NSF Engineering Research Center for Computer-Integrated Surgical Systems and Technology

Medical Robotics and Computer-Integrated Surgery

NSF Workshop on Status of Robotics in the United States
Arlington, Virginia
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Disclosures

- Russell Taylor is a member of the Scientific Advisory Board of Integrated Surgical Systems and of Image Guide, Inc., and he consequently has (an exceedingly small) financial interest in these companies, and he may join other Advisory Boards.
- Some of Dr. Taylor’s patents have been licensed by Image Guide, Incorporated, and he consequently has a small financial interest in IG,
- ISS, IG, GE, Siemens, Medtronic, Burdette Medical, and several other companies whose systems were discussed in this talk are affiliates of the NSF CISST ERC, of which Dr. Taylor is the Director.
- Dr. Taylor also enjoys fishing

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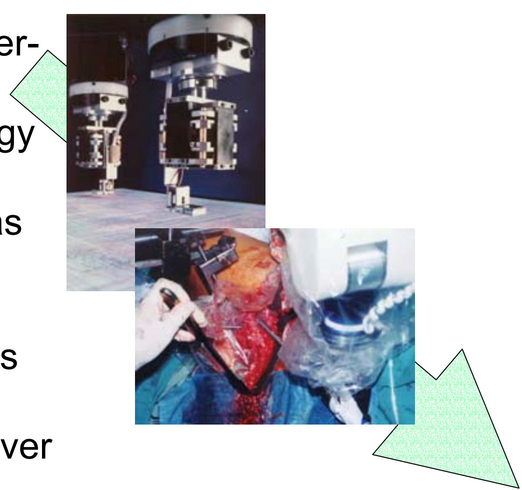
- Multi-institution, multi-disciplinary center
  - Johns Hopkins University + Medical Institutions
  - MIT + Brigham & Women's Hospital
  - CMU + UPMC
  - Others: Morgan State, Georgetown, Harvard, Penn
- Funding
  - NSF core grant: $25.7M (1997-2006); $3.7M (2004)
  - Total annual budget approximately $5.3M (2004)
- University researchers, <u>clinicians</u>, industry
- Research, Systems, Education, Outreach

Prediction

The impact of computer-integrated surgical systems and technology on medical care in the next 20 years will be as great as the impact of computer-integrated manufacturing systems and technology on industrial production over the past 20 years.



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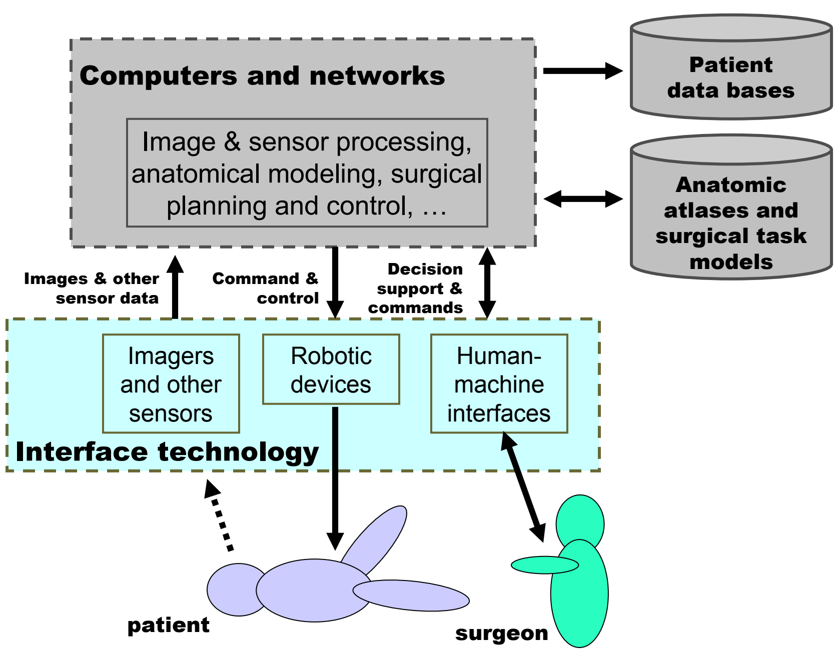
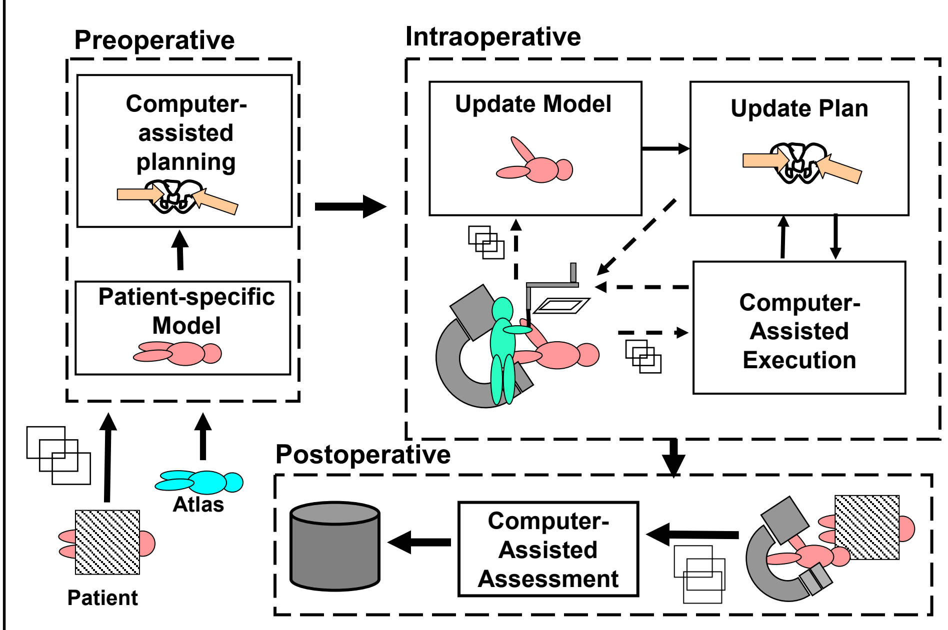
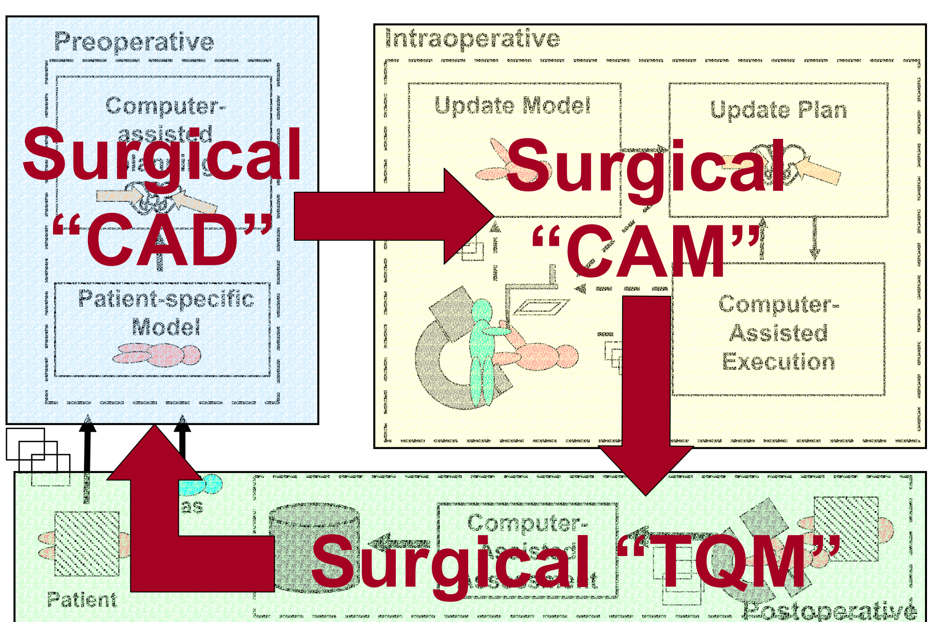
Basic means for fulfilling prediction: systems that integrate information to action

- Provide new capabilities that **transcend human limitations** in surgery
- Increase **consistency and quality** of surgical treatments
- Promote **better outcomes** and more **cost-effective** processes in surgical practice

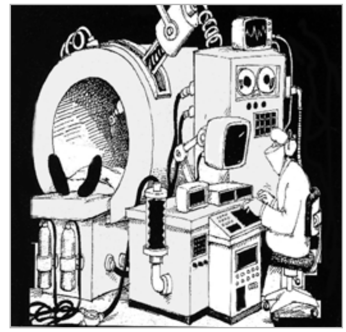



Preoperative
Computer-assisted planning
Patient-specific Model
Atlas
Patient
Intraoperative
Update Model
Update Plan
Computer-Assisted Execution
Postoperative
Computer-Assisted Assessment


Surgical "CAD"
Surgical "CAM"
Surgical "TQM"
Preoperative
Intraoperative
Postoperative
Patient

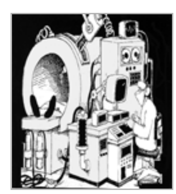
Vision: "One stop shopping" therapy

- Fully integrated and optimized planning, execution, assessment, and follow-up of **minimally invasive** interventional procedures
- … for a broad spectrum of clinical conditions
- … anywhere in the body
- … **with convenience comparable to current outpatient diagnostic procedures.**

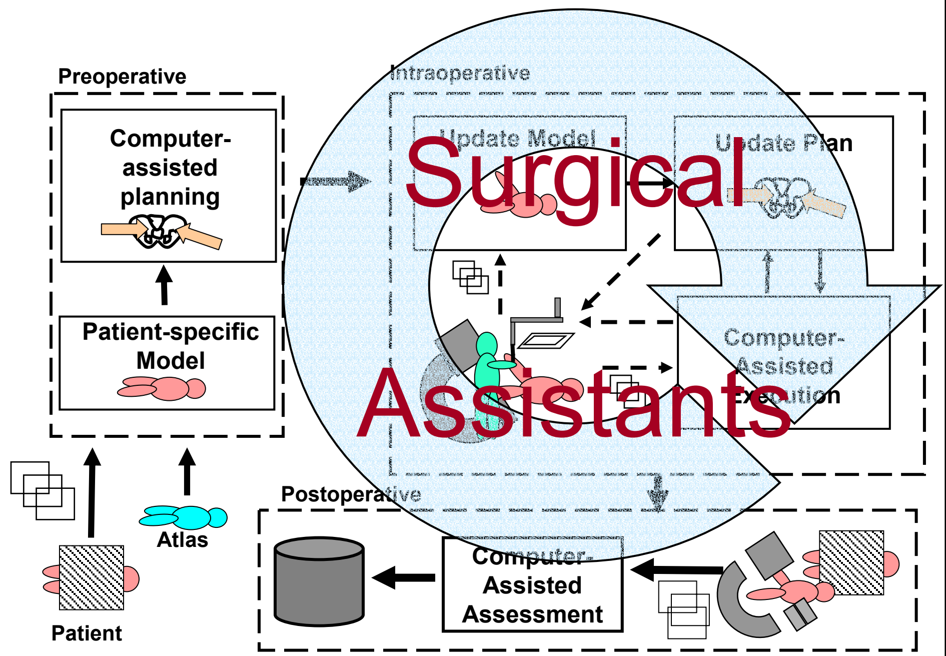


Sketch: Ferenc Jolesz

Vision: "Plug and Play" Surgery

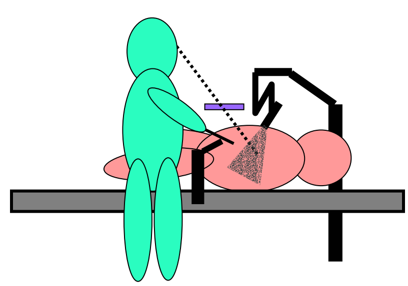


- A modular family of subsystems, including
  - imaging devices and methods
  - modeling & analysis algorithms
  - robotic devices
  - visualization & human-machine interfaces
  - systems development tools …
- which can be **quickly integrated** with novel therapeutic end effectors to produce …
- complete and effective surgical CAD/CAM systems with **predictable and certifiable performance** …
- for **multiple** organ systems, therapeutic approaches, and imaging modalities.



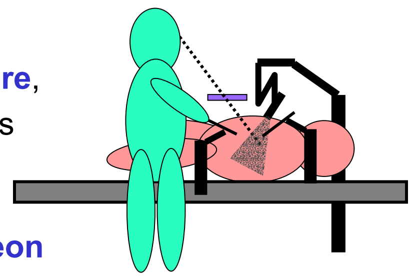
"Information-intensive" surgery

- Surgical systems interfacing to an information-rich surgical environment
- … and capable of using this information to maintain **patient-specific models**
- … **registered in real time** to the physical reality of the operating room
- … with the ability to use these models to **assist surgeons in carrying out complex surgical procedures**
- … through robotic assists and information display devices.

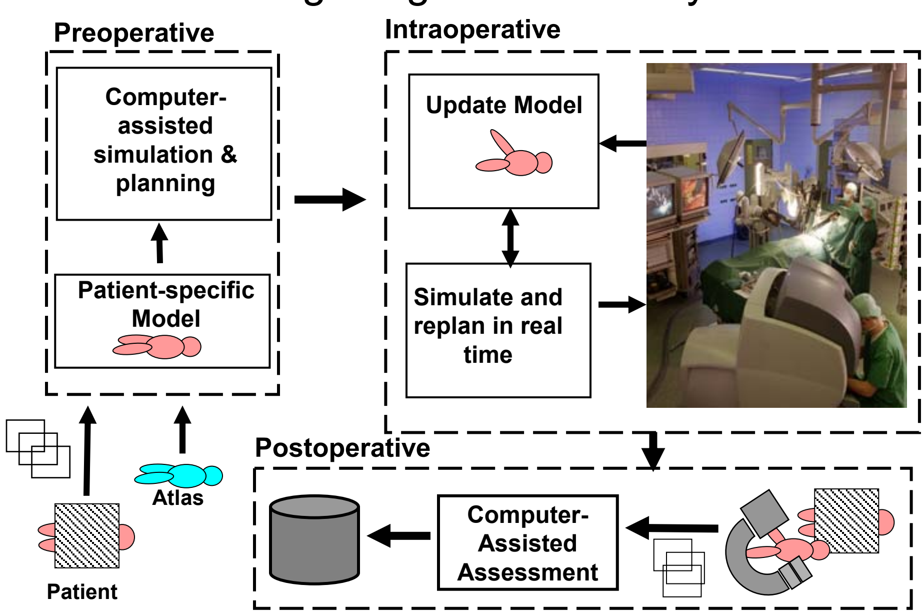


“Super-human” surgical teams

- Surgical systems capable of **modeling and following the progress of a surgical procedure**,
- … and able to use robotic devices and sensors extending human performance
- … **cooperatively with the surgeon**
- … in order to improve the quality of surgical procedures and to enable interventions that would be otherwise impossible.

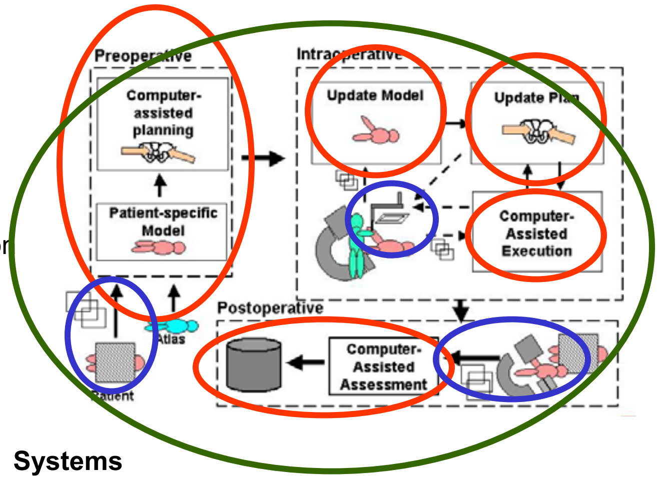


Eventual goal: grand unified system



Research and technology barriers

Modeling & analysis
- Segmentation
- Registration
- Atlases
- Optimization
- Visualization
- Task characterization
- *etc.*

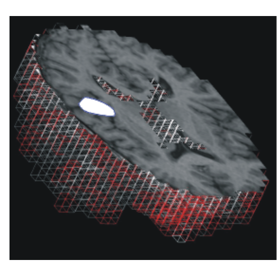


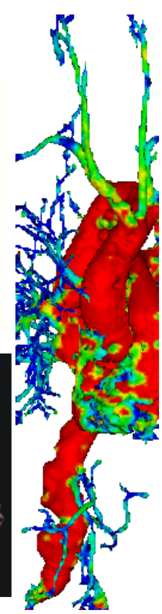
Interface Technology
- Sensing
- Robotics
- Human-machine interfaces

Systems
- Safety & verifiability
- Usability & maintainability
- Performance and validation

Modeling & Analysis

- Extracting & combining information from multiple sources and sensors
- Combining functional and geometric information
- Representing and reasoning about uncertainty
- Managing complexity

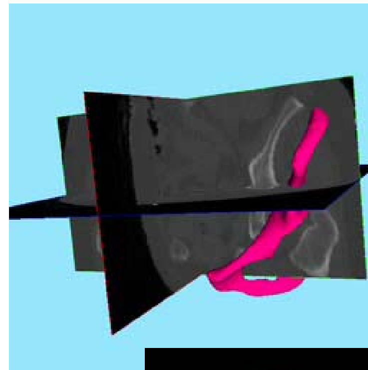


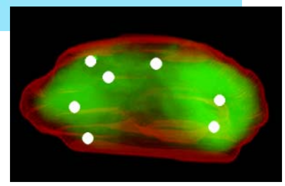


Core Challenge: Develop computationally effective methods for patient-specific modeling and analysis

Modeling and Analysis Highlights

- Explosion of 3D imaging modalities
  - MRI, CT, Ultrasound, etc.
- Patient-specific models based on images
- Statistical atlases and deformable models are emerging as crucial enabling technologies within CIS
- Beginning to see application of real-time computer vision methods

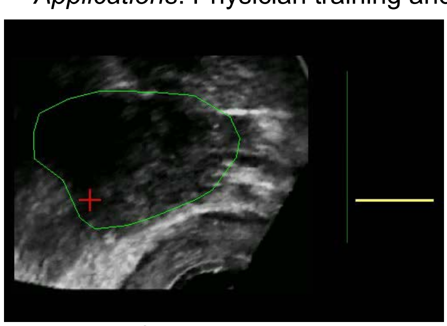




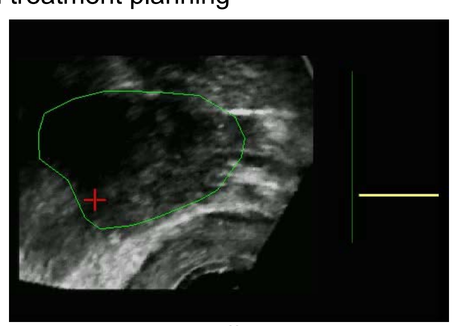
Example: Biomechanical Simulation of Medical Needle Insertion

Ron Alterovitz, Ken Goldberg (UC Berkeley)
Jean Pouliot, I-Chow Hsu (UCSF)

- *Goal*: Reduce radioactive seed placement error in prostate cancer brachytherapy treatment using biomechanical simulation
- Developed 2D dynamic finite element model of needle insertion in tissue
- Interactive simulation: 24 fps on a 750MHz PC
- *Applications*: Physician training and treatment planning



Tissue deformations cause seed placement error

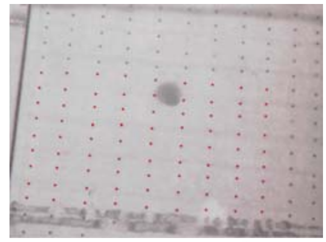


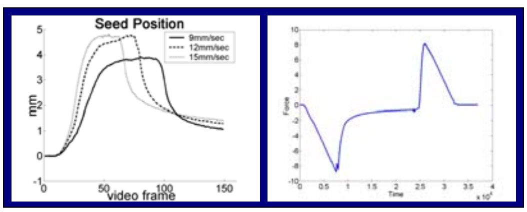
Planner computes offsets to compensate for simulated tissue deformations

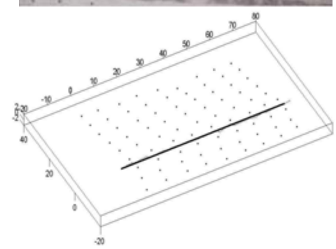
Needle Insertion Modeling

Jessica Crouch, Allison Okamura, Chad Schneider, Josh Wainer

- ***Goal:*** Improve needle targeting for biopsy, brachytherapy by modeling tissue deformation
- ***Strategy:***
  - *Reproduce* deformation with phantom & robotically controlled needle
  - *Record* deformation & force data
  - *Fit* finite element models to data
  - *Predict* deformations with FE model and intelligently guide insertion
- ***Status:*** on-going research



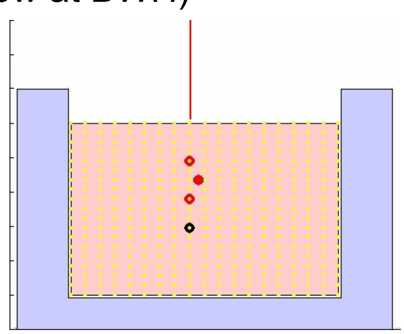




3D model of needle and fiducials

Other related work on deformable soft tissue modeling

- Simon DiMaio (UBC, now at BWH)



S. DiMaio (UBC)

- Rob Howe (Harvard)
- Various groups in Europe, Japan

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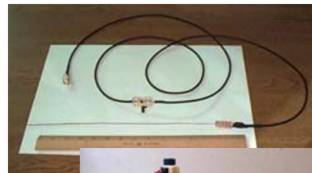
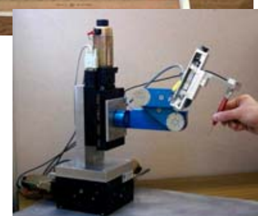
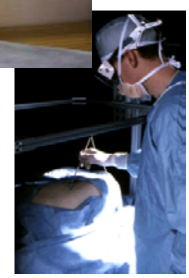
Interface Technology

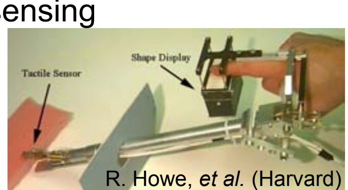
- Imaging and sensing
- Robotics
- Human-machine interfaces

Core Challenge: Fundamentally extend the sensory, motor, and human-adaptation abilities of computer-based systems in an unusually demanding and constrained environment

Interface Technology Highlights

- Emergence of robot manipulator designs specifically designed for surgical applications
  - E.g., RCM, MRI compatible systems, “snake” robots, …
- Cooperative control for human skill augmentation
- Specialized systems with tissue or image sensing


S. Salcudean *et al.* (UBC)



R. Howe, *et al.* (Harvard)

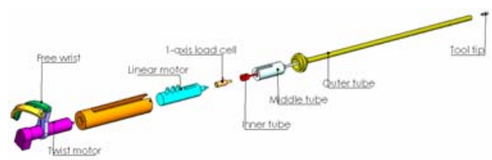

R. Taylor, *et al.* (JHU)

*Haptic Interaction in Robotic Endoscopic Surgery **

M. Tavakoli, R.V. Patel, M. Moallem
Canadian Surgical Technologies & Advanced Robotics (CSTAR) and
Department of Electrical and Computer Engineering, University of Western Ontario
London, Ontario, Canada

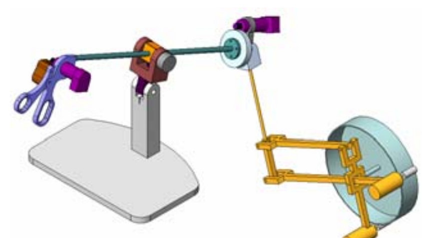
Instrumented endoscopic end effector:

- Non-invasive measurement of forces/torques in all five DOFs; no sensor on the tip jaws
- Detachable tips
- Outer tube diameter < 1 cm
- Applications:
  - Robotic surgery
  - Surgical skills assessment; study of force/torque signatures



Force-reflective interface for endoscopic manipulation:

- Force feedback in all five DOFs
- Fairly large workspace for the instrument tip
- Partial static balancing
- Applications:
  - Robotic surgery
  - VR-based simulation and training; haptics-assisted guidance



Simplified CAD drawing

* M. Tavakoli, R.V. Patel and M. Moallem, Design Issues in a Haptics-Based Master-Slave System for Minimally Invasive Surgery, *In proceedings of the 2004 IEEE International Conference on Robotics and Automation*, April 2004, New Orleans, LA.

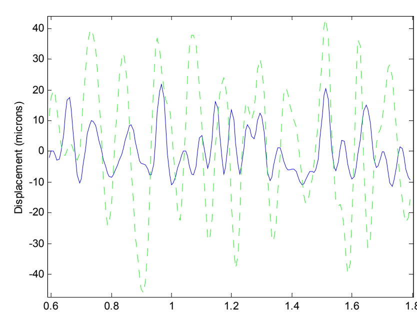
Micron:
Active Cancellation with Freehand Device

Riviere, Ang, *et al.* (CMU)

Micron incorporates motion sensing and endpoint control

- small, hand-held design
- active tremor cancellation
- new system meets goal of < 10μm rms motion

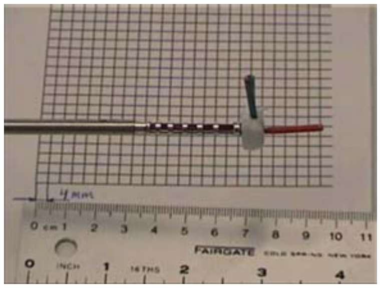
Precise control of piezoelectric actuators is needed for effective active tremor compensation.

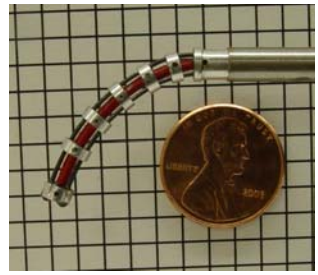


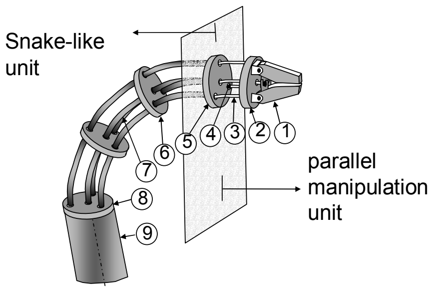
Active error compensation via Micron, displaying uncompensated (green) vs. compensated (blue) results.

Telesurgical robot for throat surgery

Nabil Simaan, Russell Taylor, Paul Flint, MD







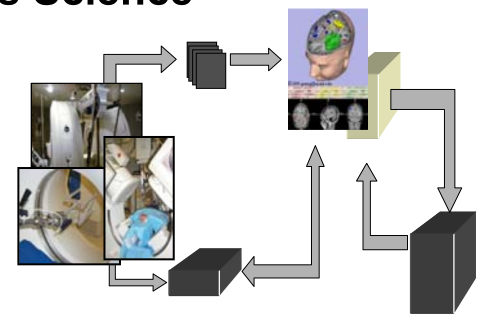
1 gripper
2 moving platform
3 parallel stage flexible links
4 Gripper actuation link
5 end disk
6 spacer disk
7 central backbone tube
8 base disk
9 DDU holder

Surgical Robot Technology Work Elsewhere

- Asia
  - Ikuta, Mitsuishi, Fujii, Hata, Sakuma, Dohi, Masamune, Nakamura, Kwon, Fukuda, …<<more to be added>>
- Europe + Israel
  - Davies, Dombre, Mathelin, Krupa, Dario, Herzinger, Fischer, Nelson, Shoham, Radermacher, Degoulange, Ortmaier, Woern, Troccaz, Papadopoulos, … …<<more to be added>>
- North America
  - Sastry, Salcudean, Hannaford, Allen, Howe, Fichtinger, Stoianovici, Whitcomb, Taylor, Simaan, Okamura, Patel, McBeath, Charles, Salisbury, Peshkin, Riviere, …<<more to be added>>
- See, *e.g.*, Taylor's & Dario' survey articles in recent *IEEE Transactions Special Issue*

Systems Science

- Modularity & Standards
- Robustness & Safety
- Customization
- Validation
- Information management



Core Challenge: Develop architectures, building blocks, and analysis techniques that facilitate rapid development and validation of versatile CIS systems & processes with predictable performance

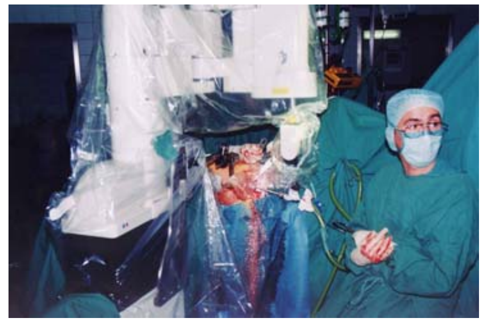
Systems Highlights

- Commercial systems
  - CAD/CAM: Robodoc, Arthrobot, Neuromate, Accuray, Image-Guide, …
  - Assistants: daVinci, Zeus, AESOP, …
- Research systems being clinically evaluated
  - E.g., JHU in-MRI prostate robot, US guided robots, …
- Recognized need for testbed architectures &shared components
- New interest in systems as enablers for biomedical research

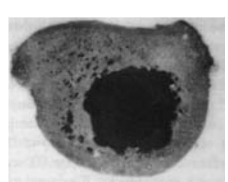
Intuitive Surgical daVinci

CIS Systems Examples

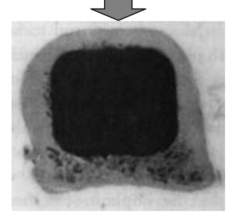
- **Surgical CAD/CAM Systems**
- Surgical Assistant Systems
- Some concluding remarks



Robotic Joint Replacement Surgery

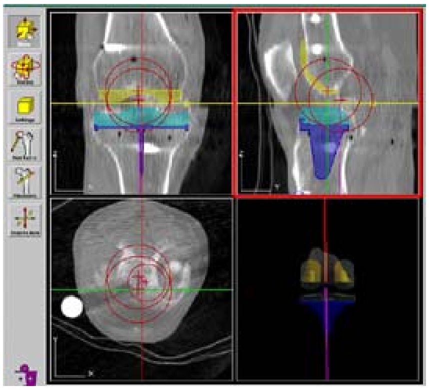


Manual Surgery



Robotic Surgery

Robotic Knee Replacement Surgery



Robotic THR & TKR Systems in Research Phases (Partial List)

- Parallel link approaches
  - Aachen (GRIGOS)
  - KAIST
  - Technion
- “Conventional” arms
  - Northwestern
  - U. Washington
  - Rizzoli Institute
- Cooperative Control
  - Imperial College (ACROBOT)
  - Grenoble (PaDyc)

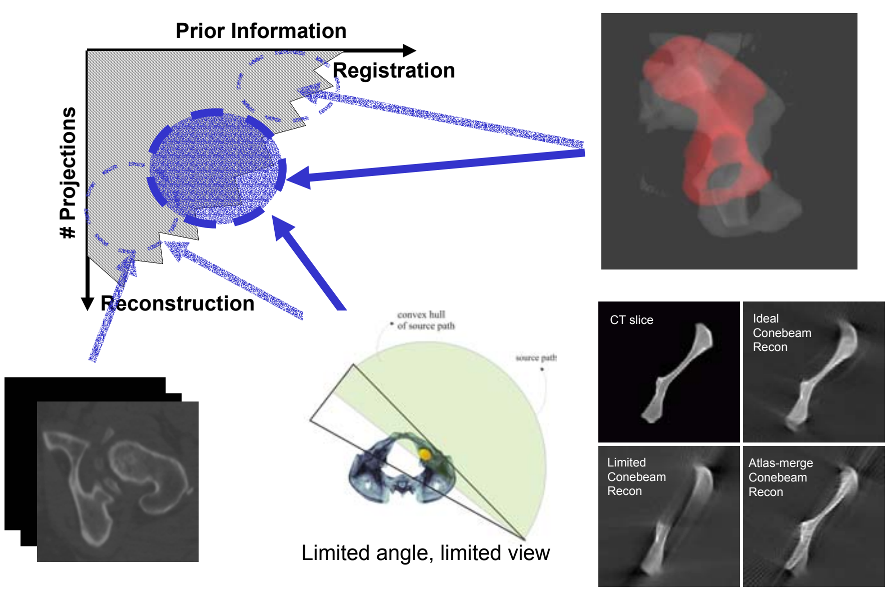
Movie: KAIST

Movie: Brian Davies

X-ray based registration

3D models from limited x-ray projections

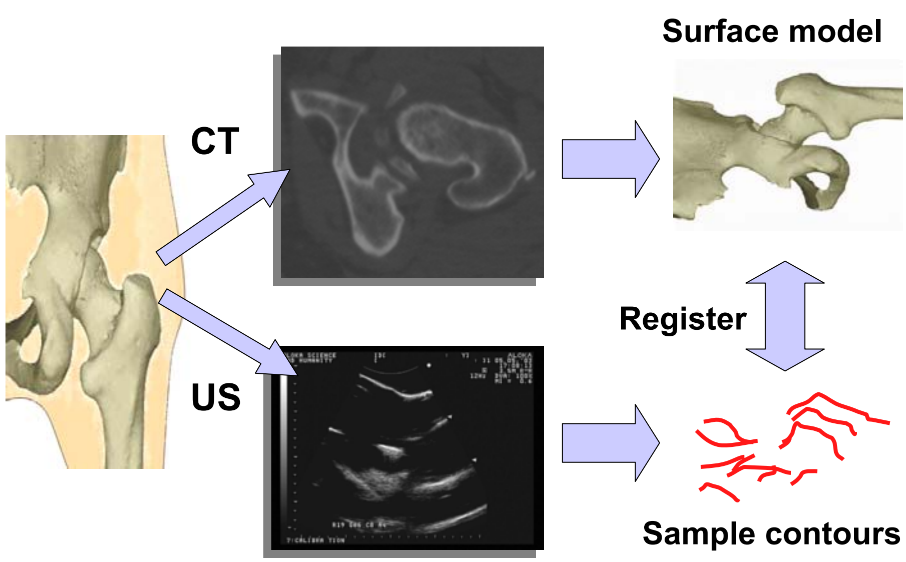
Taylor, Prince, Yao, Sadowsky, Ramamurthi, *et al.*

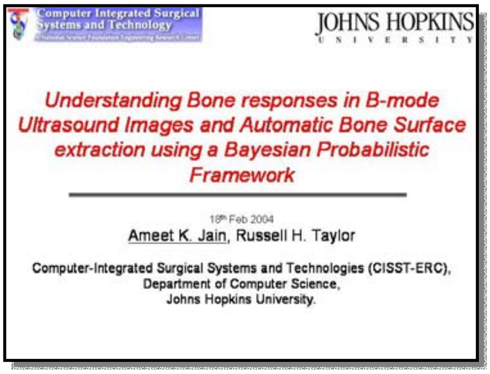


Other related work on statistical atlases with strong tie to interventions

- C. Davatzikos & D. Shen (U. Penn)
- T. Peters & A. Fenster (Robarts)
- R. Kikinis, S. Warfield, *et al.* (BWH)
- D. Hawkes, C. Taylor, *et al.* (Guy's Hospital)
- N. Ayache *et al.* (INRIA)
- Many more groups in US, Europe, Asia

Ultrasound-based registration





Computer Integrated Surgical Systems and Technology

JOHNS HOPKINS UNIVERSITY

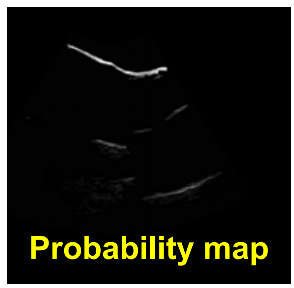
Understanding Bone responses in B-mode Ultrasound Images and Automatic Bone Surface extraction using a Bayesian Probabilistic Framework

18th Feb 2004

Ameet K. Jain, Russell H. Taylor

Computer-Integrated Surgical Systems and Technologies (CISST-ERC), Department of Computer Science, Johns Hopkins University.

- **Construct 3D surface probability map from multiple tracked 2D US images**
- **Compute segmented contours from probability map**
- **Presented SPIE 2004**



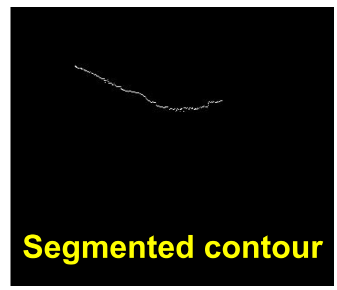
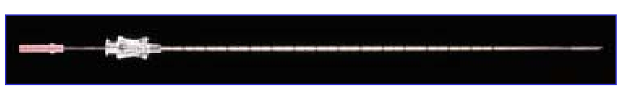
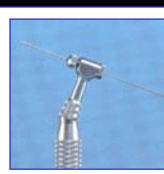
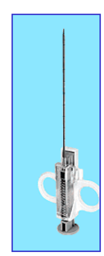


Image-Guided Needle-Based Interventions







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**

Current clinical scope

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

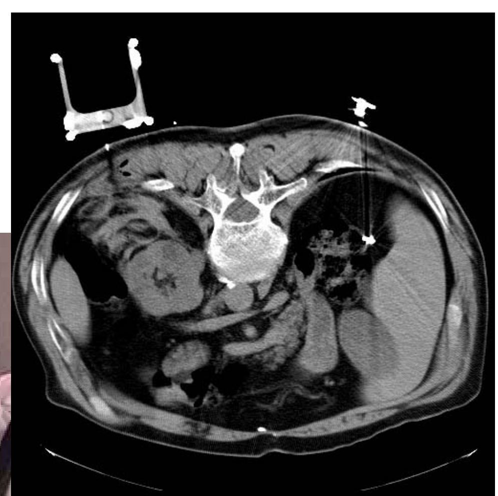
United States numbers

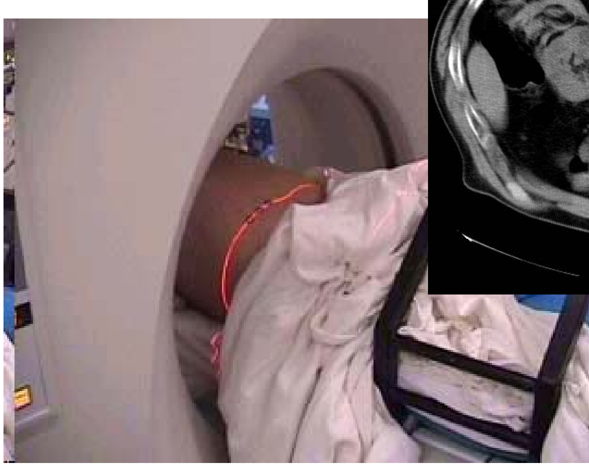
Why these?

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

Clinical example

- Kidney biopsy
- Robot registered to CT from single image using markers on end-effector





Photos: D. Stoianovici, L. Kavoussi, A. Patriciu, S. Solomon (JHU Bayview)
Other contributors: R. Susil, G. Fichtinger, K. Masamune, R. Taylor (JHU WSE)

NSF Engineering Research Center for Computer Integrated Surgical Systems and Technology

Robotically Assisted Spinal Pain Blocks

K. Cleary, V. Watson (Georgetown), D. Stoianovici (Hopkins)

- Assist physician in needle placement for spinal blocks

- Joystick controlled robot
- Steady needle holder
- Physician can manipulate needle in real-time without radiation exposure

- FDA and IRB approved clinical trial completed

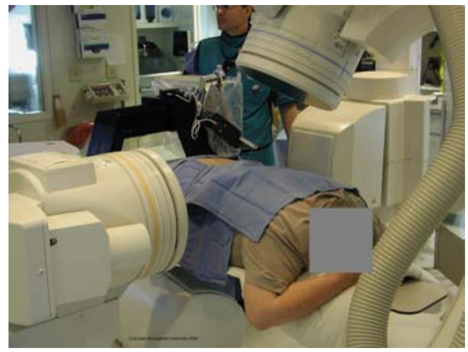


Photo: Image Guide, Inc.

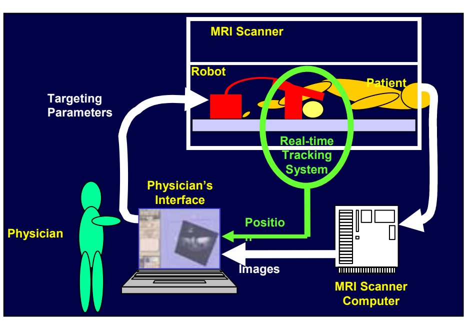
NSF Engineering Research Center for Computer Integrated Surgical Systems and Technology

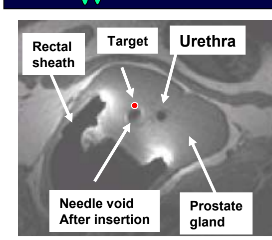
Robotically Assisted Lung Biopsy

K. Cleary (Georgetown), R. Taylor (Hopkins), C. White (Maryland)

- Automatically take lung biopsy sample under CT fluoroscopy
- Needle driver robot
- Frame grab images
- Predict lung motion and command robot
- Phantom and swine studies in progress

Intra-Cavity Robot in Closed MRI

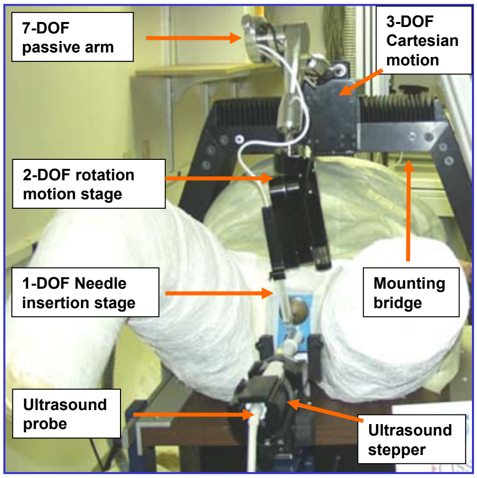


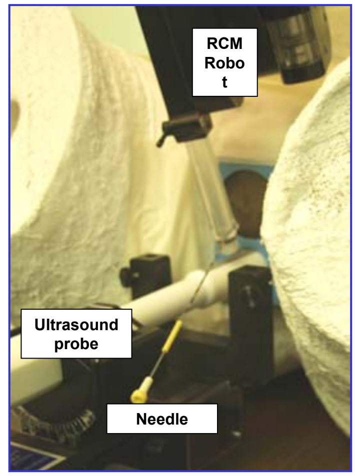


In clinical trial at NIH for prostate biopsy and seed implant.

JHMI: Ergin Atalar (Radiology), Ted DeWeese (RadOnc)
WSE: Gabor Fichtinger, Louis Whitcomb, Axel Krieger

TRUS-Guided Prostate Therapy



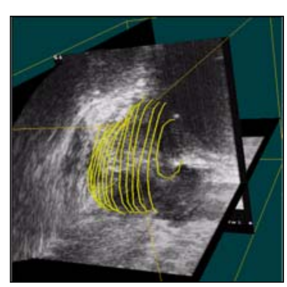


JHMI: Stoianovici, Kavoussi (Urology), TedDeWeese (RadOnc)
WSE: Fichtinger, Whitcomb
Industry: Burdette Medical Systems

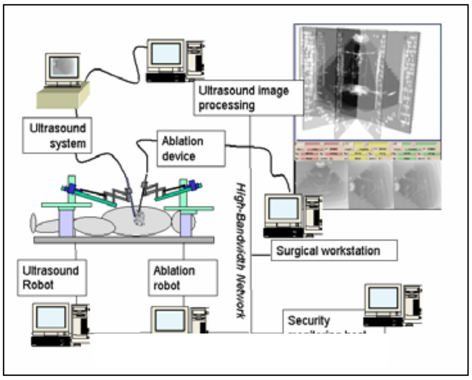
3D ULTRASOUND GUIDED & ROBOT AIDED PROSTATE BRACHYTHERAPY

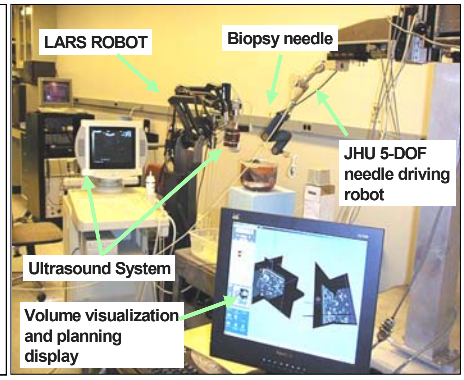
A. Fenster (Robarts)

- Conventional robot holds needle guide
- 3D TRUS targeting & needle tracking
- In-vitro test results
  - Needle placement accuracy: 0.145 mm
  - Needle placement accuracy: 0.09° at 15°
  - Needle targeting accuracy: 1.54 x 0.78 x 0.22 mm3 at 95% confidence
  - 3D Prostate segmentation accuracy: 95%
  - Needle tracking accuracy: 0.8 mm



Robot-Assisted US-Guided Liver Therapy

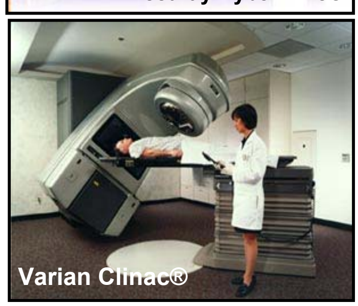




JHMI: Choti (Surg), Kavoussi (Urology) , Solomon (Radiology)
WSE: Fichtiger, Taylor, Boctor, Jain, Fischer, Vishwanathan, *et al.*
Industry : Burdette Medical, Intuitive Surgical, Aloka, Siemens

Stereotactic Radiosurgery Robots

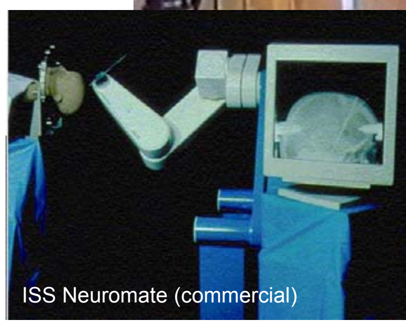
- **Radiosurgery systems**
  - Aim beam at patient from multiple directions
  - Typically multiple sessions
  - Millions of procedures per year (breast, prostate, brain, …)
- **Key "robotics" issues**
  - Planning
  - Registration to patient
  - Patient motion



Stereotactic Neurosurgery Robots

- First clinical application of robots
  - Kwoh, *et al.*
  - Lavallee*, et al.*
  - Benabid, *et al.*
  - …
- Commercialized
  - E.g., ISS Neuromate

IGOR (Lavallee, Troccaz, et al)



ISS Neuromate (commercial)

Project neuroArm™

UNIVERSITY OF CALGARY

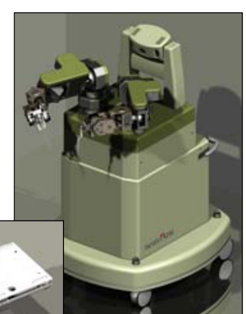
G.R. Sutherland, P.B. McBeth, D.F. Louw

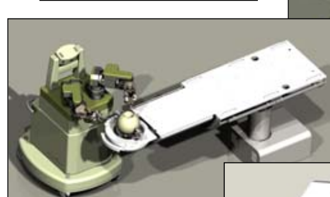
University of Calgary, Calgary, Alberta, Canada

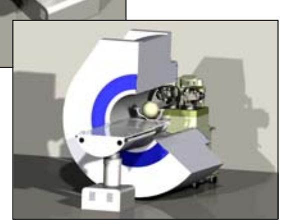
- Micro-neurosurgery
- Stereotaxy

- Master-Slave Control
- MR Compatibility
- Image Guidance
- Haptic Feedback

- Status: In Development
  - 2yrs from clinical application







CAS Systems Examples

- Surgical CAD/CAM Systems
- **Surgical Assistant Systems**
- Some concluding remarks

Robotic "Third Hand" Assistants

- Limb positioners
- Retractors
- Endoscope holders
  - Aesop
  - IBM/JHU LARS
  - etc.
- Can incorporate sophisticated HMI, voice, vision, etc.

Credit: Yulun Wang

Telerobotic Surgical Augmentation

- Commercial systems include Zeus, daVinci
- Teleoperated MIS surgery
  - Late 1990s robotics implementing late 1980s techniques
- Great potential to go beyond this
  - Information fusion
  - "Virtual fixtures"
  - Truly remote access

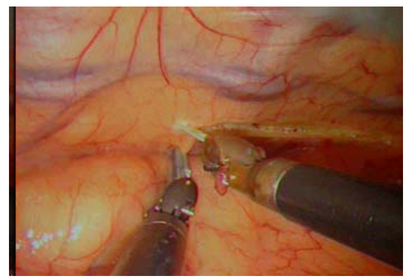
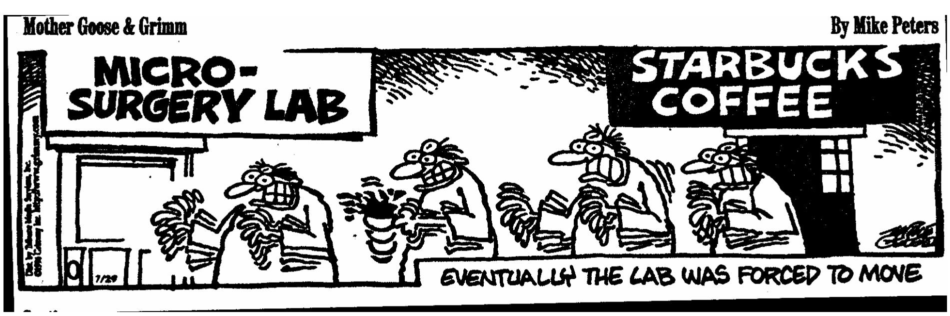
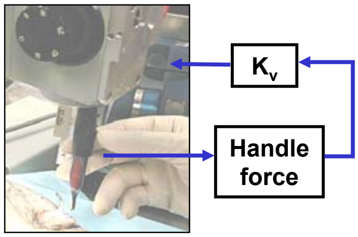


Photo: Intuitive Surgical

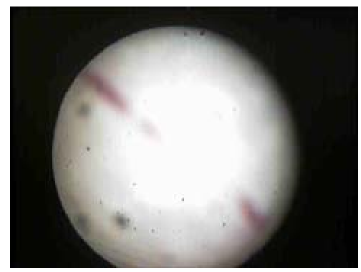
Robotic Assistants for Microsurgery



Steady Hand Guiding for Microsurgery



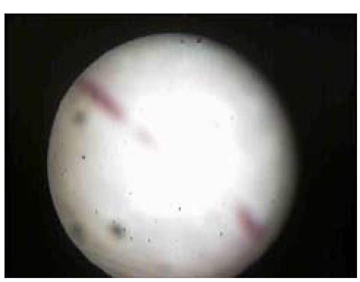
Free hand motion



Steady hand motion

R. Taylor & R. Kumar

Stable platform for interventions

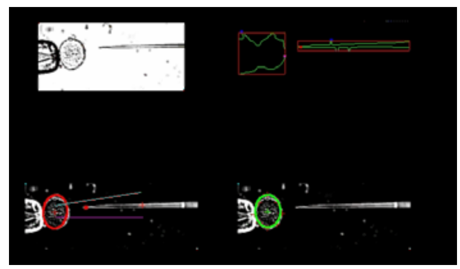


R. Kumar, 2001

Biomanipulation with a steady hand robot

Rajesh Kumar[1], Ankur Kapoor[2], Russ Taylor[2]

- Cooperatively controlled robot for single-cell scale biomanipulation tasks
- Multiple control modes
  - Simple compliant guiding
  - "Augmented" compliant guiding
  - Shared/supervised autonomy
- Future work includes:
  - Next generation system
  - Visual "virtual fixtures"



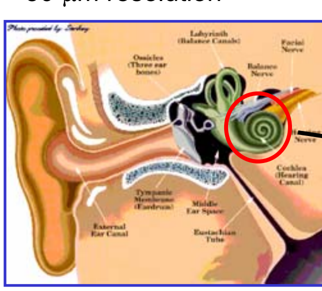
(1) Foster-Miller; (2) CISST ERC, JHU

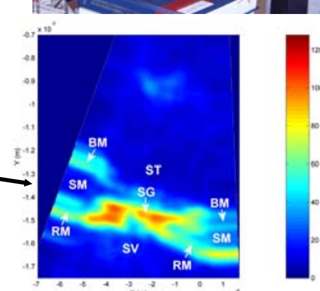
High Precision Ultrasound Guided Needle Placement

Rothbaum/Roy/Mustafa/Niparko/Francis/Whitcomb

Goal: to access the scala-media under ultrasound guidance

- Novel high resolution US device (collaboration with K. Shung and the Biomedical Ultrasonics Laboratory at USC)
- <30 μm resolution





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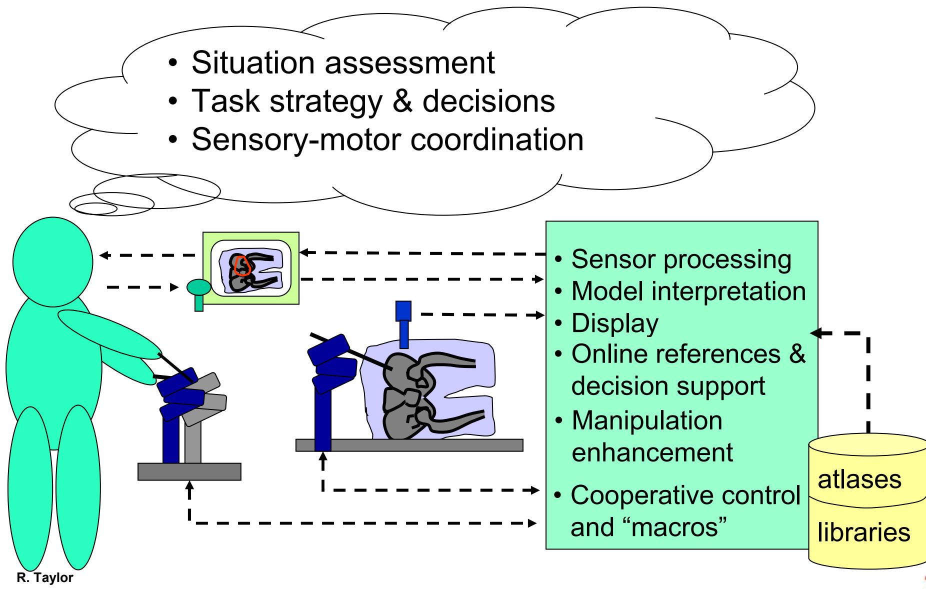
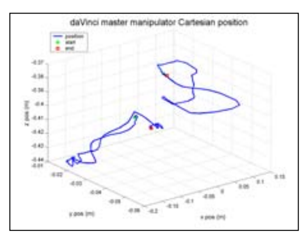
Evolution to human-machine partnership

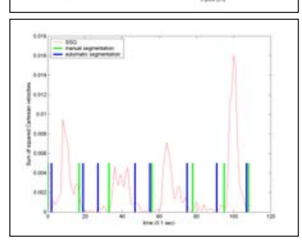


Objective Surgical Skill Evaluation

Todd E. Murphy, Allison M. Okamura (Johns Hopkins Mechanical Engineering), David D. Yuh (Johns Hopkins Cardiac Surgery)

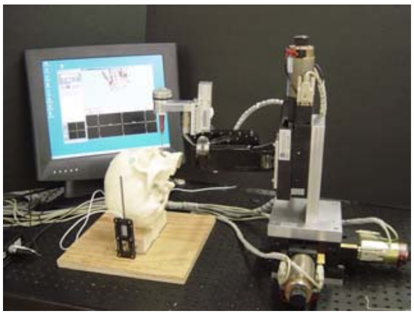
- Project goal: identify learning curves for surgeons new to the da Vinci® system
- Approach: exploit the robotic nature of the da Vinci® to collect detailed motion information
  - Develop models to enable automatic recognition of basic motions
  - Use sequence of motions to evaluate skill
- Hidden Markov Models (HMMs) are used for motion recognition
- Status: achieved 85% correct motion recognition rate for motions used during a simple training task
  - Further work to develop a more generalized motion vocabulary and definition of appropriate examination tasks

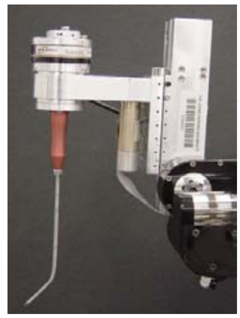


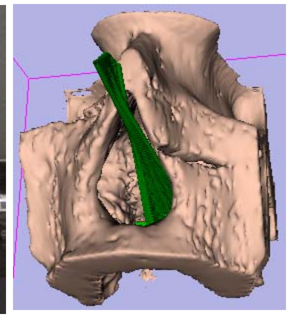


Steady-hand sinus surgery with virtual fixtures derived from CT models

Ming Li, Russell Taylor

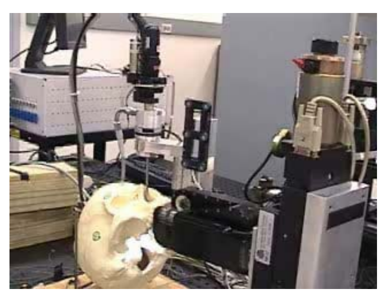






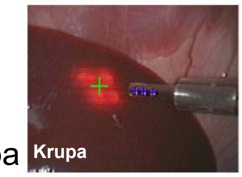
Sample task: steady hand path tracing

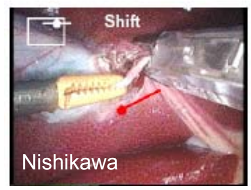
- Optimal control with “virtual fixture” constraints automatically generated in real time from preoperative CT models
- Compare with free-hand
  - Approx 2:1 improvement in path following accuracy
  - Approx 1.5:1 improvement in time to complete task



Related work on "virtual fixtures", "verbs" & sensor-based servoing for medical robots

- **North America**
  - Hannaford (U. Wash.)
  - Howe (Harvard)
  - Okamura, Hager, … (JHU)
  - …
- **Europe**
  - Dombre (Montpelier), Mathelin & Krupa (Strasbourg), Knoll (Munich), Martelli (Pisa) …
- **Asia**
  - Nishikawa (Osaka)
  - …





Related work on spatial planning

- North America
  - Howe (Harvard) & Dupont (BU)
  - Latombe (SU) & Kavraki (Rice)
- Europe
  - Adhami & Coste-Maniere (INRIA)
  - …

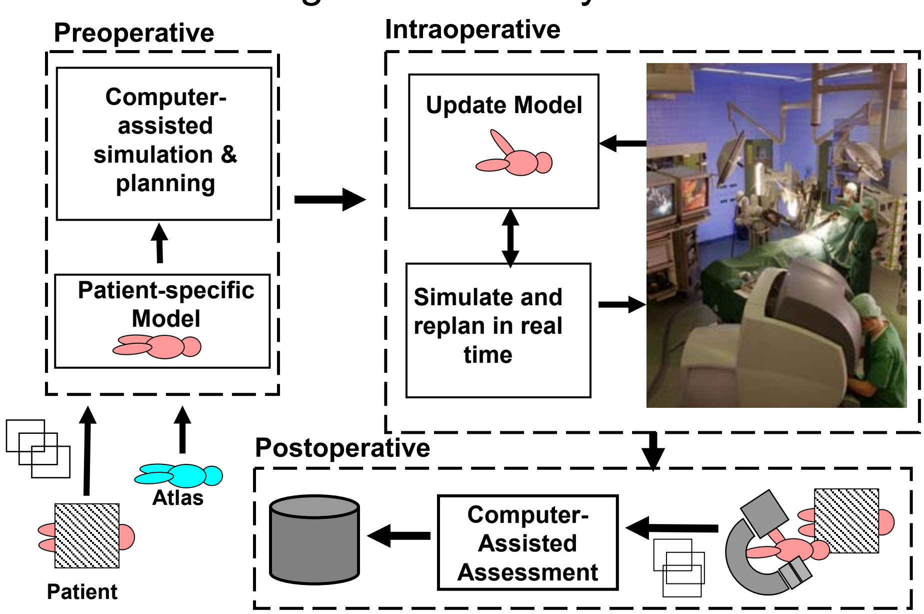
Adhami & Coste-Maniere

A few "grand challenge" areas

- **Grand Unified System***
  - Real-time patient-specific models
  - Surgical total information awareness
  - Active human-machine partnerships
  - Correlate performance to outcome
- **"Fanstastic Voyage"***
  - Micro-invasive interventions on tiny structures
- **Surgery on cells & microstructures**

* From Turf Valley Workshop (March 2003)

The grand unified system*



* From Turf Valley Workshop (March 2003)

A few "grand challenge" areas

- **Grand Unified System**
  - Real-time patient-specific models
  - **Surgical total information awareness**
  - Active human-machine partnerships
  - Correlate performance to outcome
- **"Fanstastic Voyage"***
  - Micro-invasive interventions on tiny structures
- **Surgery on cells & microstructures**

Surgical Total Information Awareness

- **Real time sensing & modeling of surgical situation**
  - Patient-specific models
  - Surgical tools & tool-tissue interations
  - Surgeon movements
  - Etc.
- **Application drivers**
  - Assistance (robots & information support)
  - Outcomes assessment
- **Technology drivers**
  - Imaging, computer vision, image analysis
  - Sensors, sensor networks
  - Biomechanics, statistical modeling
  - Human-machine interfaces, haptics
  - Performance/task modeling

“Fantastic Voyage”

- **Micro-invasive microsurgery robots**
  - Very small robots that get to the target anatomy & perform very precise interventions
  - Multiple/flexible access paths
  - Dexterity needed to do task. Break conventional “two hands/two eyes” paradigm
  - Integration with special devices for diagnosis & therapy
- **Example procedures**
  - Robotic Maze procedures, beating heart surgery, micro-neurosurgery, nerve root decompressions, …
- **Technology drivers**
  - Micro/MEMS robots & sensors, tiny dexterous mechanisms
  - Navigation/remote control
  - Human-machine integration
  - Sensor nets / team robots

* From Turf Valley Workshop (March 2003)

Cell & microstructure surgery

- **General goal**
  - Extremely precise robotic systems for manipulating structures in single cells or small assemblages of cells
- **Application drivers**
  - Basic biology research ⇦
  - Therapeutic interventions
- **Technology drivers**
  - MEMS, micro-sensors, **really tiny** dexterous mechanisms
  - Novel imaging,
  - Visual servoing
  - Human-machine systems

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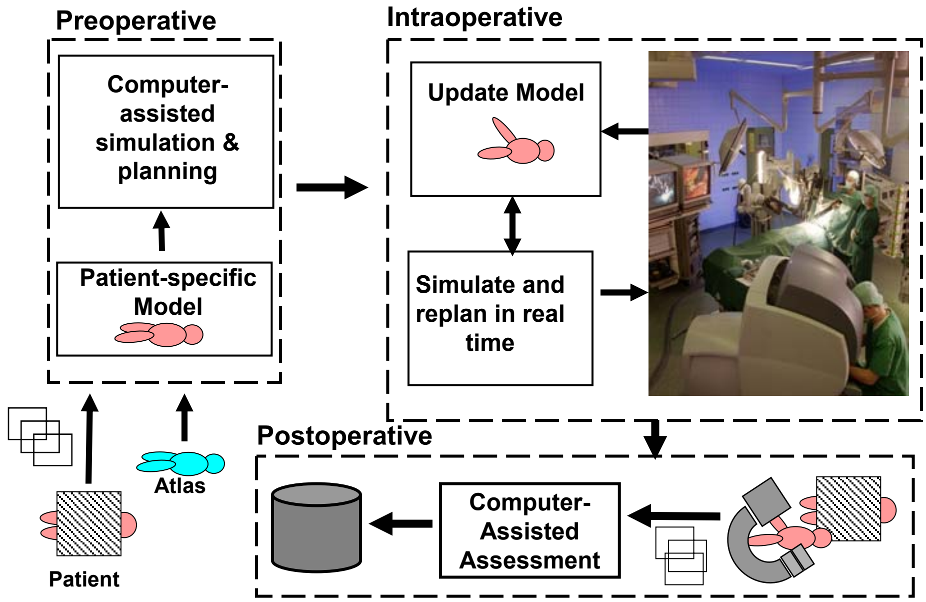
The grand unified system*



* From Turf Valley Workshop (March 2003)

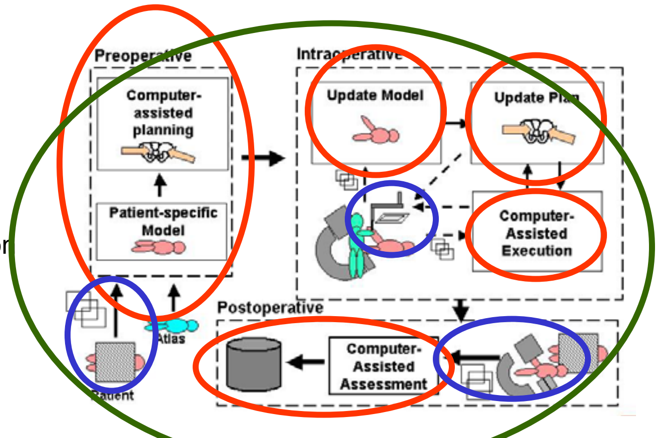
Drivers for adoption

- **Error-free surgery**
  - Designs & systems to make things safer
  - Integration of imaging, computer assistance, etc.
- **Enablers for otherwise infeasible interventions**
  - Superhuman capabilities (access, precision, …)
  - Delivery systems for novel image-guided therapies
- **Enablers for research & development**
  - Consistency, capability & data gathering
- **Capture of information about cases**
- **Use of robots as training tools**
  - Mentoring
  - Simulation integrated with robotics

* From Turf Valley Workshop (March 2003)

Research and technology barriers

Modeling & analysis
- Segmentation
- Registration
- Atlases
- Optimization
- Visualization
- Task characterization
- *etc.*



Interface Technology
- Sensing
- Robotics
- Human-machine interfaces

Systems
- Safety & verifiability
- Usability & maintainability
- Performance and validation

Table 1: A Sampler of Surgical CAD/CAM Systems

System	Institution	Country	Year	Guidance/Control	Clinical Area	Applied to	Commercial / Regulatory Status	Mount	Positioning Arm	DOF	RCM Type	Back-drivability	Ref
Acrobot	Imperial College	UK	2001	Synergetic	Orthopedic	Human	-	Floor trolley Table clamps	6 dof active + brakes	3	-	Low	[158]
Arthrobot	KAIST	Korea	2002	Gauge-Based	Orthopedic	Phantom	-	Bone	-	4	Programmable	Low	[17]
Brigham MRI	AIST / Brigham & Women Hospital	Japan / USA	1999	MRI Guided	Prostate Brachytherapy	Phantom	Non-commercial	MRI Scanner	-	5	-	Low	[19]
Breast MRI System	Karlsruhe University	Germany	2000	MRI Guided	Breast Biopsy	Animal	-	Scanner Table	-	6	-	Low	[91]
CyberKnife	Accuray	USA	1999	X-Ray Guided	Radiosurgery	Human	Commercial	Floor	-	6	-	Very Low	[159]
GRIGOS	Helmholtz Inst; TIMC-IMAG	Germany; France	1997	Surgical CAD /CAM	Orthopaedics	Phantom	-	Table	-	6	-	Low	[77]
KEN-MRI	University of Tokio	Japan	1995	MRI Guided	Neurosurgery	Phantom	-	Table	-	6	Goniometer Arc	Low	[93]
Minerva	University of Lausanne	Switzerland	1993	X-Ray Guided	Neurosurgery	Human	-	Floor	3 transl dof	3	-	Low	[160]
IGOR	Grenoble University	France	1992	Preoperat. Imaging and Tracking	Neurosurgery	Human	Non-commercial	Floor	-	6	-	Very Low	[78]
Neuro Mate	Integrated Surgical Systems	France / USA	1996	Preoperat. Imaging and Tracking	Neurosurgery	Human	Commercial / FDA Cleared	Floor Trolley	-	6	-	Very Low	-
PAKY-RCM	Johns Hopkins	USA	1998-2003	X-Ray Guided	Percutaneous Access	Human	Transfer/FDA - IDE	Table Mount	7 dof	3	Belt Parallelogram	Very Low	[22]
PADyC	TIMC/IMAG	France	1995 - 2001	Synergetic	Cardiac	Animal	-	Floor	-	6	-	Very High with Brakes	[27, 161]
PinPoint	Philips / Marconi Medical Systems	USA	2000	CT Tracker Arm	CT Interventions	Human	Commercial	Ceiling	6	-	-	Very High	[26]
PROBOT	Imperial College	UK	1995	US Guided	Urology	Human	Non-commercial	Floor	Slider	3	Goniometer Arc	Low	[162]
ROBODOC	Integrated Surgical Systems	USA	1992	CT-based preop. plan	Orthopedic	Human	Commercial/ Cleared in Europe	Floor with fixator to bone	Modified SCARA	6	-	Low	[69, 70]
Robards-breast	Robards Research Inst.	Canada	2001	Ultrasound	Breast biopsy	animal	-	Table	Cartesian	3	-	Low	[94]
RX-90	Karlsruhe University / orthoMarquet	Germany	1999	Synergetic	Maxillo-facial	Animal	Commercial	Floor	-	6	-	Low	[163]
Siemens CT	Siemens, AG	Germany	2000	Manual + Active	In-CT percutaneous	Animal	-	Table	Passive arm + 2dof active	2	5 bar parallel linkage	Low?	[38]
SS-Orthop	Scuola Superiore Saint'Anna	Italy	1998	CT-based preop plan	TKA	Cadaver	-	Floor?	-	5	-	Low	[164]
AcuBot	Johns Hopkins / Georgetown University	USA	2001	X-ray & CT Guided	Percutaneous Access	Cadaver	Transfer / FDA - IDE	Bridge Scanner Table Mount	7 dof	6	Belt Parallelogram	Very Low	[84]
WAM	Z-KAT Inc. / Barrett Technology	USA	2002	Synergetic	Spine	Phantom	-	Floor	-	4+1	-	Low	[29]

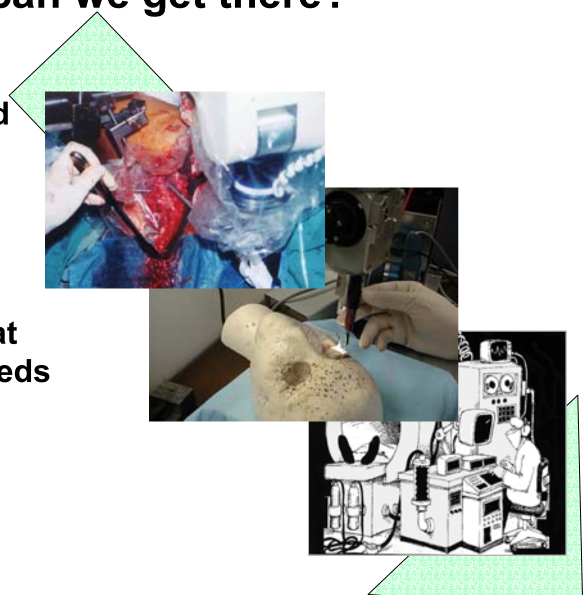
R. H. Taylor and D. Stoianovici, "Medical Robotics in Computer-Integrated Surgery," *IEEE Transactions on Robotics and Automation*, vol. 19(5), pp. 765-781, 2003.

Table 2: A Sampler of Surgical Assistant Systems

System	Institution	Country	Year	Guidance/Control	Clinical Area	Applied to	Commercial / Regulatory Status	Mount	Positioning Arm	DOF	RCM Type	Backdrivability	Ref
AESOP	Computer Motion	USA	1992	Pad, Foot, Voice, Remote	Laparoscopy	Human	Commercial / FDA Cleared 1994	Cart and Table Mount	-	3	Passive	Low	[12]
BlueDRAGON	University of Washington, Seattle	USA	2002	Haptic Device	Laparoscopy	Phantom	-	Table	-	4	Bar Parallelogram	Very High	[165]
CLEM	TIMC/IMAG	France	2002	-	Laparoscopy	Phantom	-	Table	-	3	Compliant	High	[45]
daVinci	Intuitive Surgical	USA	1999	Master-Slave	Laparoscopy	Human	Commercial / FDA Cleared 2000	Floor Trolley	Passive, breaks	2*6 +4	Bar Parallelogram	High	[14]
LARS	IBM	USA	1995	Synergetic / Image Guided	Laparoscopy / Percutaneous Access	Animal	-	Floor Trolley	-	6	Bar Parallelogram	Low	[37]
SCALPP	LIRMM	France	2001	Surgical Assistant	Skin harvesting	?	-	Floor	Augmented SCARA	6	-	?	[133]
SS-Colon	Scuola Superiore Saint'Anna	Italy	1997-2002	Surgical Assistant; Master-slave	Colonoscopy	Cadaver	-	Free mount	-	1?	-	Low	[143]
Steady Hand	Johns Hopkins	USA	1999	Synergetic	microsurgery	cadaver	Non-commercial	Table	-	7	Belt Parallelogram	Mixed	[123, 124]
SurgiScope	Humboldt University / Jojumarie Intelligente Instrumente /Elekta	Germany	1997	Navigation + Surgeon inputs	Microscope holder; brachytherapy	Human (microscopes); animals (brachytherapy)	Commercial	Ceiling	Parallel	6	-	Low	[166]
TER	TIMC/IMAG	France	2001	Master-slave	Tele-Echography	phantom	-	Table/patient	Parallel	2	Constraint at entry port	High	[156]]
UBC-US	University of British Columbia	Canada	1999	3D Ultrasound	Arterial exams	Human	-	Floor Trolley	-	6	5 Bar Parallelogram	High	[142]
UBC-MW	University of British Columbia	Canada	1997	Master-slave	Microsurgery	phantom	-	Table	6DOF active robot	6	-	High	[104]
UCB/UCSF	UC Berkeley UC San Fran.	USA	1999, 2003	Master-slave	Laparoscopy	Animal	-	Floor trolley	6 DOF	6	Passive	High	[167, 168]
UT-LAP	University of Tokyo	Japan	1999	Gyro Sensor / Foot	Laparoscopy	Phantom	-	Table	-	4	Passive (Bar Parallelogram Included)	High	[39]
Zeus	Computer Motion	USA	1998	Master-Slave	Laparoscopy	Human	Commercial	Table Mount	-	3	Free wrist with constrained isocenter	Low	[13]

R. H. Taylor and D. Stoianovici, "Medical Robotics in Computer-Integrated Surgery," *IEEE Transactions on Robotics and Automation*, vol. 19(5), pp. 765-781, 2003.

How can we get there?



Strong and committed teams

- Surgeons
- Engineers
- Industry

Focus on systems that address important needs

Rapid iteration with measurable goals

Have fun!

The real bottom line: patient care

- Provide new capabilities that **transcend human limitations** in surgery
- Increase **consistency and quality** of surgical treatments
- Promote **better outcomes** and more **cost-effective** processes in surgical practice