaz et al.: Patient-mounted 6-DOF robot

- No trajectory limitation
- Embedded localization
- Pneumatic actuation
- Accuracy <1.5mm





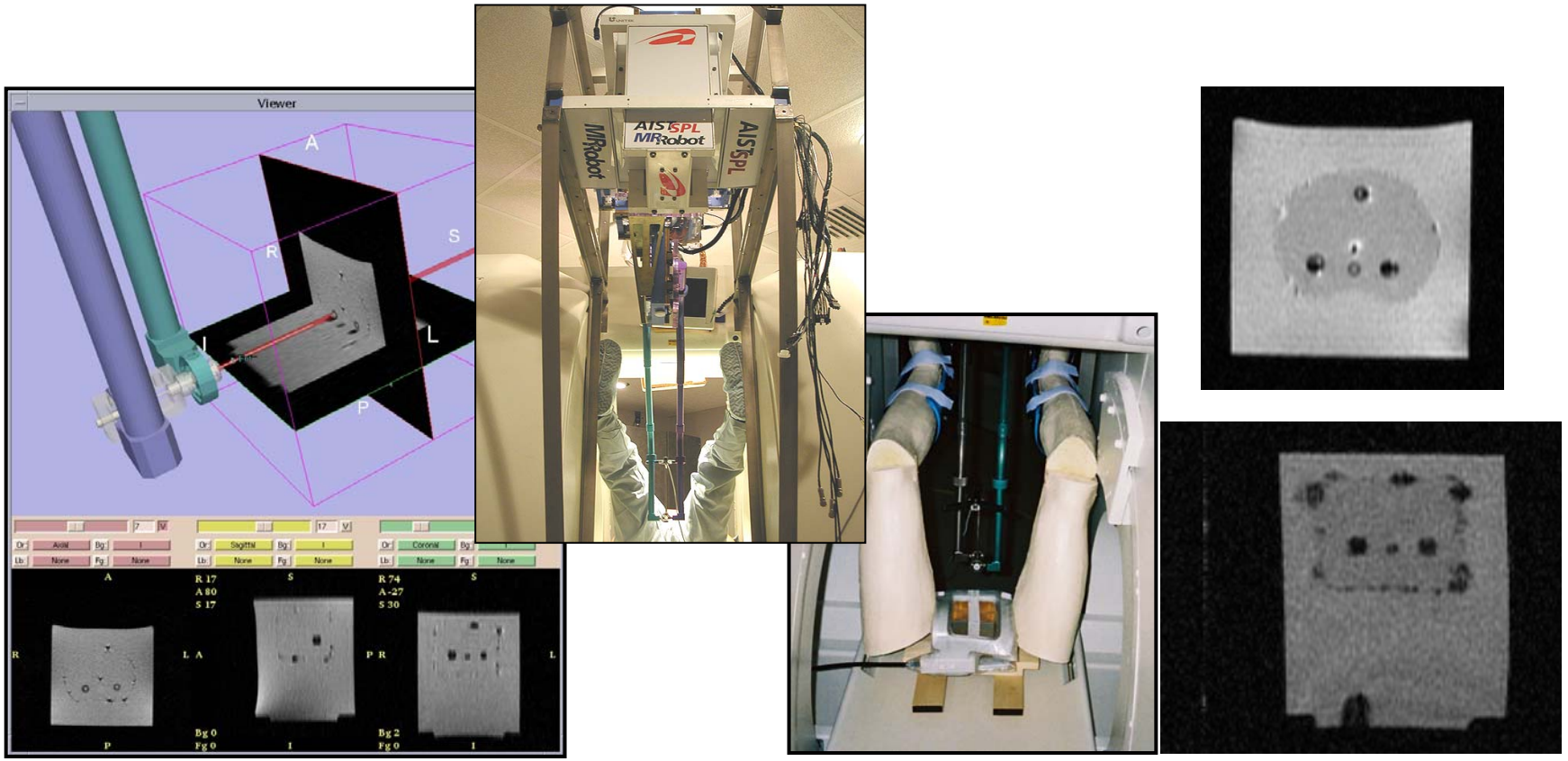
Fischer et al.: in-MRI breast Biopsy



Credit: Fischer et al, Karlsruhe

Brigham open MRI robot testbed

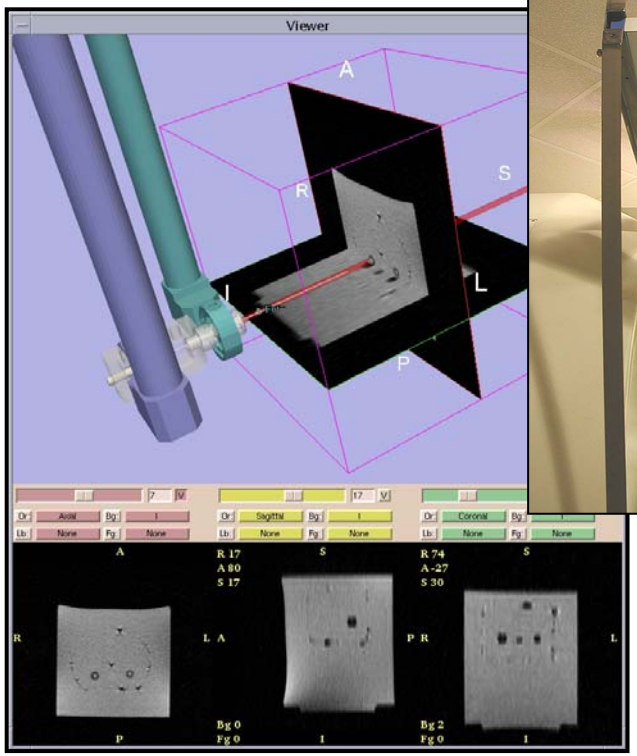
IRB-approved for Robot-Assisted Prostate Biopsy/Brachytherapy in Open-MRI

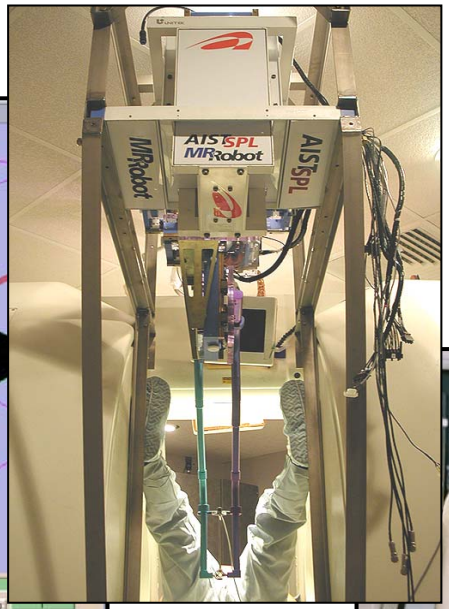


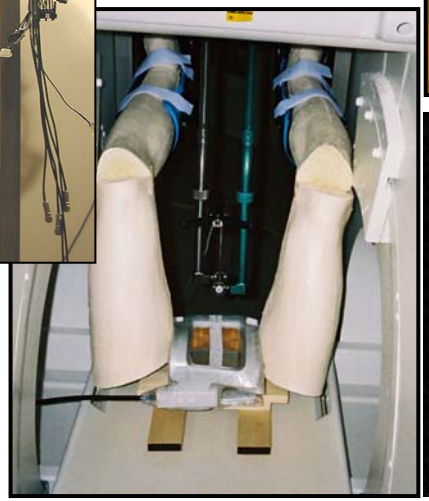
Credit: DiMaio, Chinzei, Hata, Kikinis, Jolesz, Tempany

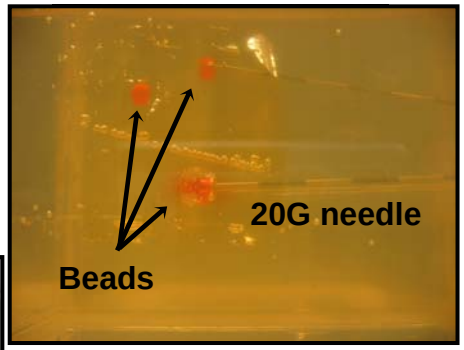
Brigham open MRI robot testbed

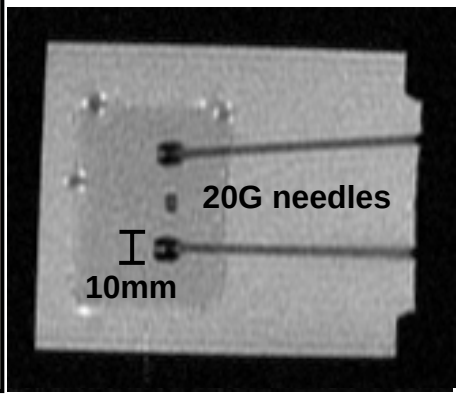
IRB-approved for Robot-Assisted Prostate Biopsy/Brachytherapy in Open-MRI





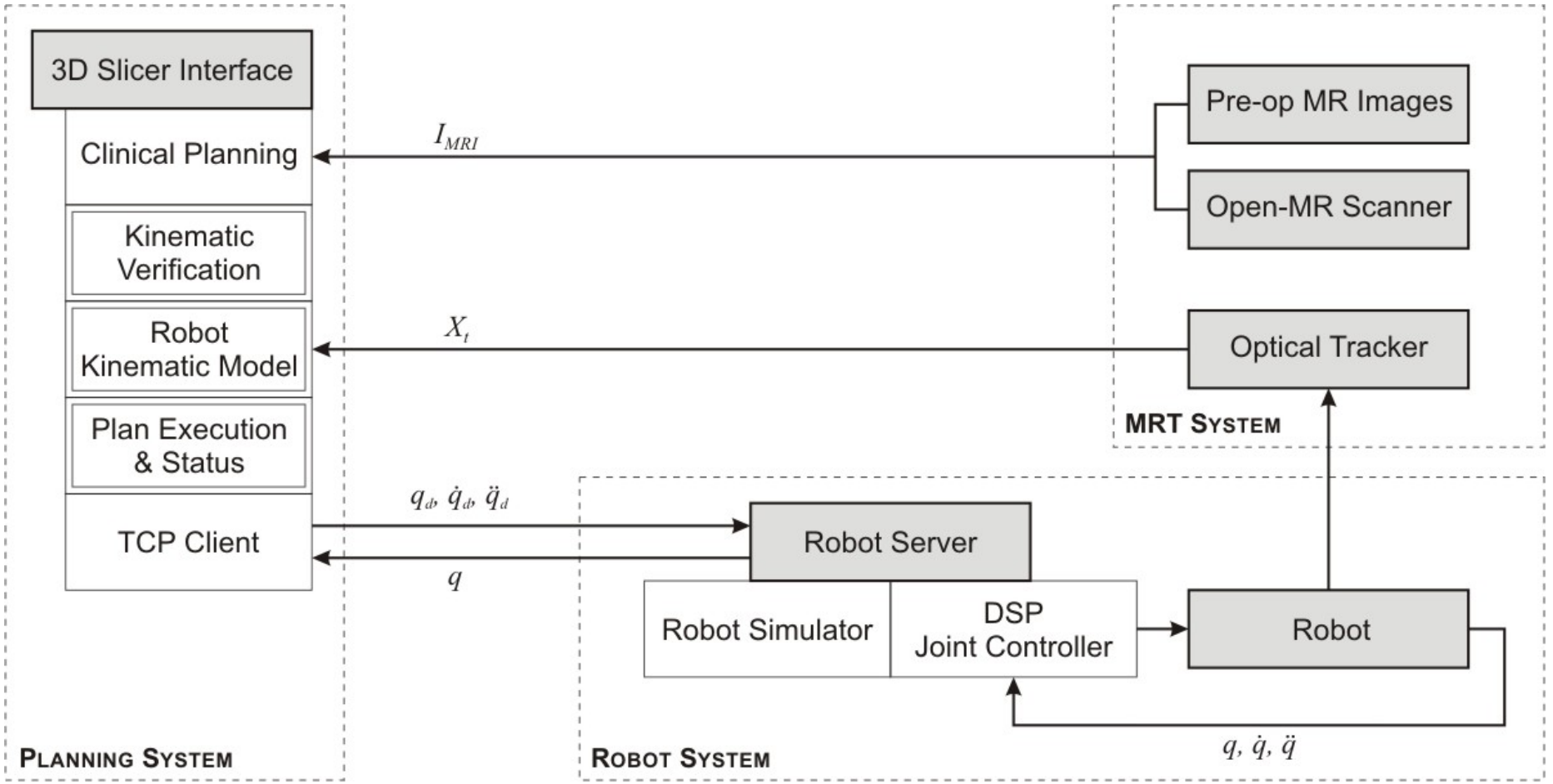






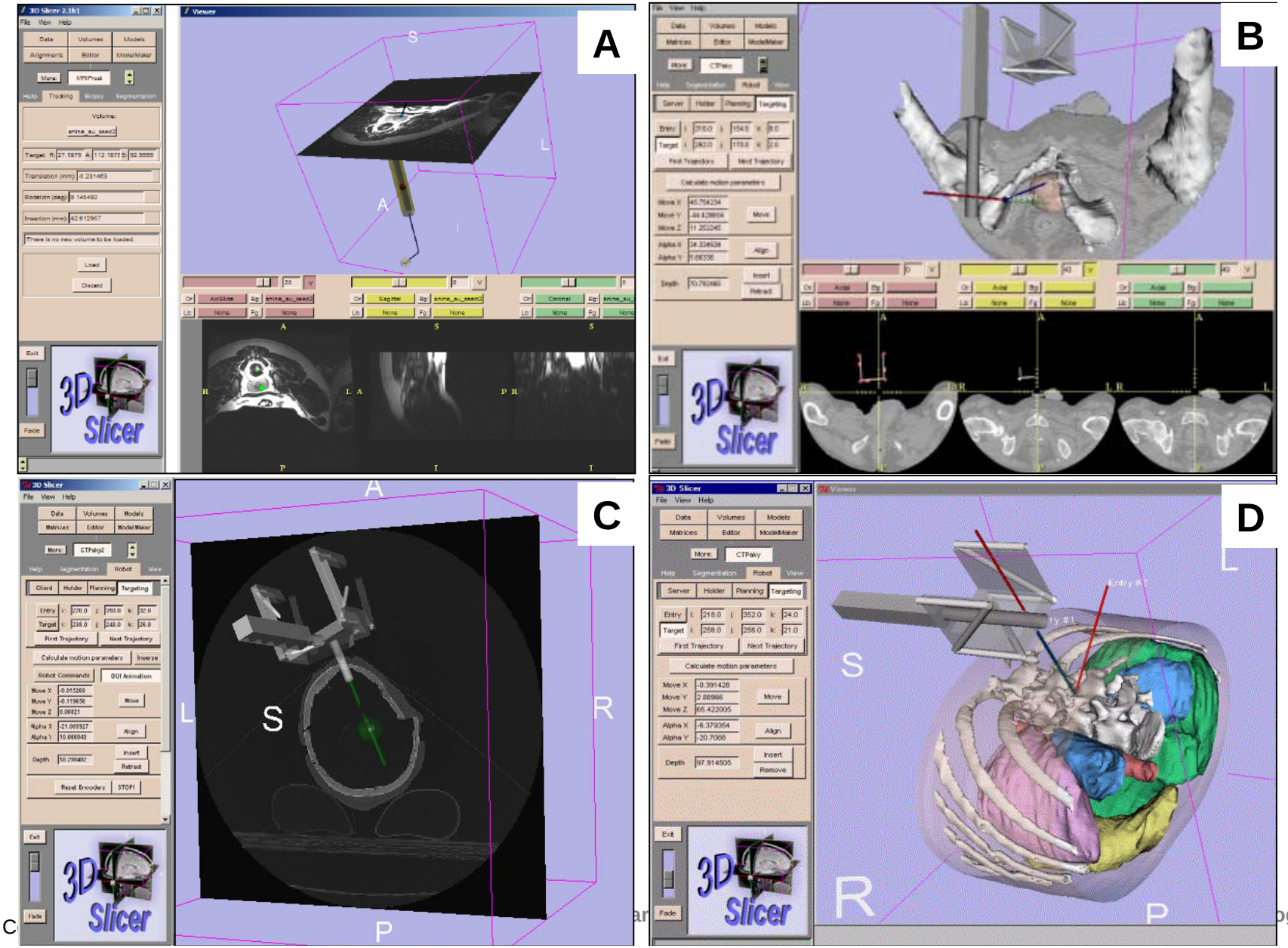
Credit: DiMaio, Chinzei, Hata, Kikinis, Jolesz, Tempany

Common system architecture

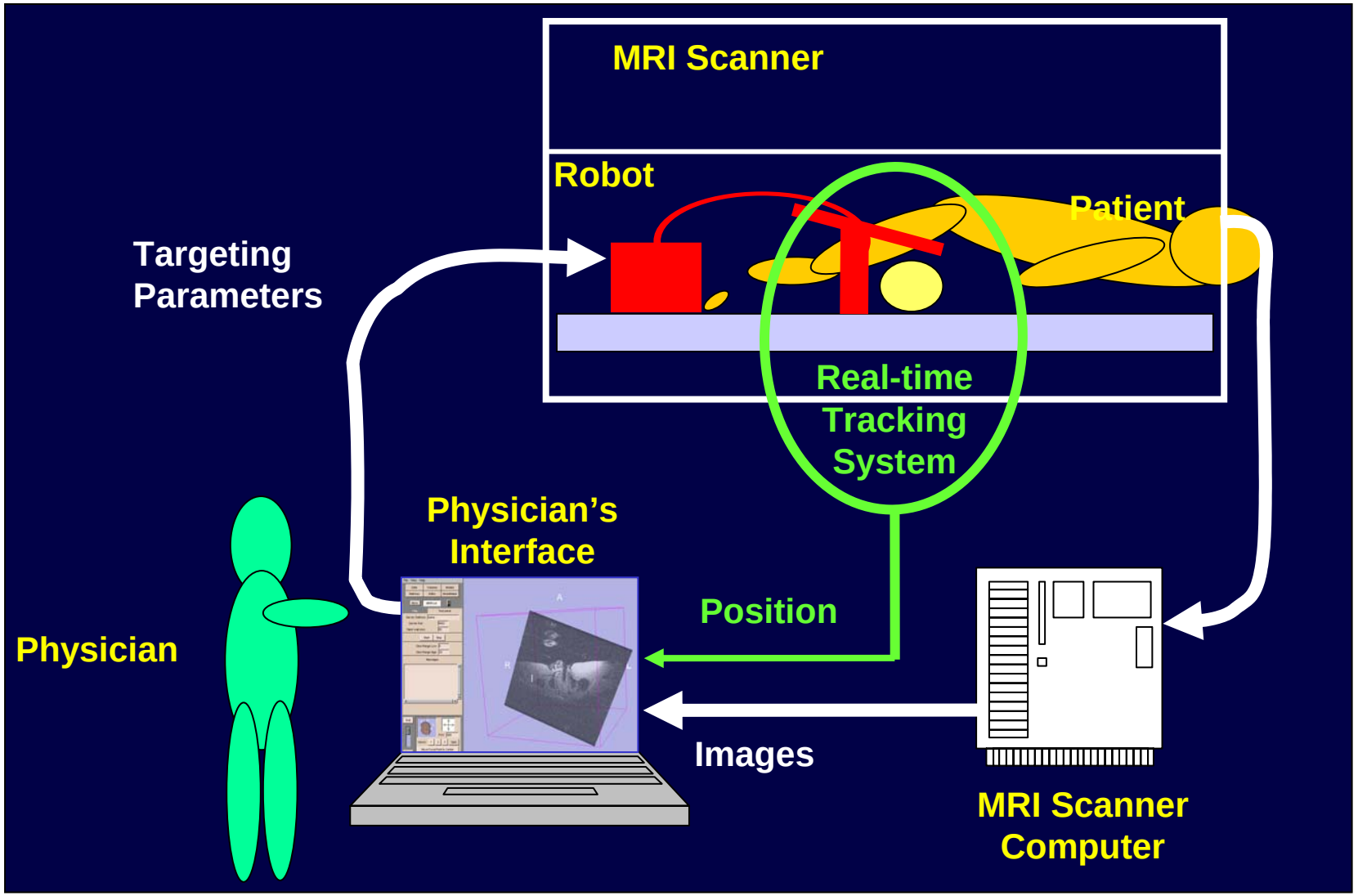


Credit: DiMaio, Kikinis

Common system interface

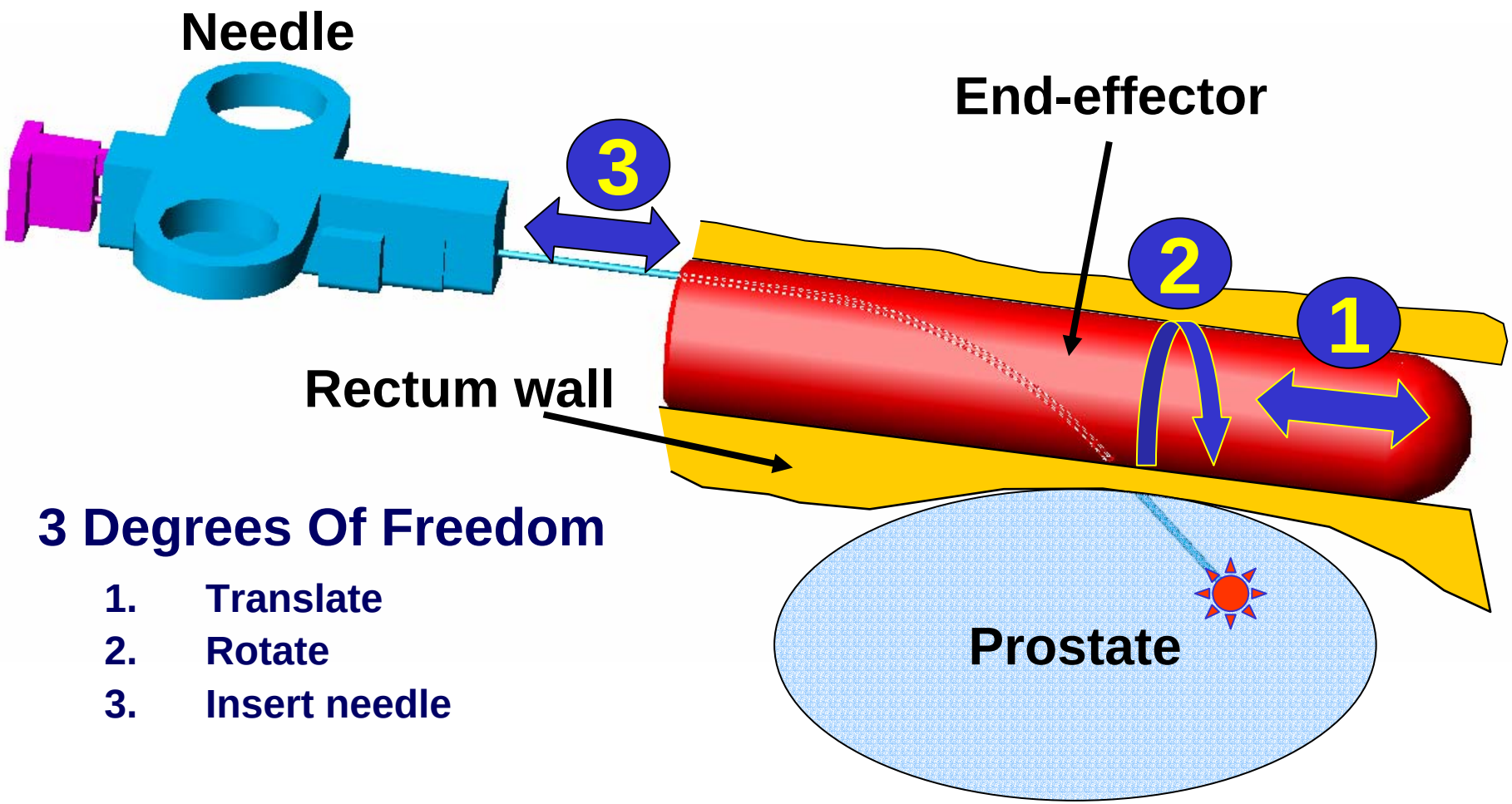


Prostate interventions in high-field MRI



Credit: Susil, Krieger, Menard, Coleman, Whitcomb, Atalar, Fichtinger

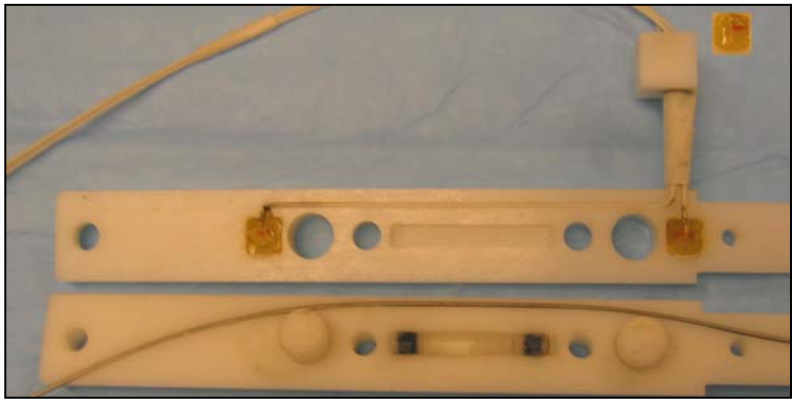
Kinematic concept: decoupled 3-DOF

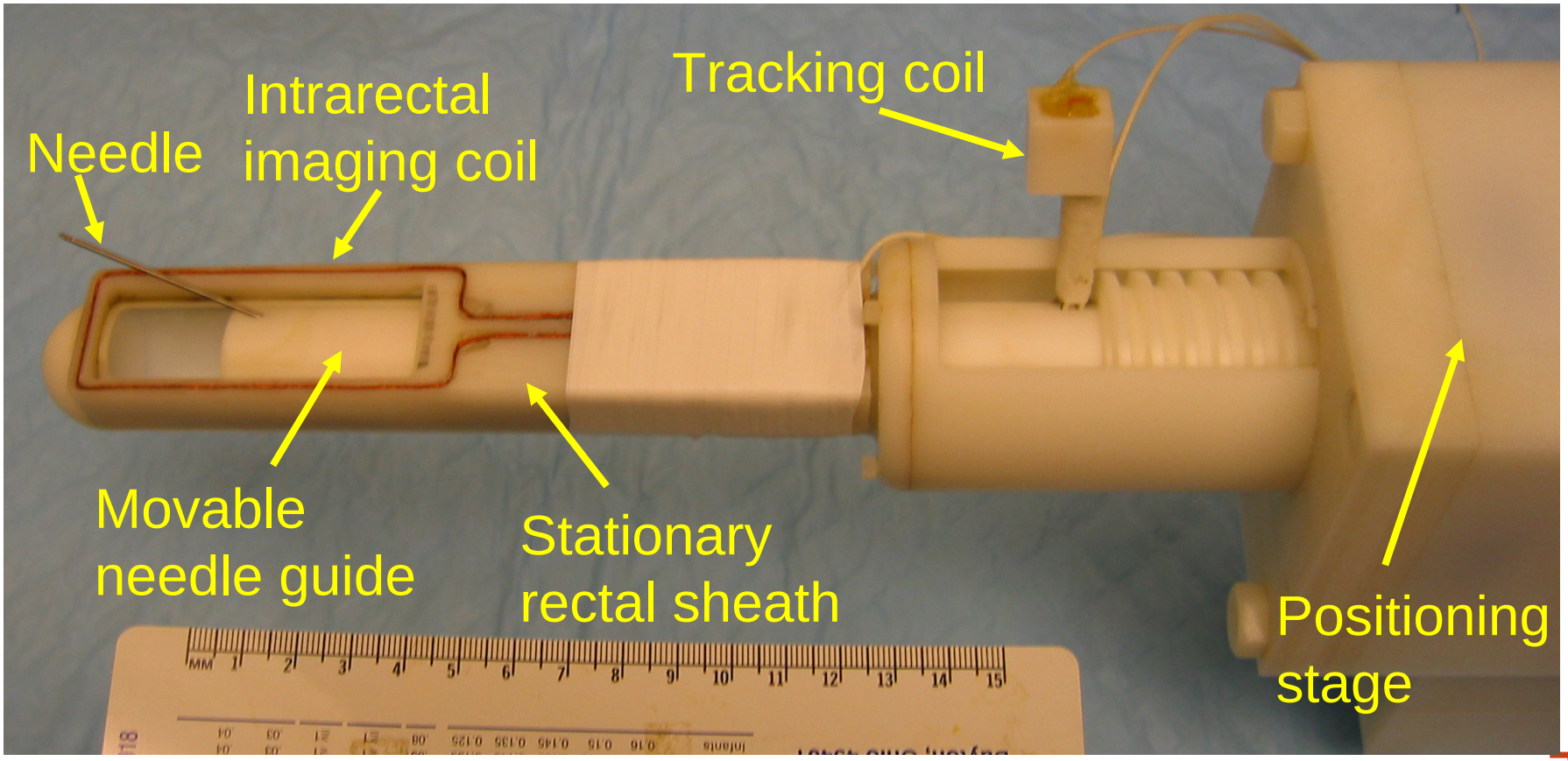


3 Degrees Of Freedom

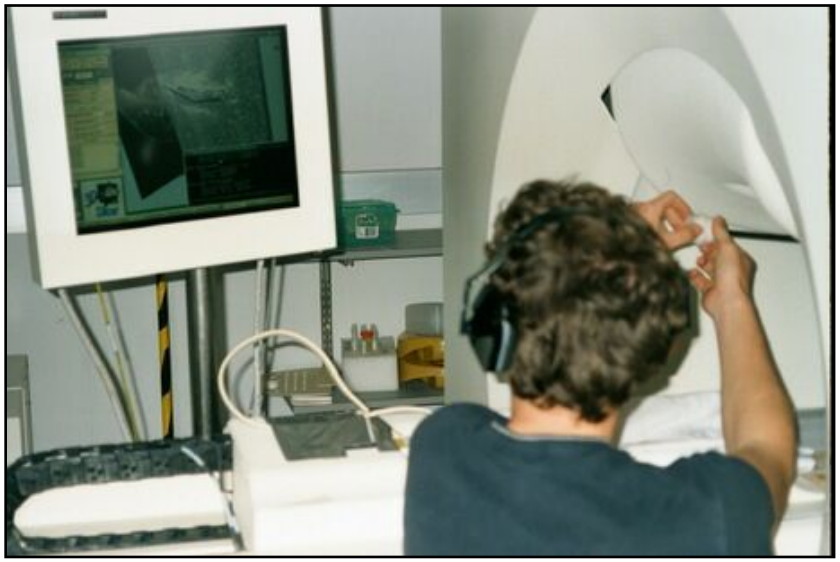
1. Translate
2. Rotate
3. Insert needle

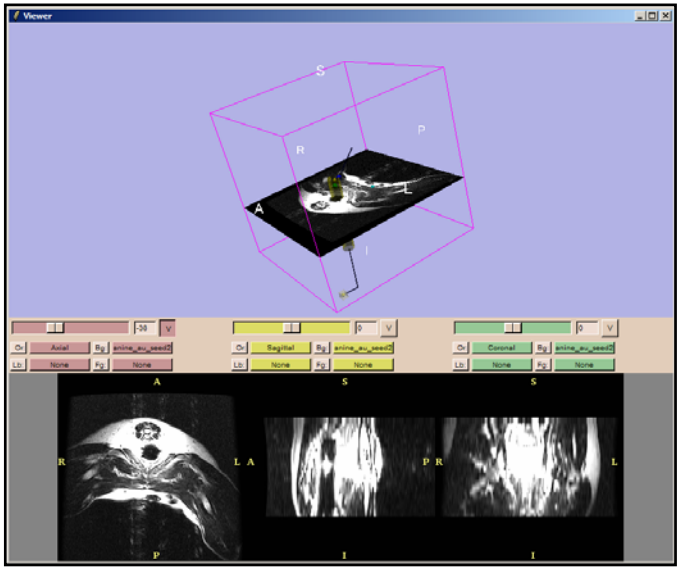
The end-effector

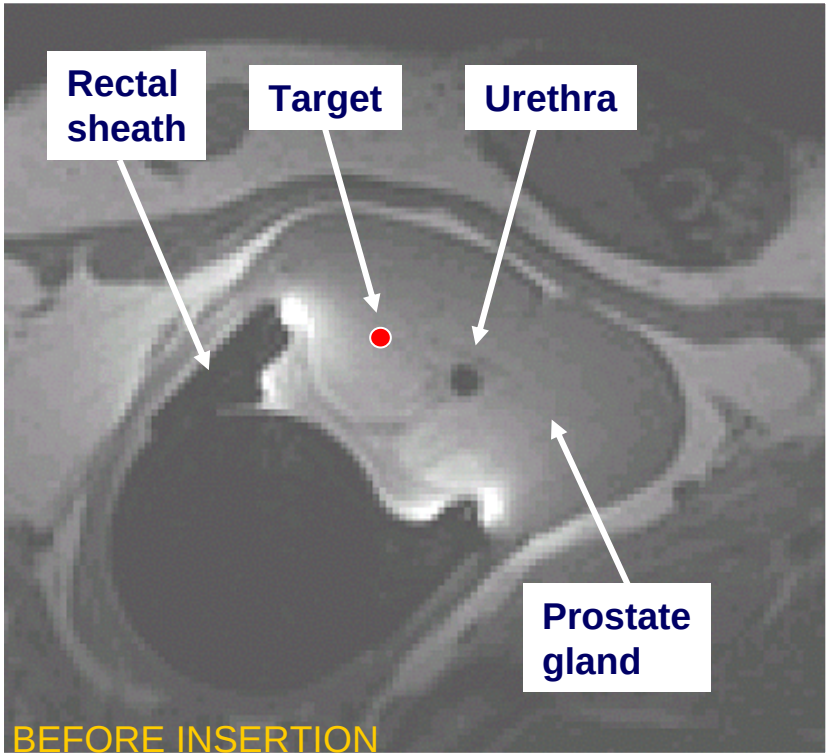


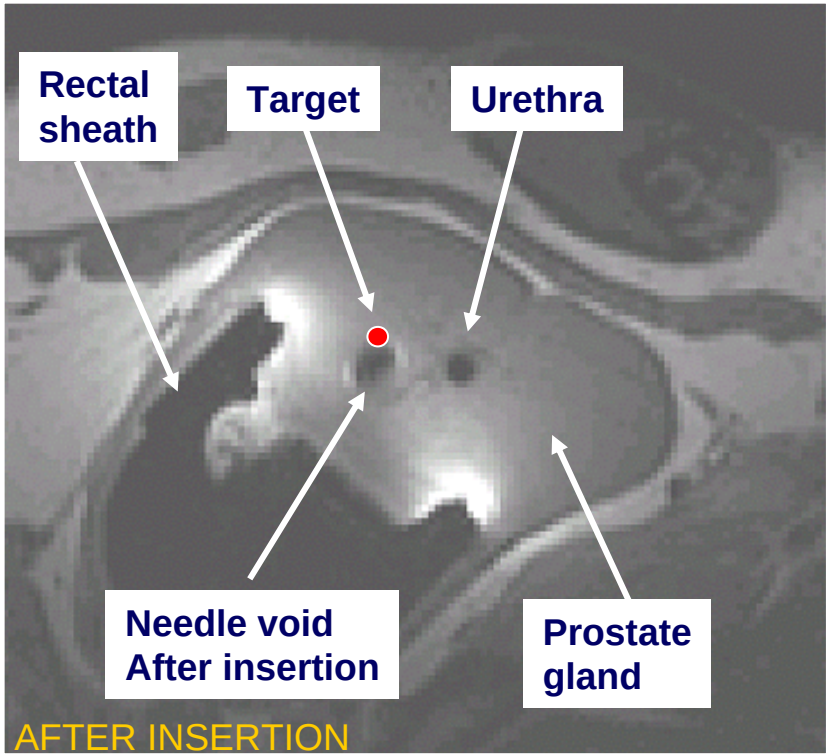


Integrated robot in canine studies

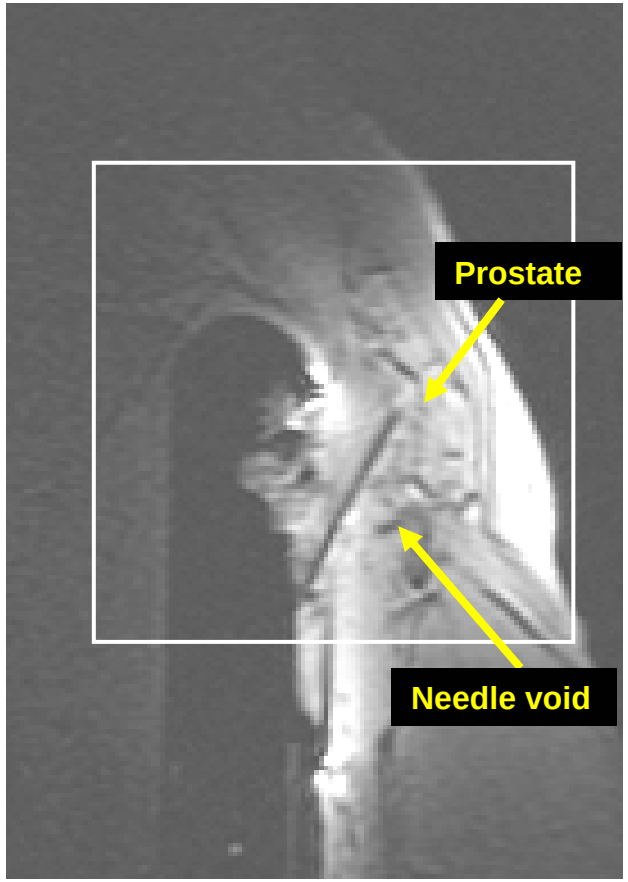




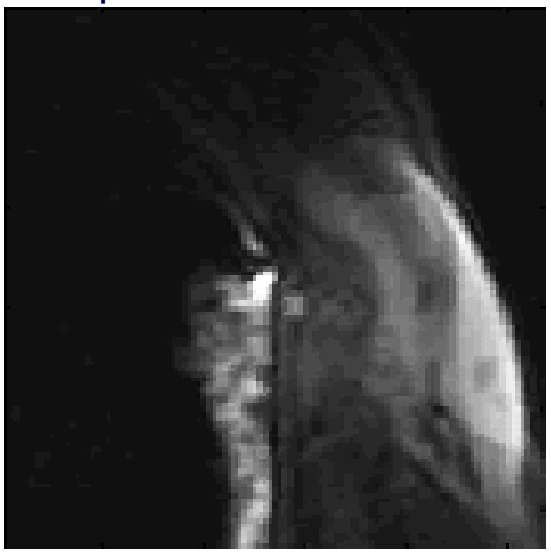




Liquid injections in dog



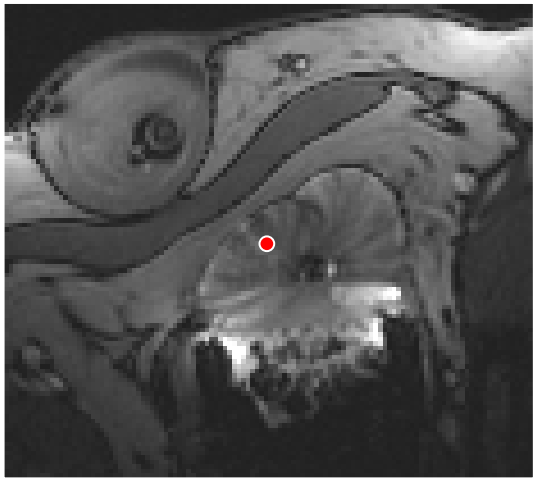
Real-time image in the plane of the needle



FSPGR
TE = 1.2
TR = 6
FA = 90º
BW = 62.5KHz
0.80 sec/image

FOV = 24x24cm
ST = 10mm
256x128

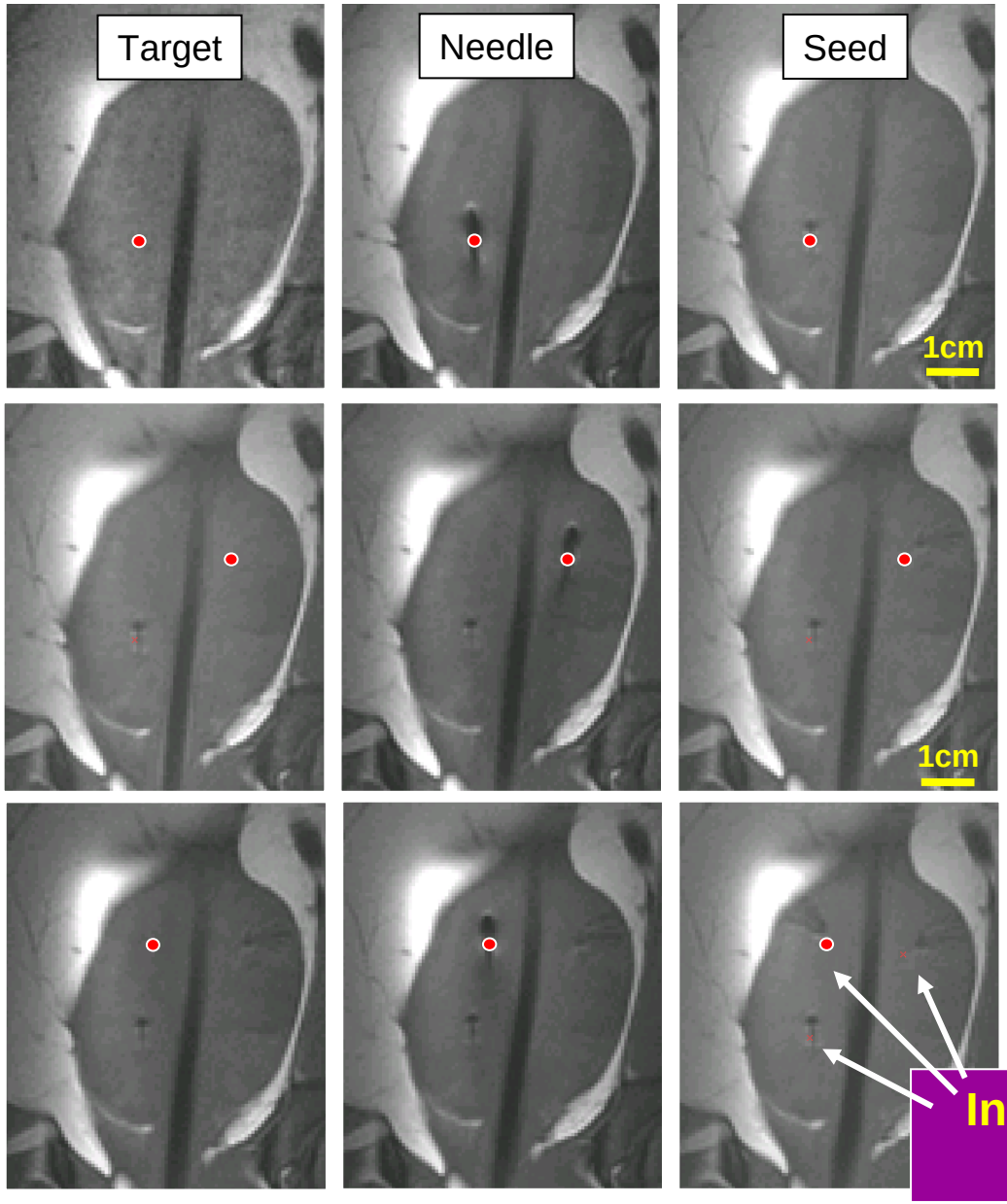
Coverage of a 5 mm transverse slice at a time



FSPGR
TE = 2.8
TR = 85
FA = 60º
BW = 31.25KHz
Scan time = 3:00

FOV = 16x16cm
ST = 3mm
256x256
NEX=4

Seed placement in dog



Seed #1

error ~ 2 mm
no motion

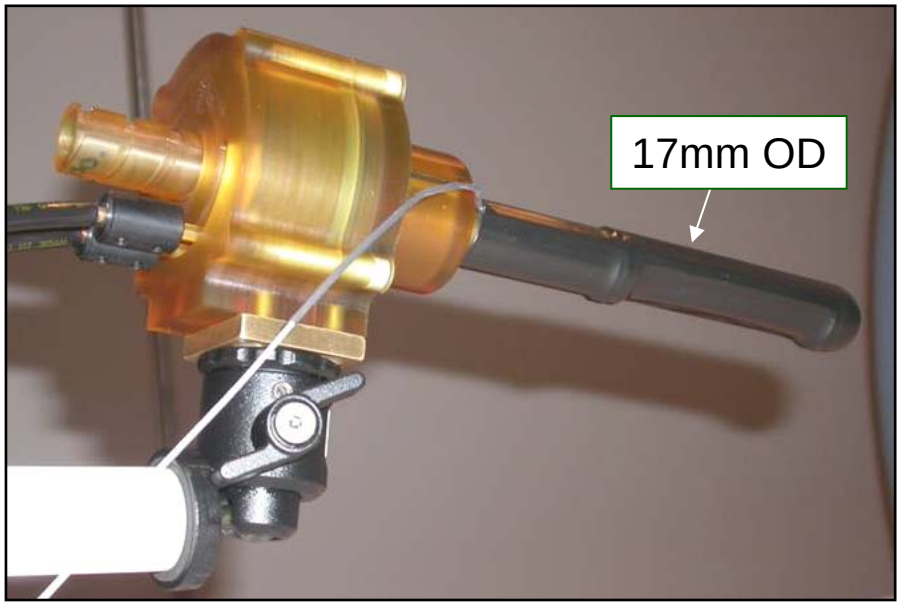
Seed #2

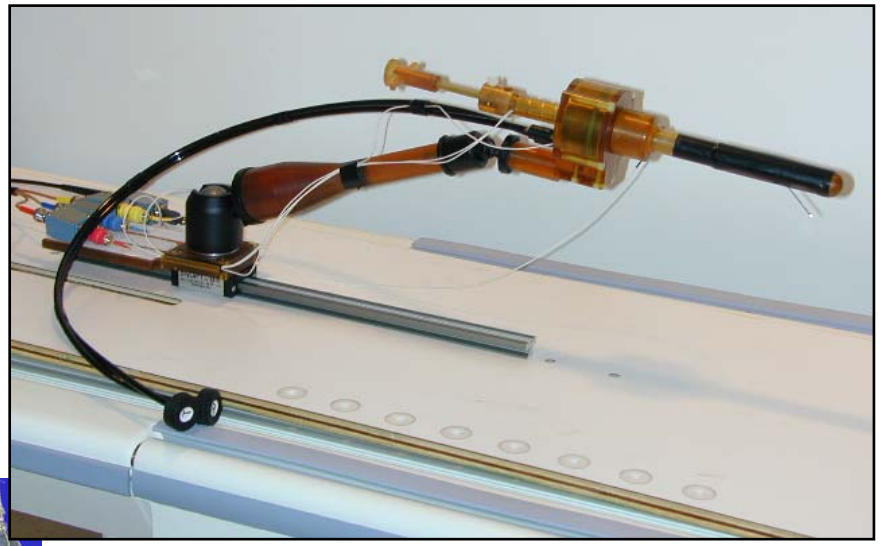
error ~ 2 mm
no motion

Seed #3

error ~ 2 mm
no motion

Human-grade device

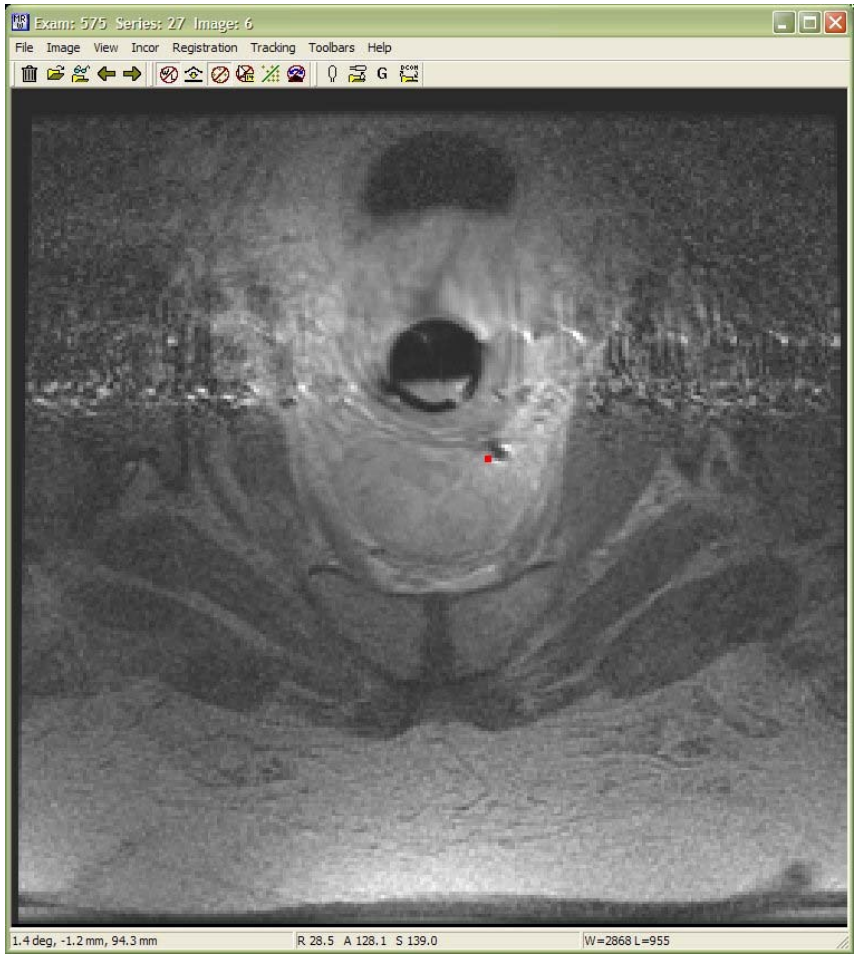




Clinical trials in progress

Biopsy result 1

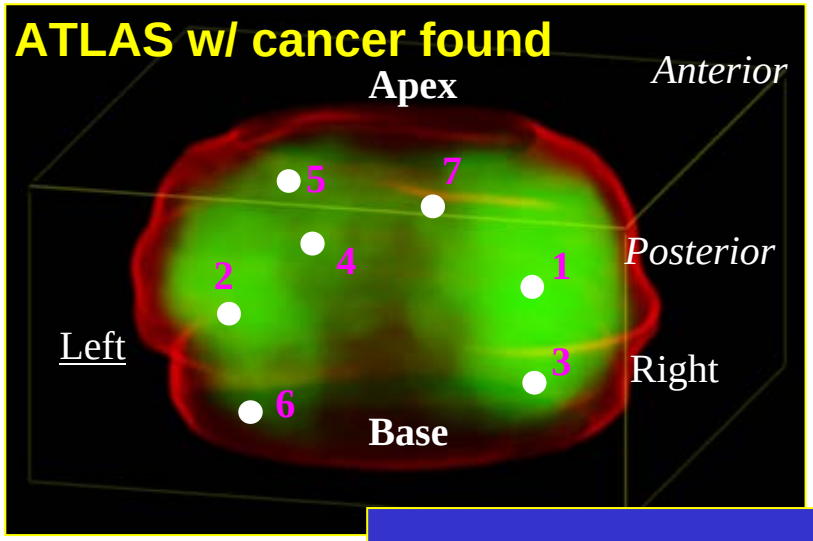
Biopsy result 2



Some lessons learned

- ***Tissue motion and deformation remain the greatest unsolved problems***
- "Brute force" solutions can help only to some extent
- Image-based and sensory tracking provides only part of the solution (and we are not even there)
- Predictive models will play a role
- Needle steering will play a role
- Deploy needle from close range
  - ☺ shorter needle – less deflection
  - ☹ less room for actuation and maneuvering
- Intracavity needle deployment is most promising
- ***Future: deformable statistical atlases with tissue properties linked to anatomical structures and medical conditions***

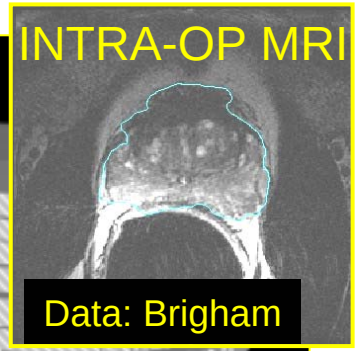
Statistical Atlas for Optimal Prostate Biopsy



98% sensitivity from 7 needles

Template

Samples: 200+ prostates w/ pathology at CDPR



Credit: Davatzikos, Shen, Tempany, Fichtinger

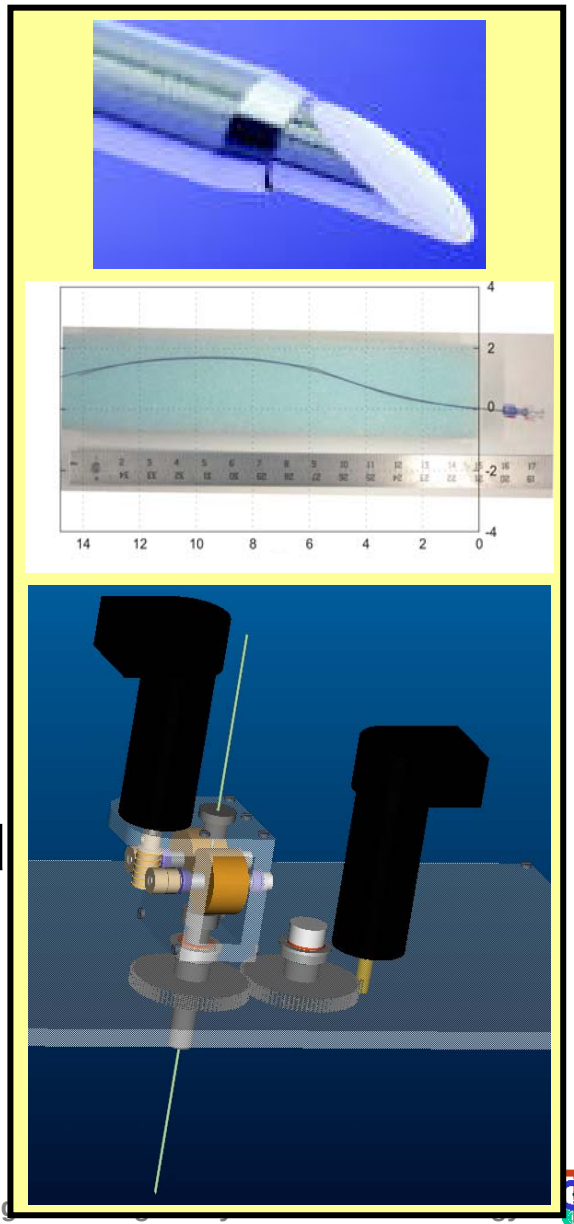
Active needle steering

Status:

- Developed a *kinematic model* to describe needle bending in soft tissue due to the asymmetry of a bevel tip
- Developed an *apparatus* to insert and steer very flexible needles

Plans:

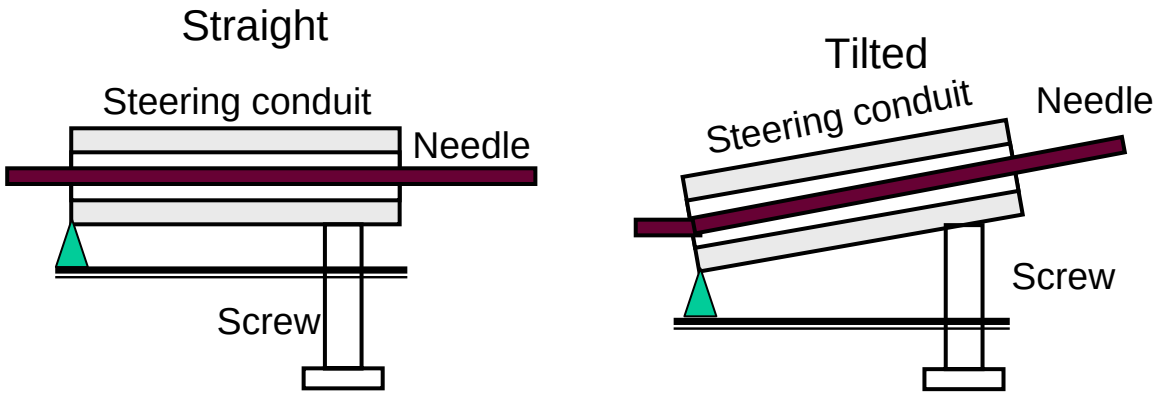
- *Validate deterministic and stochastic models* for needle steering
- Develop *computer simulations* that include needle bending for training and planning



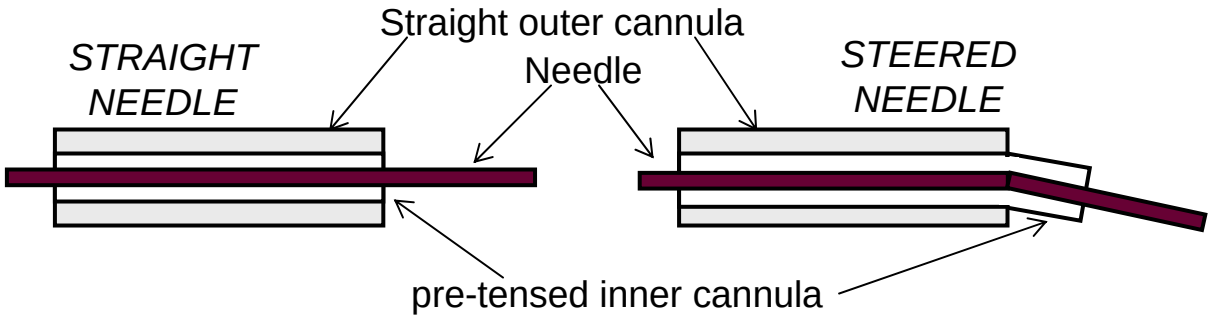
CLICK FOR MOVIE

Credit: A. Okamura, N. Cowan, G. Chirikjian, T. DeWeese, K. Murphy

Passive needle steering



Steerable nozzle idea: patent by Fichtinger et. al



Telescopic cannula patented by Salcudean, Rohling, et al.

Credit: Fichtinger, et. al