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

Russell H. Taylor
John C. Malone Professor of Computer Science,
with joint appointments in Mechanical Engineering, Radiology & Surgery
Director, Center for Computer-Integrated Surgical Systems and Technology
Director, Laboratory for Computational Sensing and Robotics
The Johns Hopkins University
rht@jhu.edu

WHITING
SCHOOL OF
ENGINEERING
THE JOHNS HOPKINS UNIVERSITY

Acknowledgments

- **<u>This is the work of many people</u>**
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- Some of the work reported in this talk incorporates intellectual property that is owned by Johns Hopkins University and that has been or may be licensed to outside entities, including including Intuitive Surgical, Varian Medical Systems, Philips Nuclear Medicine, Galen Robotics and other corporate entities. Prof. Taylor has received or may receive some portion of the license fees. These arrangements have been reviewed and approved by JHU in accordance with its conflict of interest policy.
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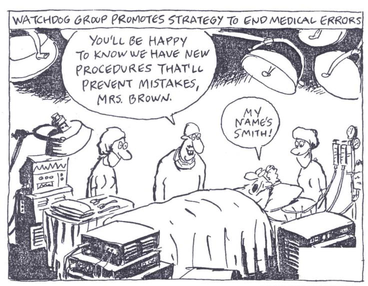
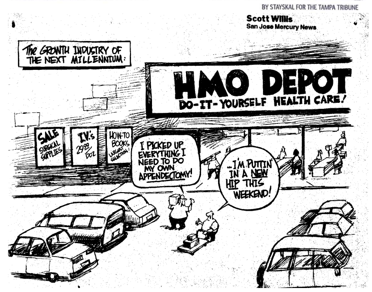
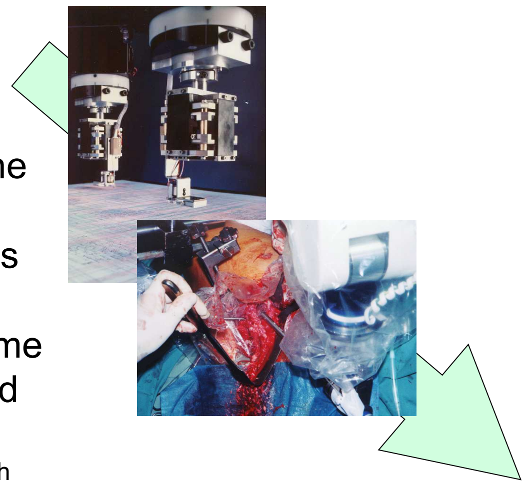


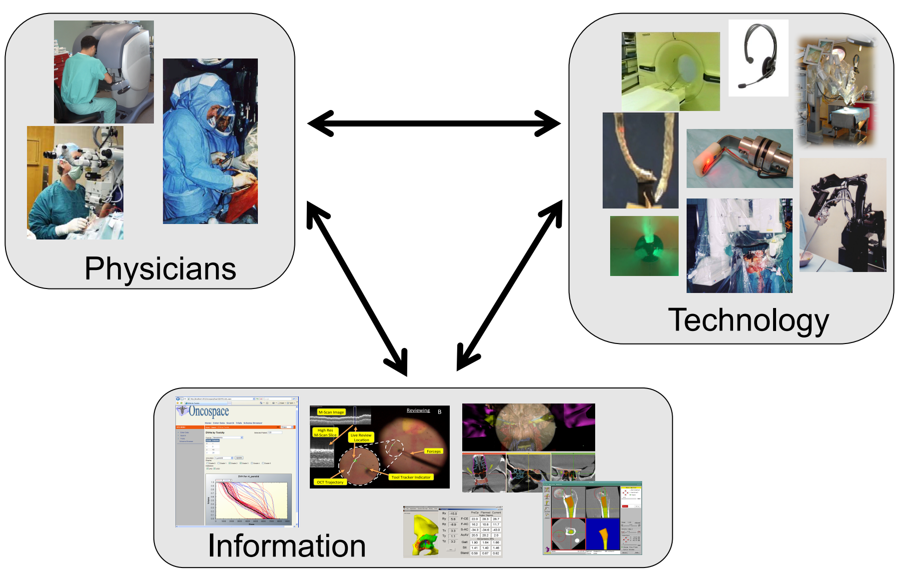


Motivating Insight

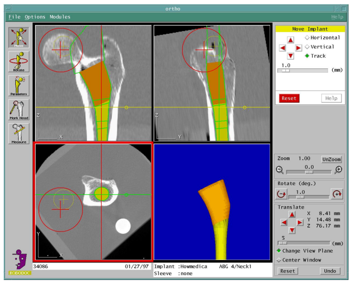
A partnership between human clinicians and computer-based technology will fundamentally change the way surgery and interventional medicine is performed in the 21st Century, in much the same way that computer-based technology changed manufacturing in the 20th Century

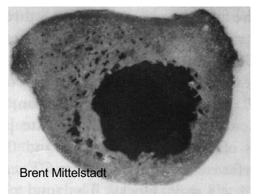


Goal: Human-machine partnership to fundamentally improve interventional medicine

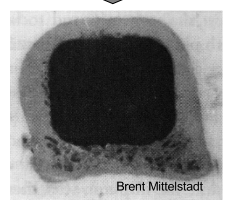


Over 25 years ago: Robotic Joint Replacement Surgery





Manual Surgery

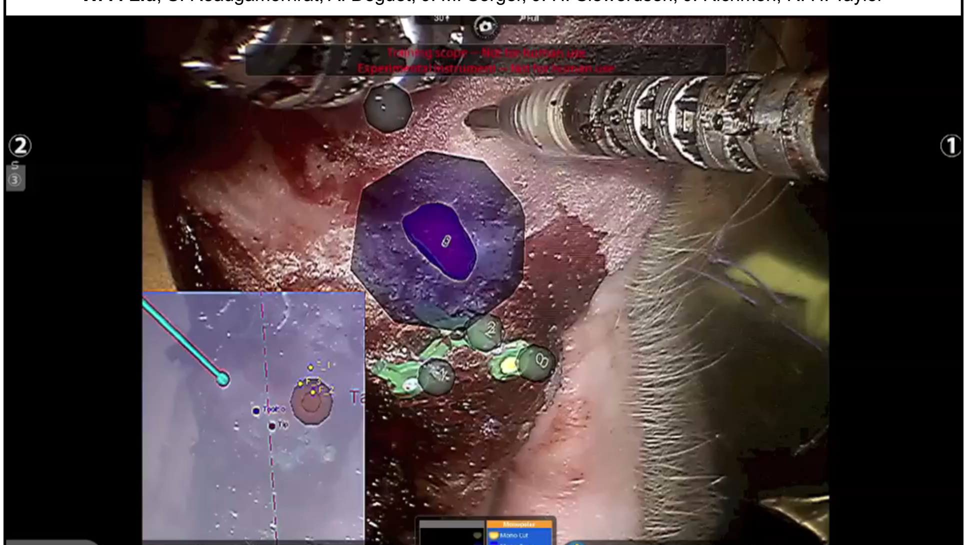


Robotic Surgery

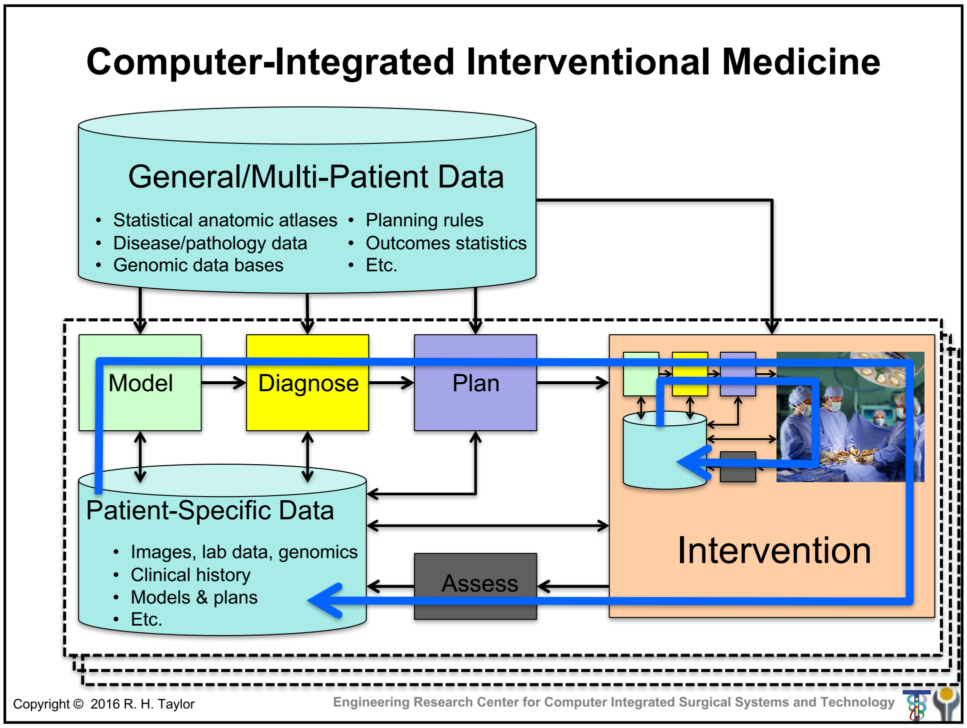
Taylor, Kazanzides, Paul, Mittelstadt, *et al.*

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


Computer-Integrated Interventional Medicine
General/Multi-Patient Data
• Statistical anatomic atlases
• Disease/pathology data
• Genomic data bases
• Planning rules
• Outcomes statistics
• Etc.
Model
Diagnose
Plan
Patient-Specific Data
• Images, lab data, genomics
• Clinical history
• Models & plans
• Etc.
Assess
Intervention
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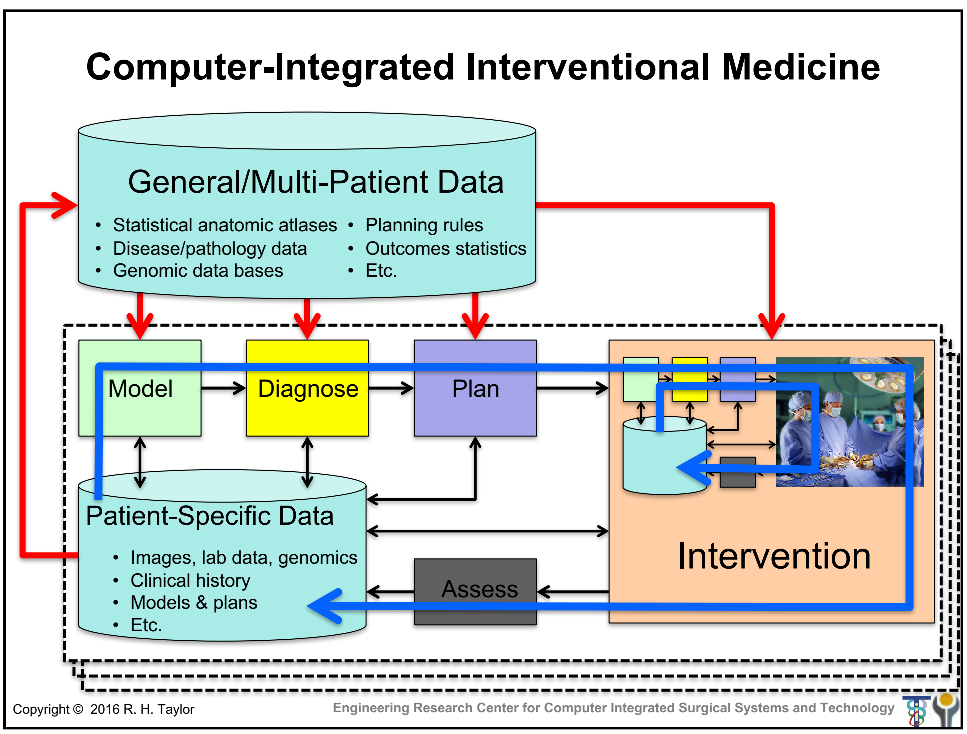
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• Images, lab data, genomics
• Clinical history
• Models & plans
• Etc.
Assess
Intervention
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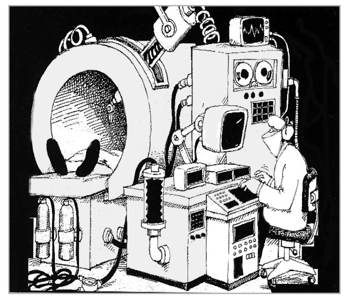
This Paradigm has not changed since Imhotep's day

27th Century BCE

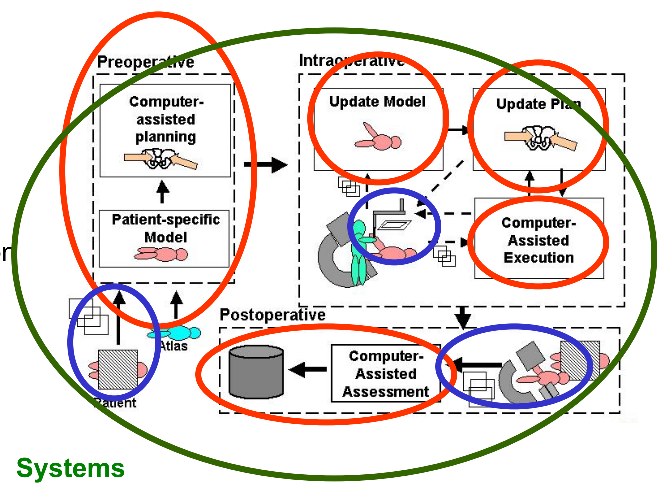
But medical robots and computer-integrated interventional systems will make it much more effective



21st Century CE

Multidisciplinary Integration is Crucial

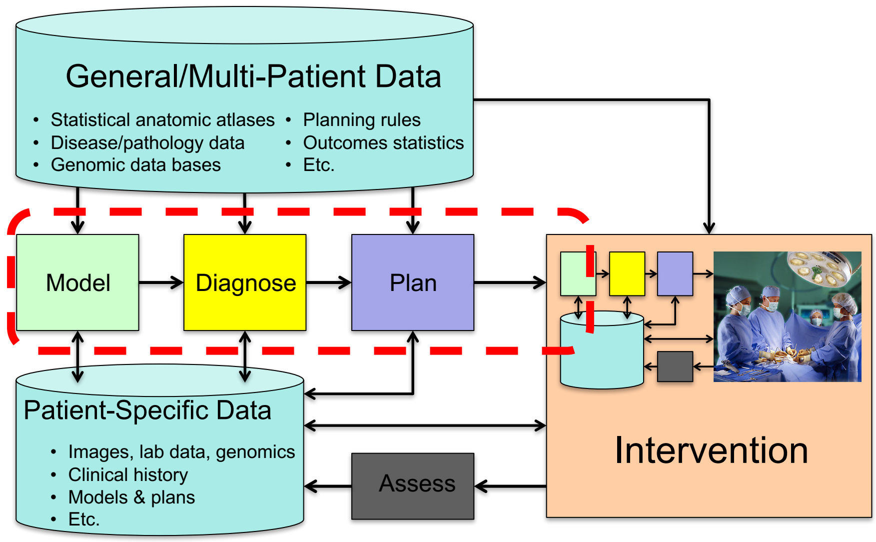
Modeling & analysis
- Segmentation
- Registration
- Atlases
- Optimization
- Visualization
- Task characterization
- *etc.*



Interface Technology
- Sensing
- Robotics
- Human-machine interfaces

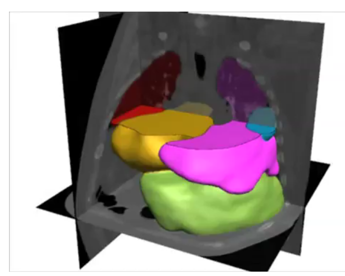
Systems
- Safety & verifiability
- Usability & maintainability
- Performance and validation

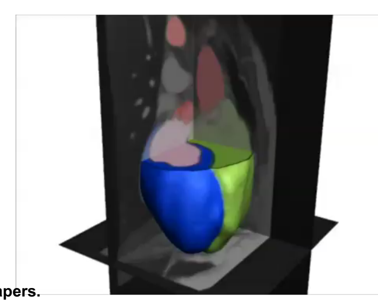
Image-based modeling & analysis



Patient-Specific Models for Interventions

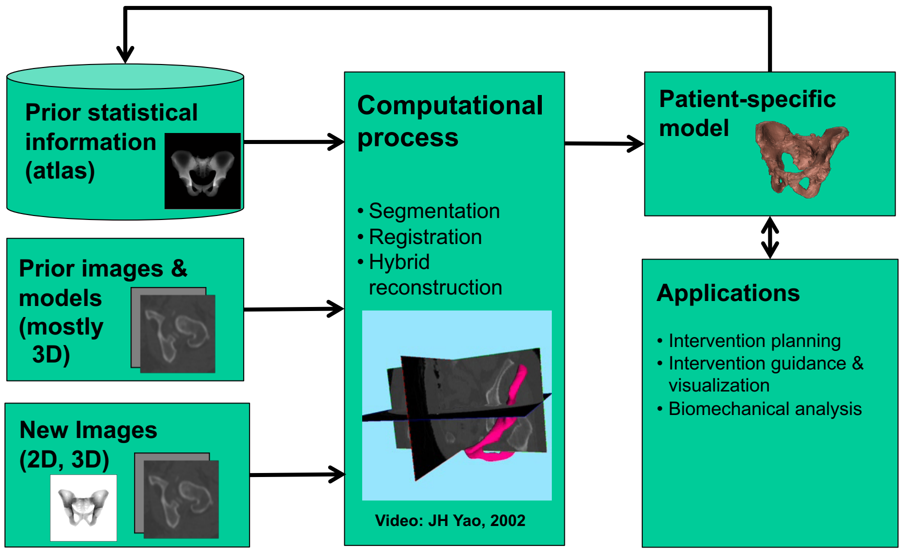
- Computationally efficient **representation of patient** enabling computer to assist in planning, guidance, control, and assessment of interventional procedures
- Generally focus on **anatomy**, but may sometimes include biology or other annotations
- Predominately derived from medical images and image analysis
- Increasingly reference statistical "**atlases**" describing patient populations



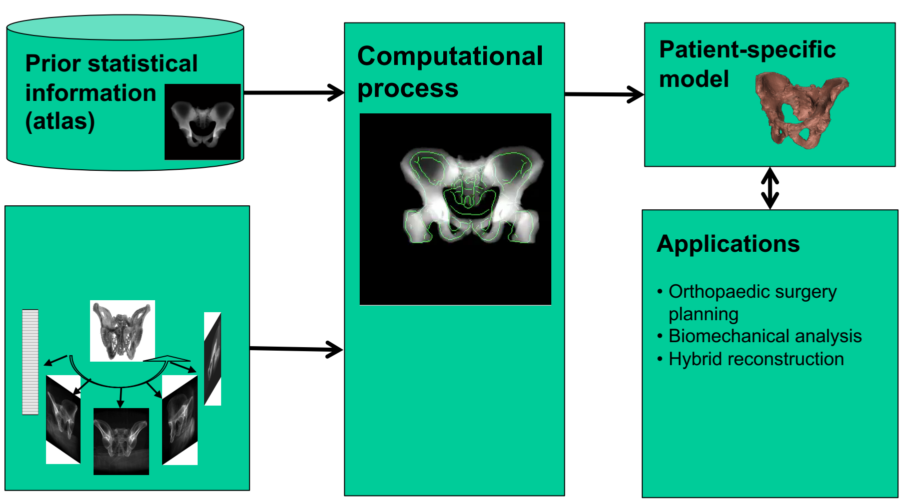


Video: Blake Lucas, "SpringLS…", *MICCAI 2011* & subsequent papers.
Data courtesy of Terry Peters and Eric Ford

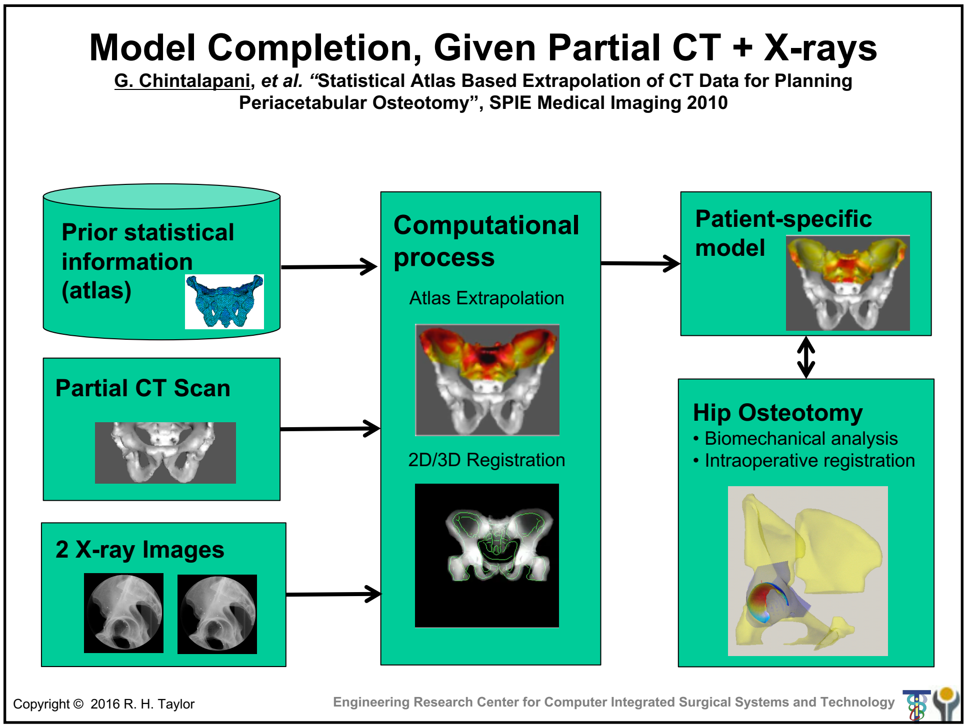
Combining prior knowledge with online images



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
G. Chintalapani, et al. "Statistical Atlas Based Extrapolation of CT Data for Planning Periacetabular Osteotomy", SPIE Medical Imaging 2010
Prior statistical information (atlas)
Partial CT Scan
2 X-ray Images
Computational process
Atlas Extrapolation
2D/3D Registration
Patient-specific model
Hip Osteotomy
• Biomechanical analysis
• Intraoperative registration
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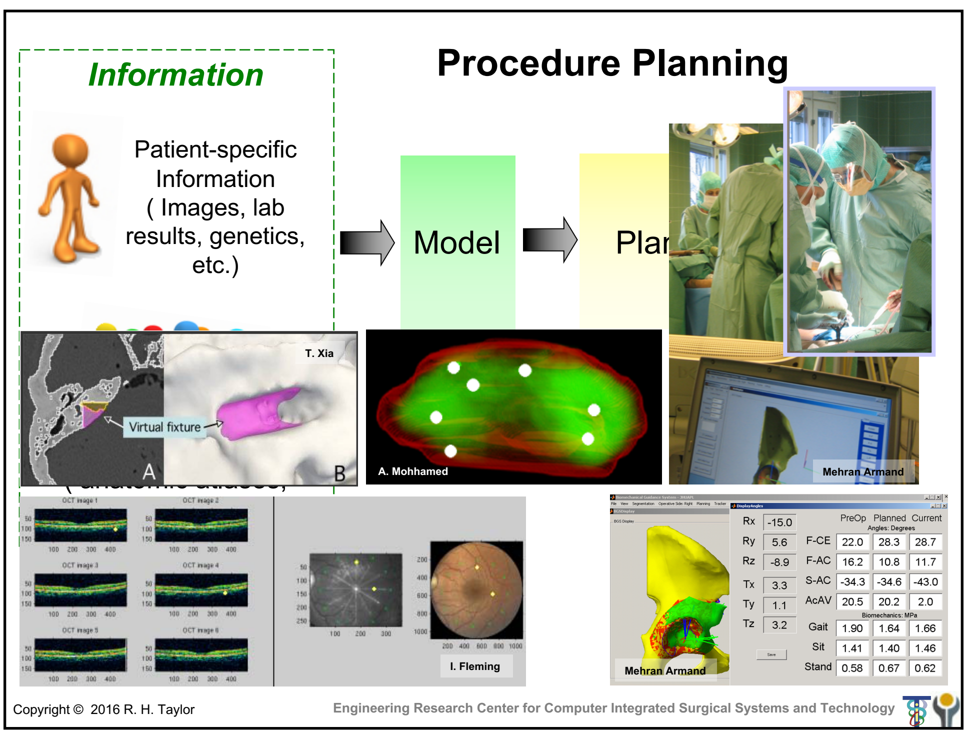

Information
Procedure Planning
Patient-specific Information (Images, lab results, genetics, etc.)
Model
Plan
T. Xia
Virtual fixture
A
B
A. Mohhamed
Mehran Armand
I. Fleming
Mehran Armand
Rx -15.0
Ry 5.6
Rz -8.9
Tx 3.3
Ty 1.1
Tz 3.2
PreOp Planned Current
Angles: Degrees
F-CE 22.0 28.3 28.7
F-AC 16.2 10.8 11.7
S-AC -34.3 -34.6 -43.0
AcAV 20.5 20.2 2.0
Biomechanics: MPa
Gait 1.90 1.64 1.66
Sit 1.41 1.40 1.46
Stand 0.58 0.67 0.62
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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

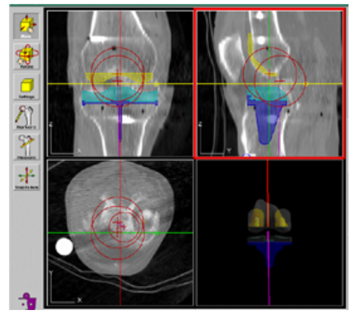
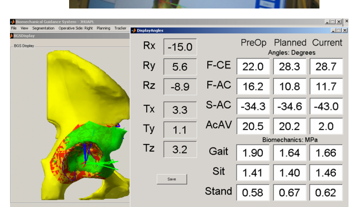


Photo: Integrated Surgical Systems

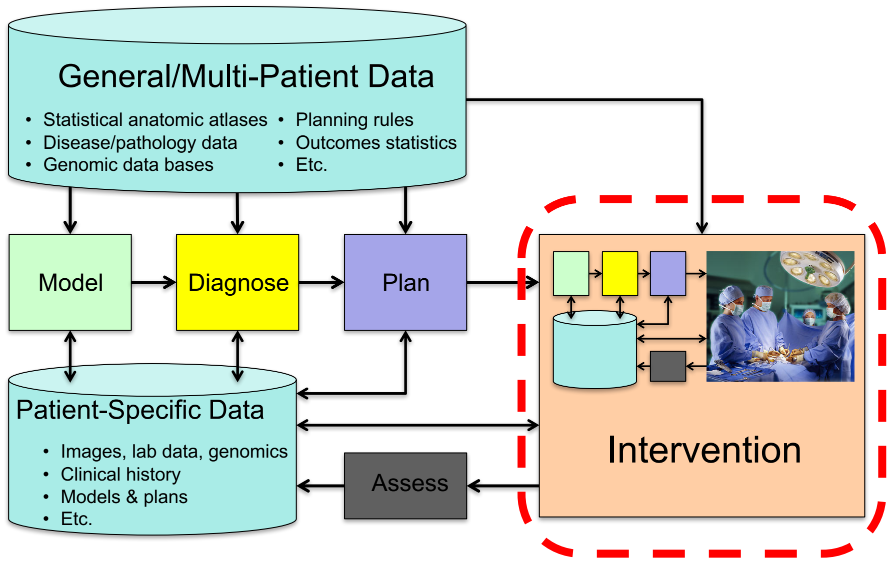
Procedure Planning

- **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

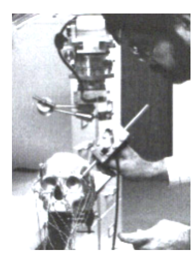
Procedure Execution



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, ...

Procedure Execution

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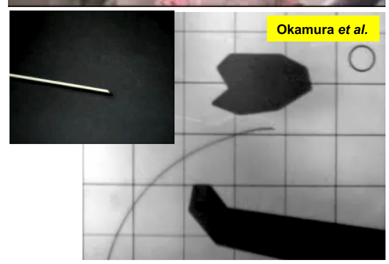

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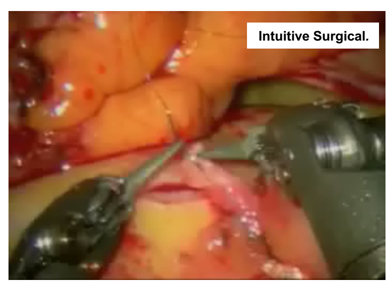

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Taylor, Hager, Handa, Kazanzides, Kang, Iordachita, Gehlbach, *et al.*

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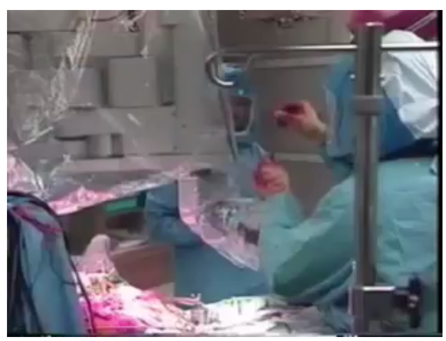

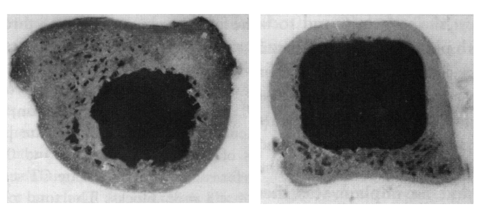

Procedure Execution

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- **But robots can transcend human limitations**
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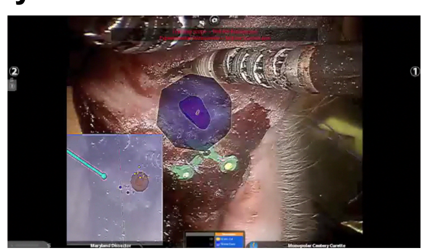
  - more precise,
  - more consistent,
  - and safer

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

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

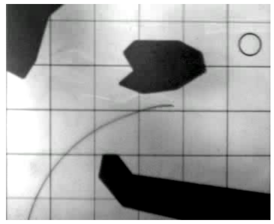


W. Liu, J. Sorger, J. Richmon, R. Taylor, *et al*

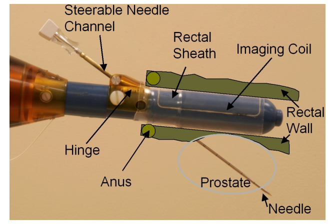
Stoianovici, Taylor, Whictomb, *et al.*

Image-guided needle placement

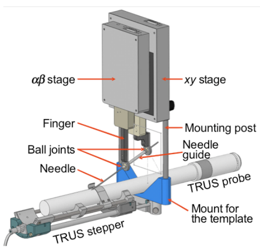
Masamune, Fichtinger, Iordachita, …



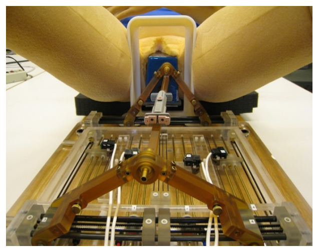
Okamura, Webster, …



Krieger, Fichtinger, Whitcomb, …



Fichtinger, Kazanzides,Burdette, Song …

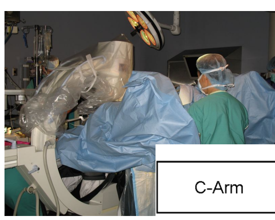


Iordachita, Fischer, Hata…

Taylor, Masamune, Susil, Patriciu, Stoianovici,…

TRUS Robot for Prostate Brachytherapy

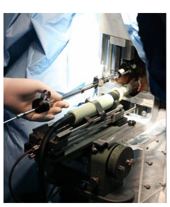
Kazanzides, Iordachita, Burdette, Song, et al. *NSF SECO 1246356*

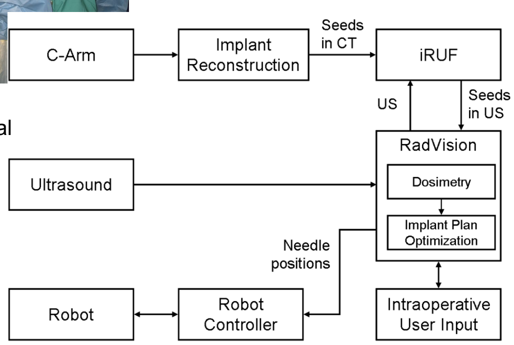


Current efforts:

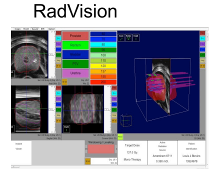
- Integration with RadVision / RUF project
- Needle quick-release mechanism
- Intraoperative user interface (sterile touchscreen)

Robot clinical trial



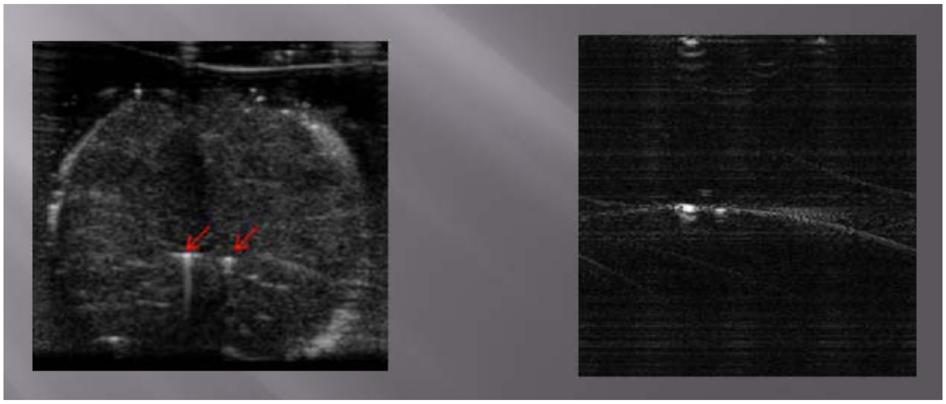


RadVision



Prototype sterile touchscreen: Digital Dash

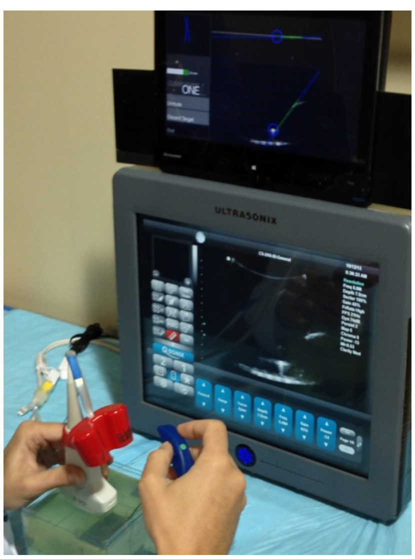
Prostate brachytherapy seed localization using combined photoacoustic and ultrasound imaging
Boctor/Kang/Prince (JHU), Burdette (AMS)



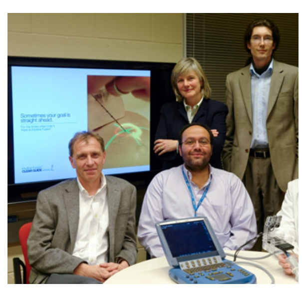
B-mode PA-mode

CLEAR GUIDE MEDICAL

Clear Guide ONE

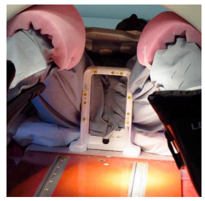


CG1 enables
more doctors to perform
more needle-based procedures
more places,
more effectively and
more quickly.



MRI-guided Surgical Manipulator for Transperineal Prostate Interventions - Clinical Workflow

Patient ready on scanner table

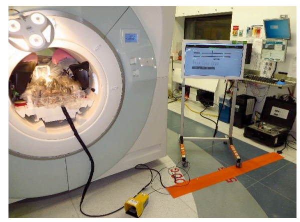


Z-frame in position

Drape robot, attach needle guide

Slide in robot until hit Z-frame

Lock robot in place



Robot ready for targeting

NIH 2R01CA111288: C. Tempany, Iordachita, Fischer, Tokuda, Hata, …

Information-enhanced robotic surgery

augmented
reality displays
imaging

safety barriers
shared control
“virtual fixtures”

SAW

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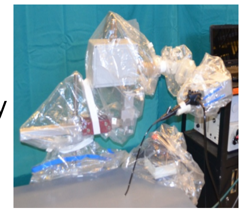
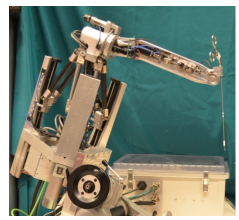
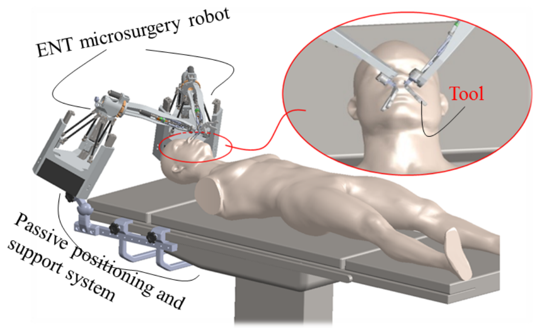
Engineering Research Center for Computer Integrated Surgical Systems and Technology

Robots for Head and Neck Surgery

- **Collaboration with JHU Department of Otolaryngology**
- **Robot to manipulate flexible endoscopes (RoboELF)**
  - Prototype for flexible laryngoscope
  - "No significant risk" from FDA; IRB approved at JHU
- **Steady-hand robot for head and neck surgery (REMS)**
  - Initial targets: laryngeal, sinus, ear, open microsurgery
  - Readily adapted for spine, brain, other microsurgery
  - First prototype constructed





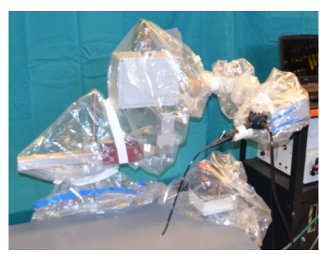


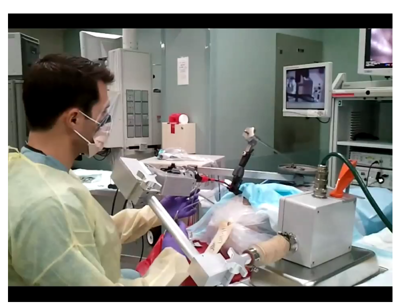
Kevin Olds

A Robotic Assistant for Trans-Oral Surgery: The Robotic Endo-Laryngeal Flexible (Robo-ELF) Scope

K. Olds, A. Hillel, E. Cha, J. Kriss, A. Nair, L. Akst, J. Richmon, R. Taylor

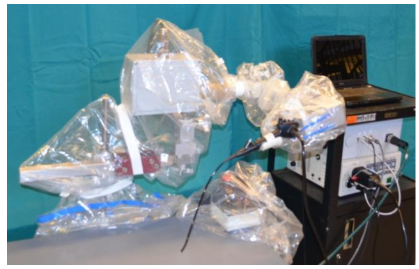
- **Goals**
  - Develop clinically usable robot for manipulating flexible endoscope in throat and airways
  - Permit bimanual surgery
  - Manipulation of ablation catheter
- **Approach**
  - Simple hardware for manipulating unmodified flexible scope
  - Simple joystick control
  - Platform for image guidance
- **Status**
  - "No significant risk" determination from FDA
  - IRB approved clinical trial starting





Robo-ELF Scope Clinical Prototype

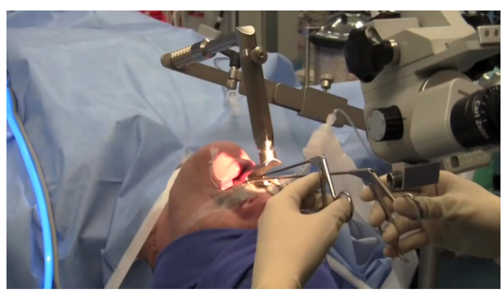
- FMEA
- Extensive documentation
  - User manual etc.
- New scope holder and draping system
- FDA approved as NSR
- JHU Clinical engineering approval
- JHU IRB approval
- Clinical study starting this summer

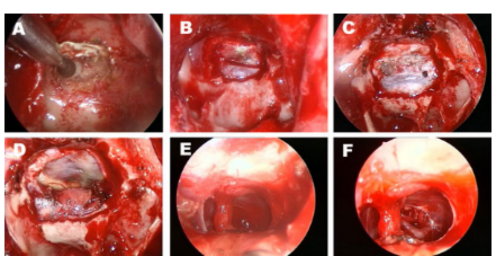


Kevin Olds, Russ Taylor, Jeremy Richmon, *et al.*

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

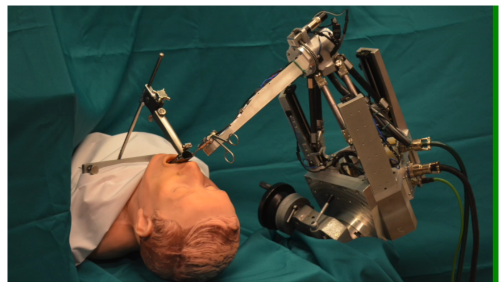




The Robotic ENT Microsurgery System (REMS)

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

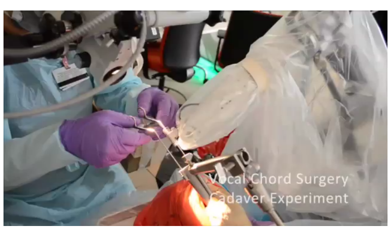
Technical specs:
- Up to 0.025 mm precision on-demand
- 6 degrees of freedom
- 125x125x125mm work volume
- Calibrated accuracy ~50-150µm



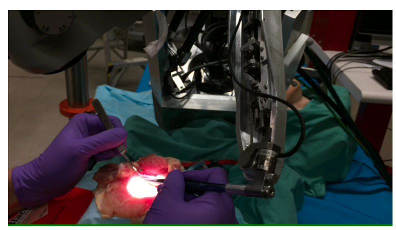
Control modes:
- Free hand
- Remote center of motion
- Virtual fixture avoidance
- Teleoperation

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

REMS Typical Applications



Laryngeal / Vocal Cord



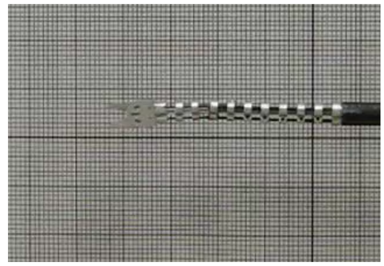
Open Microsurgery

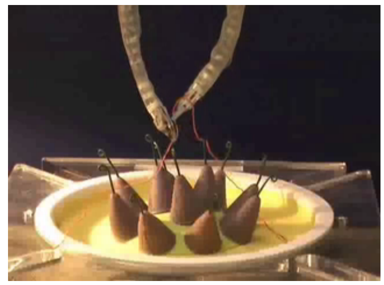
Image-guided sinus surgery with virtual fixtures

Other applications include:
- Otology
  - Stapes surgery
  - Mastoidectomy
  - Cochlear implant
- Craniotomy
- Spine
- Hand
- …

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**
  - Evaluation of prototype ongoing
  - Licensed to industry partner
- **Funding**
  - NIH R21, CISST ERC, JHU, Columbia
  - NIH proposals pending

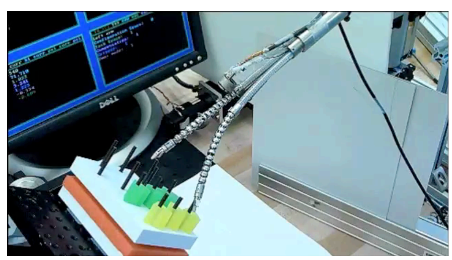


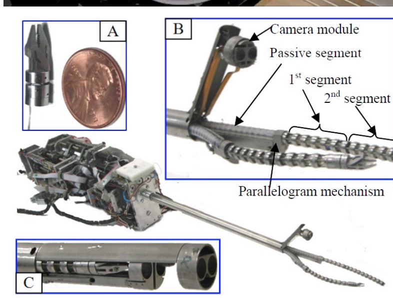


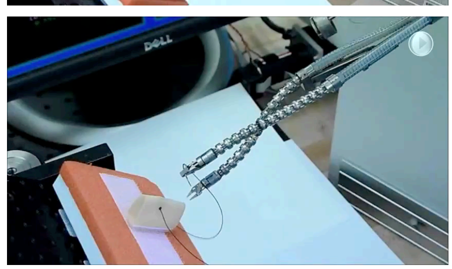
R. Taylor, N. Simaan, *et al.*

Single Port Access Surgery

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

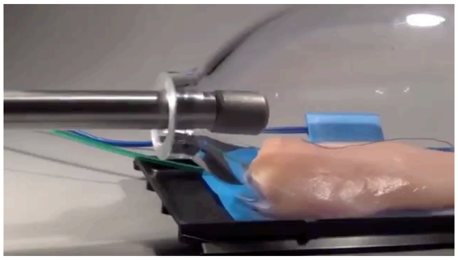






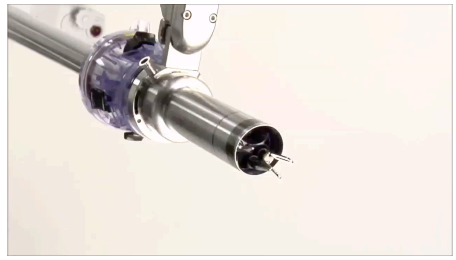
New technology finally allows true evaluation of the potential of single port access surgery. Systems raise new questions about control and telemanipulation infrastructure/cooperative control.

Single Port Access Robotic Surgery



Titan Medical Sport

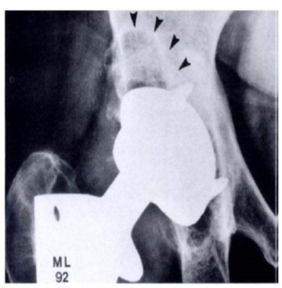
https://www.youtube.com/watch?v=jIvjvcKA6xQ

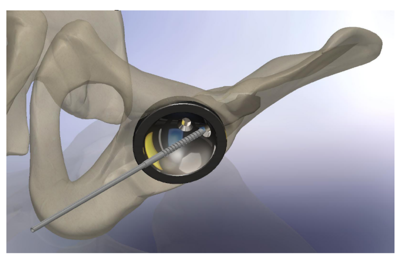


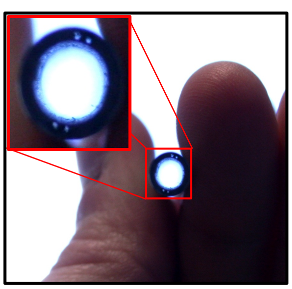
Intuitive Surgical Sp

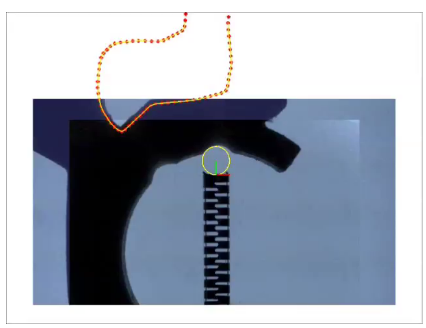
https://www.youtube.com/watch?v=-jm63JdTrp4

APL Minimally-Invasive Osteolysis Curettage



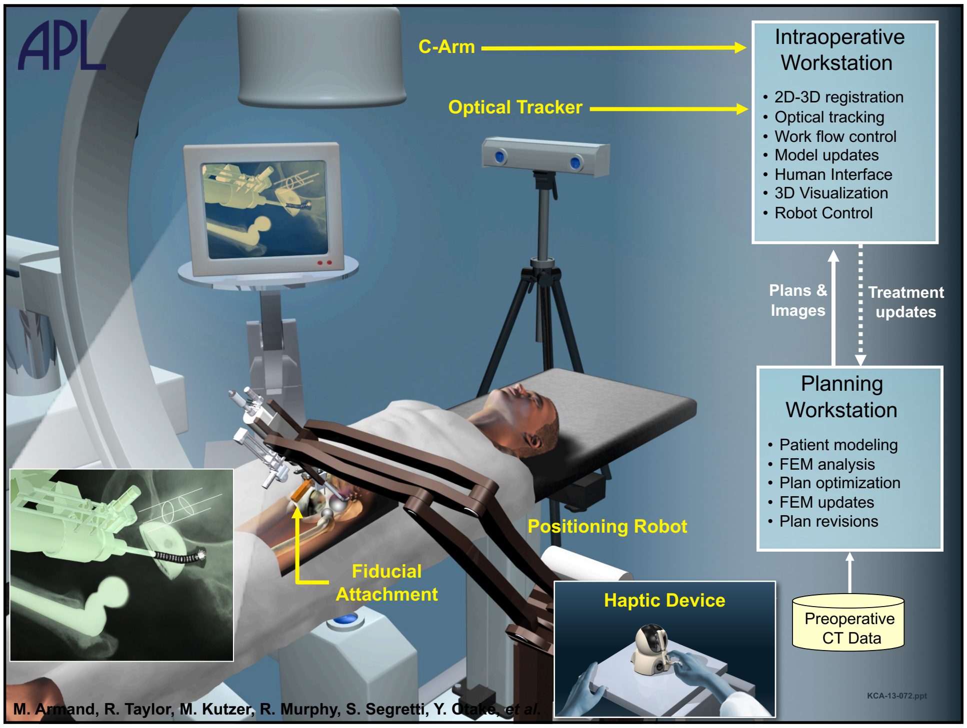






M. Armand, R. Taylor, M. Kutzer, R. Murphy, S. Segretti,, *et al.*

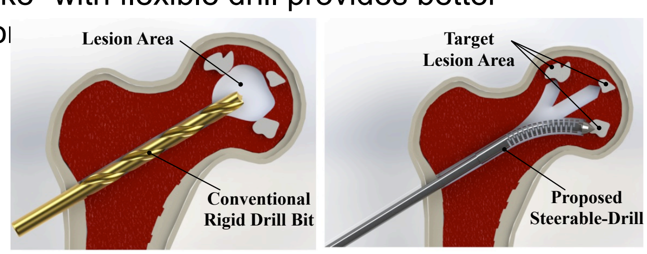
Engineering Research Center for Computer Integrated Surgical Systems and Technology



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 o



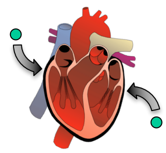
Farshid Alambeigi, Yu Wang, Shahriar Sefati, Ryan. J. Murphy, Iulian Iordachita, Russell H. Taylor, Harpal Khanuja, and Mehran Armand, "Curved-Drilling Approach in Core Decompression of the Femoral Head Osteonecrosis Using a Continuum Manipulator", *Proc. ICRA 2017*

Foreign Bodies in the Heart

Causes

Thrombi, Shrapnel

Iatrogenic



Symptoms

Cardiac Tamponade

Hemorrhage

Arrhythmia

Infection

Shock

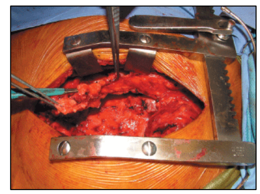
Embolism

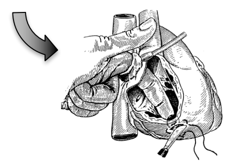
Valve Dysfunction

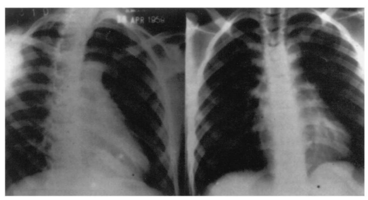
Conventional Treatment

Median Sternotomy

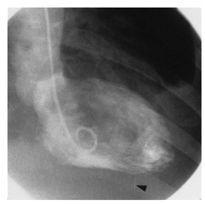
Cardiopulmonary Bypass







(Actis Dato, 2003)

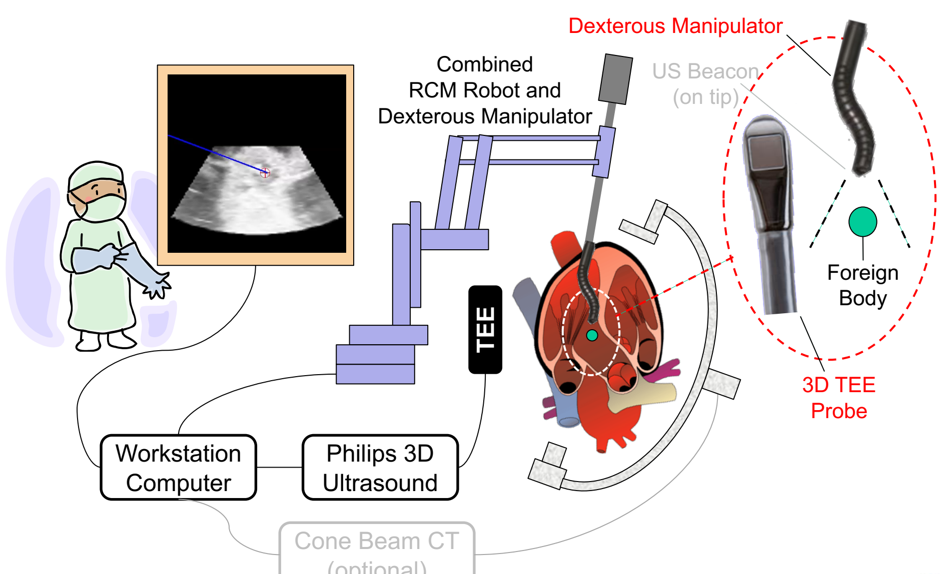


(LeMaire, 1999)

 PHILIPS Engineering Research Center for Computer Integrated Surgical Systems and Technology

Beating Heart MIS with 3D US Guidance

Paul Thienphrapa, Aleksandra Popovic, Russell Taylor



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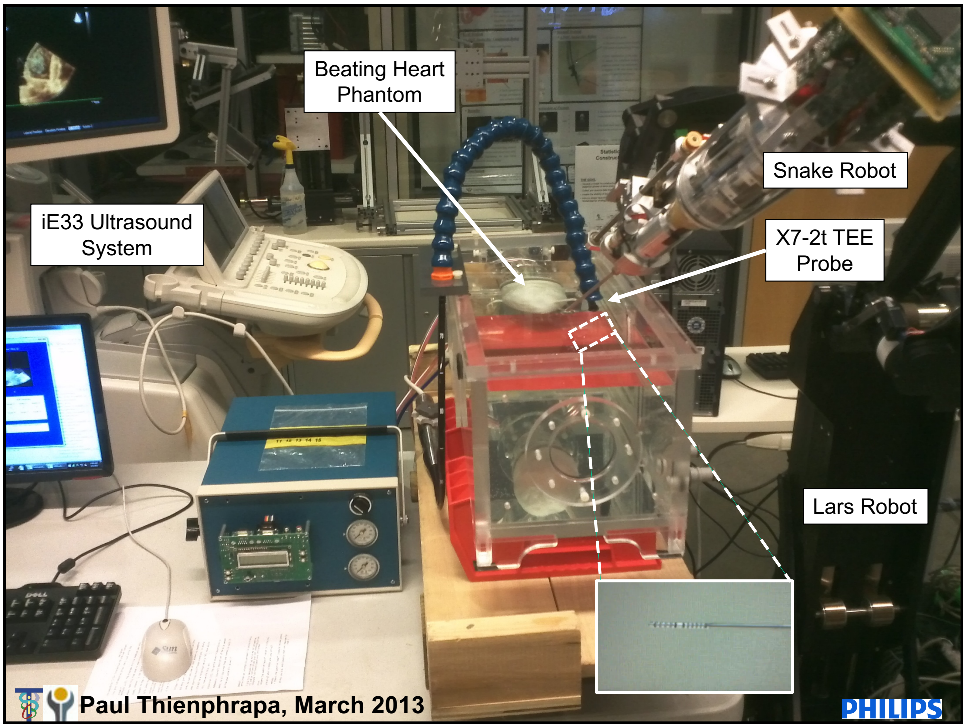
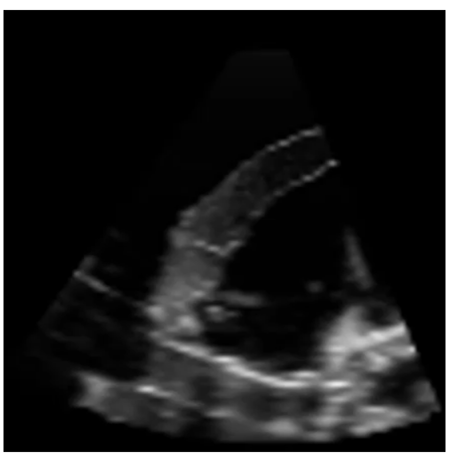
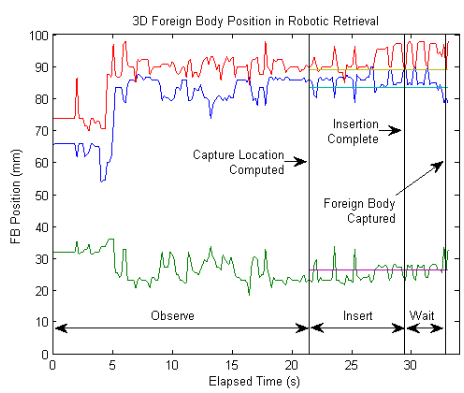


Retrieval Experiment Results





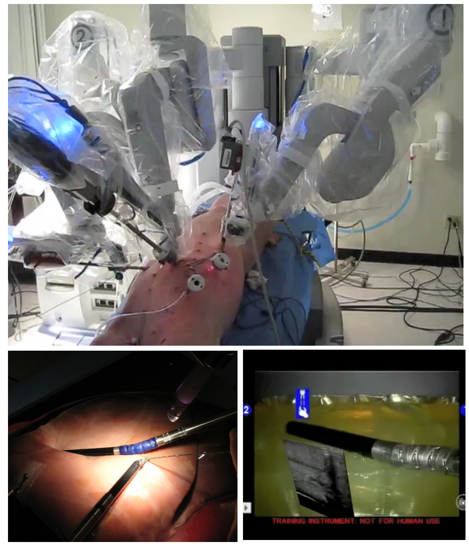
PHILIPS

Thienphrapa *et al.* 2013

Robotically Assisted Laparoscopic Ultrasound

C. Schneider, P. Peng, R. Taylor, G. Dachs, C. Hasser, S. Dimaio, and M. Choti, "Robot-assisted laparoscopic ultrasonography for hepatic surgery", *Surgery*, Oct 5. (Epub), 2011.

- 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



Research DaVinci Application – Not for Human Use

Ultrasound Elastography with DaVinci

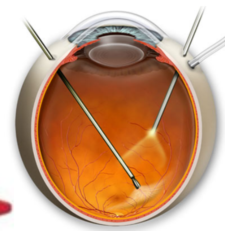
(Boctor, Billings, Taylor)

Human-robotic collaboration for in-vivo detection of tumors and monitoring of therapy

(Research DaVinci Application – Not for Human Use)

Vitreoretinal Microsurgery

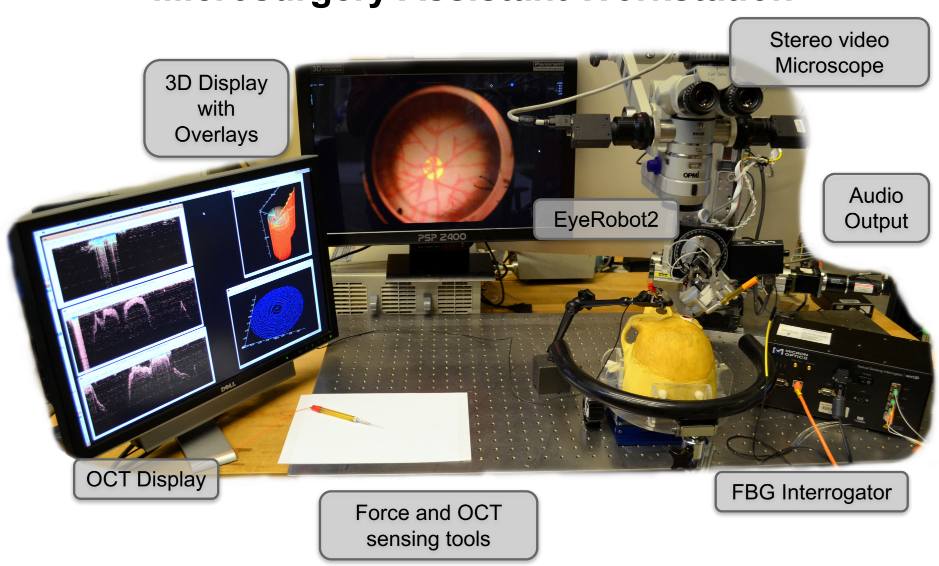
British Journal of Ophthalmology 2004 - Akifumi Ueno et al



www.eyemdlink.com

Alcon Vitreosurgery Instrument

Microsurgery Assistant Workstation



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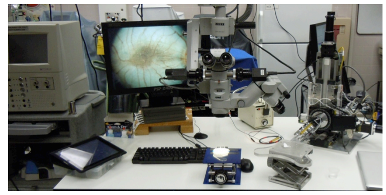
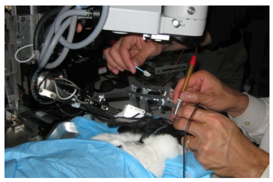
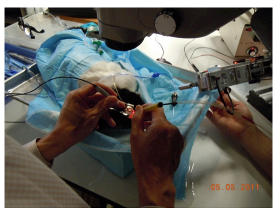
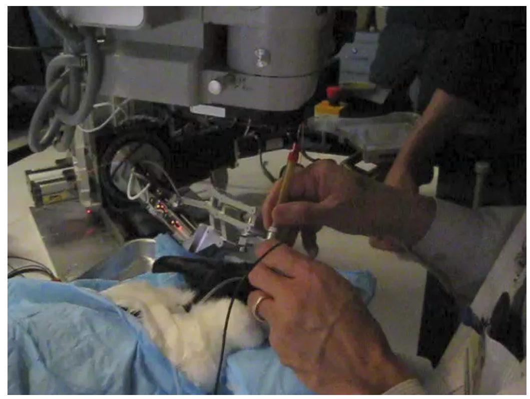
In-Vivo Experiments

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

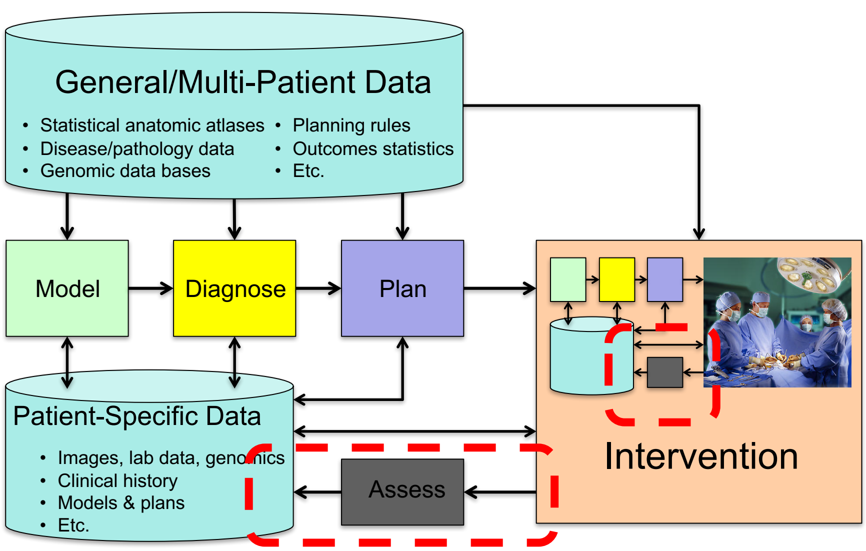




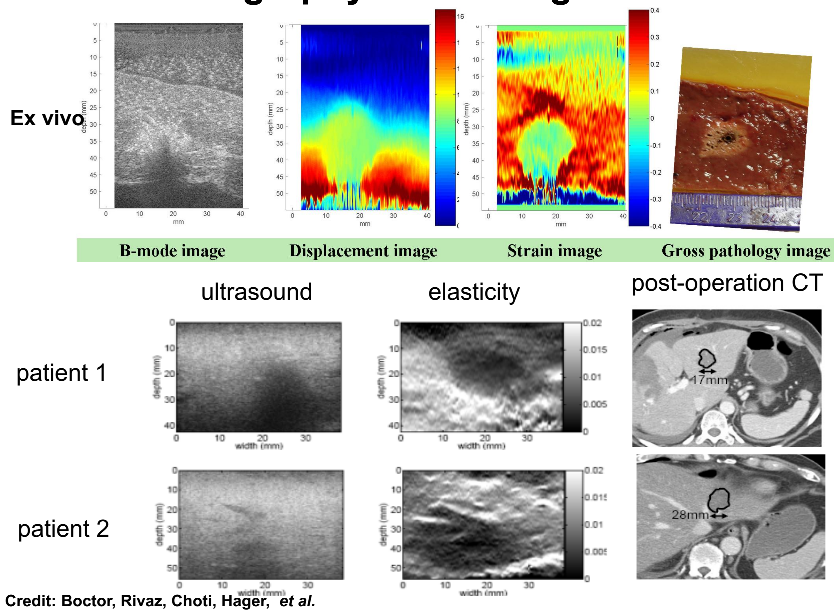




Patient-specific assessment and feedback

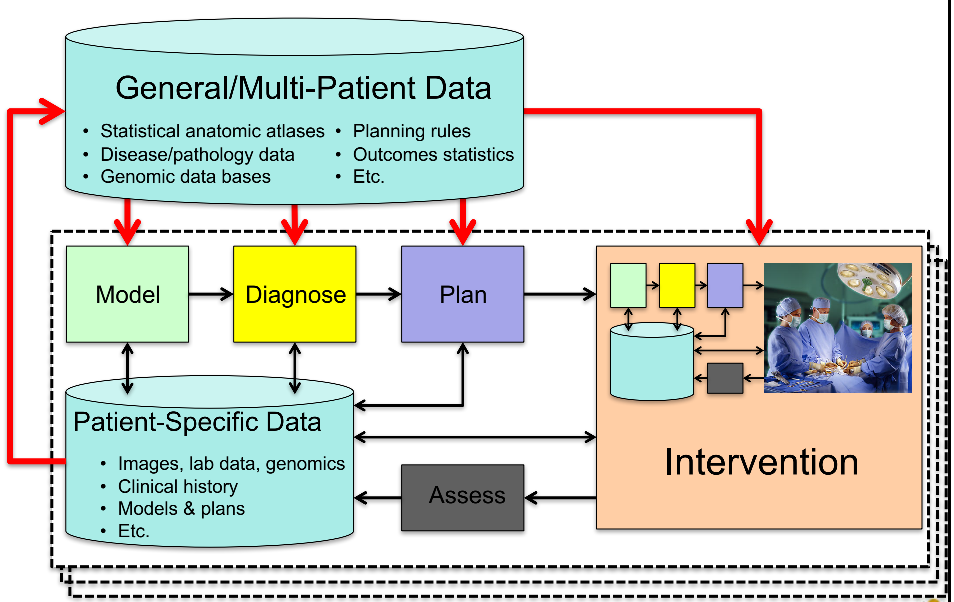


Elastography monitoring of ablations



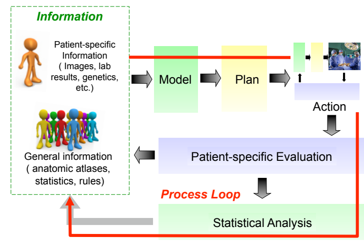
Credit: Boctor, Rivaz, Choti, Hager, *et al.*

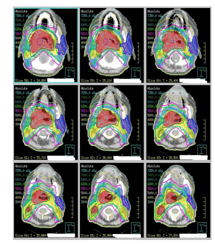
Statistical Analysis and Decision Support



Information-Integrated Process Learning

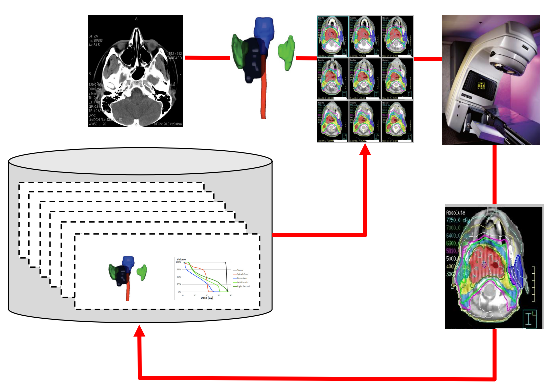
- **Key idea**
  - Medical robots and CAI systems inherently generate data and promote consistency
  - Eventually, outcomes are known
  - Combine this information over many patients to improve treatment plans / processes
- **Issues / Themes**
  - Very large data bases combining heterogeneous data
  -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





Credit: Todd McNutt

Statistical process control for radiation therapy



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

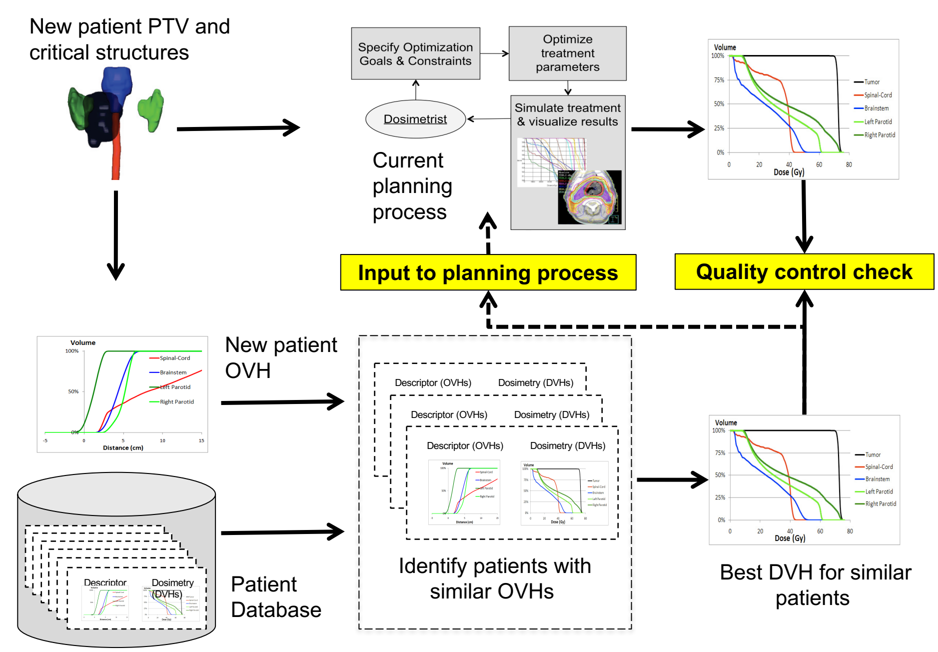
Team:

CS: R. Taylor, M. Kazhdan, P. Simari, A. King

BME: R. Jacques

Rad. Oncology: T. McNutt, J. Wong, B. Wu, G. Sanguinetti (MD)

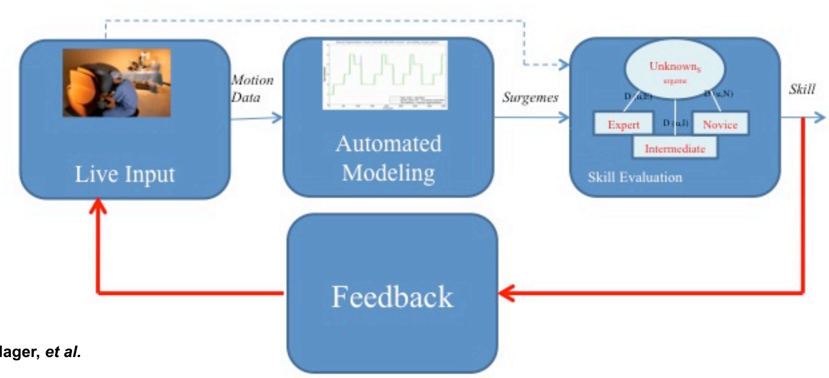
Support: Paul Maritz, Philips, JHU internal funds



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

Applications Of Surgical Motion Models

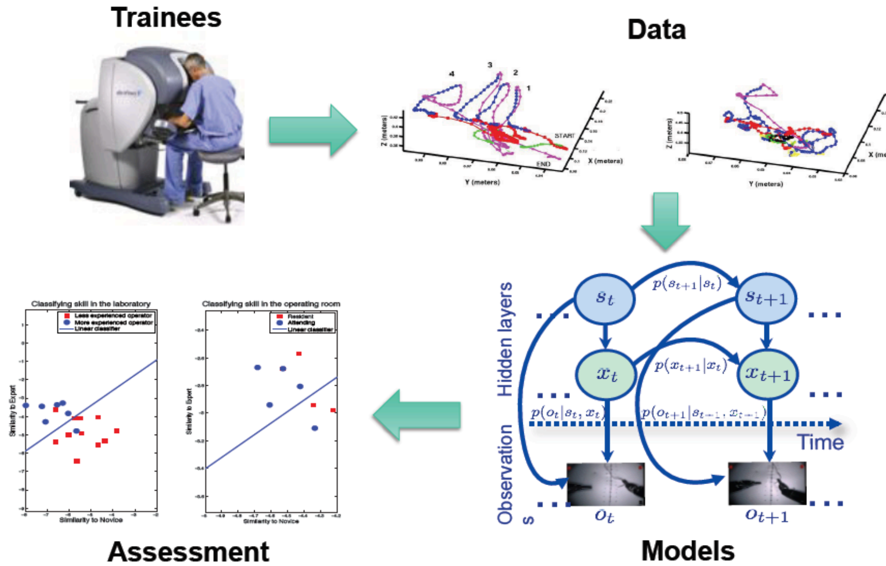
Underlying hypothesis: Learned motion models of experts can be used for teaching, training, and automation of surgical actions.



G. Hager, *et al.*

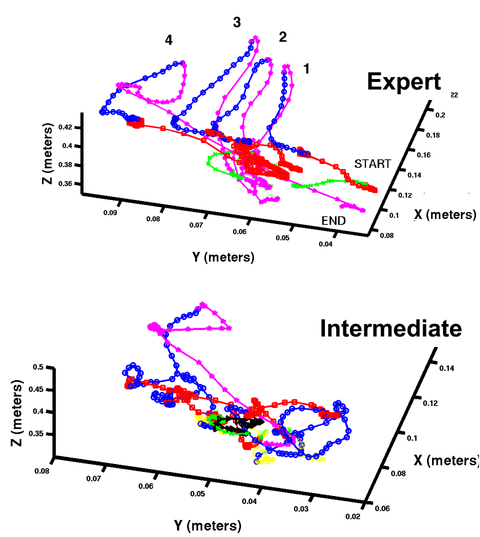
The Language of Surgery

Hager, Khudanpur, Vidal + Chen, Lee, Ishii



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

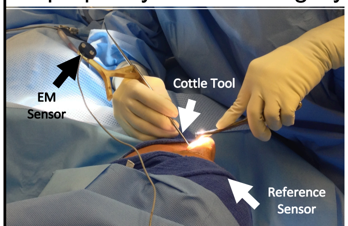
- Goals:
  - Automatic recognition of different surgical motions
  - Comparison of skill level differences between surgeons
- Method
  - Extract features from position and velocity traces
  - Linear discriminant analysis with probabilistic Bayesian classifier

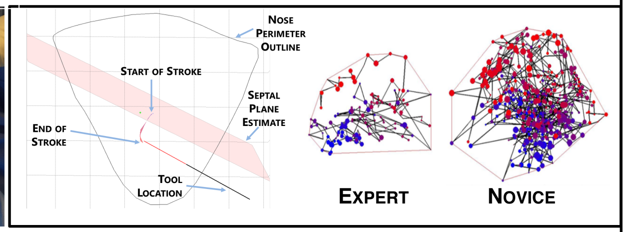


H. Lin, I. Shafran, T. Murphy, D. Yuh, A. Okamura, G. Hager (MICCAI 2005)

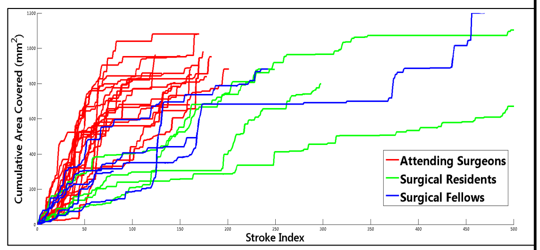
Unstructured surgeries: Discovering "teachable" tactics

Septoplasty: "index" surgery





Automatic Segmentation of Strokes in Nasal Septoplasty

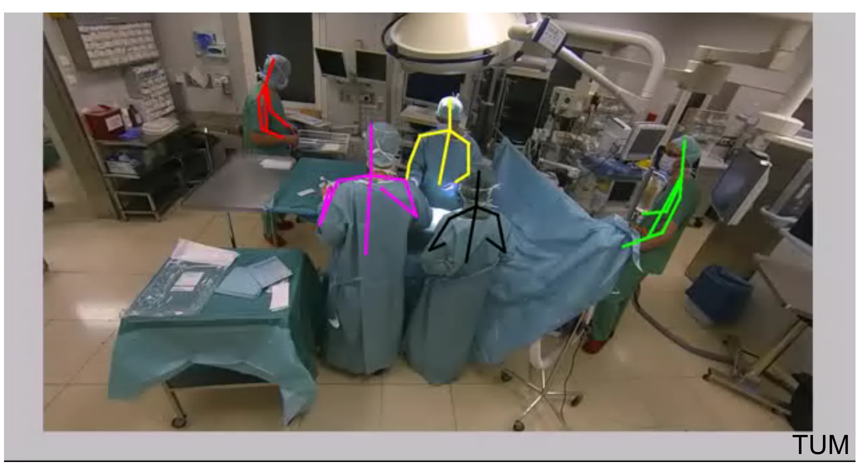


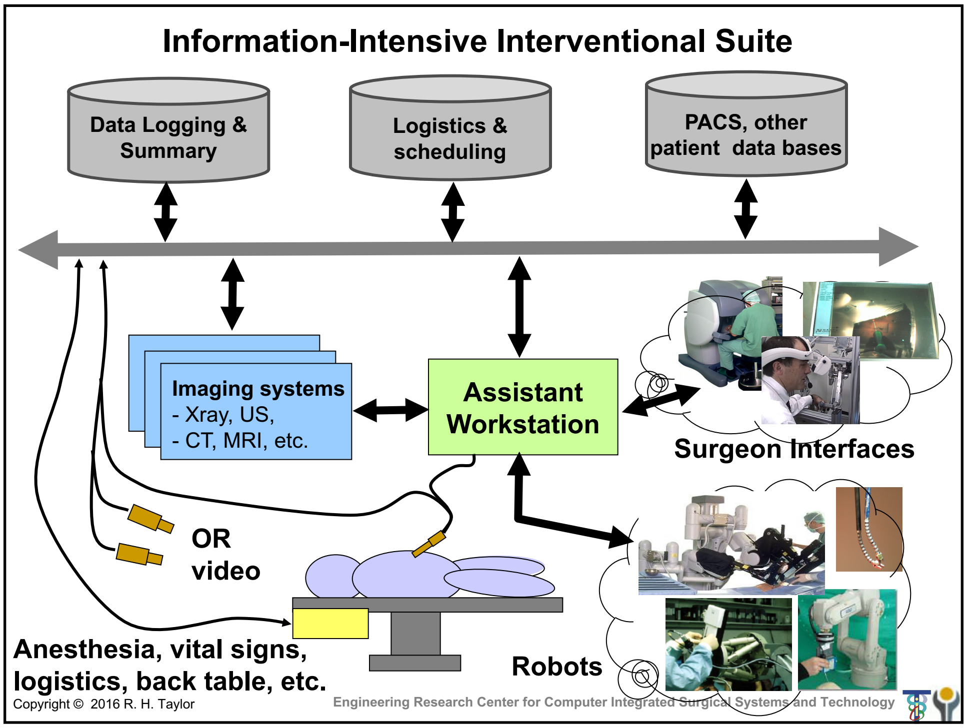
Feedback: Stroke Curvature Consistency: Draw similar-shape curves (instead of straight lines) sequentially
Stroke Duration Consistency: Spend the same amount of time drawing the curves
Coverage Rate: Practice strong enough brushing motions to elevate mucosa

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
Data Logging & Summary
Logistics & scheduling
PACS, other patient data bases
Imaging systems
- Xray, US,
- CT, MRI, etc.
Assistant Workstation
Surgeon Interfaces
OR video
Robots
Anesthesia, vital signs, logistics, back table, etc.
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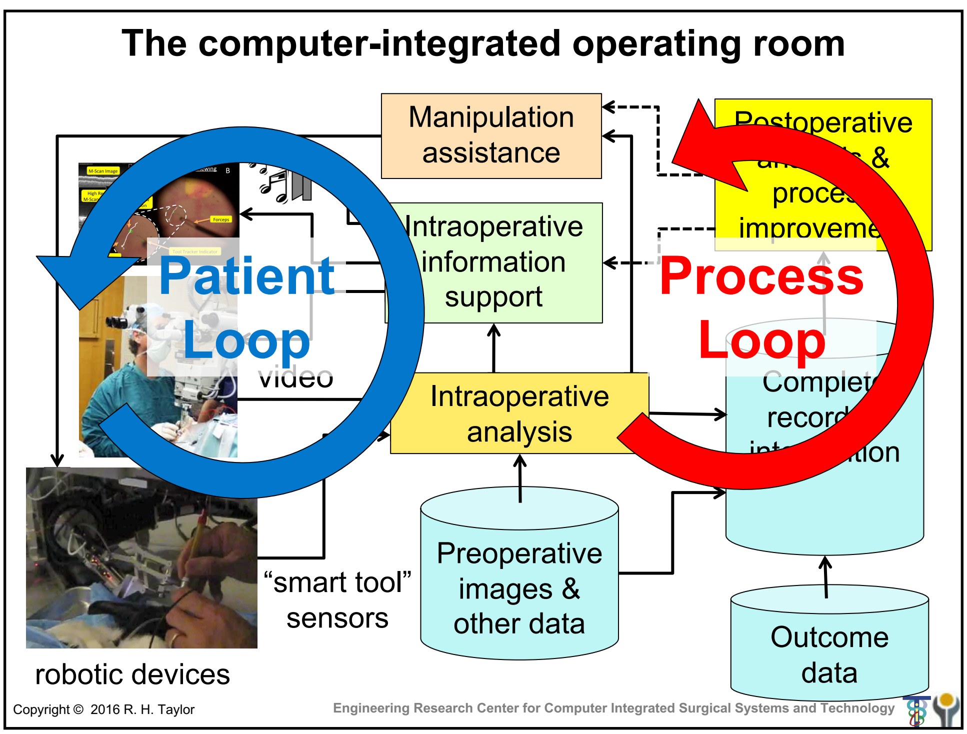
The computer-integrated operating room
Manipulation assistance
Postoperative
Intraoperative information support
Patient Loop
Process Loop
video
Intraoperative analysis
Preoperative images & other data
"smart tool" sensors
robotic devices
Outcome data
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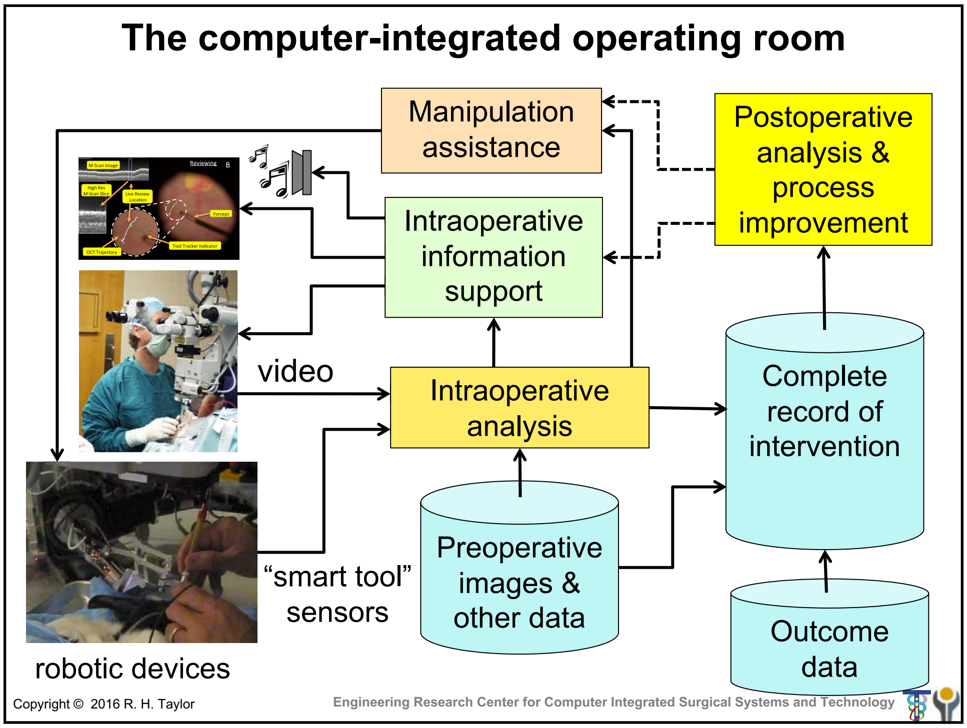
The computer-integrated operating room
Manipulation assistance
Postoperative analysis & process improvement
Intraoperative information support
video
Intraoperative analysis
Complete record of intervention
"smart tool" sensors
Preoperative images & other data
Outcome data
robotic devices
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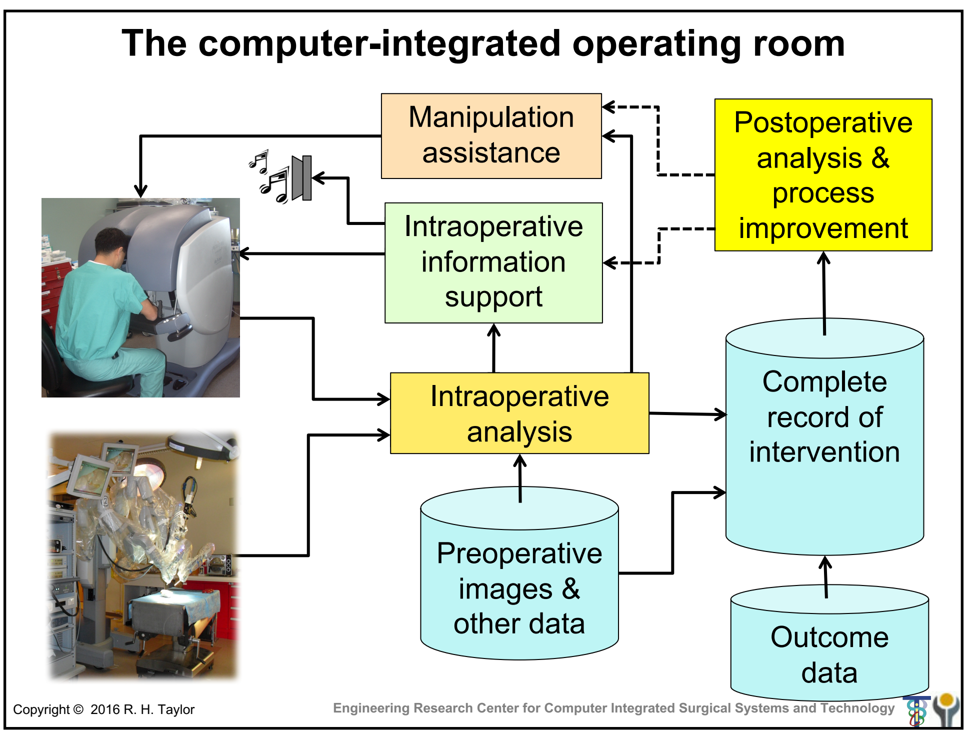
The computer-integrated operating room
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Intraoperative analysis
Complete record of intervention
Preoperative images & other data
Outcome data
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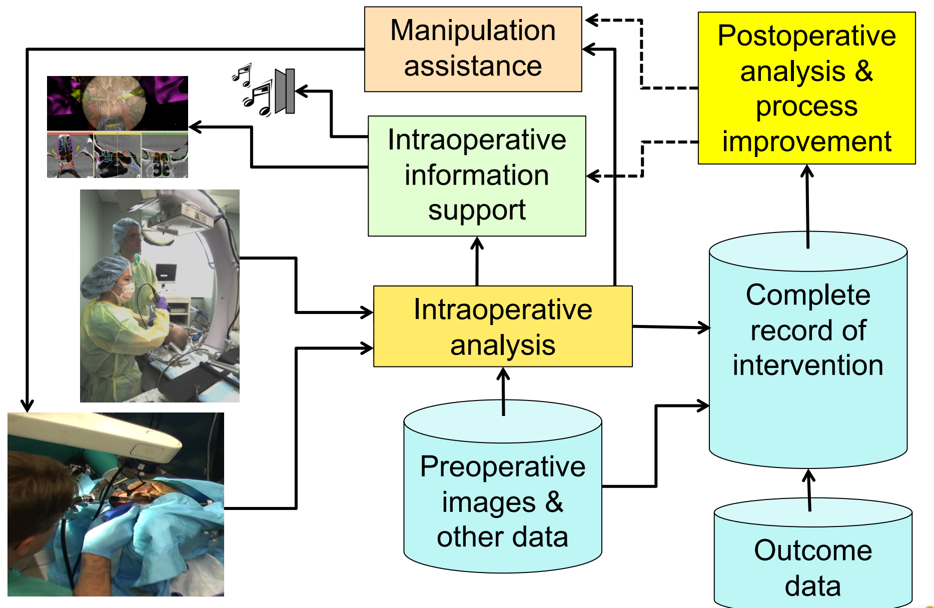
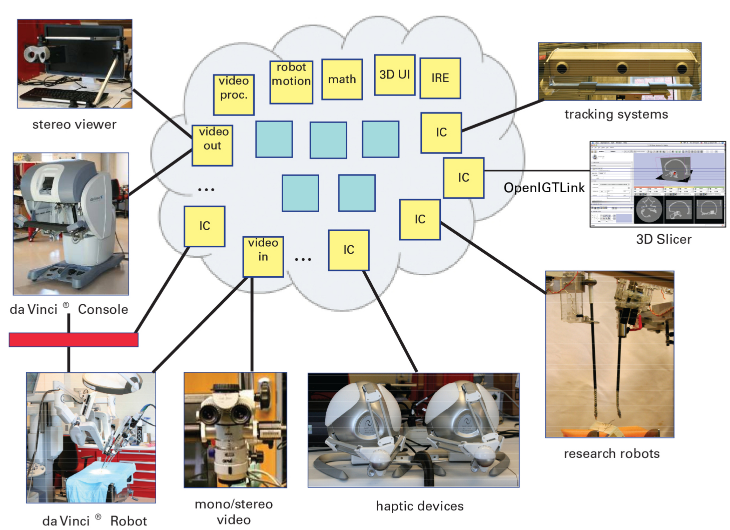
The computer-integrated operating room



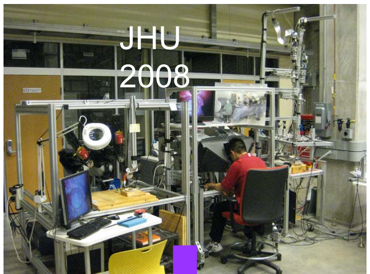
cisst libraries and Surgical Assistant Workstation

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

Discussion