NSF Engineering Research Center for Computer Integrated Surgical Systems and Technology

LABORATORY FOR Computational Sensing + Robotics THE JOHNS HOPKINS UNIVERSITY

# Medical Robotics and Computer-Integrated Interventional Systems:

## Integrating Imaging, Intervention, and Informatics to Improve Patient Care


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WHITING SCHOOL OF ENGINEERING
THE JOHNS HOPKINS UNIVERSITY



# Acknowledgments


- **<u>This is the work of many people</u>**
- Some of the work reported in this presentation was supported by fellowship grants from Intuitive Surgical and Philips Research North America to Johns Hopkins graduate students and by equipment loans from Intuitive Surgical, Think Surgical, Philips, Kuka, and Carl Zeiss Meditec.
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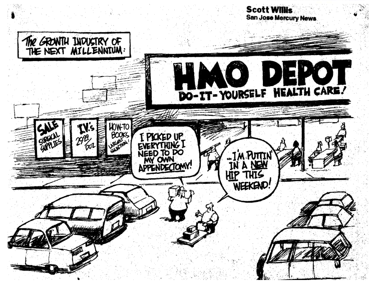
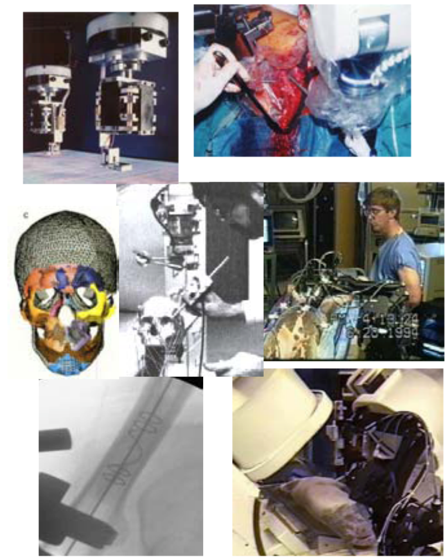
BY STAYSKAL FOR THE TAMPA TRIBUNE

Scott Willis
San Jose Mercury News



## A short personal background: Russ Taylor

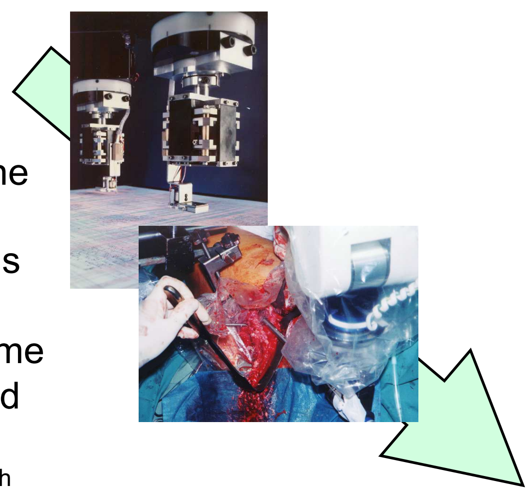
- **1970: BES from Johns Hopkins**
- **1976: PhD in CS at Stanford**
- **1976-1988: Research/management in robotics and automation technology at IBM**
- **1988 - 1996: Medical robotics & computer-assisted surgery at IBM**
  - Robodoc
  - Surgical navigation
  - Robotically assisted MIS and percutaneous 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.
- **1997 - now: NSF ERC; LCSR**



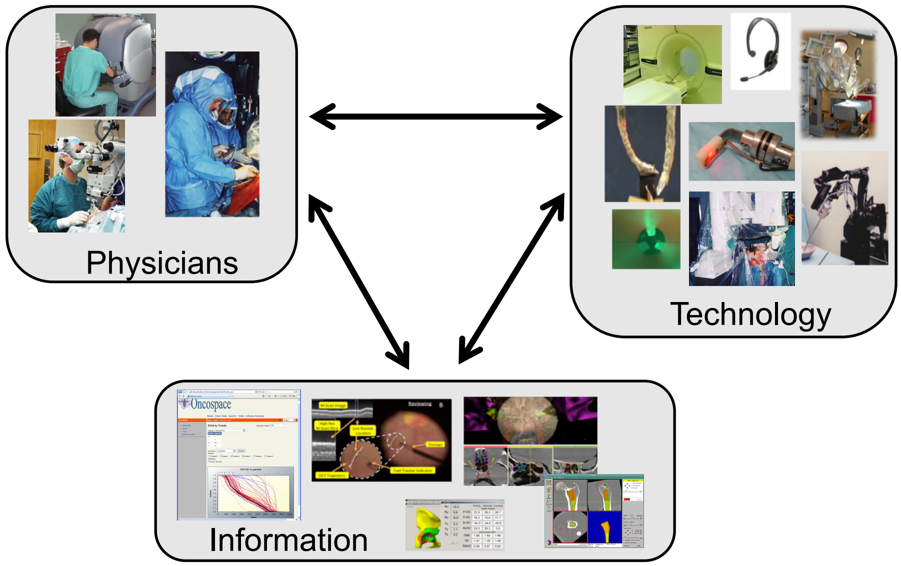



## Motivating Insight

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



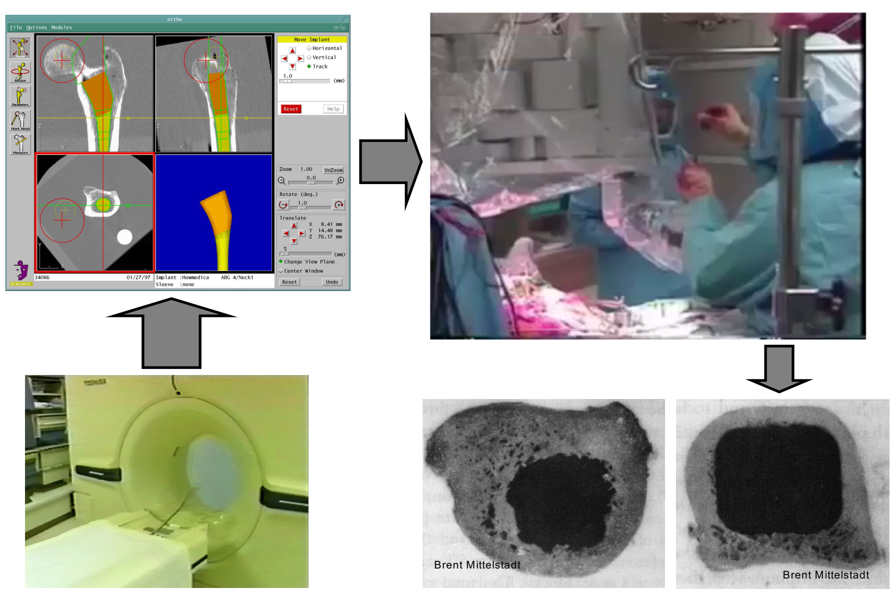
## Goal: Human-machine partnership to fundamentally improve interventional medicine







## Over 25 years ago: Robotic Joint Replacement Surgery



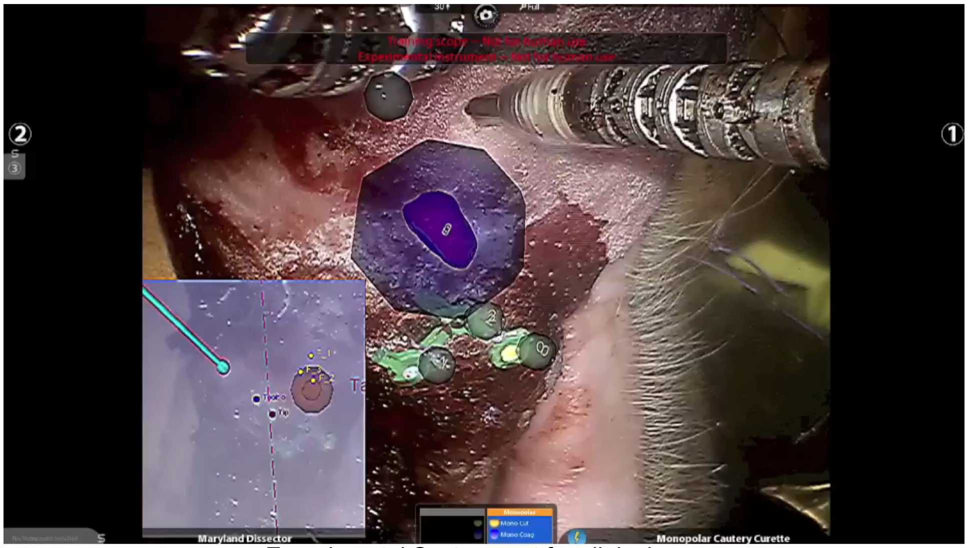

Manual Surgery

Robotic Surgery

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

## Emerging: Information-Augmented Robotic Surgery

**W. P. Liu**, S. Reaugamornrat, A. Deguet, J. M. Sorger, J. H. Siewerdsen, J. Richmon, R. H. Taylor




Experimental System: not for clinical use

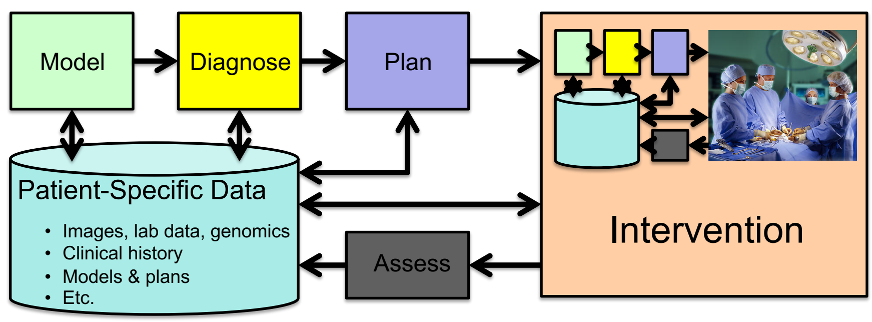



## Emerging: Augmented Reality in the OR

M. Unberath* , J. Fotouhi* , J. Hajek* , A. Maier, G. Osgood, R. Taylor, M. Armand, N. Navab. “Augmented Reality-based Feedback for Technician-in-the-loop C-arm Repositioning” To appear in *2018 AE-CAI MICCAI workshop*.

* Joint first authors

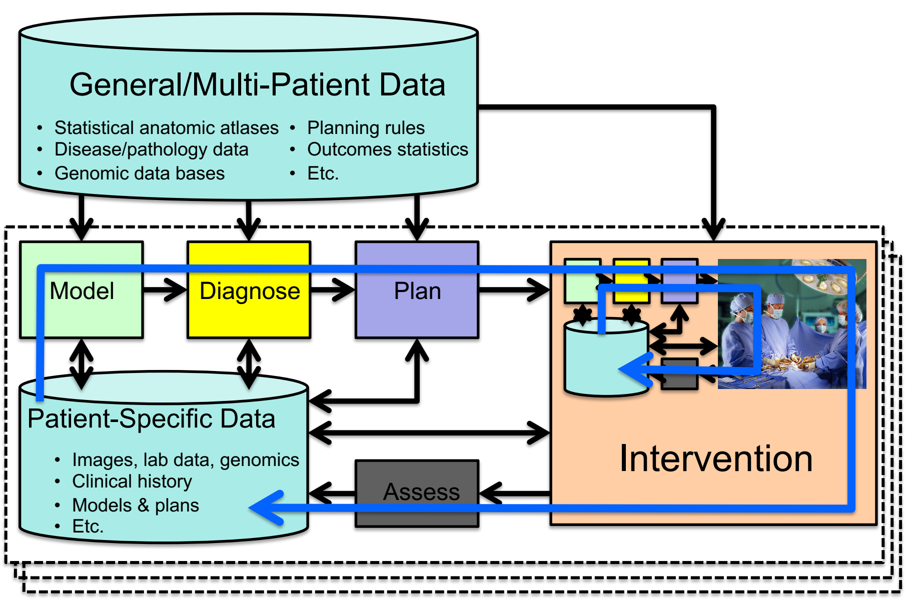
## Computer-Integrated Interventional Medicine



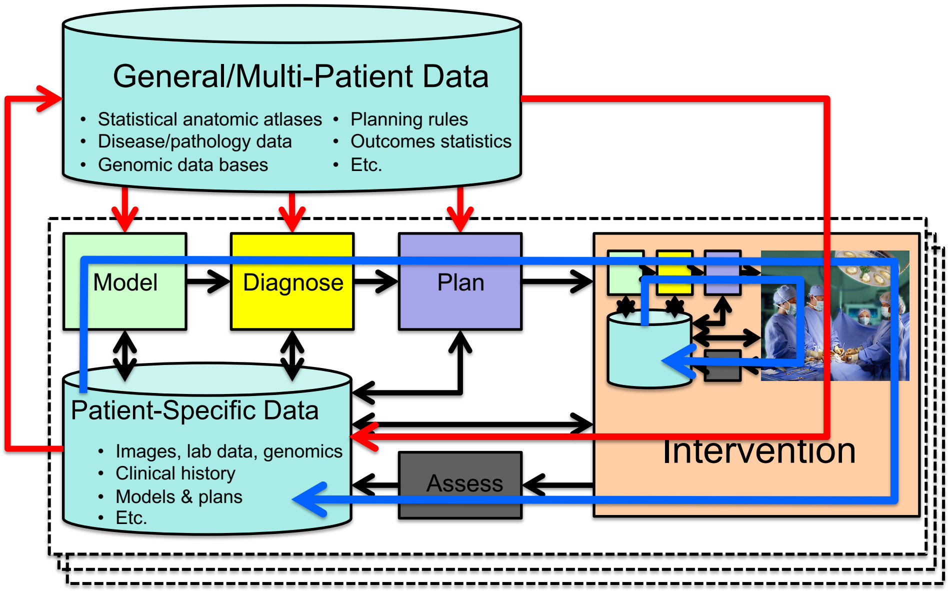




## Computer-Integrated Interventional Medicine



## Computer-Integrated Interventional Medicine



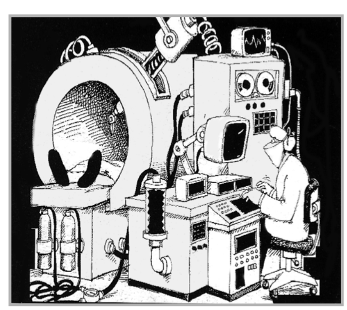





## This Paradigm has not changed since Imhotep's day

27th Century BCE

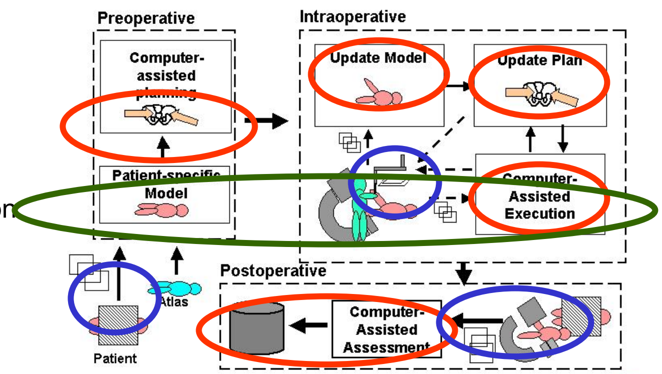
But medical robots and computer-integrated interventional systems will make it much more effective



21st Century CE

# Multidisciplinary Integration is Crucial

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

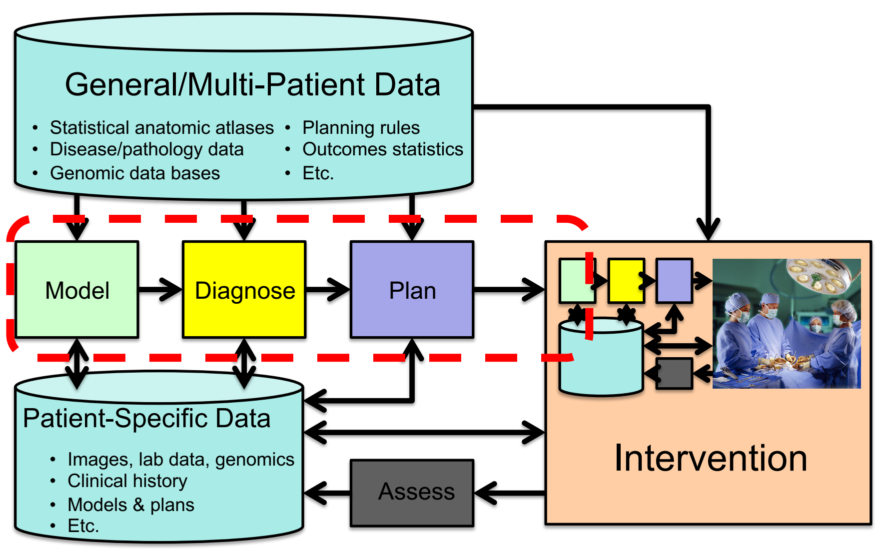



**Interface Technology**
- Sensing
- Robotics
- Human-machine interfaces

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

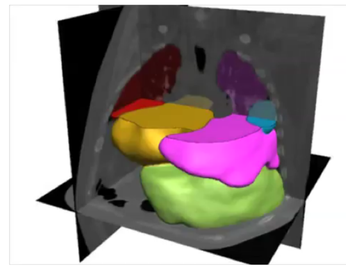


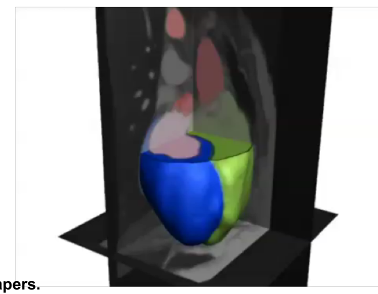

# Image-based modeling & analysis



## 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
- Predominately derived from medical images and image analysis
- Increasingly reference statistical "**atlases**" describing patient populations

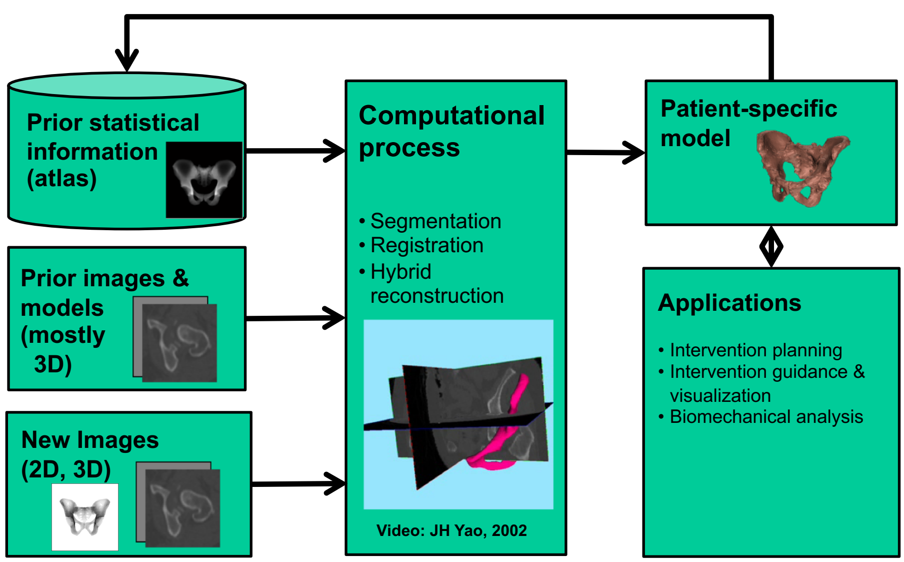




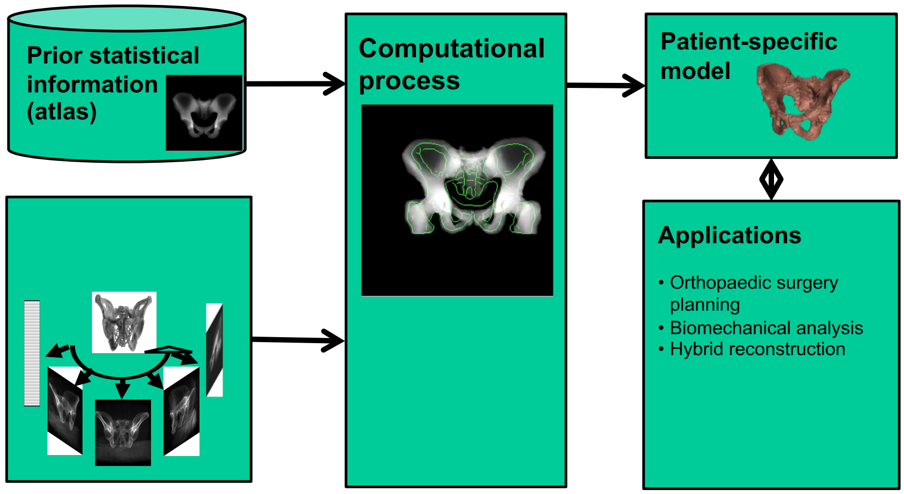
**Video: Blake Lucas, "SpringLS…", *MICCAI 2011* & subsequent papers.**
**Data courtesy of Terry Peters and Eric Ford**




## Combining prior knowledge with online images



## Deformable 2D/3D Registration to Statistical Atlas

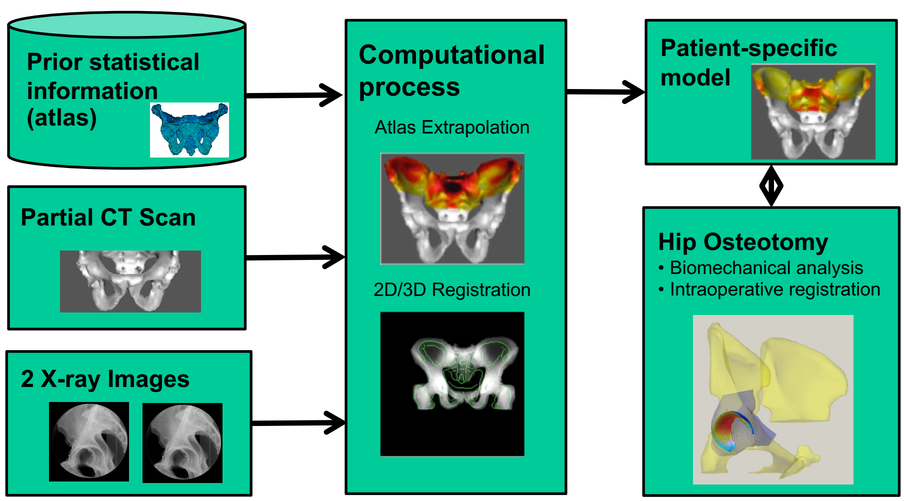



**Examples:** R. Taylor, J. Yao, O. Sadowsky, G. Chintalapani, O. Ahmad, …




## Model Completion, Given Partial CT + X-rays

<u>G. Chintalapani</u>, *et al.* "Statistical Atlas Based Extrapolation of CT Data for Planning Periacetabular Osteotomy", SPIE Medical Imaging 2010



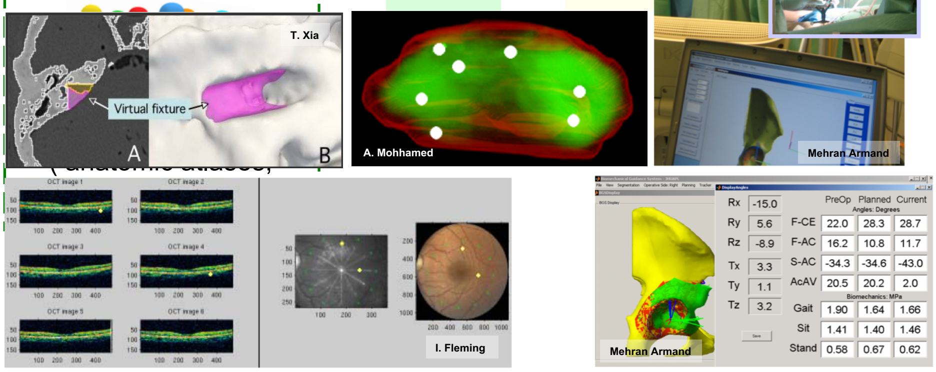
## Procedure Planning

***Information***

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

Model

Plan







## 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

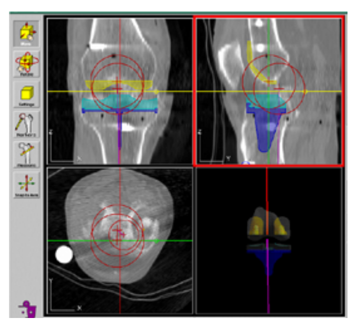
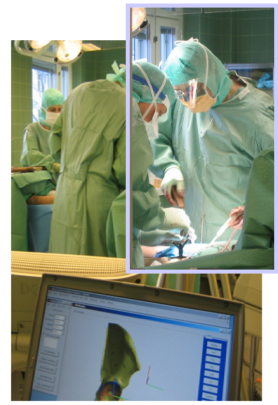
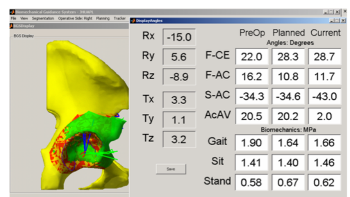


Photo: Integrated Surgical Systems

## 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

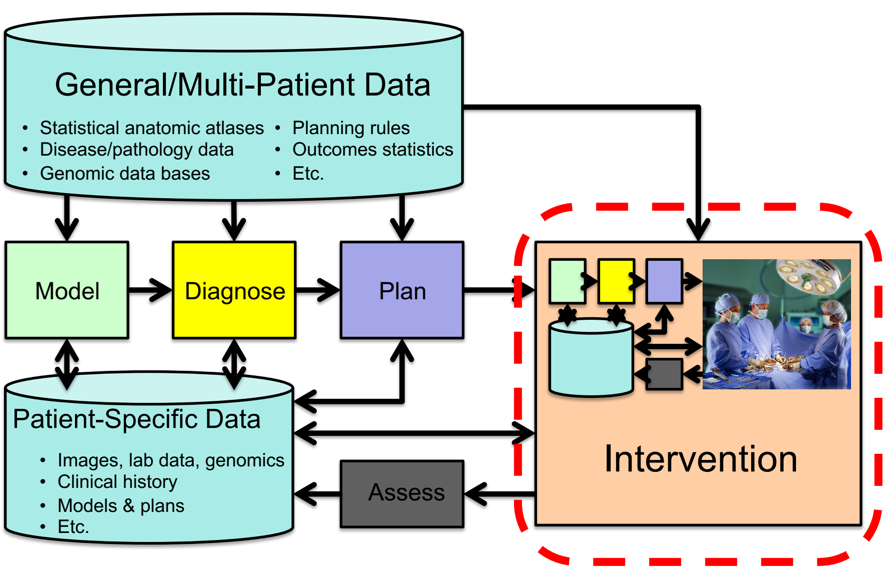





**Photos: Mehran Armand**



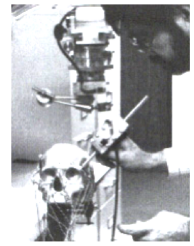

## Procedure Execution



## 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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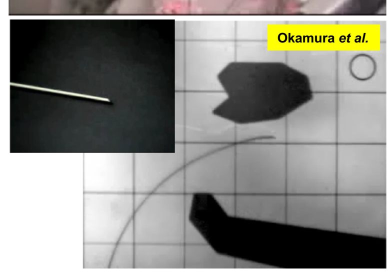

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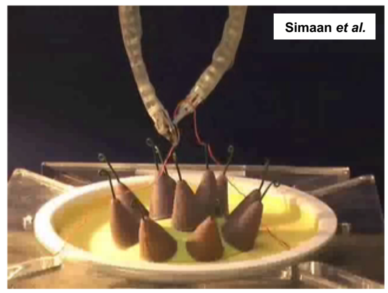





## Procedure Execution

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

## Procedure Execution

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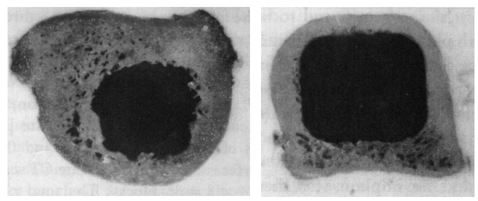




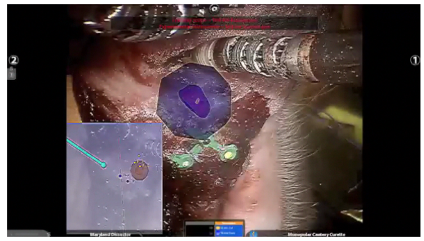

## Procedure Execution

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

- 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

## 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



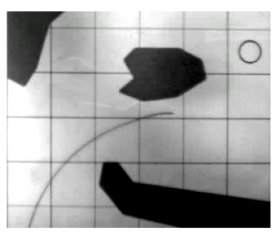
W. Liu, J. Sorger, J. Richmon, R. Taylor, *et al*

Stoianovici, Taylor, Whictomb, *et al.*

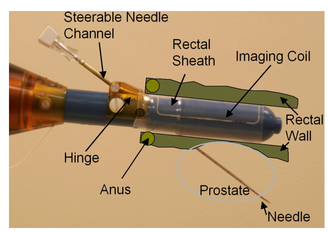



## Image-guided needle placement

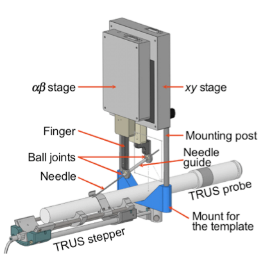
Masamune, Fichtinger, Iordachita, …



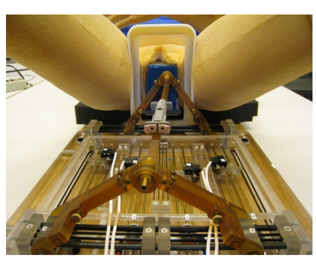
Okamura, Webster, …




Krieger, Fichtinger, Whitcomb, …




Fichtinger, Kazanzides,Burdette, Song …



Iordachita, Fischer, Hata…

Taylor, Masamune, Susil, Patriciu, Stoianovici,…

## Information-enhanced robotic surgery

augmented
reality displays
imaging

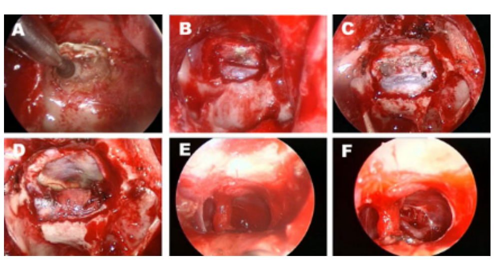
safety barriers
shared control
“virtual fixtures”

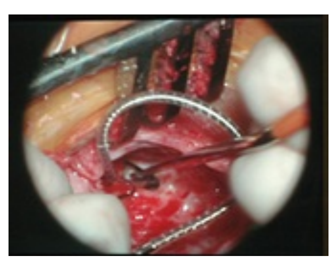
**SAW**




## Example: Challenges in Precise Minimally Invasive Head-and Neck Surgery

- Long (25cm) instruments
  – amplify hand tremor
  – reduce precision
- Tight spaces near sensitive anatomy
- Limited working area



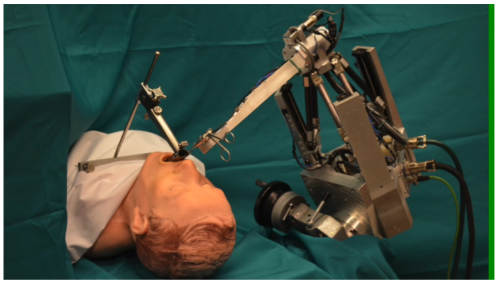



## The Robotic ENT Microsurgery System (REMS)

User interface:
- Hands-on control, surgeon “in the game”
- Foot pedal-controlled gain

Technical specs:
- Up to 0.025 mm precision on-demand
- 6 degrees of freedom
- 125x125x125mm work volume
- Calibrated accuracy ~50-150μm

Control modes:
- Free hand
- Remote center of motion
- Virtual fixture avoidance
- Teleoperation



**K. Olds, *Robotic Assistant Systems for Otolaryngology-Head and Neck Surgery,* PhD thesis in Biomedical Engineering, Johns Hopkins University, Baltimore, March 2015.**



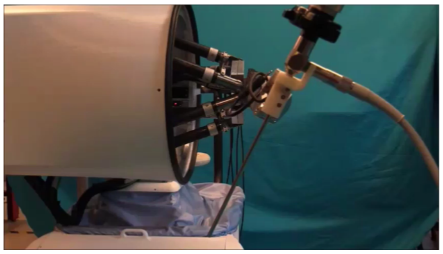

## Cadaver Study: Sinus Surgery with Virtual Fixtures


K. Olds, M. Balicki, M. Ishii, R. Taylor

GALEN ROBOTICS

## The Galen Platform

### Technology:
- Custom 5-DOF architecture
- “Steady Hand” cooperative control
- Hand tremor cancellation
- Virtual fixtures



**Disclosure:** Prof. Taylor is a paid consultant to and has equity in Galen Robotics and also may receive income from patent royalties from Galen

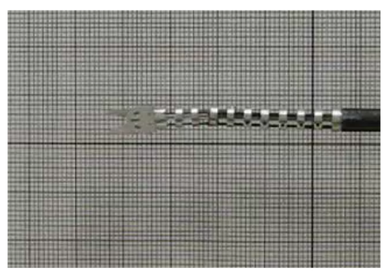
### Ease of Use:
- Same footprint as a person
- Accommodates standard instruments
- Minimal change to existing surgical workflow

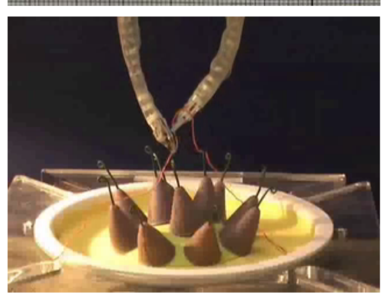
### Broad Applications:
- ENT, spine, brain, trauma, ….




## Snake-like robot for minimally invasive surgery

- **Goals**
  - Develop scalable robotic devices for high dexterity manipulation in confined spaces
  - Demonstrate in system for surgery in throat and upper airway
- **Approach**
  - “Snake-like” end effectors with flexible backbones and parallel actuation
  - Integrate into 2-handed teleoperator system with optimization controller
- **Status**
  - Licensed to industry partner
  - Significant research at Vanderbilt
- **Funding**
  - NIH R21, CISST ERC, JHU, Columbia
  - NIH proposals pending

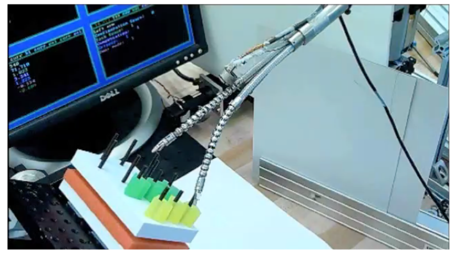


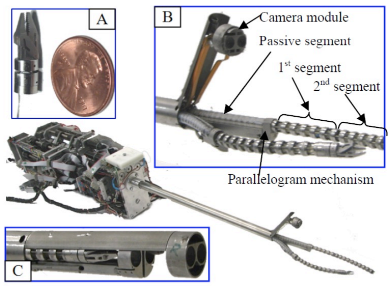


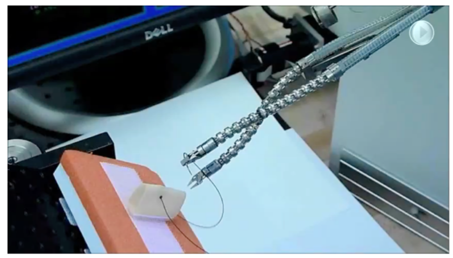
R. Taylor, N. Simaan, *et al.*

## Single Port Access Surgery

**Nabil Simaan** (Vanderbilt, Columbia), with
P. Allen (Columbia), D. Fowler (Columbia)



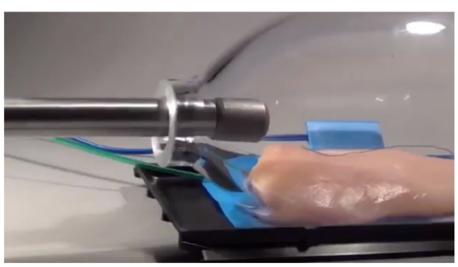


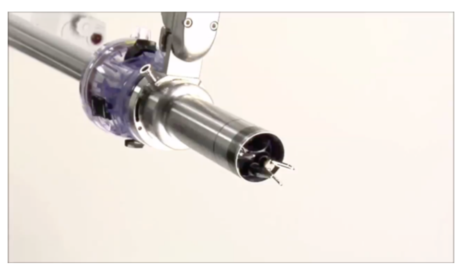



New technology finally allows true evaluation of the potential of single port access surgery. Systems raise new questions about control and telemanipulation infrastructure/cooperative control.




## Single Port Access Robotic Surgery





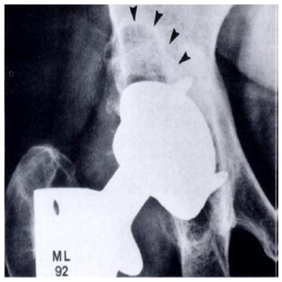
Titan Medical Sport

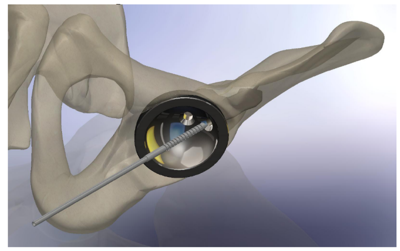
https://www.youtube.com/watch?v=jIvjvcKA6xQ

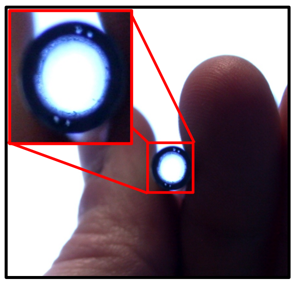
Intuitive Surgical Sp

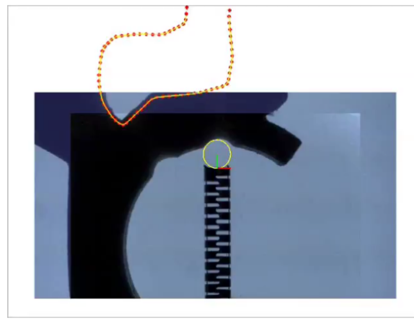
https://www.youtube.com/watch?v=-jm63JdTrp4

# Minimally-Invasive Osteolysis Curettage



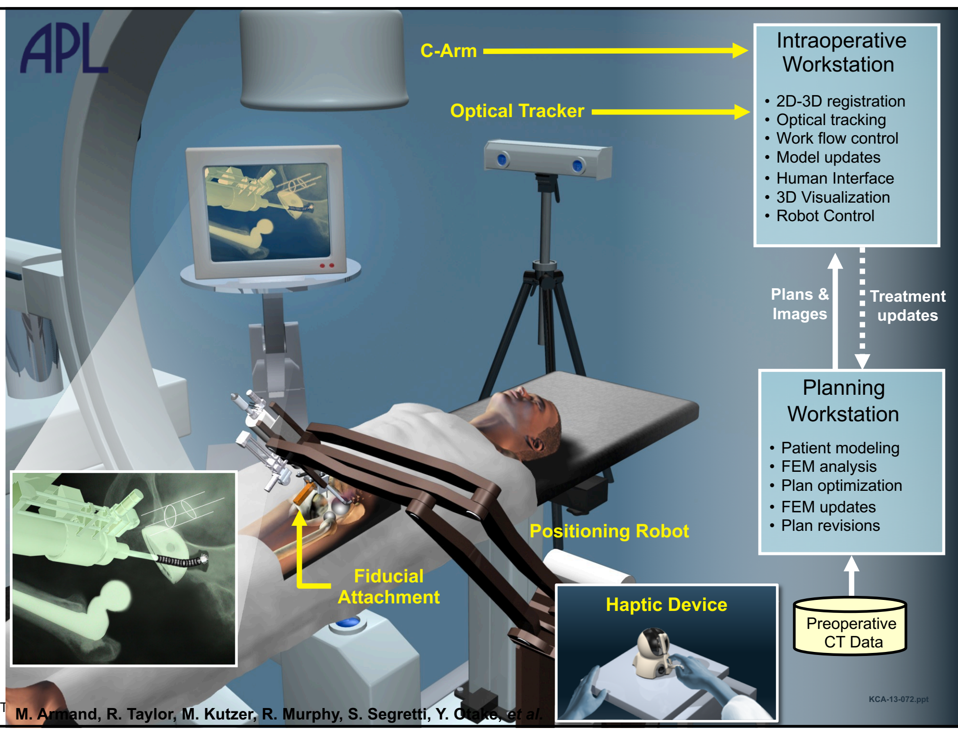




M. Armand, R. Taylor, M. Kutzer, R. Murphy, S. Segretti,, *et al.*



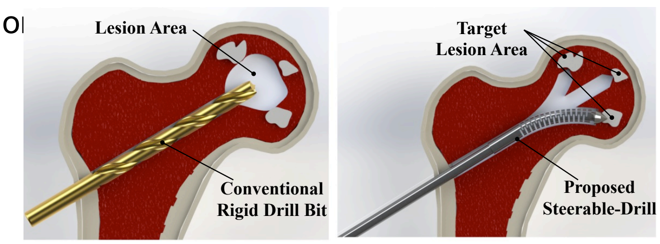
Engineering Research Center for Computer Integrated Surgical Systems and Technology



## Curved Drilling of the Femoral Head

**Alambeigi, *et al.***

- Osteonecrosis of the femoral head
  - More than 20,000 patients per year
  - To reduce the pressure in the femoral head, core decompression was developed more than three decades ago.
- Steerable "snake" with flexible drill provides better ol





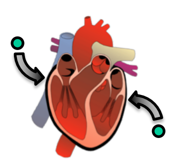
Farshid Alambeigi, Yu Wang, Shahriar Sefati, Ryan. J. Murphy, Iulian Iordachita, Russell H. Taylor, Harpal Khanuja, and Mehran Armand, "Curved-Drilling Approach in Core Decompression of the Femoral Head Osteonecrosis Using a Continuum Manipulator", *Proc. ICRA 2017*



## Foreign Bodies in the Heart

**Causes**

Thrombi, Shrapnel
Iatrogenic

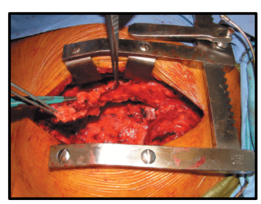


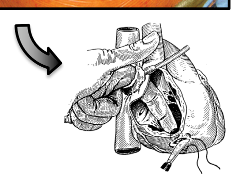
**Symptoms**

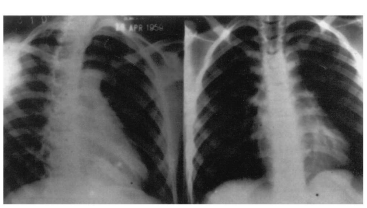
Cardiac Tamponade
Hemorrhage
Arrhythmia
Infection
Shock
Embolism
Valve Dysfunction

**Conventional Treatment**

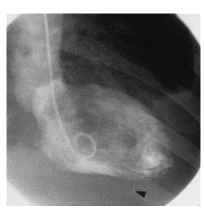
Median Sternotomy
Cardiopulmonary Bypass







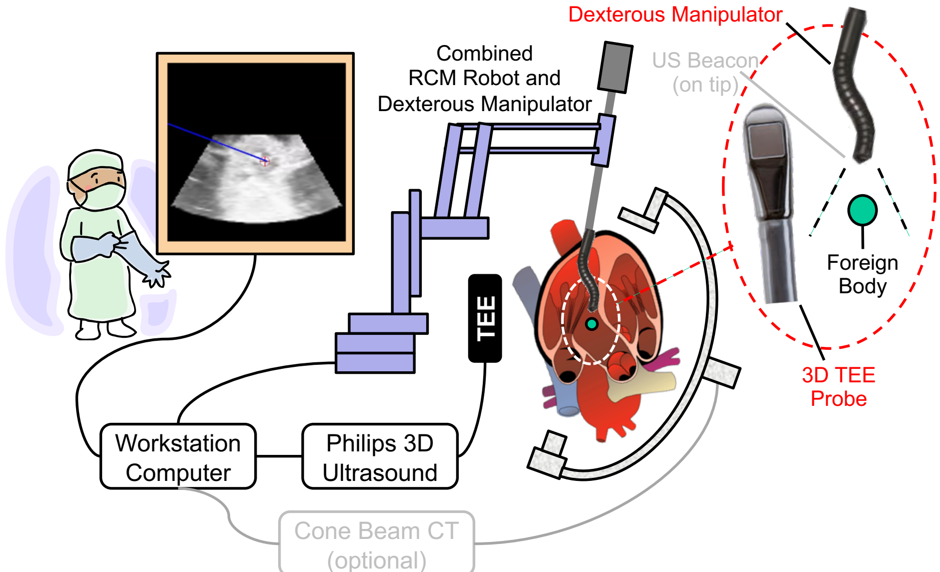
(Actis Dato, 2003)



(LeMaire, 1999)

# Beating Heart MIS with 3D US Guidance

Paul Thienphrapa, Aleksandra Popovic, Russell Taylor

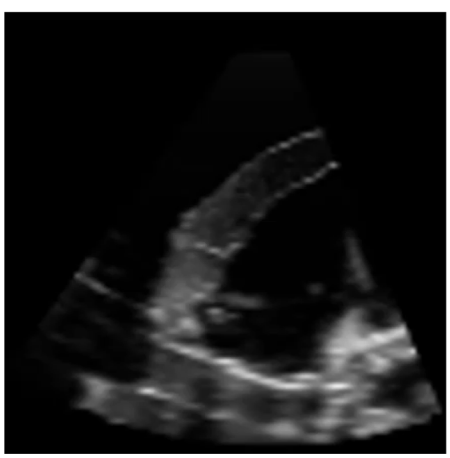


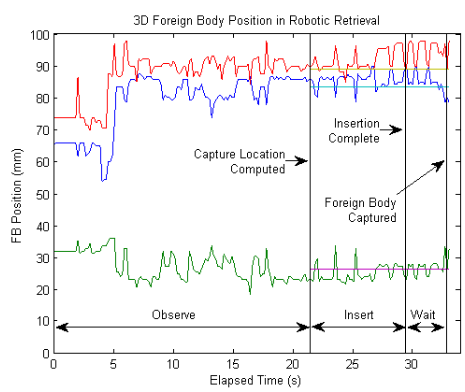



PHILIPS



# Retrieval Experiment Results



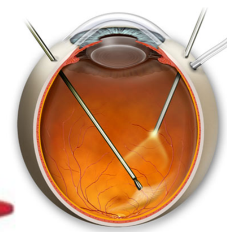



PHILIPS

Thienphrapa *et al. 2013*

# Vitreoretinal Microsurgery

British Journal of Ophthalmology 2004 - Akifumi Ueno et al



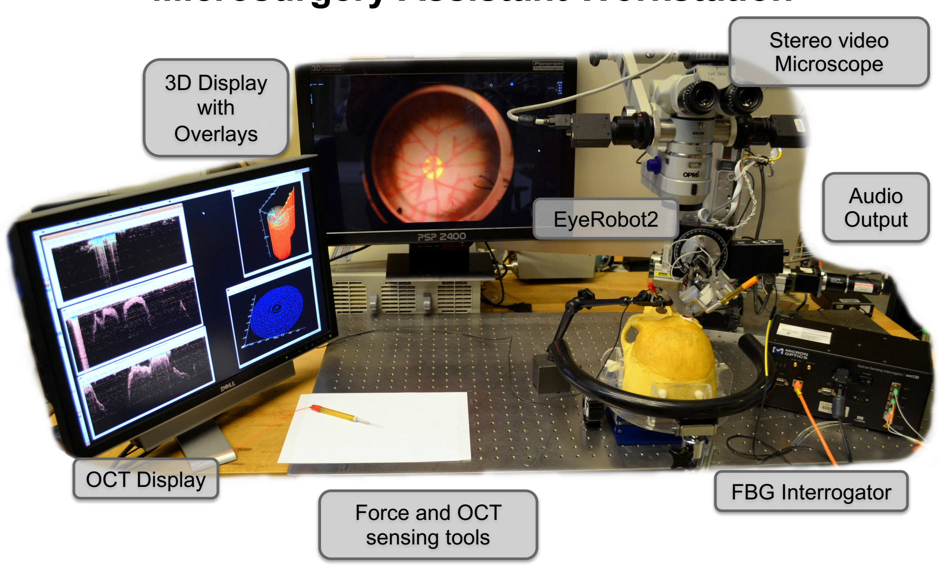
www.eyemdlink.com

Alcon Vitreosurgery Instrument



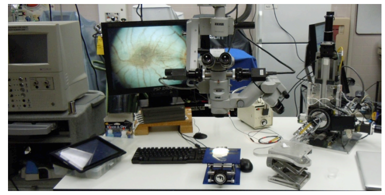


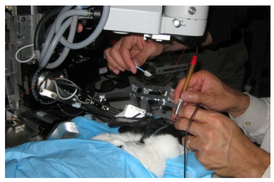
# Microsurgery Assistant Workstation

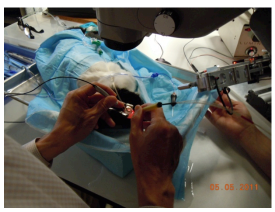


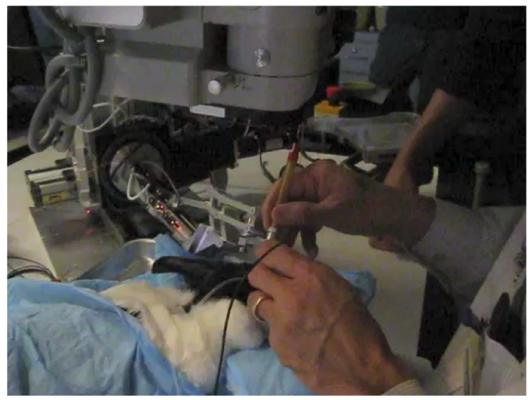
## In-Vivo Experiments

- Overall System Performance
- System Ergonomics
- Collect Data
  - Robot / Force / OCT
  - Video / Audio



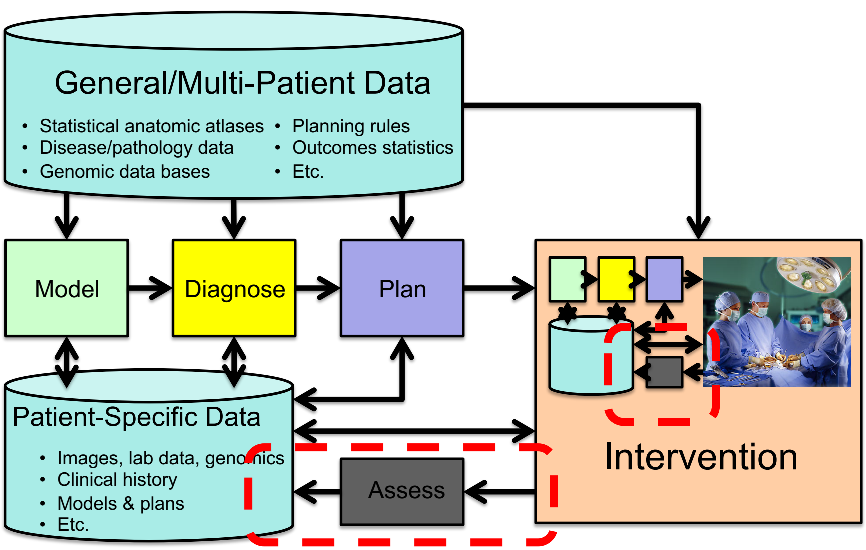




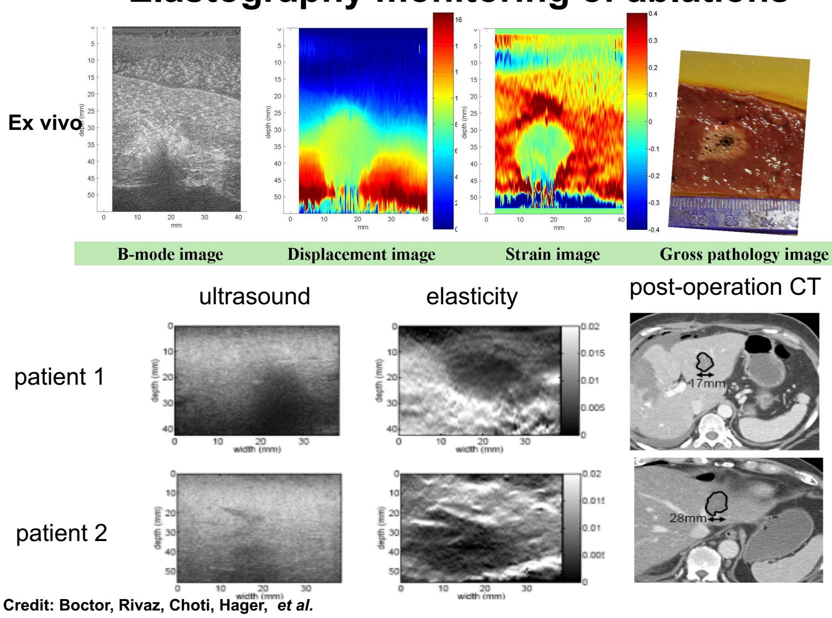





## Patient-specific assessment and feedback



## Elastography monitoring of ablations

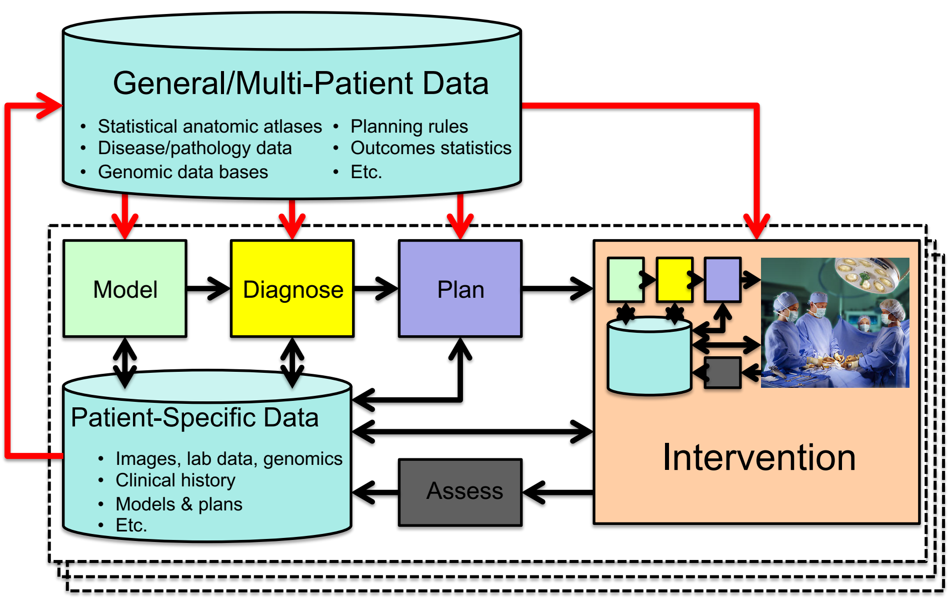



Credit: Boctor, Rivaz, Choti, Hager, *et al.*



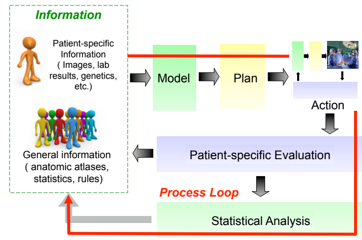


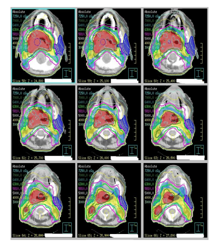
## Statistical Analysis and Decision Support



## Information-Integrated Process Learning

- **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

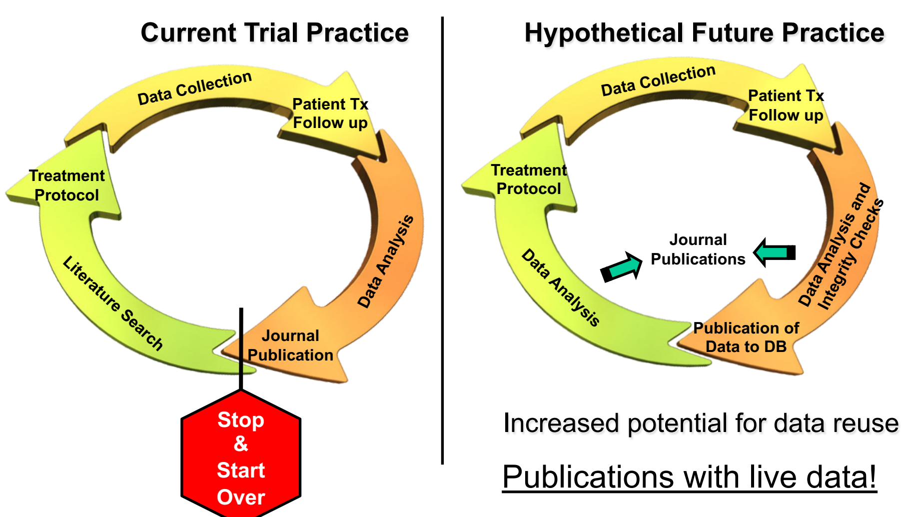


Credit: Todd McNutt




## Outer/Population Loop

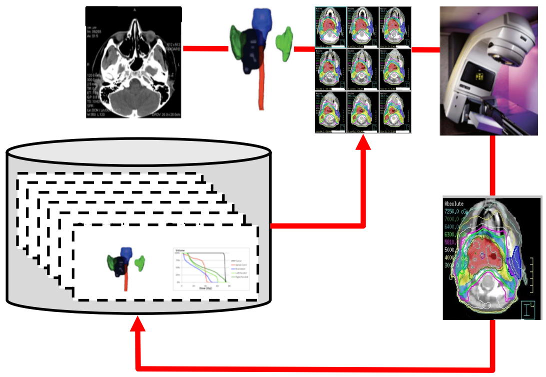



Increased potential for data reuse

Publications with live data!

Figure: Todd McNutt

## Statistical process control for radiation therapy



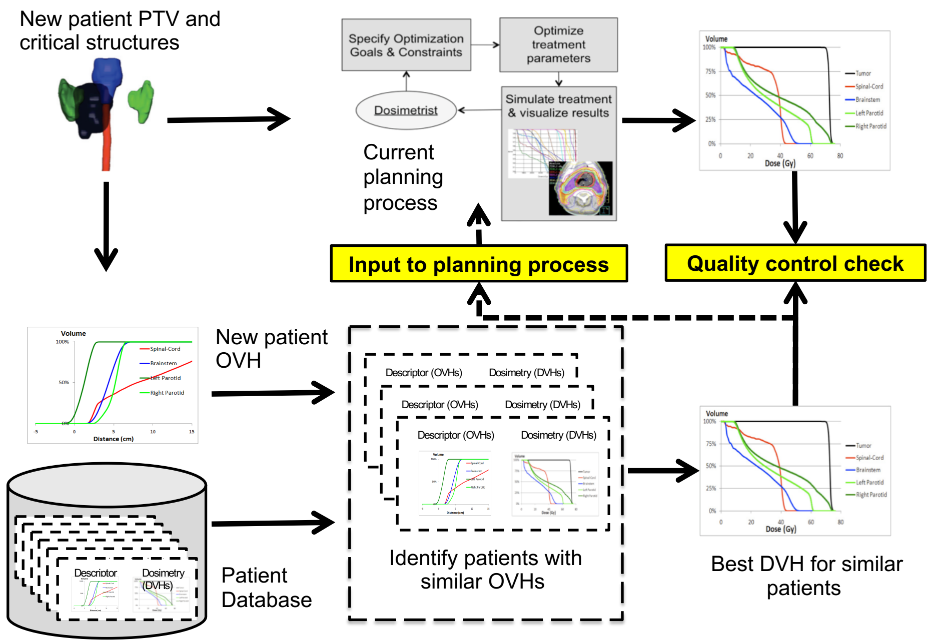
**Overall Goal:** Use a database of previously treated patients to improve radiation therapy planning for new patients

**Team:**

- **CS:** R. Taylor, M. Kazhdan, P. Simari, A. King
- **BME:** R. Jacques
- **Rad. Oncology:** T. McNutt, J. Wong, B. Wu, G. Sanguinetti (MD)

**Support:** Paul Maritz, Philips, JHU internal funds

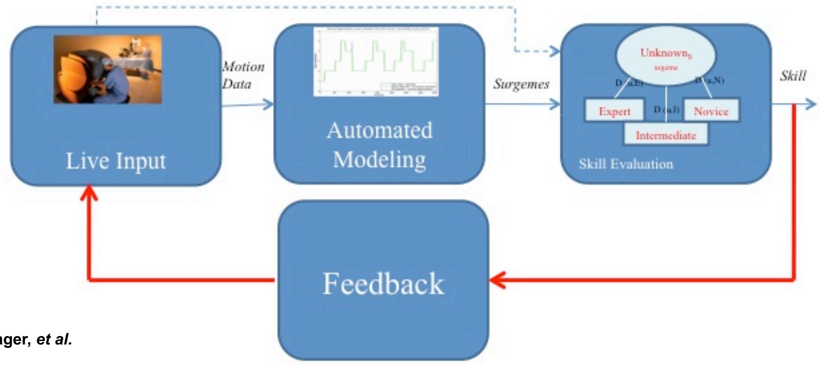



T. McNutt, B. Wu, M. Kazhdan, P. Simari, A. King, R. Jacques, J. Wong, R. Taylor

# Applications Of Surgical Motion Models

**Underlying hypothesis:** Learned motion models of experts can be used for teaching, training, and automation of surgical actions.



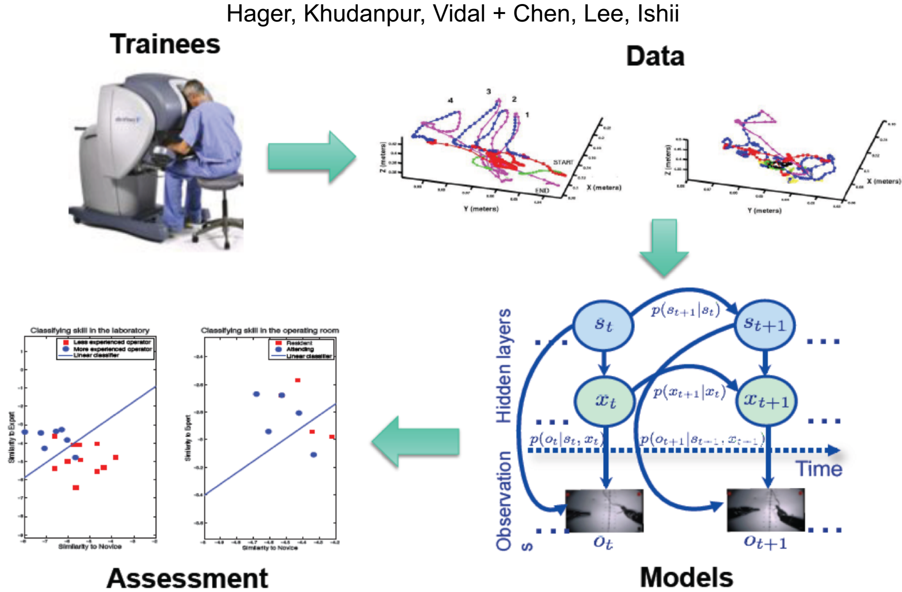

G. Hager, *et al.*





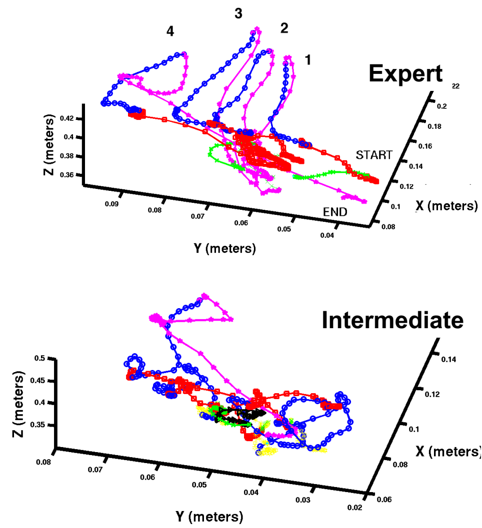

# The Language of Surgery

Hager, Khudanpur, Vidal + Chen, Lee, Ishii



## Example: Automatic Detection and Segmentation of Robot-Assisted Surgical Motions

- Goals:
  - Automatic recognition of different surgical motions
  - Comparison of skill level differences between surgeons
- Method
  - Extract features from position and velocity traces
  - Linear discriminant analysis with probabilistic Bayesian classifier

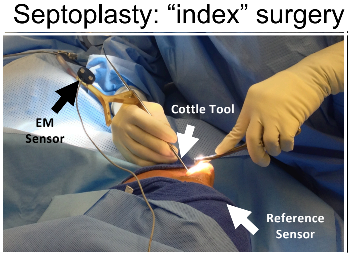


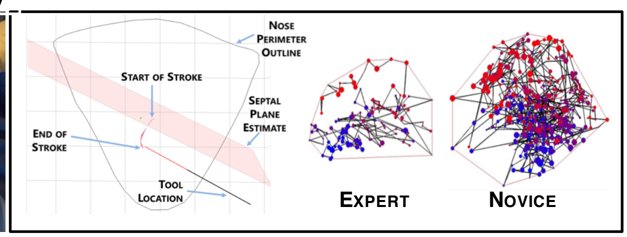

H. Lin, I. Shafran, T. Murphy, D. Yuh, A. Okamura, G. Hager (MICCAI 2005)



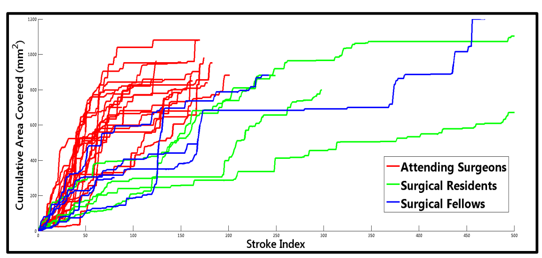

## Unstructured surgeries: Discovering "teachable" tactics

Septoplasty: "index" surgery




Automatic Segmentation of Strokes in Nasal Septoplasty

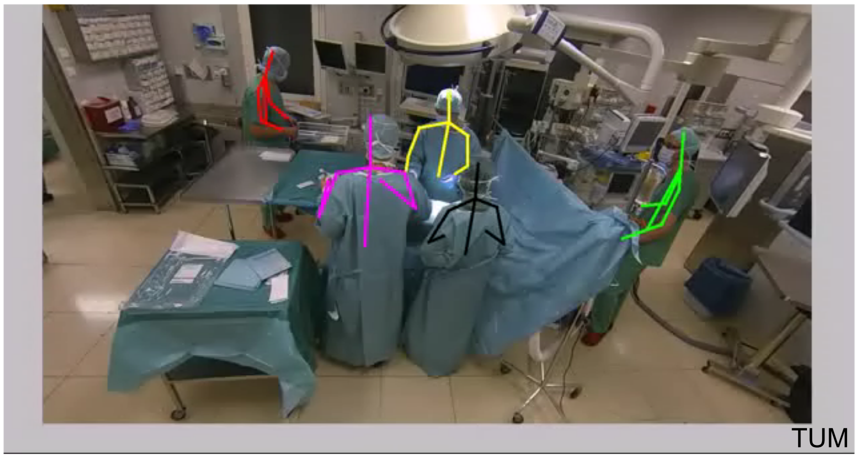



***Feedback: Stroke Curvature Consistency***: Draw similar-shape curves (instead of straight lines) sequentially
***Stroke Duration Consistency***: Spend the same amount of time drawing the curves
***Coverage Rate***: Practice strong enough brushing motions to elevate mucosa

Poddar P., Ahmidi N., Vedula S.S., Ishii, L., Hager G.D., Ishii M.: Automated Objective Surgical Skill Assessment in the Operating Room Using Unstructured Tool Motion. M2CAI 2014.

## OR Workflow Observation and Analysis

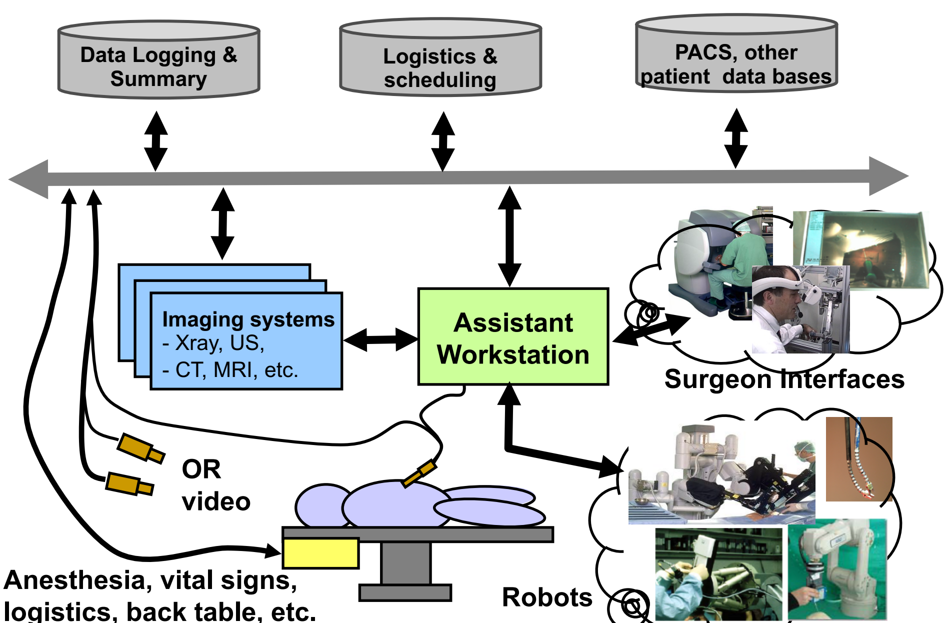
N. Navab *et al.*



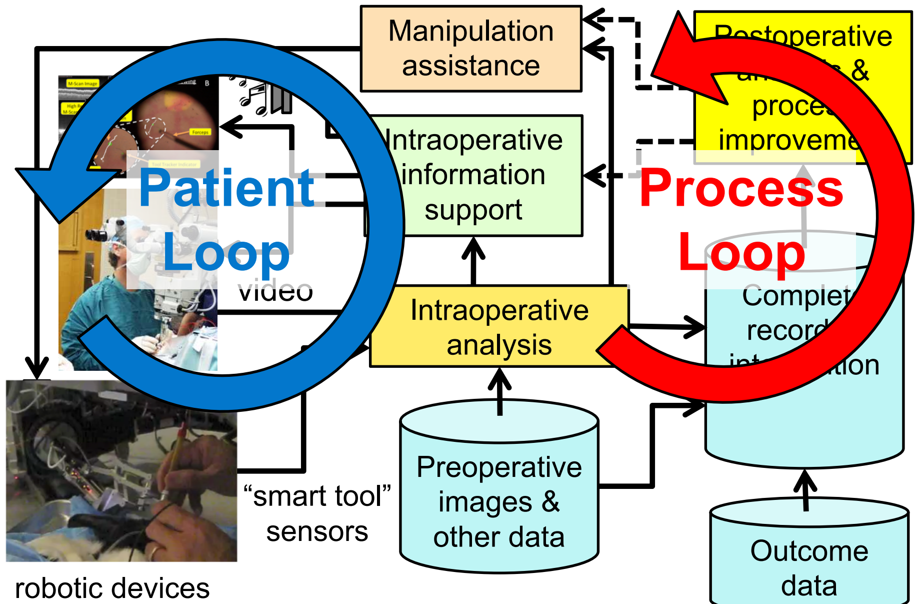





## Information-Intensive Interventional Suite



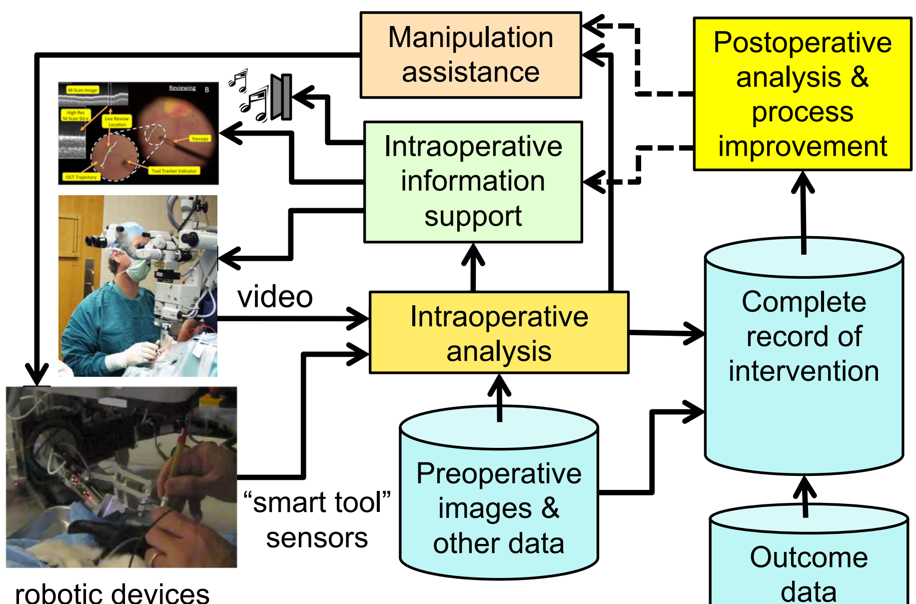
## The computer-integrated operating room



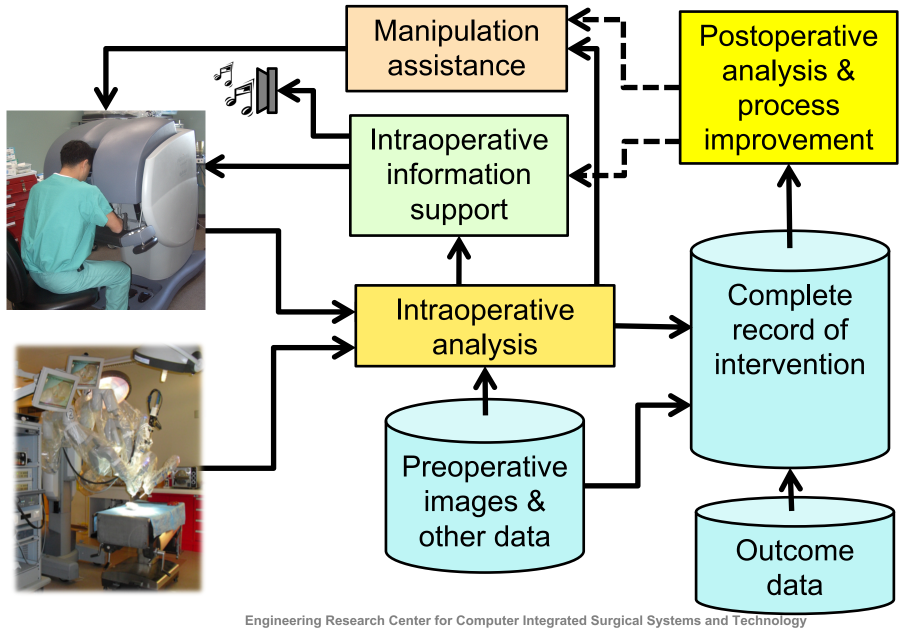




## The computer-integrated operating room



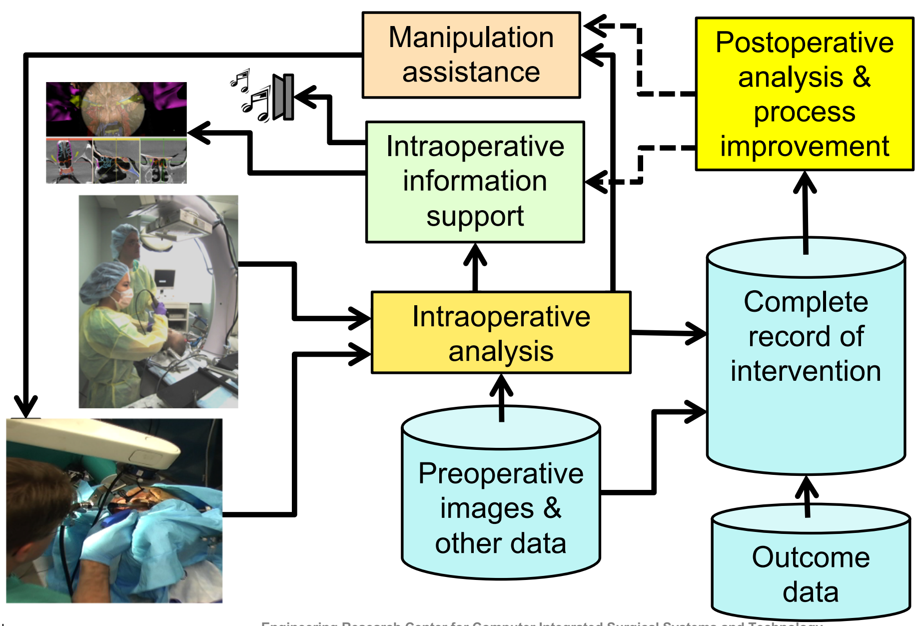
## The computer-integrated operating room





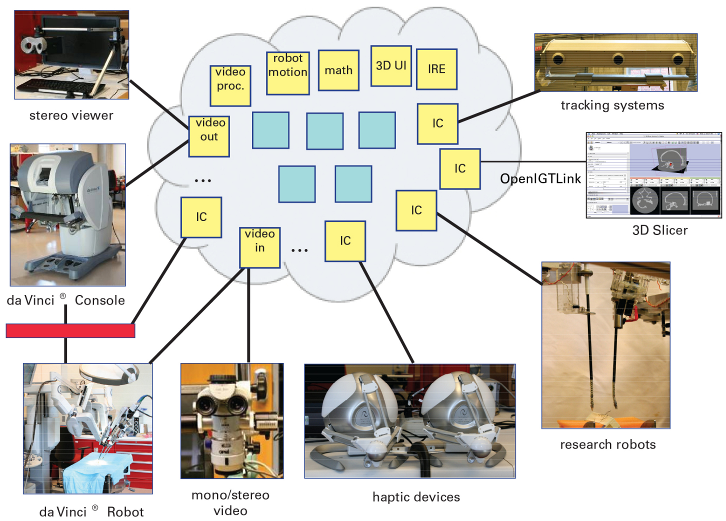


## The computer-integrated operating room



# cisst libraries and Surgical Assistant Workstation

**https://trac.lcsr.jhu.edu/cisst**




**Peter Kazanzides, Simon P. DiMaio, Anton Deguet, and many more**




# Use Case: da Vinci Research Kit


- Mechanical components from da Vinci “classic” systems
- Donated by Intuitive Surgical to selected university labs
- Consortium to provide “open source” engineering and support
  - Software – JHU (CISST/SAW)
  - Controller electronics –JHU
  - Interface electronics – ISI
  - Controller power/packaging – WPI
- Controllers and software also adapted for use with complete recycled da Vinci “classic” systems
- **http://research.intusurg.com/dvrkwiki/**

## General working model

**Use clinical applications to provide focus & key problems**

- Emphasis on surgery and interventional procedures
- Directly involve clinicians in all stages of research
- Emphasize integration into complete systems
- Point toward clinical deployment

**Some current areas include**

- Skull base and head-and-neck
- Spine and orthopaedic surgery
- Thoracic surgery
- Abdominal and solid organ procedures (kidney, liver, prostate)
- Vascular & endoluminal
- Microsurgery

**Funding models**

- NIH, other Government grants
- Collaboration with NIH intramural programs
- Industry partnerships (use master research agreements to facilitate)




## 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


Engineering Research Center for Computer Integrated Surgical Systems and Technology

## Discussion