NSF Engineering Research Center
for Computer Integrated Surgical
Systems and Technology

Medical Robotics and Computer-Assisted Interventional Systems:

Integrating Imaging, Intervention, and Informatics to Improve Patient Care

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with joint appointments in Mechanical Engineering, Radiology & Surgery
The Johns Hopkins University
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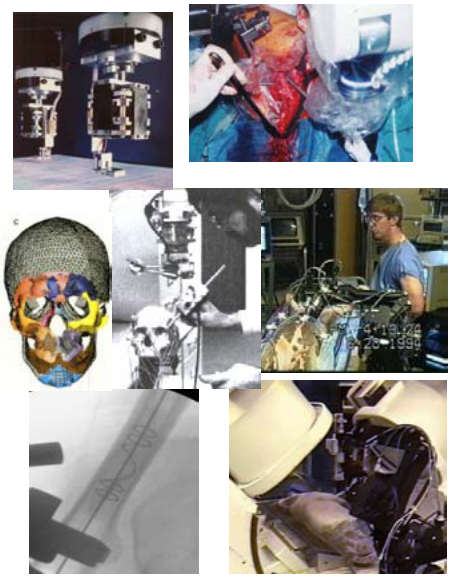
WHITING SCHOOL OF ENGINEERING
THE JOHNS HOPKINS UNIVERSITY

A short personal background: Russ Taylor

- **1976: PhD in CS at Stanford**
- **1976-1988: Research/mgt in robotics and automation technology at IBM**
- **1988 - 1996: Medical robotics & computer-assisted surgery at IBM**
  - Robodoc
  - Surgical navigation
  - Robotically assisted MIS and percutaneous interventions (with JHU)
- **1995: Moved to JHU**
  - CS with joint appts in ME, Radiology, Surgery (2005)
  - X-ray guided MIS & orthopaedics
  - "Steady Hand" microsurgery
  - Radiation therapy
  - Modeling & imaging
  - Etc.
- **1995 - 1996: NSF ERC Proposal**
- **1997 - now: NSF ERC**
- **2005 - now: I4M initiative**



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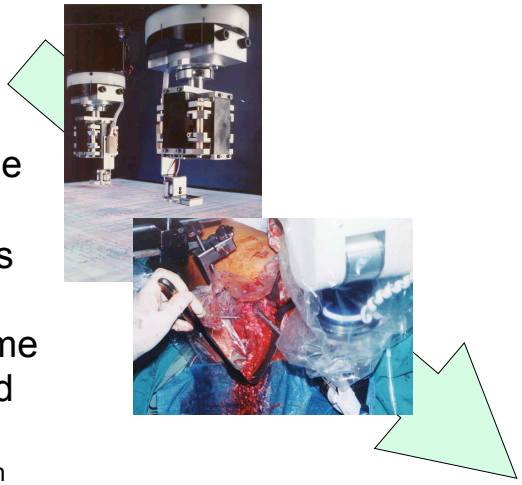
Motivating Insight

A partnership between human clinicians and computer-based technology will fundamentally change the way surgery and interventional medicine is performed in the 21st Century, in much the same way that computer-based technology changed manufacturing in the 20th Century



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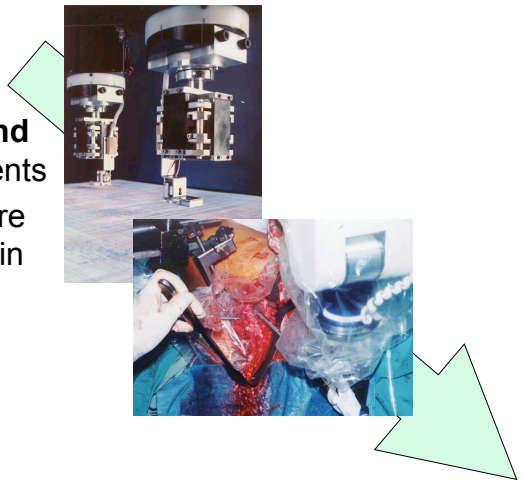
What will drive this change?

- New capabilities that **transcend human limitations** in surgery
- Increased **consistency and quality** of surgical treatments
- **Better outcomes** and more **cost-effective** processes in surgical practice



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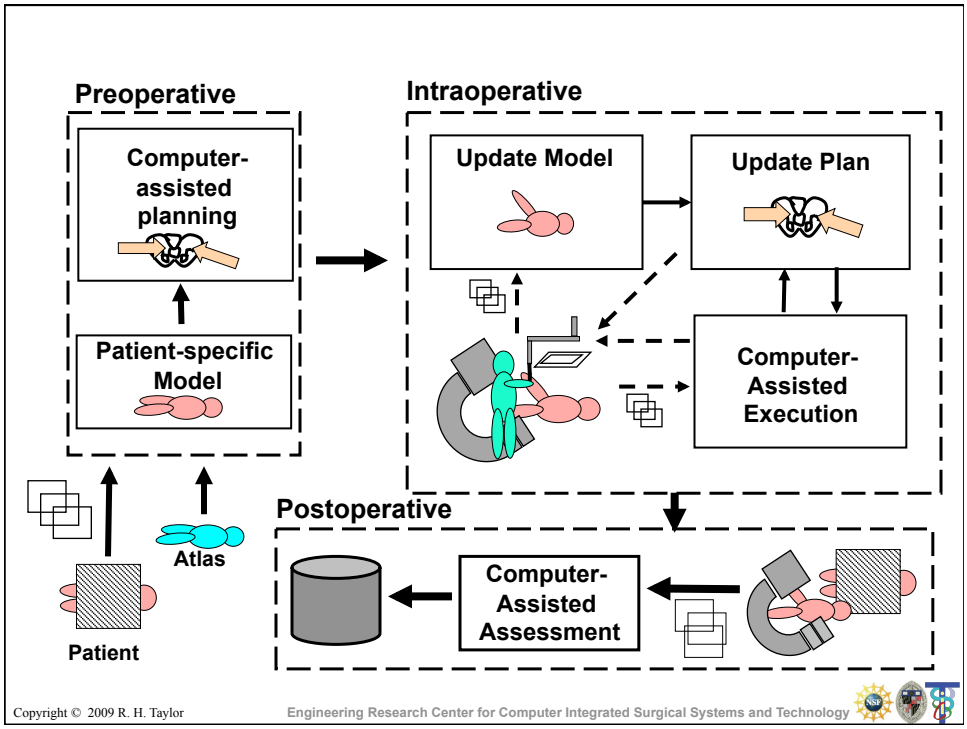
Preoperative
Computer-assisted planning
Patient-specific Model
Intraoperative
Update Model
Update Plan
Computer-Assisted Execution
Postoperative
Computer-Assisted Assessment
Atlas
Patient
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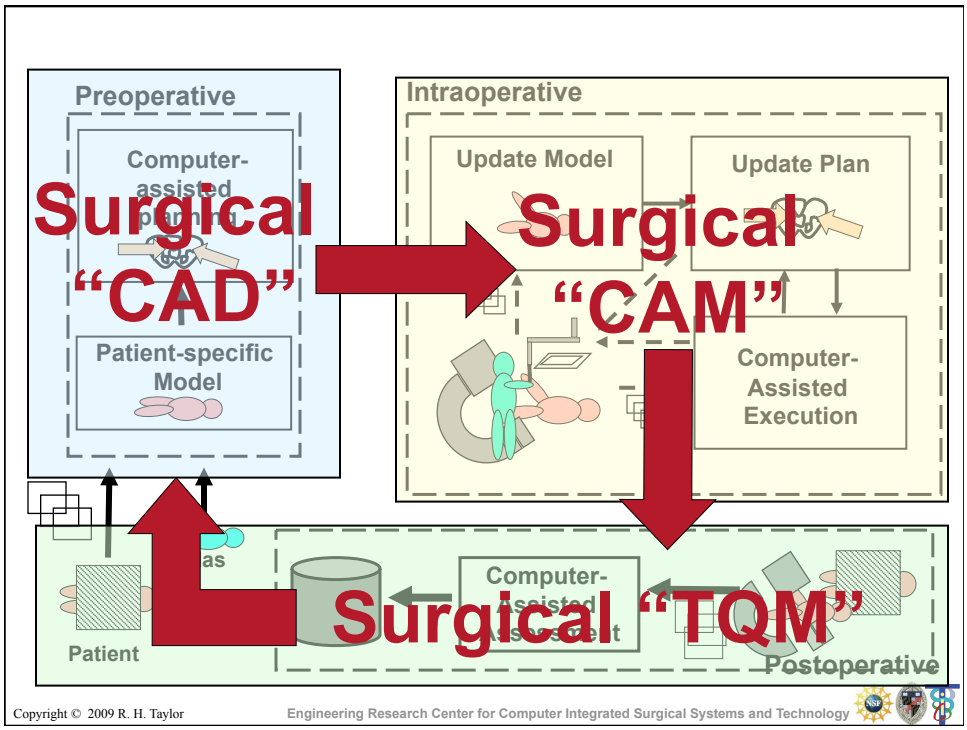
Preoperative
Intraoperative
Update Model
Update Plan
Computer-Assisted Execution
Patient-specific Model
Surgical "CAD"
Surgical "CAM"
Surgical "TQM"
Patient
Postoperative
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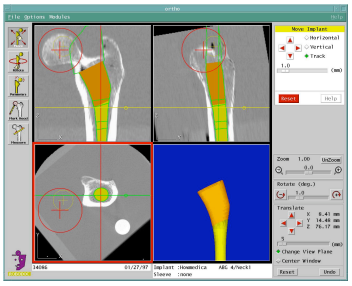
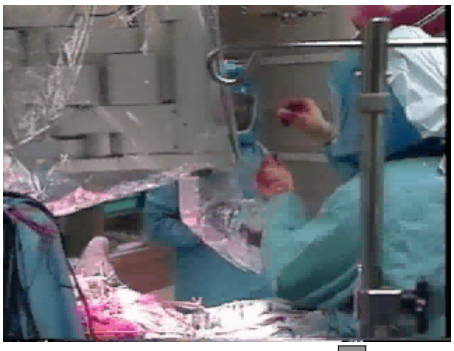
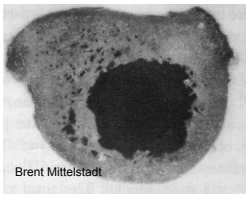
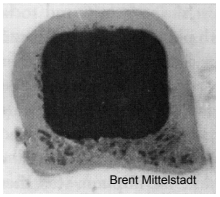
Example: Robotic Joint Replacement Surgery









Taylor, Kazanzides, Paul, Mittelstadt, *et al.*

Manual Surgery

Robotic Surgery

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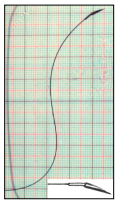
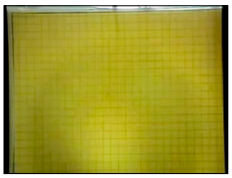
Example: Image-guided local therapy

Solomon *et al.*



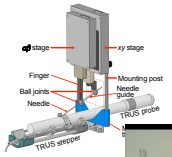
Riviere *et al.*

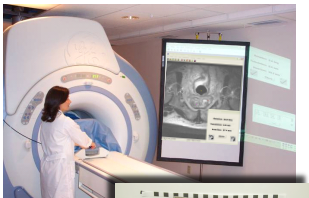


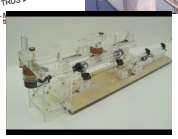
Webster *et al.*

Fichtinger *et al.*

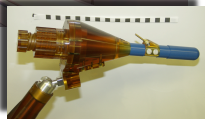
Kennedy *et al.*







G. Fischer *et al.*



Krieger *et al.*

Tempany *et al.*

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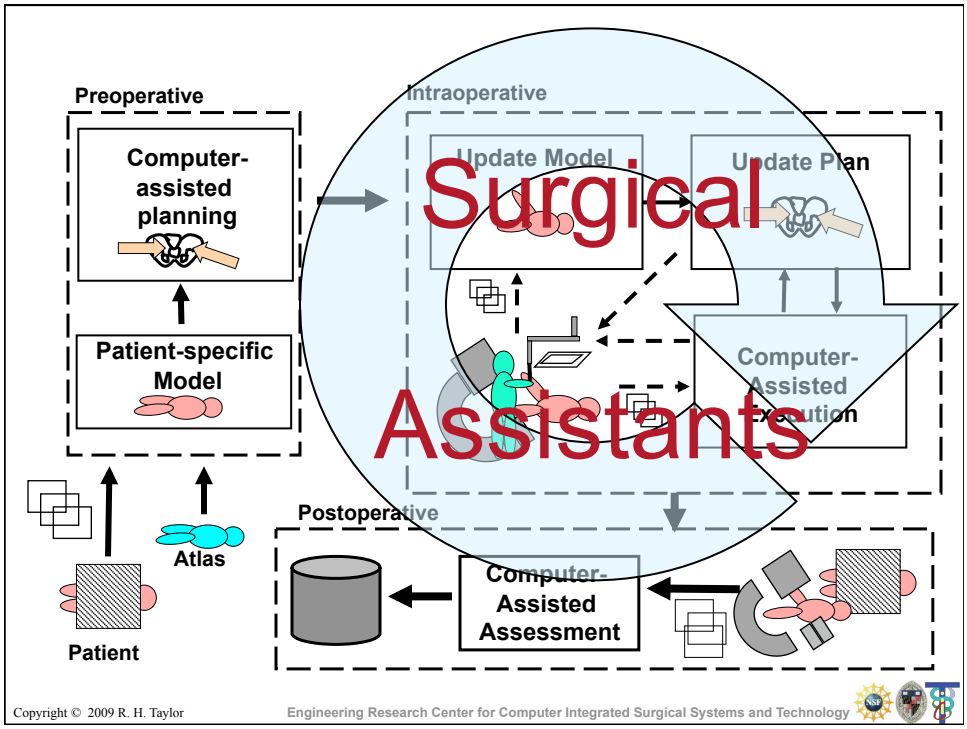

Example: Information-Enhanced Interactive Surgery

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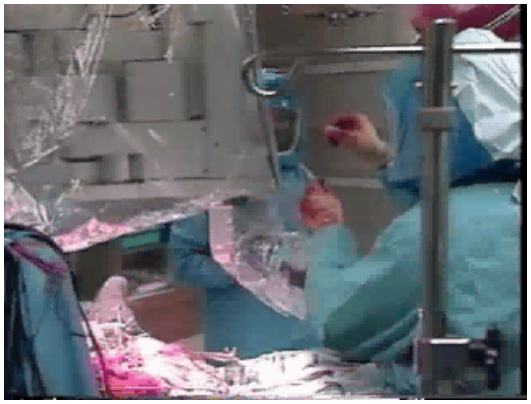
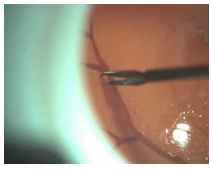
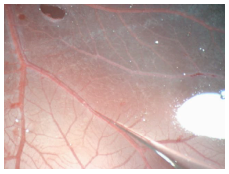
Example: Robotically-enhanced high precision surgery



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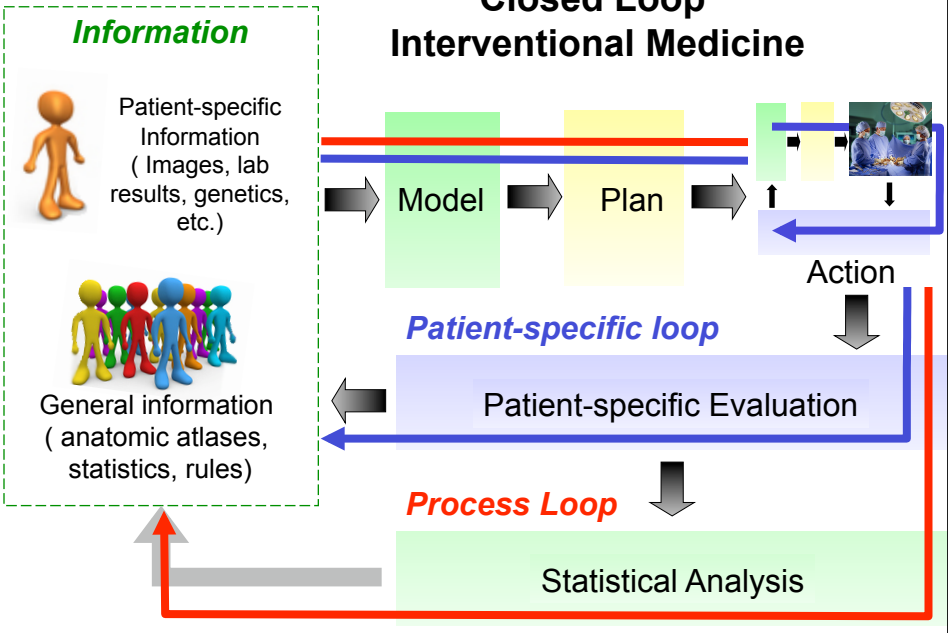
Closed Loop Interventional Medicine



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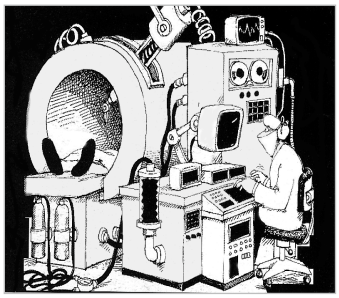
This Paradigm has not changed since Imhotep's day

27th Century BCE

But medical robots and computer-integrated interventional systems will make it much more effective



21st Century CE

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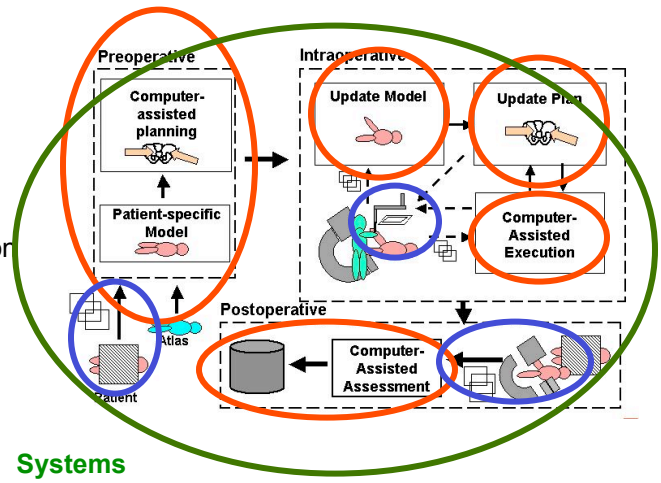
Multidisciplinary Integration is Crucial

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

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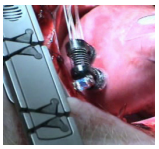
Engineering Research Center for Computer Integrated Surgical Systems and Technology (CISST ERC)



cisstweb.cs.jhu.edu

The CISST ERC is developing a family of surgical systems that combine innovative algorithms, robotic devices, imaging systems, sensors, and human-machine interfaces to work cooperatively with surgeons in the planning and execution of surgical procedures.

Areas of Research

- Robotic surgical assistants
- Image-guided interventional systems
- Focused interdisciplinary research in algorithms, imaging, robotics, sensors, human-machine systems

Institutions & Funding

- Johns Hopkins, MIT, CMU, BWH, Harvard, Penn, Morgan State, Columbia
- Years 1-10: NSF = $30.2M; Total = ~$73M

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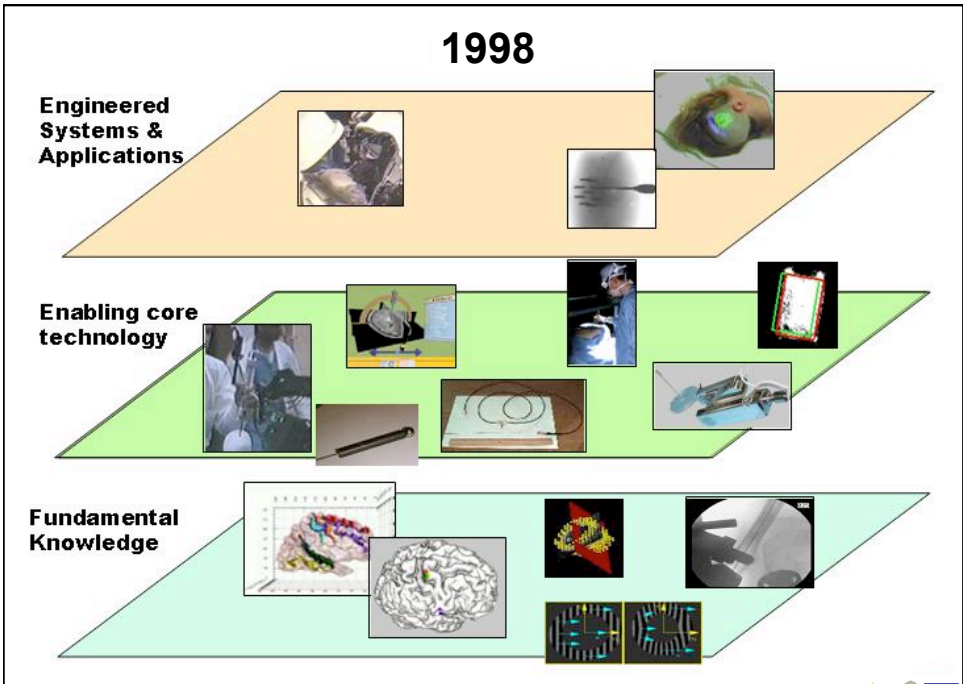

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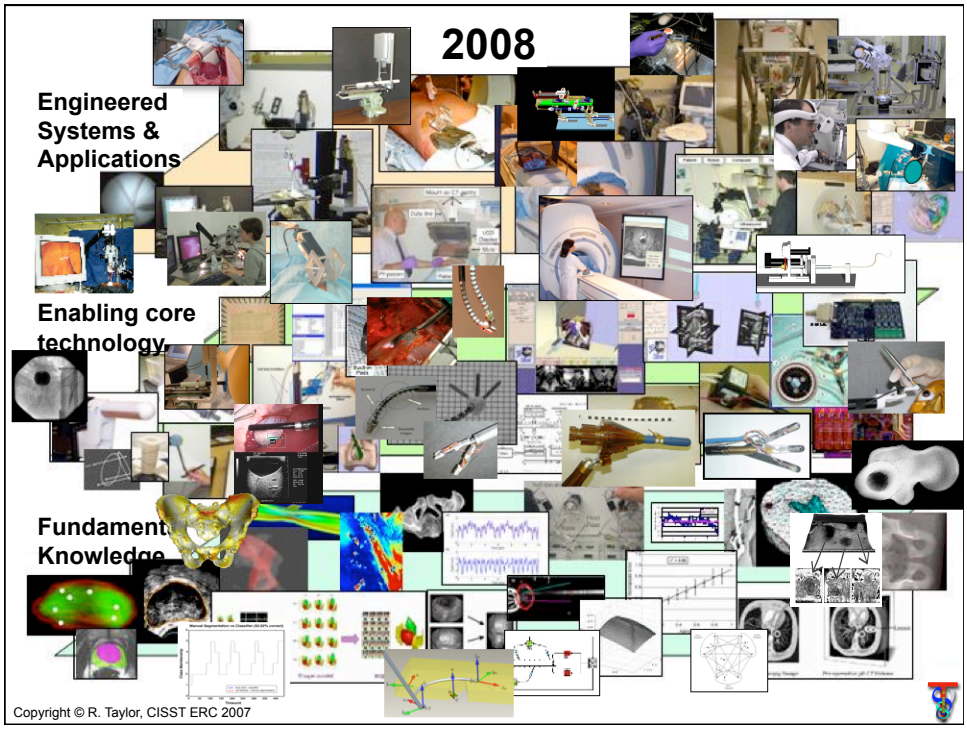
2008
Engineered Systems & Applications
Enabling core technology
Fundamental Knowledge
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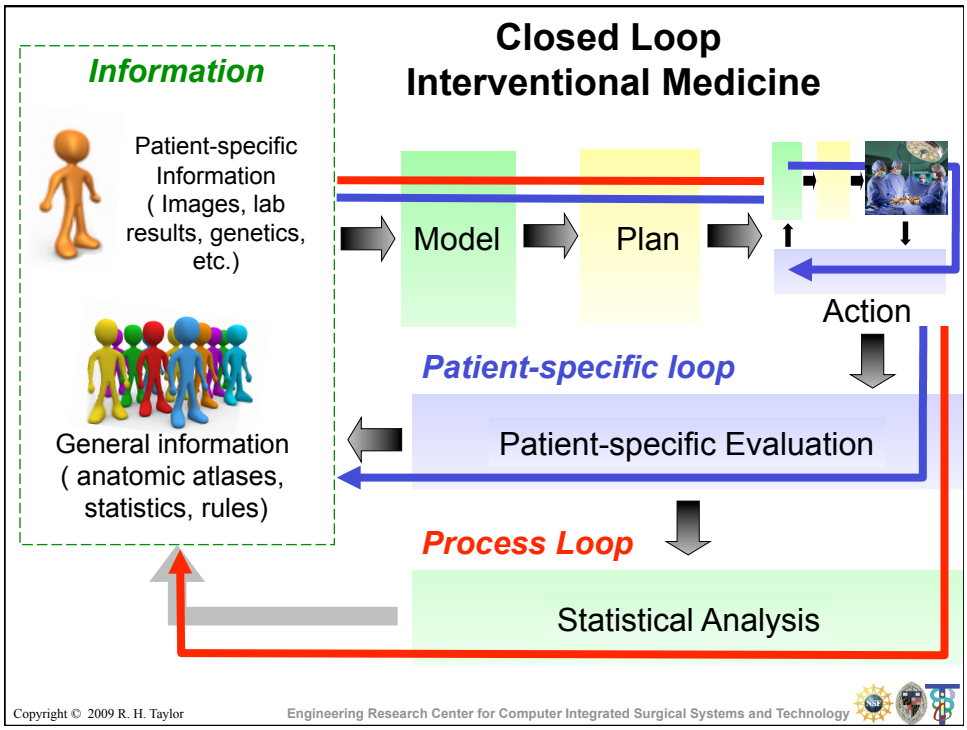
Closed Loop
Interventional Medicine
Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
Plan
Action
Patient-specific loop
Patient-specific Evaluation
Process Loop
Statistical Analysis
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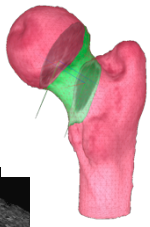
Patient-Specific Modeling

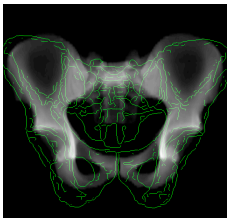
Information

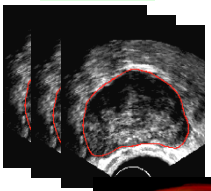
Patient-specific Information (Images, lab results, genetics, etc.)

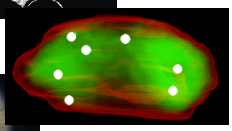
General information (anatomic atlases, statistics, rules)

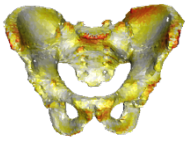
Model

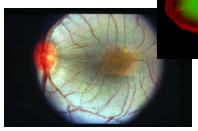


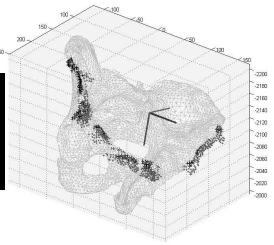












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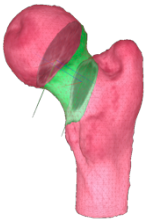
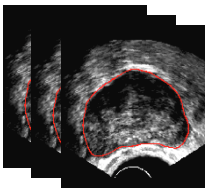
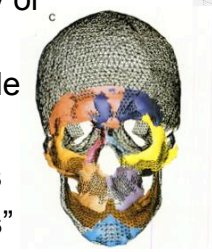
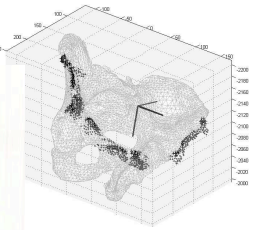
Patient-Specific Models for Interventions

- Computationally efficient **representation of patient** enabling computer to assist in planning, guidance, control, and assessment of interventional procedures
- Generally focus on **anatomy**, but may sometimes include biology or other annotations
- **Typical data structures** include
  - 2D & 3D images
  - 2D & 3D geometric meshes
- Increasingly reference "**atlases**" describing patient populations









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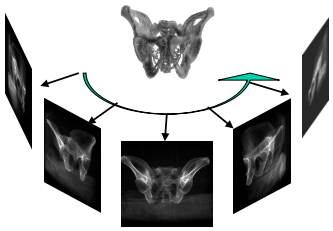
Patient-Specific Models for Interventions

- Typically constructed from 2D and 3D medical images
- Initial models often constructed from preoperative images and then registered to patient and/or updated using intraoperative images or sensors
- Buzz words include
  - Image segmentation
  - Atlas-based segmentation
  - Sensor fusion
  - Multi-modality imaging
  - Statistical shape models
  - Hybrid reconstruction



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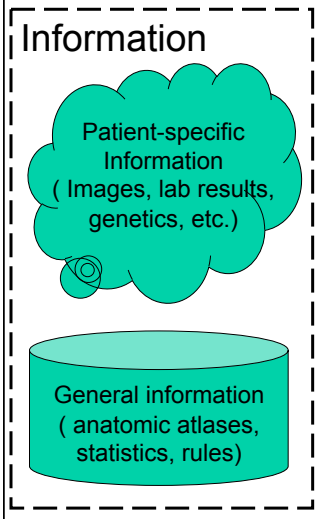
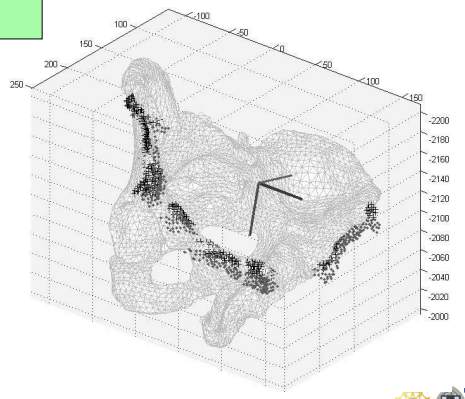
Example: Estimation of anatomical coordinates of pelvis from sparse ultrasound + atlas





P. Farougi, R. Taylor, G. Fichtinger

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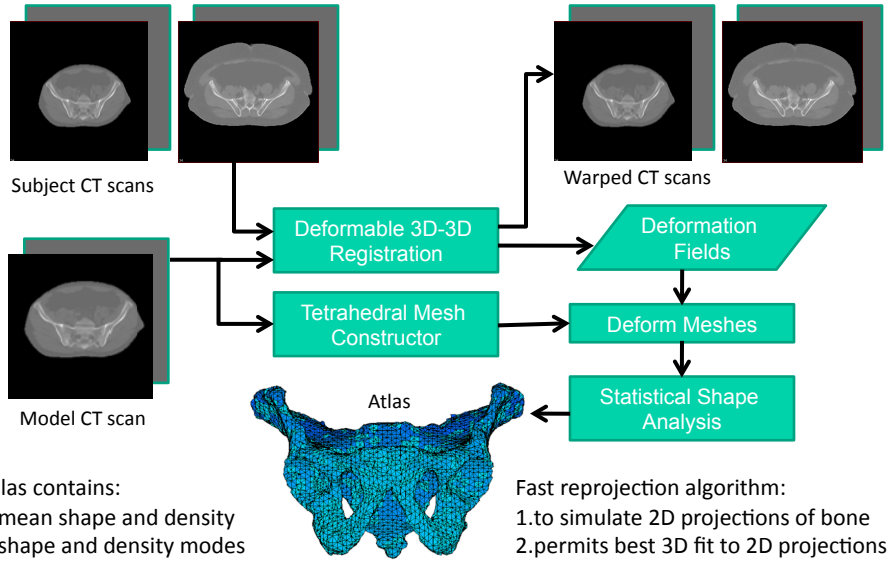
Constructing a Statistical Atlas



Atlas contains:
1.mean shape and density
2.shape and density modes

Fast reprojection algorithm:
1.to simulate 2D projections of bone
2.permits best 3D fit to 2D projections

Chintalapani, Ellingsen, Sadowsky, Ahmad, Yao, Prince, and Taylor

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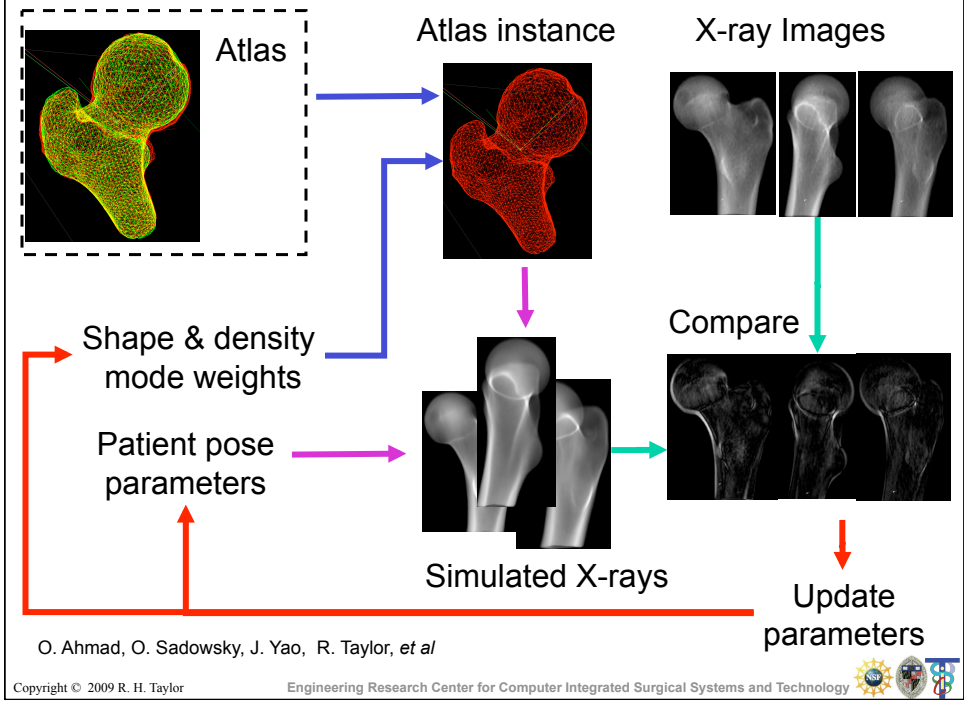

O. Ahmad, O. Sadowsky, J. Yao, R. Taylor, *et al*

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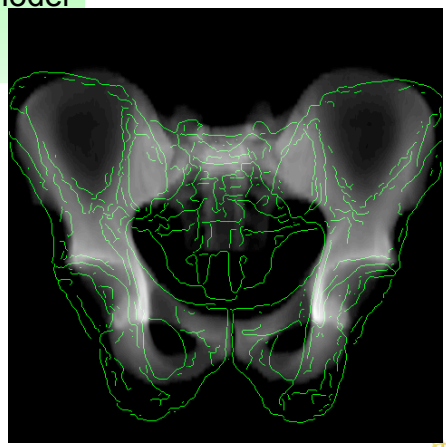
Example: 3D model of patient's pelvis from limited field of view x-ray images and atlas

Information

Patient-specific Information (Images, lab results, genetics, etc.)

General information (anatomic atlases, statistics, rules)

Model



O. Sadowsky, R. Taylor *et al*

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Example: 3D model of patient's pelvis from limited field of view x-ray images and atlas

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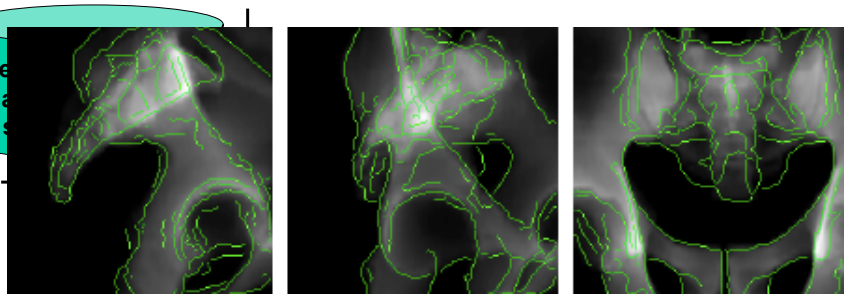

O. Sadowsky, R. Taylor

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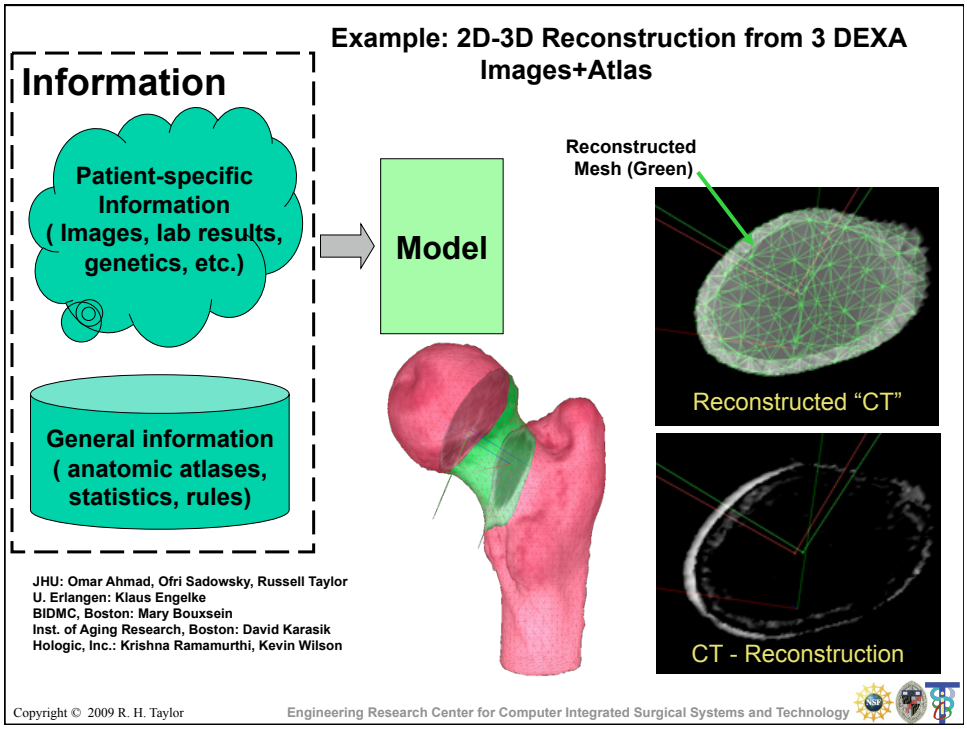
Example: 2D-3D Reconstruction from 3 DEXA Images+Atlas
Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
Reconstructed Mesh (Green)
Reconstructed "CT"
CT - Reconstruction
JHU: Omar Ahmad, Ofri Sadowsky, Russell Taylor
U. Erlangen: Klaus Engelke
BIDMC, Boston: Mary Bouxsein
Inst. of Aging Research, Boston: David Karasik
Hologic, Inc.: Krishna Ramamurthi, Kevin Wilson
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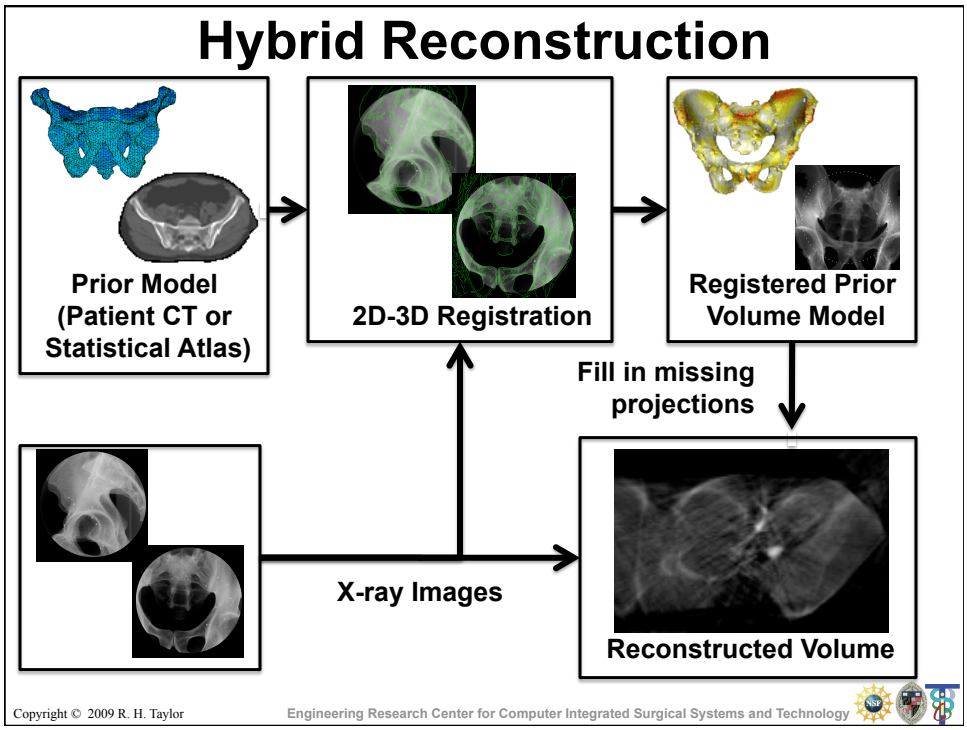
Engineering Research Center for Computer Integrated Surgical Systems and Technology


Hybrid Reconstruction
Prior Model (Patient CT or Statistical Atlas)
2D-3D Registration
Registered Prior Volume Model
Fill in missing projections
X-ray Images
Reconstructed Volume
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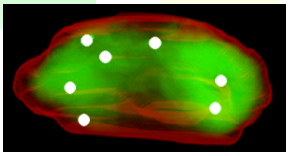
Procedure Planning

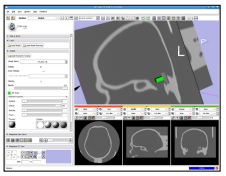
Information

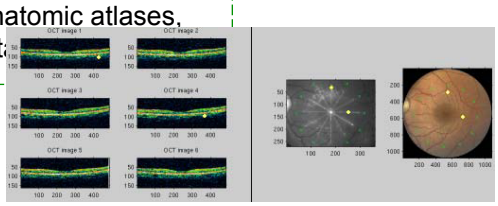
Patient-specific Information (Images, lab results, genetics, etc.)

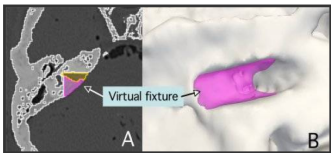
General information (anatomic atlases, st

Model → Plan









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Procedure Planning

- Highly procedure-specific
- Occurs at many time scales
  - Preoperative
  - Intraoperative
  - Preop. + intraop. update
- Typically based on images or segmented models
- May involve:
  - Optimization
  - Simulations
  - Visualization & HCI

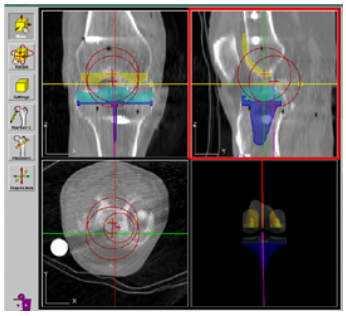

Photo: Integrated Surgical Systems

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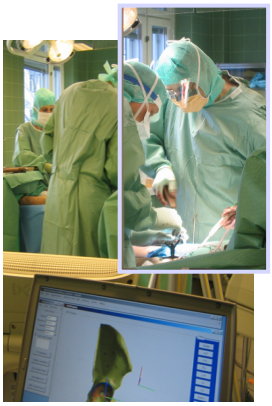
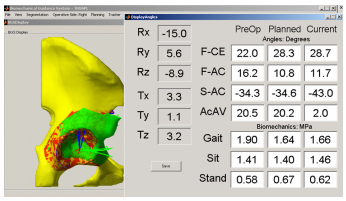
Procedure Planning

- **Typical outputs**
  - Target positions (seeds, biopsies, ablation sites, etc.)
  - Tool paths
  - Desired geometric relationships
  - Key-frame visualizations
  - Images, models & control parameters
- **Emerging themes**
  - Atlas-based planning
  - Statistical process control & integration of outcomes into plans
  - Dynamic, interactive replanning





Photos: Mehran Armand

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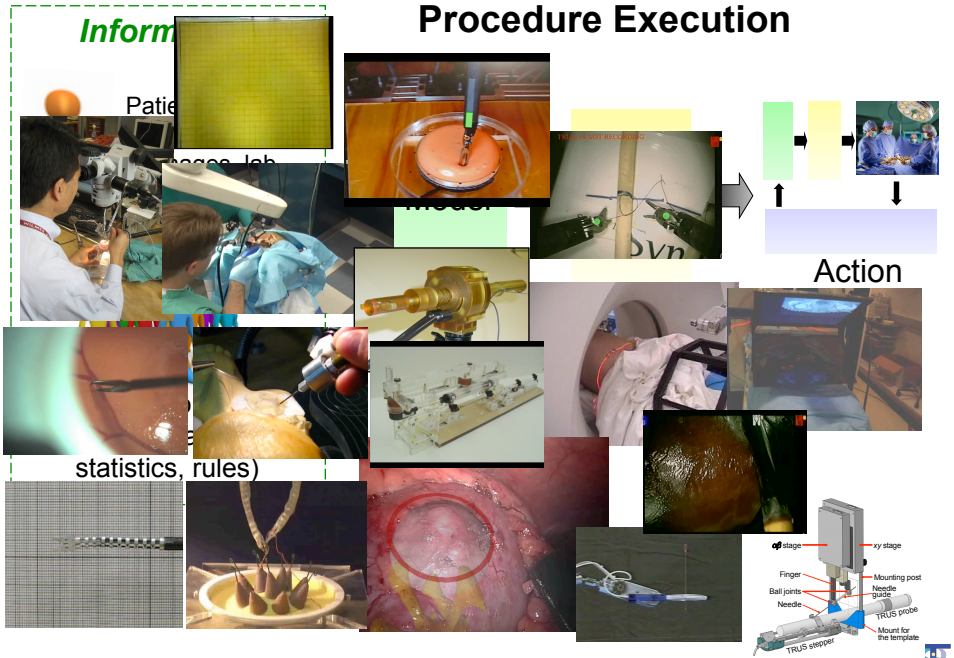
Procedure Execution



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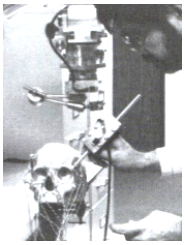
Procedure Execution

- **Highly procedure-specific**
- **Don't always have a robot**
  - Surgical Navigation
  - Image Overlay
- But robots can transcend human limitations
  - to make procedures less invasive,
  - more precise,
  - more consistent,
  - and safer

Medtronic


Taylor

Masamune, Fischer, Deguet, Csoma, Taylor, Sauer, Iorchidata, Masamune, Zinreich, Fichtinger, …

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Procedure Execution

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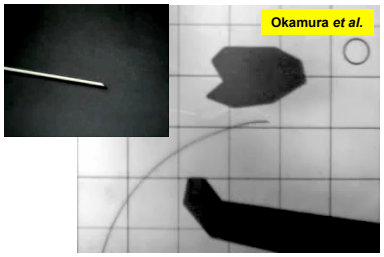
Solomon *et al.*


Okamura *et al.*

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Procedure Execution

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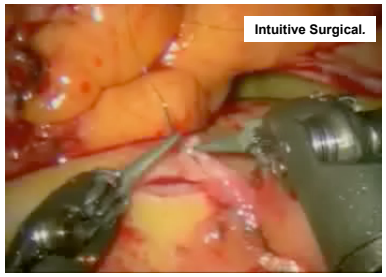

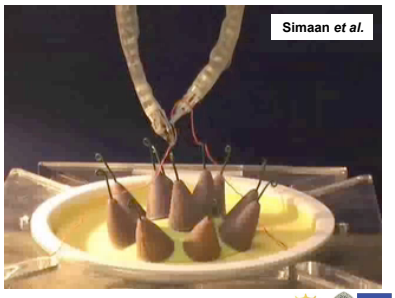

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Procedure Execution

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Taylor, Hager, Handa, Kazanzides, Kang, Iordachita, Gehlbach, *et al.*

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Procedure Execution

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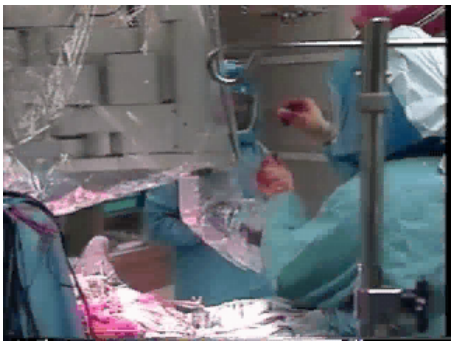

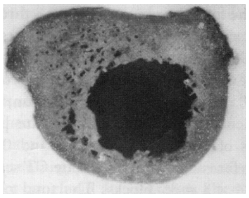

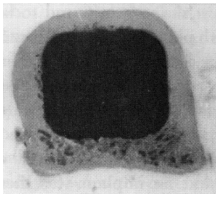

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Procedure Execution

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  - Image Overlay
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  - more consistent,
  - and safer

P. Kazanzides, T. Haiddeger, T. Xia, C. Baird, G. Jallo, N. Hata, …

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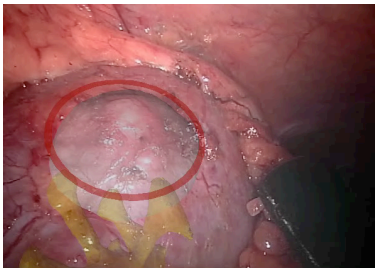
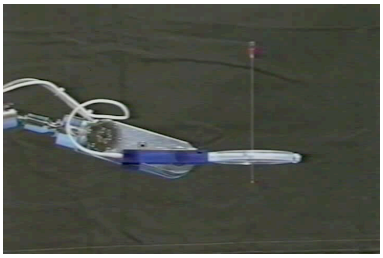
Procedure Execution

- **Intraoperative systems typically combine multiple elements**
  - Imaging
  - Information fusion
  - Robotics
  - Visualization and HMI
- **Issues**
  - Design
  - Imaging compatibility
  - OR compatibility
  - Safety & sterility
  - Intelligent control
  - Human-machine cooperation



G. Hager, B. Vagvolgyi , L-M. Su, *et al.*



Stoianovici, Taylor, Whictomb, *et al.*

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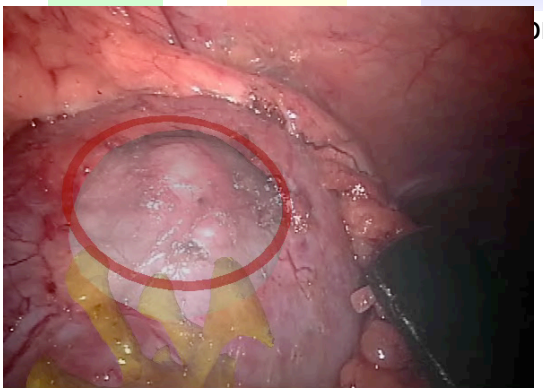
Example: Overlay of CT model onto laparoscopic video

Information

Patient-specific Information (Images, lab results, genetics, etc.)

General information (anatomic atlases, statistics, rules)

Model → Plan → ...on



G. Hager, B. Vagvolgyi , L-M. Su, *et al.*

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Example: Information-enhanced microsurgery

Transcend human limitations in retinal microsurgery

- Hand tremor
- Sensing
- Visualization
- Information fusion

Phased deployment into commercialization and clinical use

Funding

- CISST ERC
- NIH BRP ($4.8M / 5 years)
- Industry

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Example: Information-enhanced microsurgery

Team

- **JHU Whiting School of Engineering:** R. Taylor, G. Hager, J. Kang, P. Kazanzides, R. Kumar, A. Deguet, B. Vagvolgyi, I. Iordachita E. Meisner, M. Balicki, D. Mirota, R. Snitzman, J. Han, Y. Yang, X. Li, X.Liu, E. Ahmanson, …
- **JHU School of Medicine:** J. Handa, P. Gehlbach, E. Gower, L. Pinni, S. Sunshine
- **Carnegie-Mellon University:** C. Riviere, M. Blackwell, …

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Clinical Background: Retinal Surgery

- **Retinal disease is the leading cause of new blindness in the Western World**
- **Most frequent indications for retinal surgery include**
  - Retinal detachment
  - Vitreous hemorrhage
  - Macular puckers
  - Macular holes
  - Diabetic retinopathy
- **Success rates depend critically on difficult technical steps:**
  - Removing scar tissue from the retina (e.g., in retinal detachment or macular puckers)
  - Peeling the internal limiting membrane (e.g., macular holes)
  - Cannulation of tiny vessels (e.g, retinal vein occlusion)

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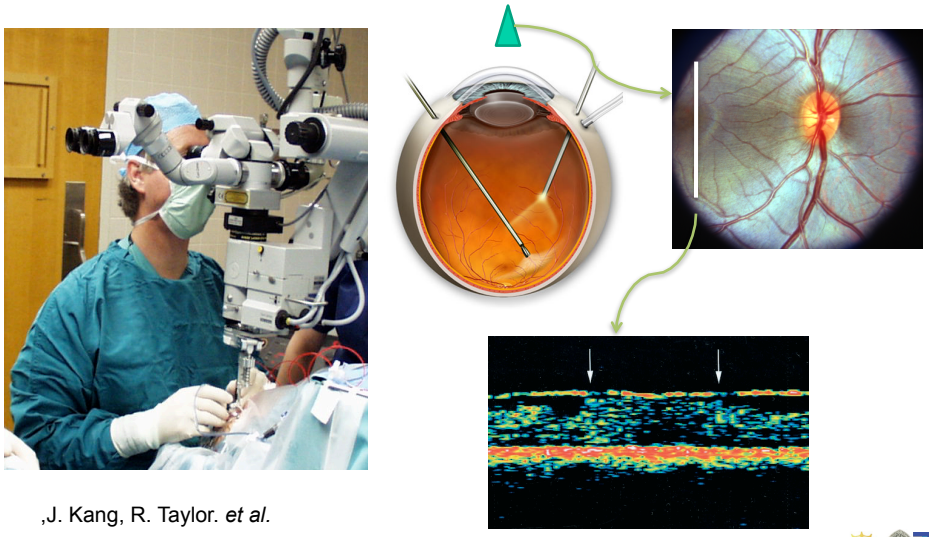

Retinal Microsurgery (epiretinal membrane peeling)

,J. Kang, R. Taylor. *et al*.

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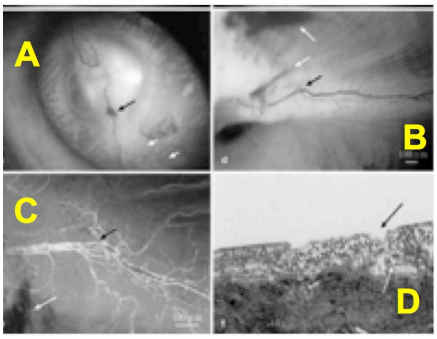
Central Retinal Vein Occlusion (cannulation of 100 micron vessel)

- Occlusions result in vision loss for over 100,000 patients/year
- Procedure
  - Identify retinal vein and cannulation site
  - Cannulate the vein
  - Maintain needle tip in vein long enough to inject drug without damaging vessel
- Challenges
  - Small caliber of vessel 100 um at limit of physiological tremor
  - Difficulty holding tip in small vessel



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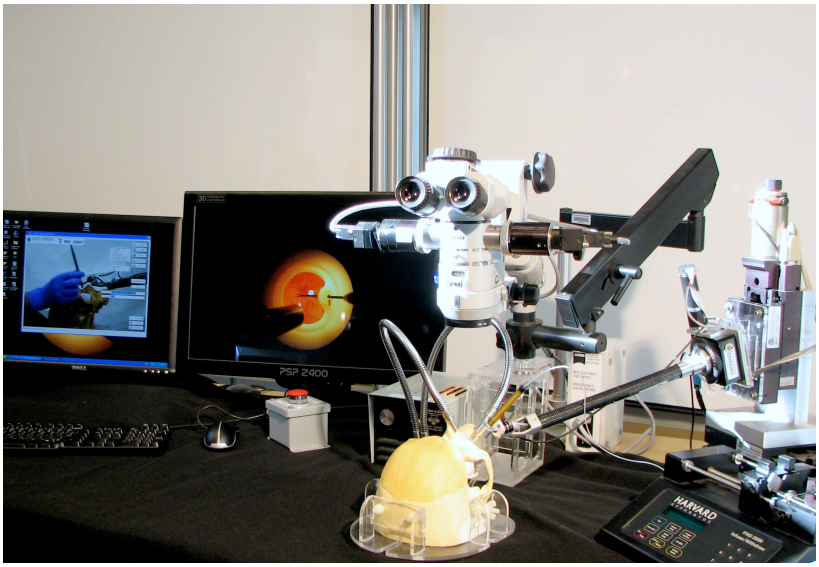
Microsurgery Assistant Workstation



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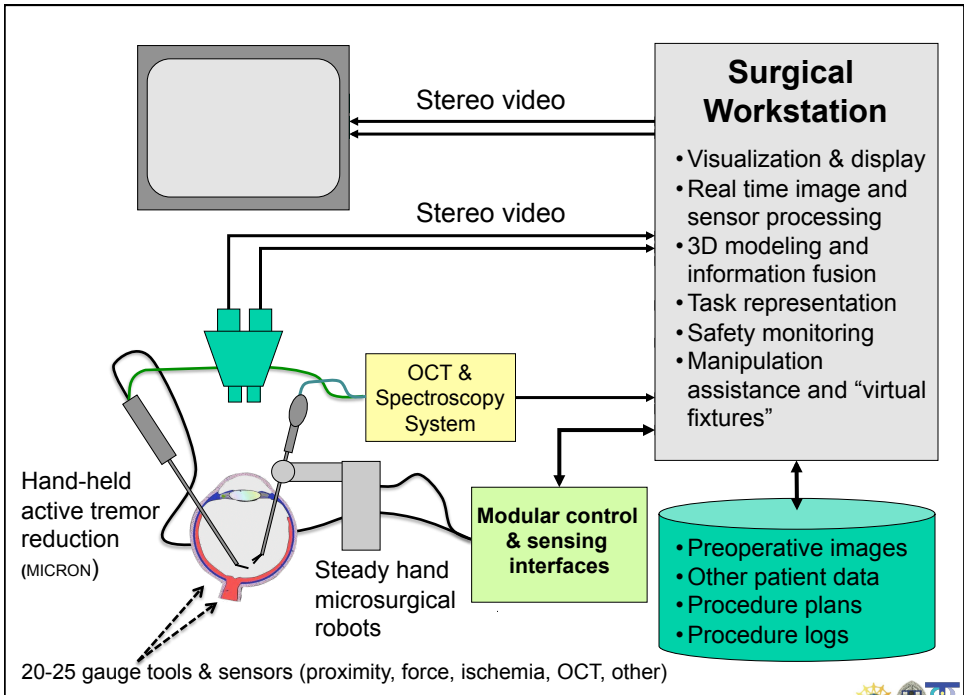

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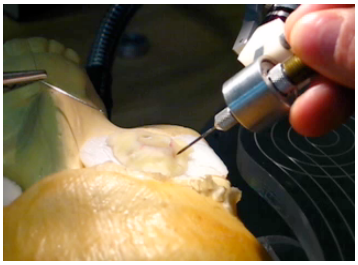
Microsurgery tremor reduction

- **Active cancellation**
  - E.g., Riviere, *et al*., Ang, *et al.* , …
  - Unencumbered, high bandwidth
  - Technically challenging
  - Virtual fixtures, etc.
- **Conventional precise robot**
  - "Steady hand" cooperative control or teleoperation
  - E.g., Iordachita, Taylor, *et al.,* Simaan *et al.,* …
  - More precise, straightforward, sometimes lower bandwidth
  - Virtual fixtures, etc.

CMU MICRON



JHU Steady Hand "Eye Robot"

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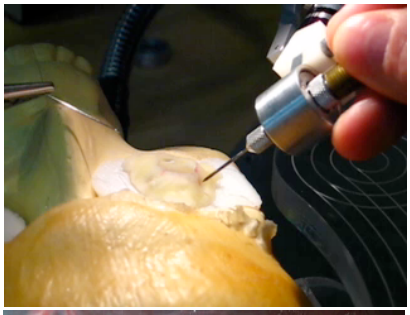
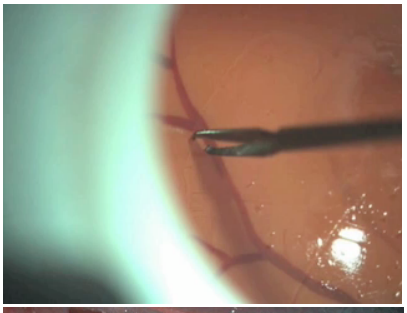
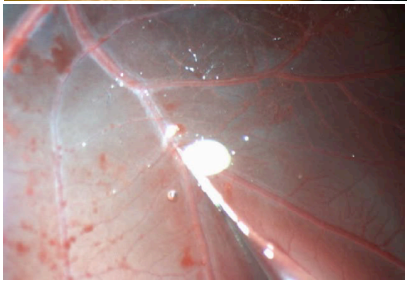
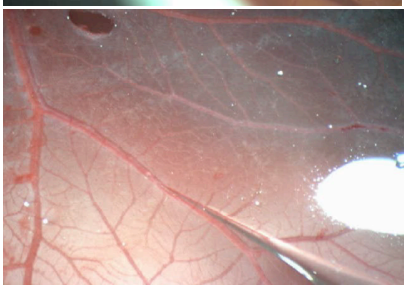
Sclera insertion (on phantom)



Membrane peeling (on phantom)







Freehand cannulation

Steady hand robot cannulation

Taylor, Iordachita, Balicki, Kapoor, Handa, Mitchell, Fleming, Gehlbach, *et al.*

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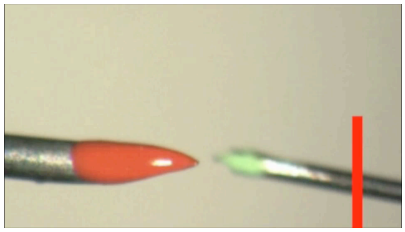
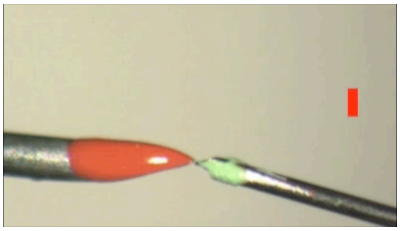
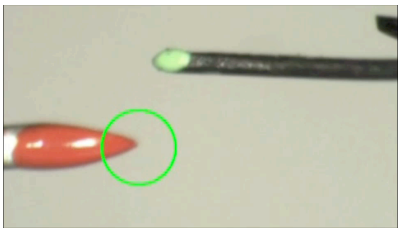
Active Guiding of MICRON with Visual Servoing



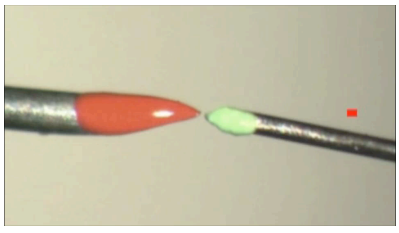
Hold point freehand – MICRON inactive



MICRON motion scaling – no visual servo



Avoidance Virtual Fixture



MICRON motion scaling – with visual servo

C. Riviere, G. Hager

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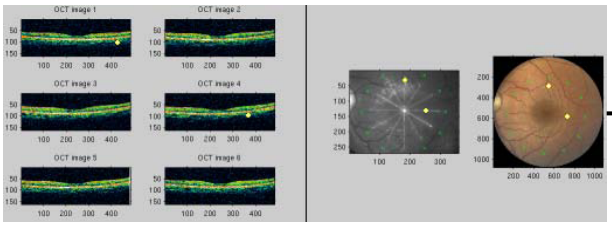
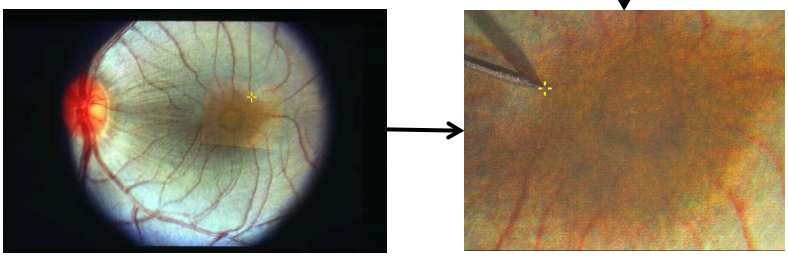
Retinal targeting based on fusing preoperative OCT & fundus images with intraoperative video microscope



Fused OCT & fundus images, with targets



Fused preoperative & intraoperative image

I. Fleming, G Hager, *et al.*

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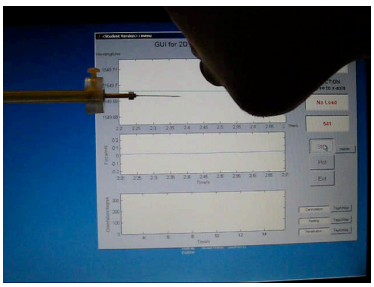
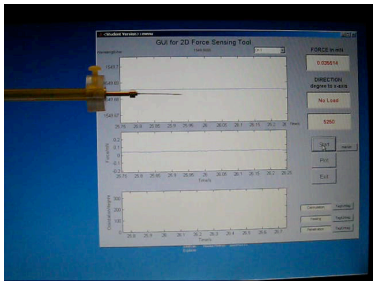
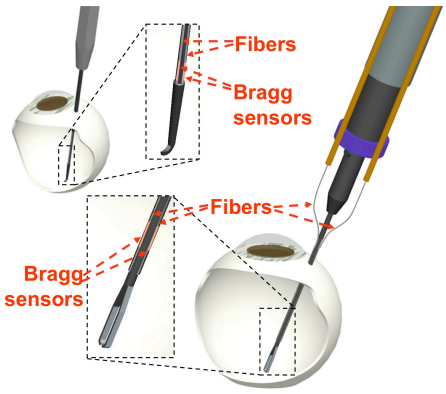
Force Sensing Surgical Instruments





- Incorporate fiber optic force sensors into 0.5 mm diameter surgical tools
- 0.25 mN force sensitivity



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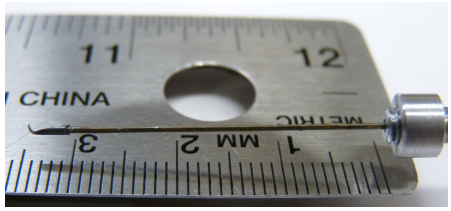
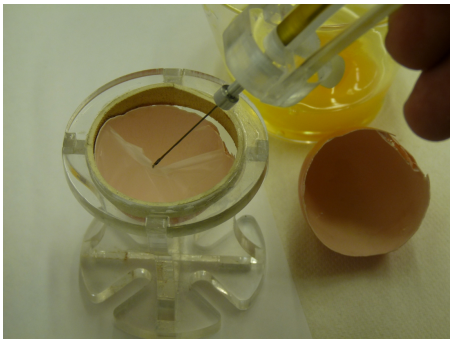
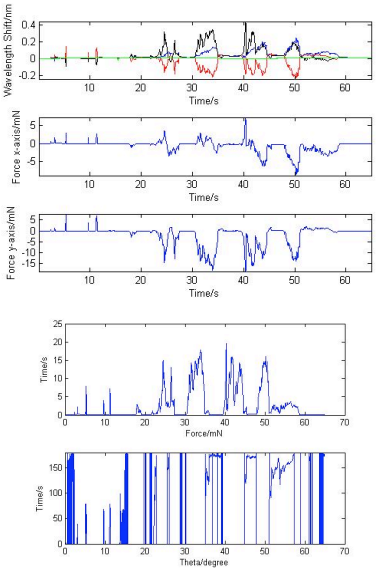
Hook tool & membrane peeling experiment







Z. Sun, I. Iordachita, R. Taylor, *et al.*

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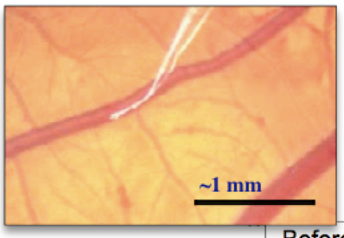
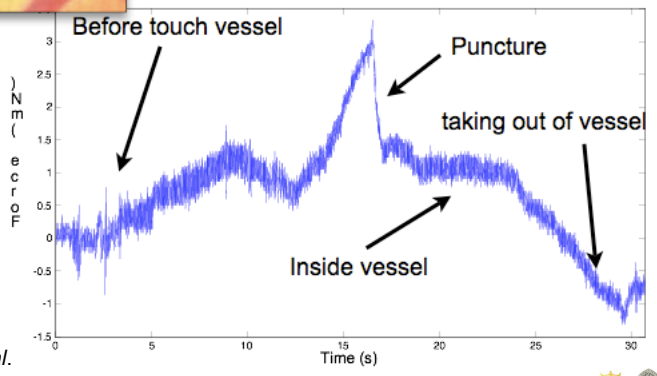
Force during cannulation of 100 micron vessel





I. Iordachita, Z. Sun, *et al.*

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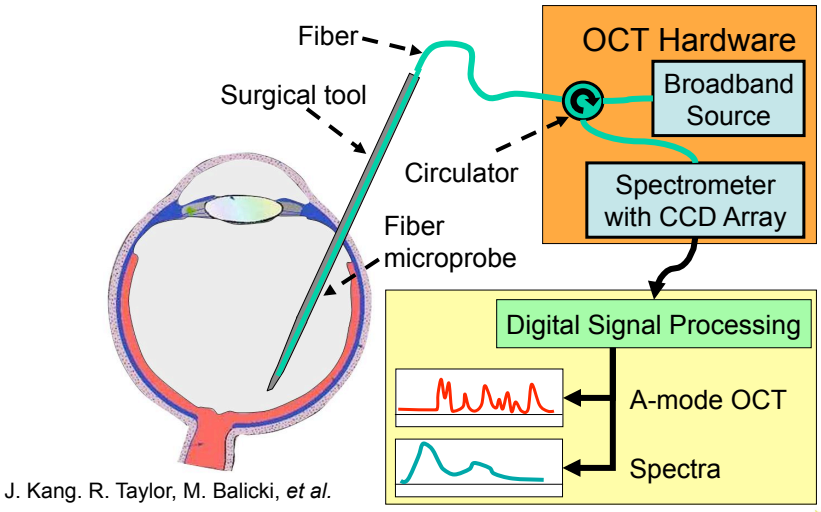
Tools with integrated optical sensors



J. Kang. R. Taylor, M. Balicki, *et al.*

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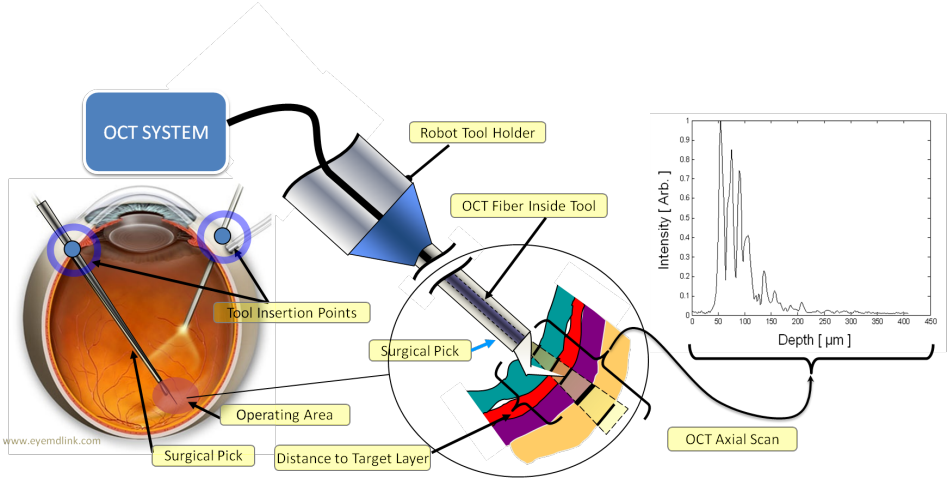
OCT Instrumented Pick Concept



M. Balicki, I. Iordachita, …, J. Handa, P. Gehlbach, J. Kang, R. Taylor

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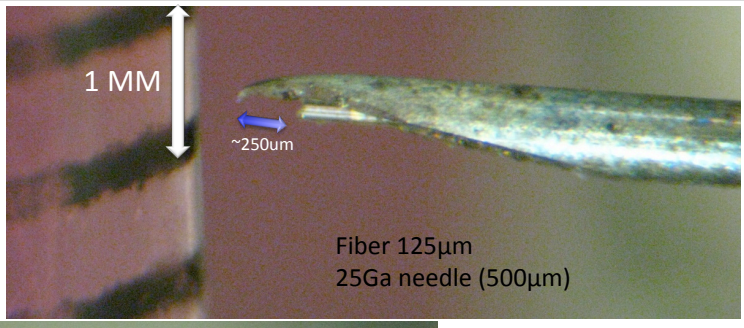
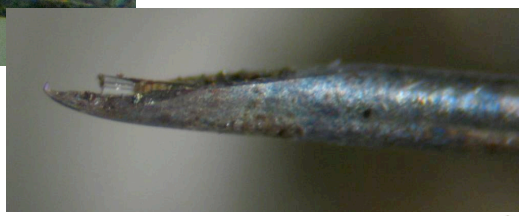


Probe 2:
Fiber is 250µm from tip



M. Balicki, I. Iordachita, J. Han, X. Liu, K. Zhang, Y. Yang, R. Romano, J. Hsu, J. Handa, P. Gehlbach, J. Kang, R. Taylor

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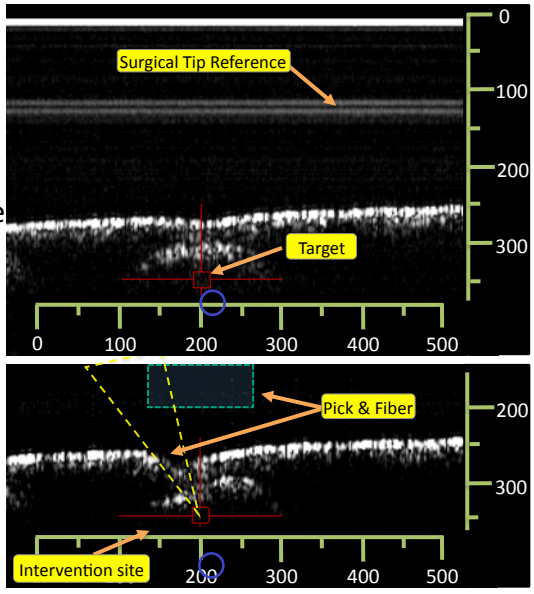
Servo to Target - Results

Before

After



M. Balicki, I. Iordachita, J. Han, X. Liu, K. Zhang, Y. Yang, R. Romano, J. Hsu, J. Handa, P. Gehlbach, J. Kang, R. Taylor

Used Probe 1

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Research Issue: Understanding intent in human-machine cooperation

Information

Patient-specific Information (Images, lab results, genetics, etc.)

General information (anatomic atlases, statistics, rules)

Model → Plan → Action

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Research Issue: Understanding intent in human-machine cooperation

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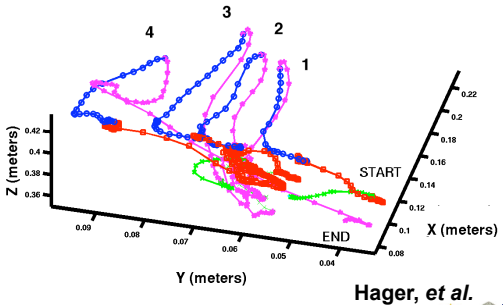

Hager, *et al.*

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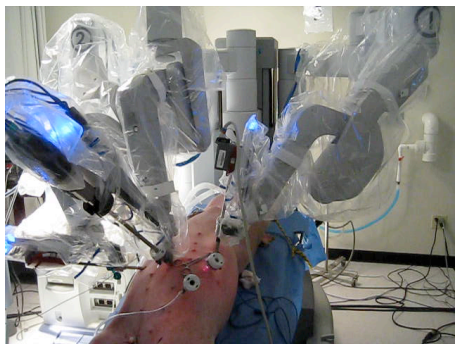
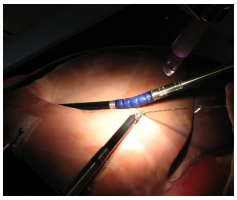
Example: Robotically Assisted Laparoscopic Ultrasound

- NIH STTR between CISST ERC and Intuitive Surgical
- Goals
  - Develop dexterous laparoscopic ultrasound instrumentation and software interfaces for DaVinci surgical robot
  - Produce integrated system for LUS-enhanced robotic surgery
  - Evaluate effectiveness of prototype system for liver surgery
- Approach
  - Custom DaVinci-S LUS tool
  - Software built on JHU/ISI "SAW" interface
- Status
  - Evaluation of prototype by surgeons





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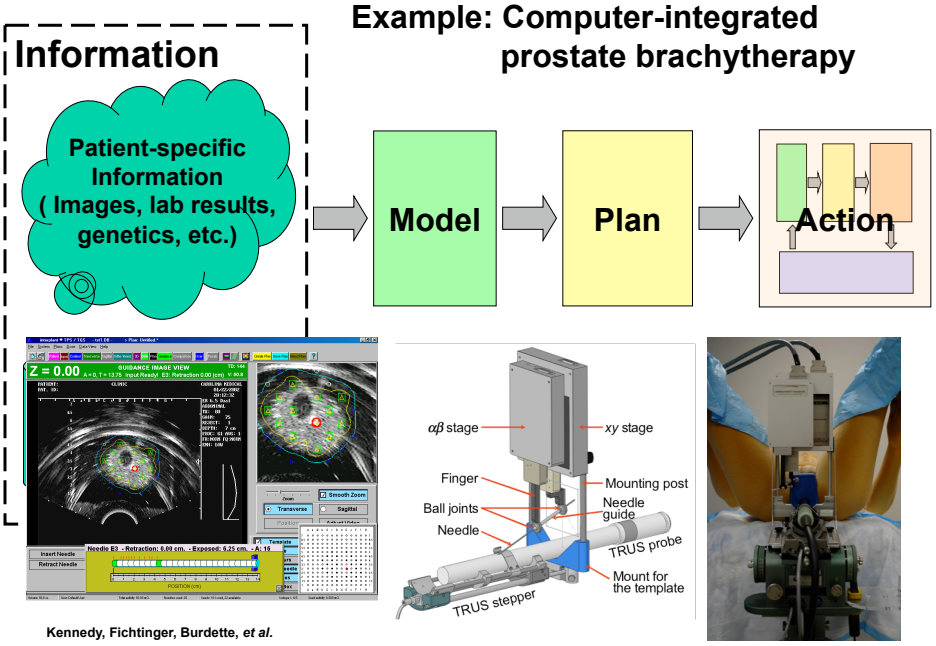
Example: Computer-integrated prostate brachytherapy



Kennedy, Fichtinger, Burdette, *et al.*

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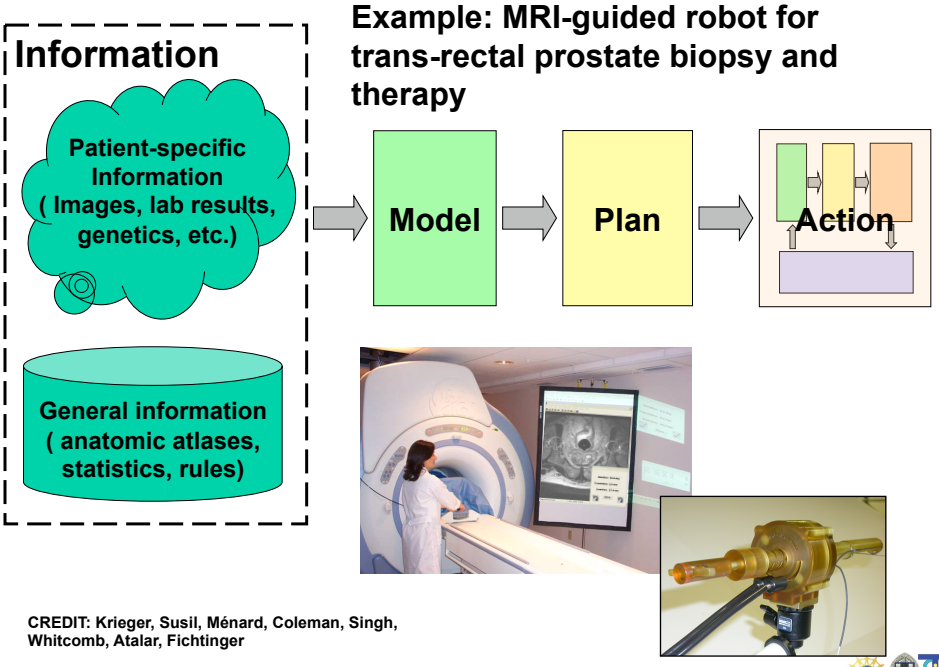
Example: MRI-guided robot for trans-rectal prostate biopsy and therapy



CREDIT: Krieger, Susil, Ménard, Coleman, Singh, Whitcomb, Atalar, Fichtinger

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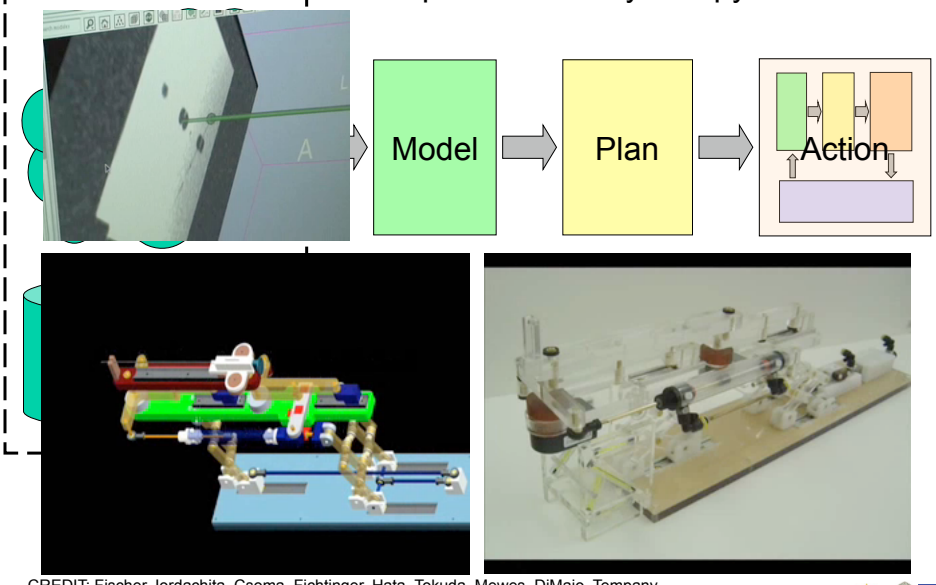
Example: MRI-guided robot for transperineal brachytherapy



CREDIT: Fischer, Iordachita, Csoma, Fichtinger, Hata, Tokuda, Mewes, DiMaio, Tempany

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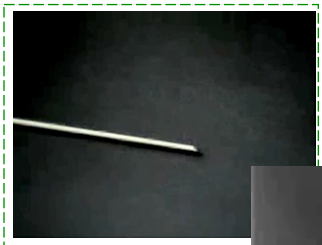
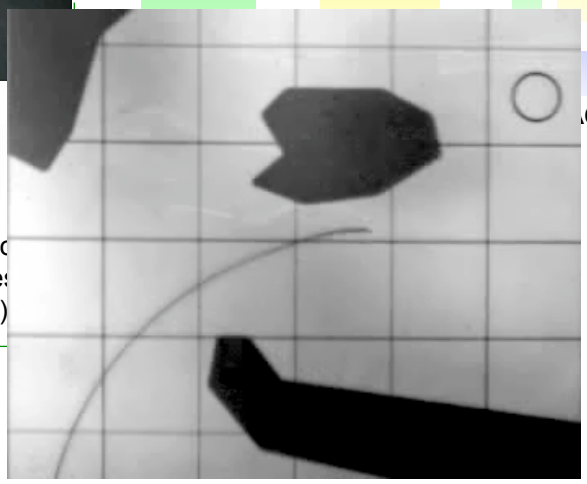
Steering the needle …





General informatic
(anatomic atlases
statistics, rules)

ction

JHU: A. Okamura, *et al.*

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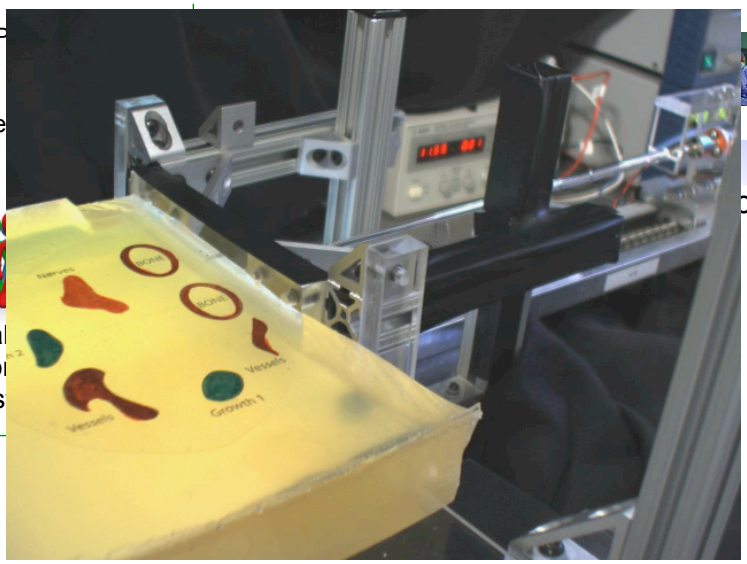
Steering the needle …

Information

P

re

General
(anato
statis



on

JHU: A. Okamura, *et al.*

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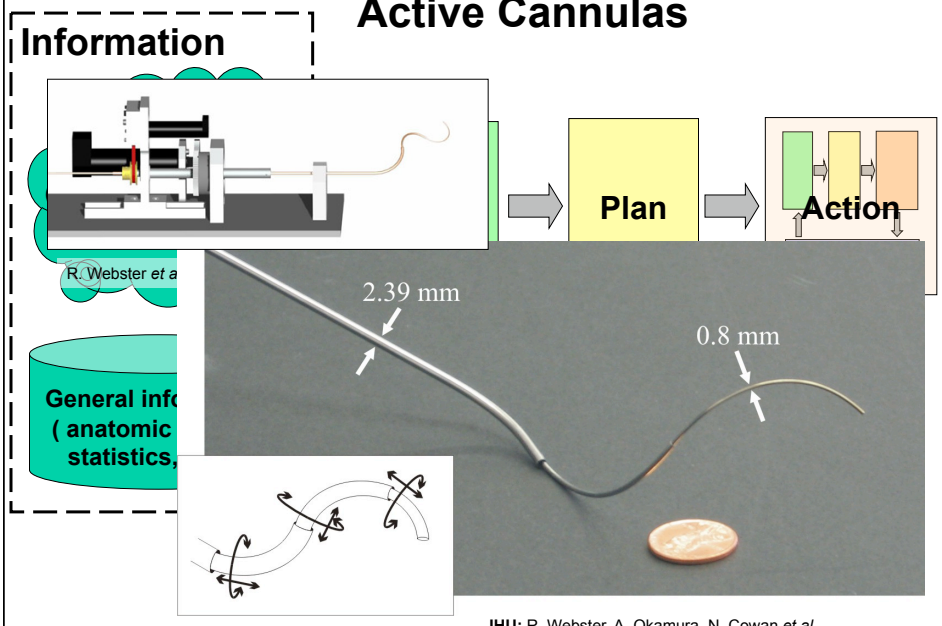
Active Cannulas



JHU: R. Webster, A. Okamura, N. Cowan *et al.*

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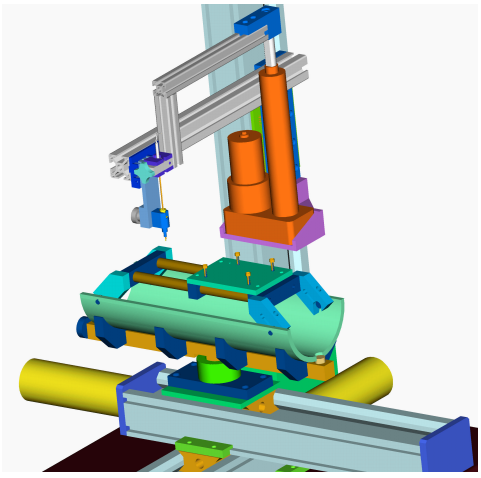
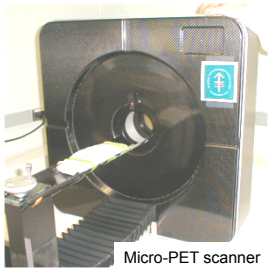
Robotic Needle Placement in Rodents

P. Kazanzides, G. Fichtinger, C. Ling



Credit: Jack Li, I. Iordachita



Micro-PET scanner

Courtesy of MSKCC

Research contract from Sloan Kettering

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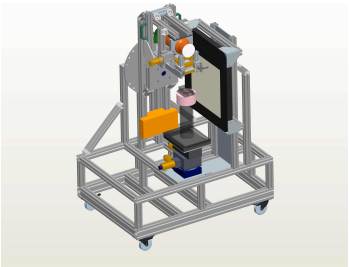
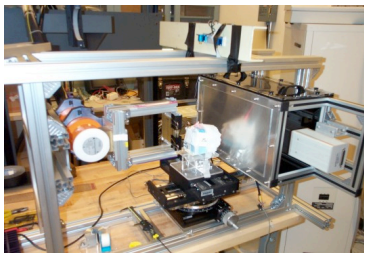
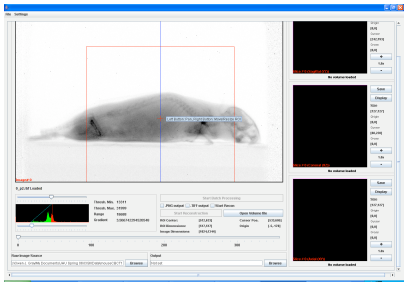
Small Animal Radiation Research Platform

John Wong (PI), Peter Kazanzides, *et al.*



- Prototype, self-contained, very compact imaging and radiation therapy research platform for small animals
- In development as collaboration between JHU Radiation Oncology and CISST ERC





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Closed Loop Interventional Medicine

Information

Patient-specific Information (Images, lab results, genetics, etc.)

General information (anatomic atlases, statistics, rules)

Model → Plan → Evaluation → Action → **Patient-specific Evaluation**

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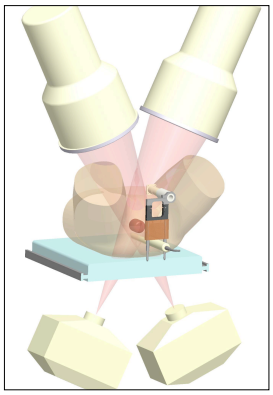
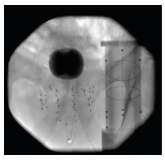
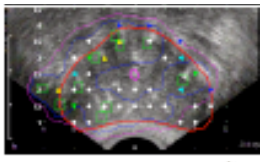
Patient-Specific Evaluation

- **Goals**
  - Verify that the planned intervention has been done
  - Provide immediate feedback for use in executing or replanning procedure
  - Provide information for follow-up
- **Issues / Themes**
  - Online imaging
  - Real-time model registration
  - Visualization and feedback



Jain *et al.*





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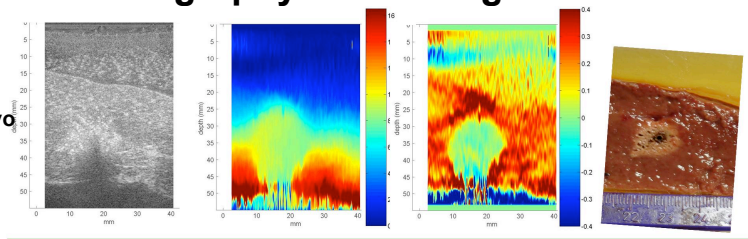
Elastography monitoring of ablations

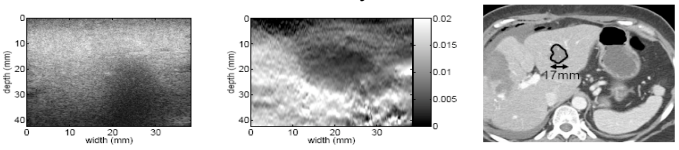
Ex vivo



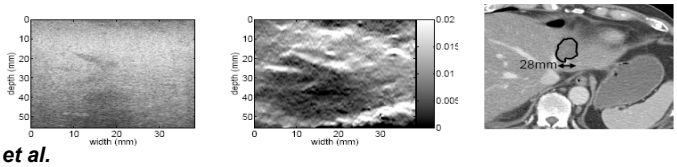
B-mode image | Displacement image | Strain image | Gross pathology image

ultrasound | elasticity | post-operation CT

patient 1



patient 2



Credit: Boctor *et al.*

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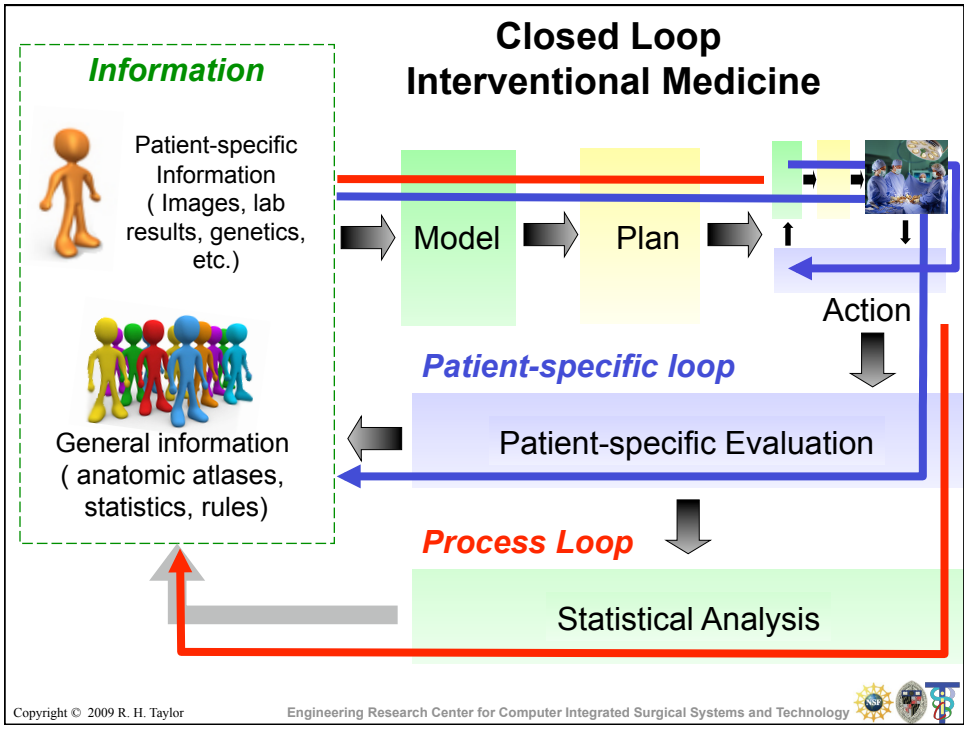
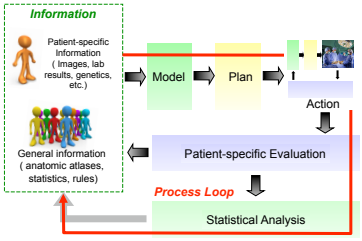
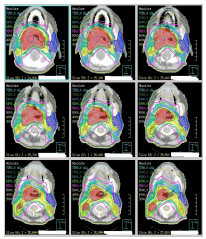


Statistical Quality Control

- **Key idea**
  - Medical robots and CAI systems inherently generate data and promote consistency
  - Eventually, outcomes are known
  - Combine this information over many patients to improve treatment plans / processes
- **Issues / Themes**
  - Very large data bases combining heterogeneous data
  - Statistical modeling of patients, procedures, and outcomes
  - Online tracking of procedures





Credit: Todd McNutt

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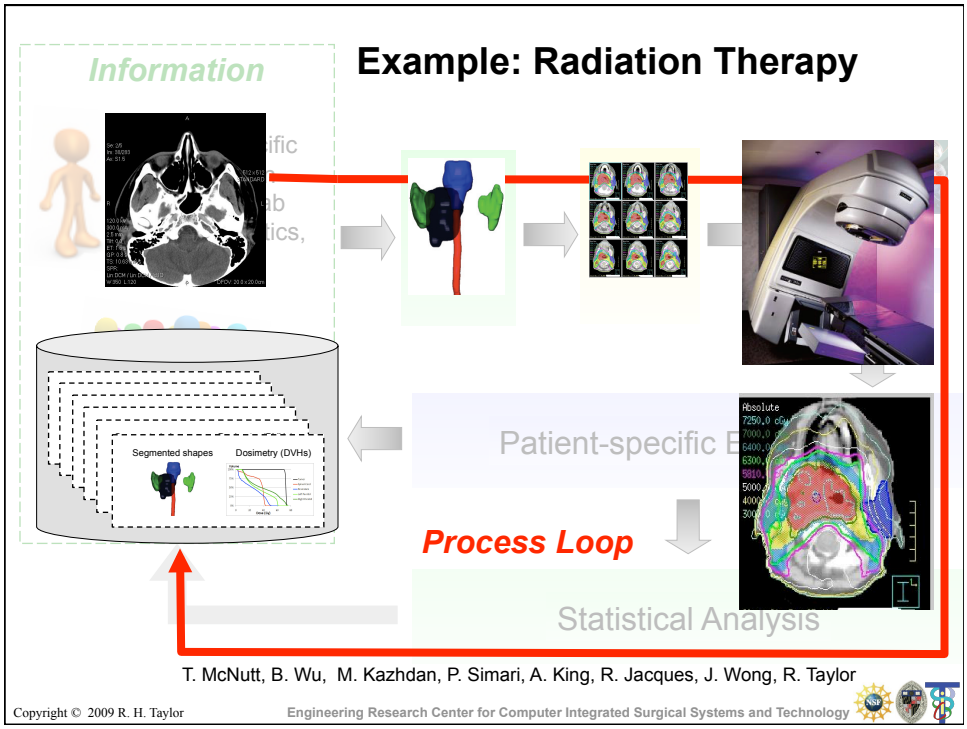
Engineering Research Center for Computer Integrated Surgical Systems and Technology


Information
Example: Radiation Therapy
Segmented shapes
Dosimetry (DVHs)
Patient-specific
Process Loop
Statistical Analysis
T. McNutt, B. Wu, M. Kazhdan, P. Simari, A. King, R. Jacques, J. Wong, R. Taylor
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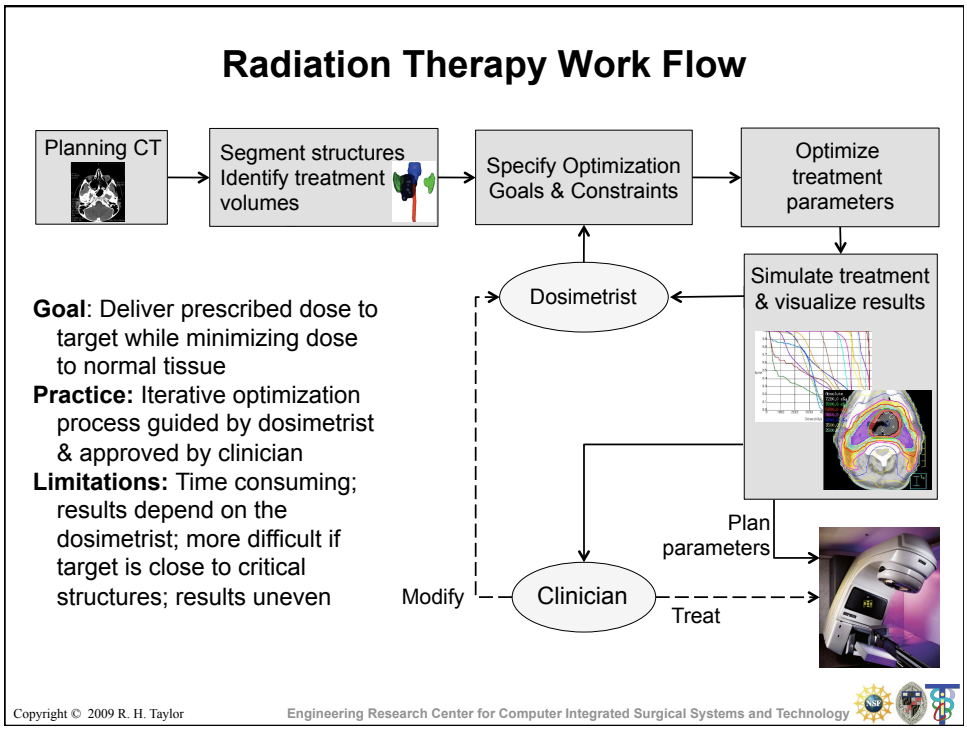
Radiation Therapy Work Flow
Planning CT
Segment structures
Identify treatment volumes
Specify Optimization Goals & Constraints
Optimize treatment parameters
Simulate treatment & visualize results
Dosimetrist
Plan parameters
Clinician
Modify
Treat
Goal: Deliver prescribed dose to target while minimizing dose to normal tissue
Practice: Iterative optimization process guided by dosimetrist & approved by clinician
Limitations: Time consuming; results depend on the dosimetrist; more difficult if target is close to critical structures; results uneven
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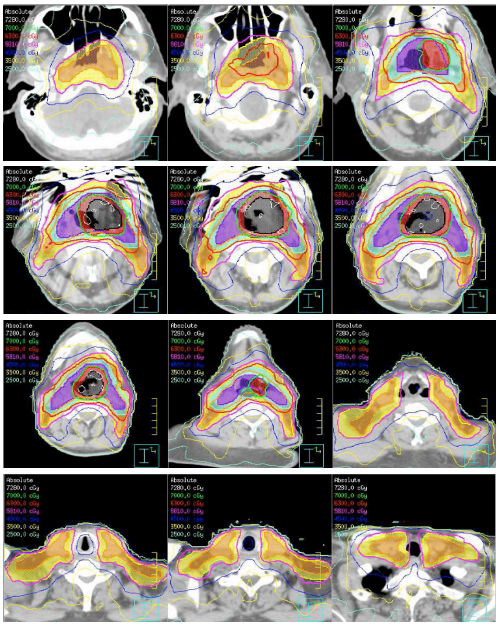
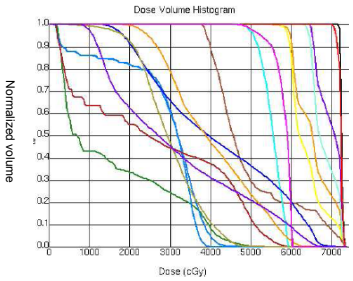
Engineering Research Center for Computer Integrated Surgical Systems and Technology





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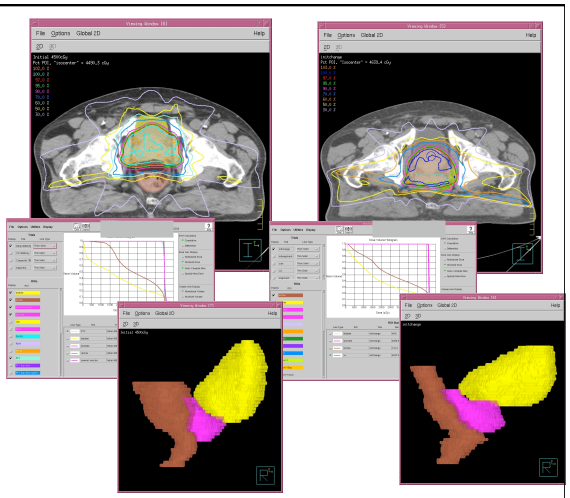
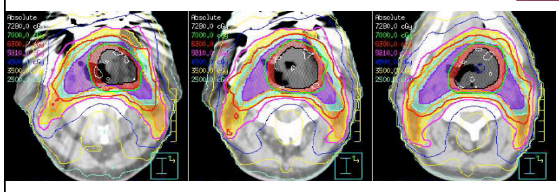
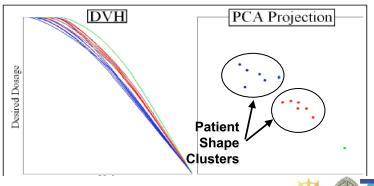
Influence of Shape

- Shape Characteristics
  - Volume
  - Positional relationships between structures
  - Separation of surfaces
- Shape Change in Time
- Influence
  - Plan quality (IMRT)
  - Ability to achieve treatment goal
    - Motion management
  - Toxicity
- Simplification of information without loss of relevance?







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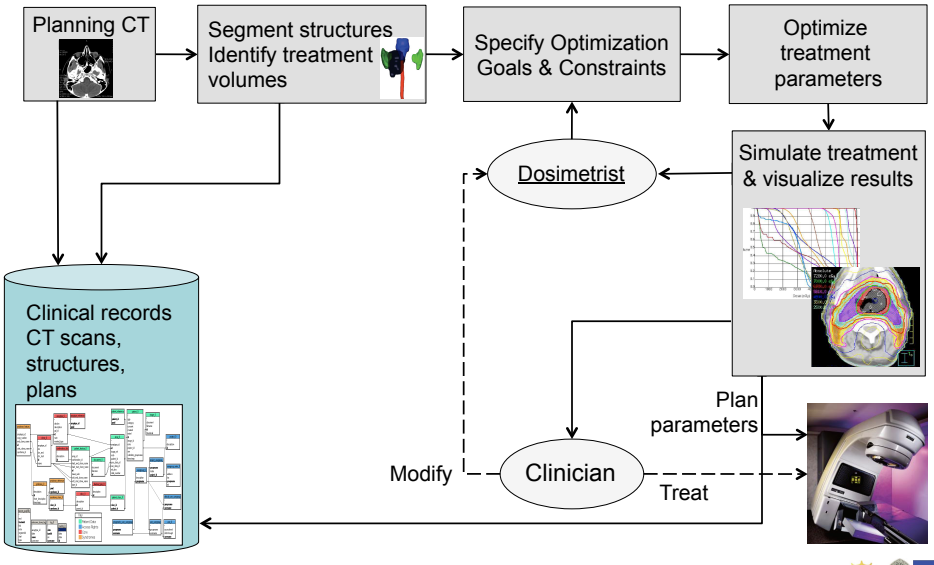
Background: "Oncospace" Project at JHU



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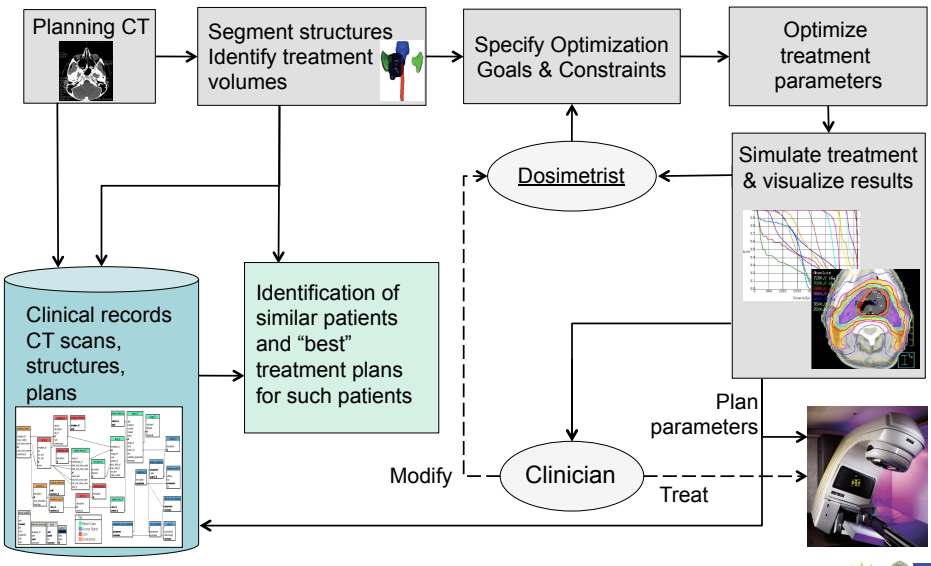
Use of the database …



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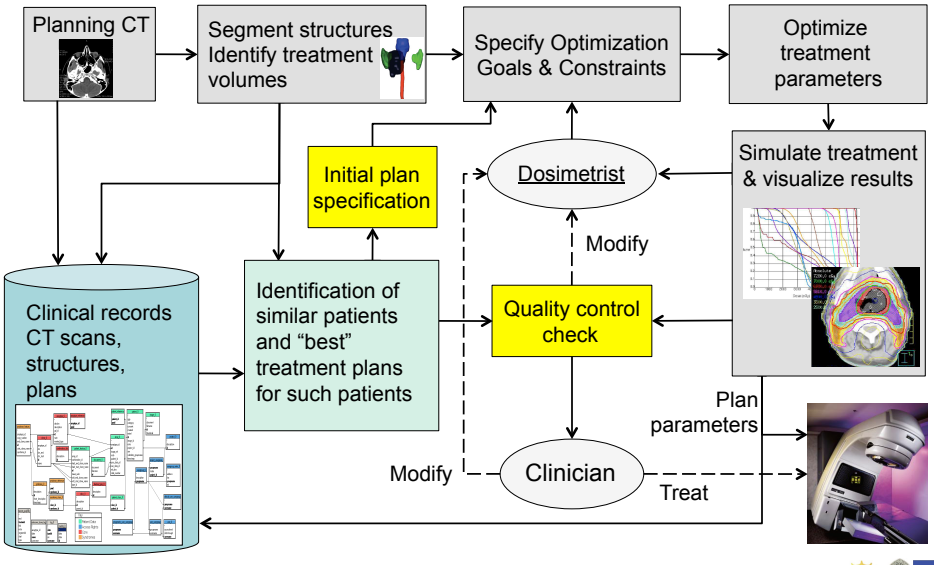
… to improve quality and efficiency of treatment



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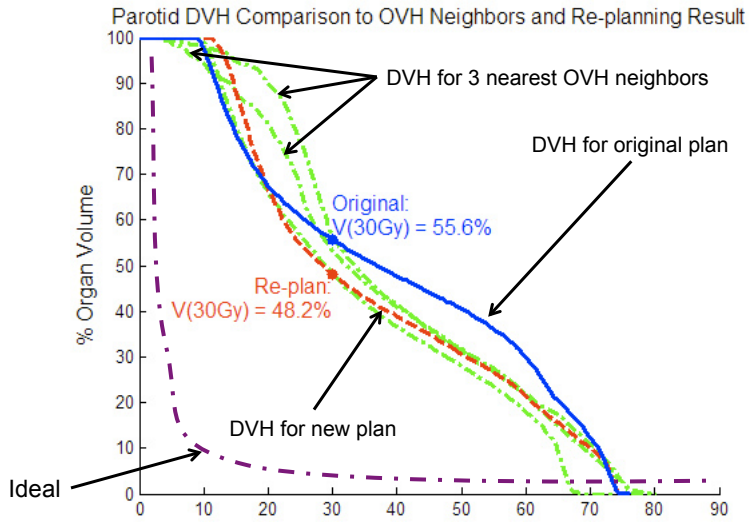
Typical example: Dose to critical organ



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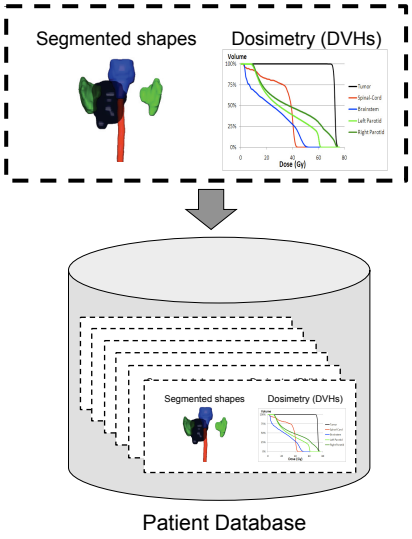
Step 1: Build Data Base



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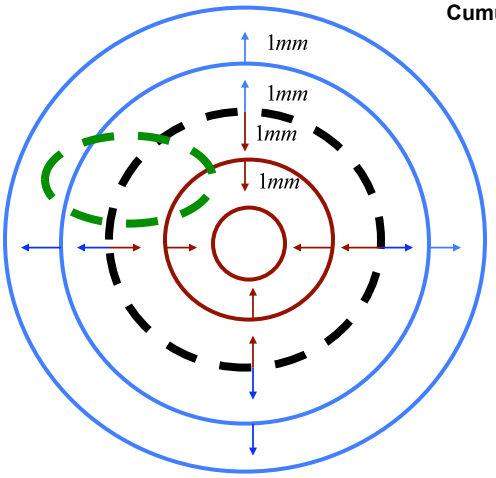
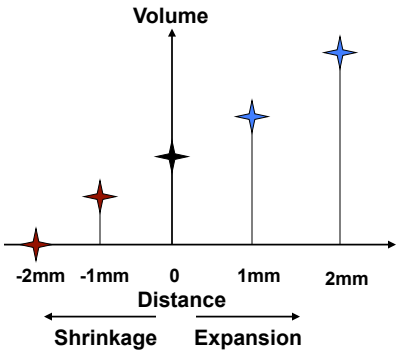
Shape descriptor: Overlap Volume Histogram

OVH maps the shape of organ at risk to a volume-distance plane through target **expanding** and **shrinking**.



Cumulative Overlap Volume Histogram (COVH)



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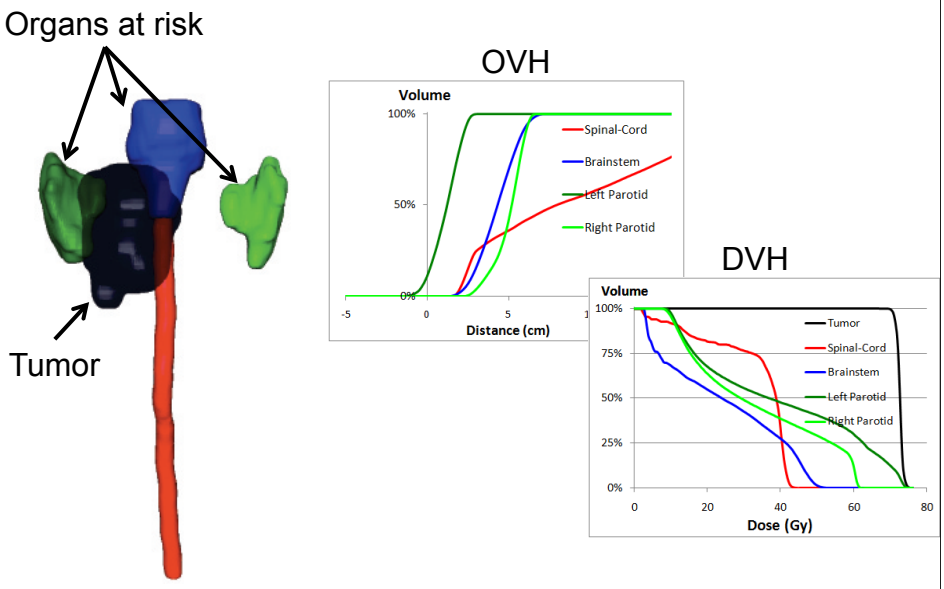
Overlap Volume Histogram (OVH)



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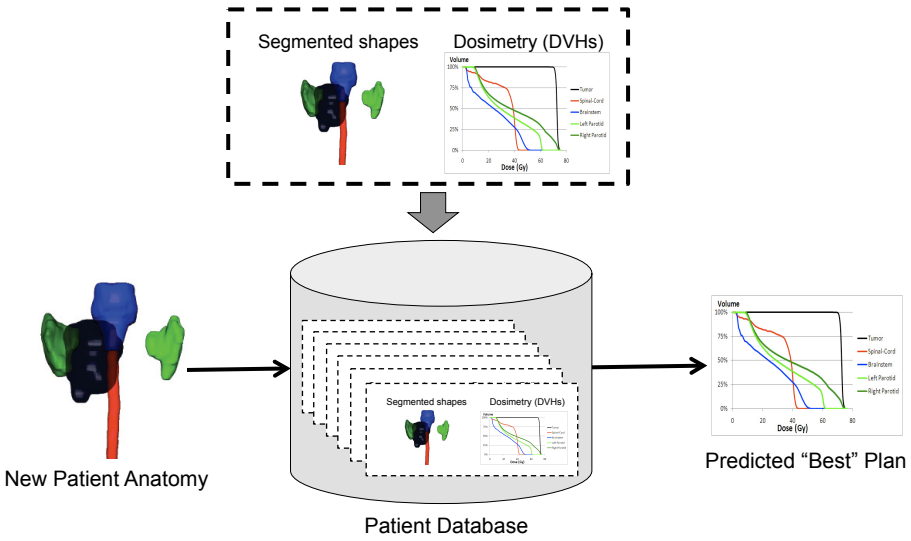
Step 2: Retrieve plans of similar patients



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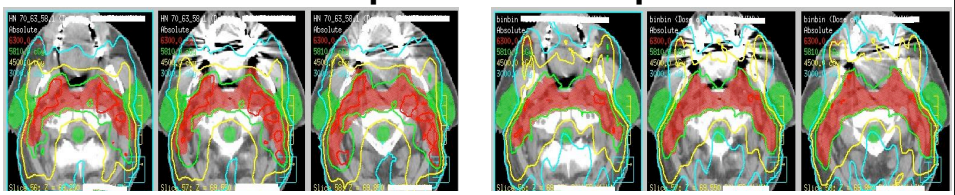
Re-plan results of patient 1

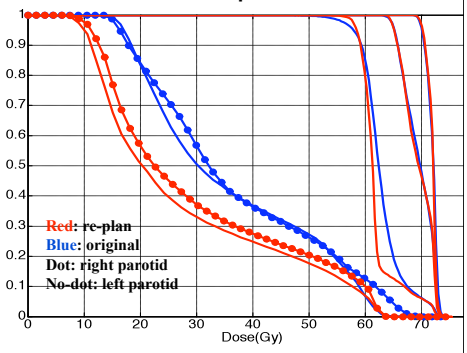


Original plan

Re-plan

Re-plan results for other Organs at Risk

Patient 1	brain (Gy)	Brainstem (Gy)	Cord4mm (Gy)	L inner ear (Gy)
original	61.25	54.58	41.75	57.18
re-plan	56.33	46.48	37.89	43.72
Patient 1	**R inner ear (Gy)**	**mandible (Gy)**	**larynx for edema**	**esophagus (Gy)**
original	40.57	66.58	61%	63.74
Re-plan	38.38	63.78	59%	61



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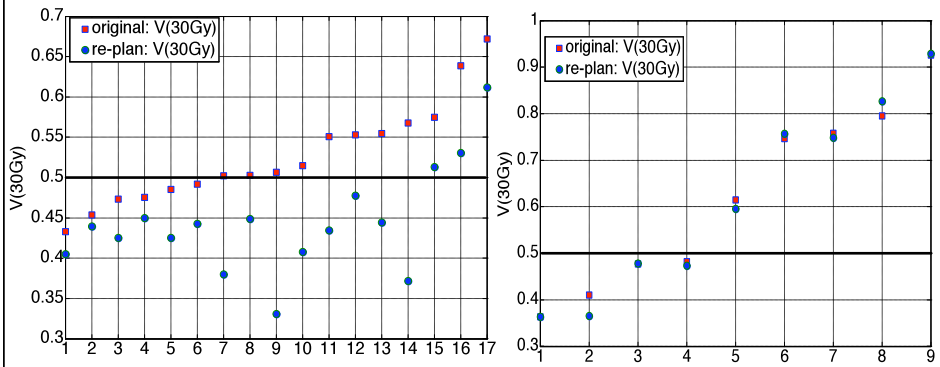
Re-plan results of 13 outlier patients

Clinical goal (parotid): V(30Gy)<0.5



17 outlier parotids

9 non-outlier parotids

- Among the 13 re-plan patients, 17 parotids are outliers indicated by the OVH.
- During re-plan, the dose on 9 non-outlier parotids also tried to be minimized.
- After re-plan, V(30Gy) of 8 parotids among the 17 outlier parotids are reduced to below 50%!
- All 13 re-plans are reviewed by physician.

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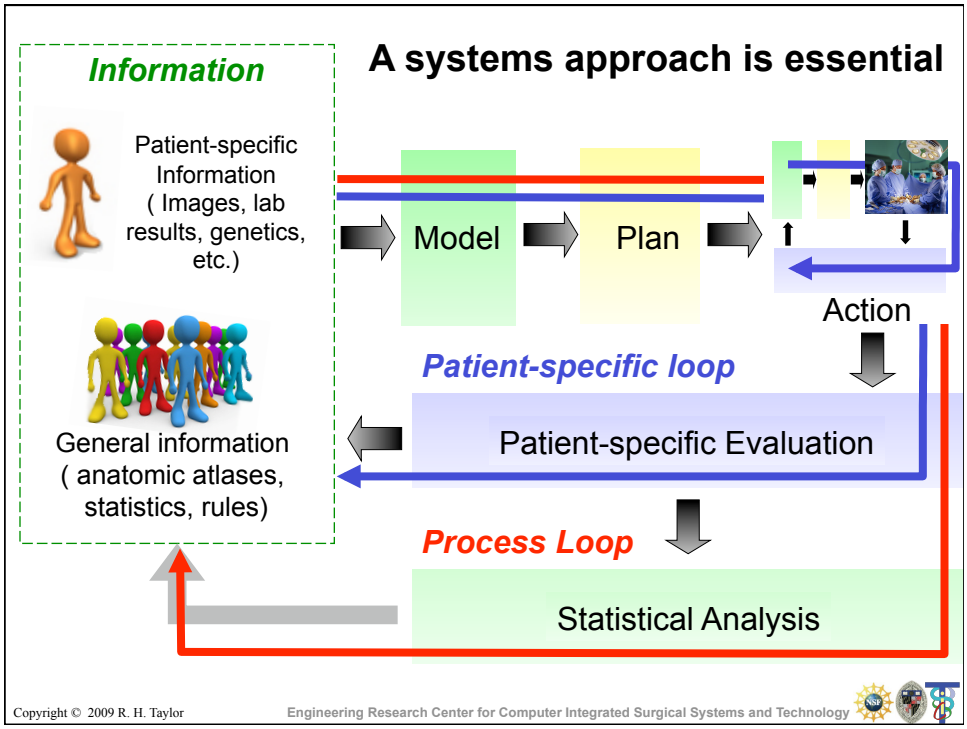
A systems approach is essential
Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
Plan
Action
Patient-specific loop
Patient-specific Evaluation
Process Loop
Statistical Analysis
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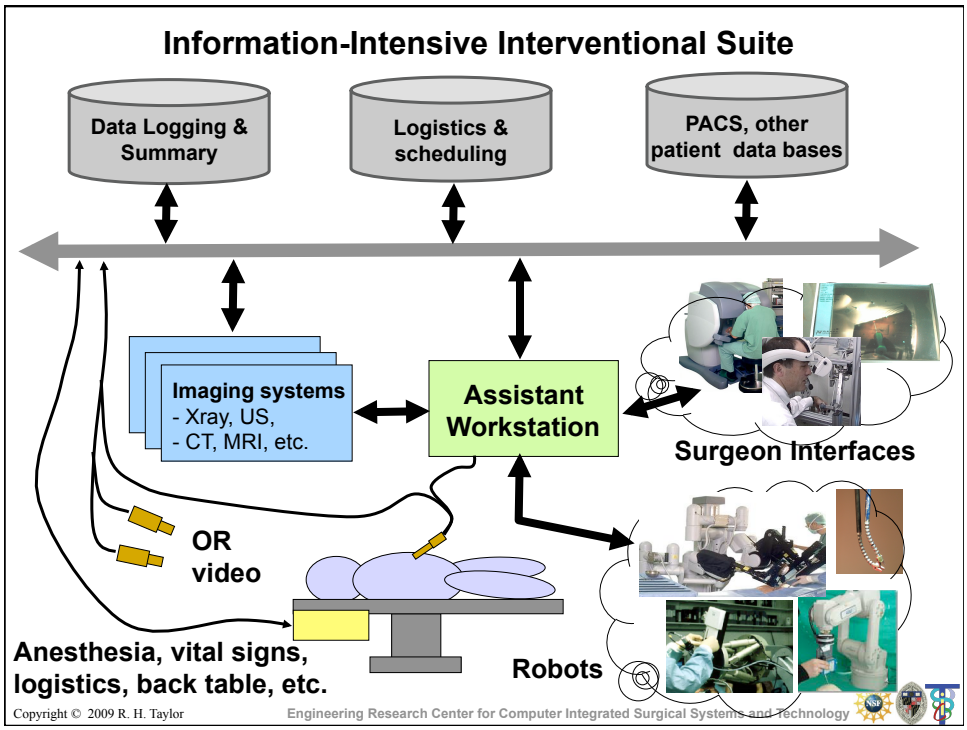
Information-Intensive Interventional Suite
Data Logging & Summary
Logistics & scheduling
PACS, other patient data bases
Imaging systems
- Xray, US,
- CT, MRI, etc.
Assistant Workstation
Surgeon Interfaces
OR video
Anesthesia, vital signs, logistics, back table, etc.
Robots
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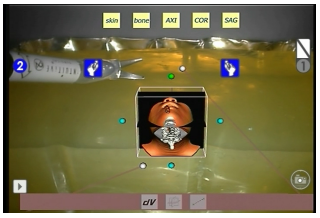
Engineering Research Center for Computer Integrated Surgical Systems and Technology

Surgical Assistant Workstation

- Open source research environment for interactive medical robotics systems
- Multi-institutional collaboration
  - JHU, Intuitive Surgical, TUM, others welcome
- Open interfaces, multiple levels
  - DaVinci (with ISI license)
  - Trackers, own robots, etc.
  - Other open source, open interface packages
- Video & visualization pipeline
- Telesurgery framework
- Virtual Fixtures
- www.cisst.org/saw



Balazs Vagvolgyi, Simon P. DiMaio, Anton Deguet, Peter Kazanzides, Rajesh Kumar1 Christopher Hasser, Russell H. Taylor

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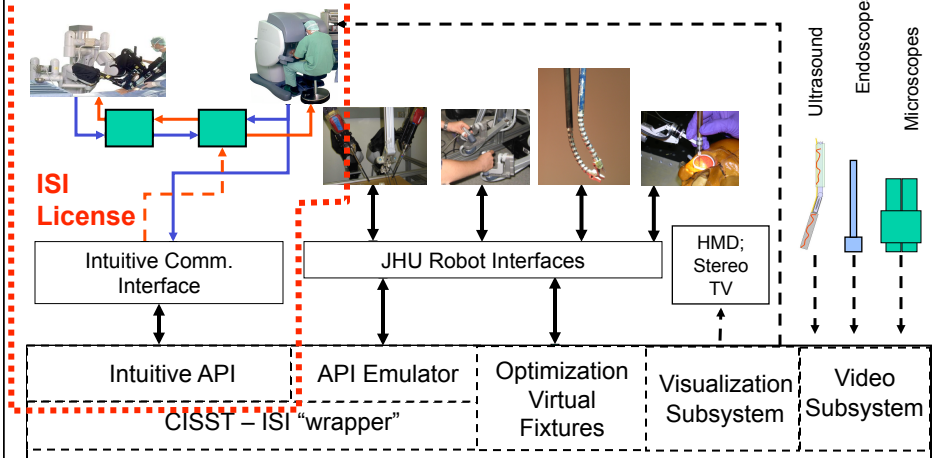

Research Applications and Subsystems

- Stereo processing
- Tool tracking
- Image registration
- Interactive visualization
- Ultrasound
- Haptics
- Task modeling
- Skill Assessment
- Remote telesurgery
- Etc.

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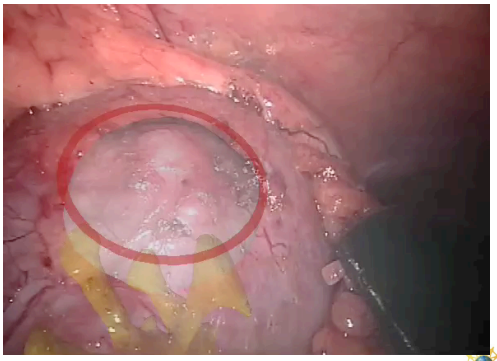
Example: Overlay of CT model onto laparoscopic video

Information

Patient-specific Information (Images, lab results, genetics, etc.)

General information (anatomic atlases, statistics, rules)

Model → Plan → Action



G. Hager, B. Vagvolgyi , L-M. Su, *et al.*

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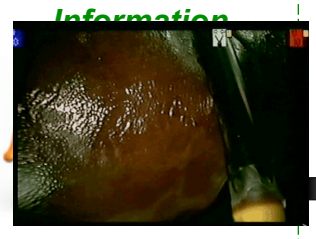
Example: Intraoperative Laparoscopic Ultrasound with daVinci

Information



Model → Plan → Action

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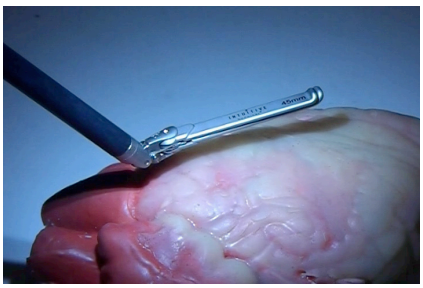
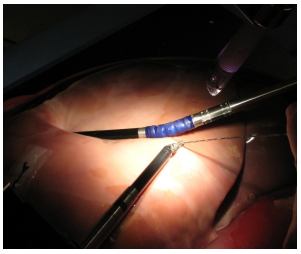
Use Cases: Superimposed Behaviors

Rolling



Palpating



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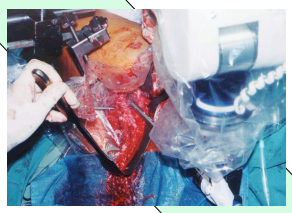
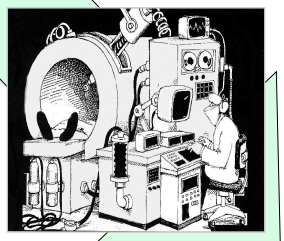
How can we get there?

Strong and committed teams

- Clinicians
- Engineers
- Industry



Focus on systems that address important needs



Rapid iteration with measurable goals

Have fun!

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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

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Discussion

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