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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Acknowledgments

- **This is the work of many people**
- 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.
- 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 Intuitive Surgical, Varian Medical Systems, Philips Nuclear Medicine, Virtuoso Technologies, Galen Robotics and other corporate entities. Prof. Taylor and the University are entitled to royalty distributions related to this technology, and Dr. Taylor has received or may receive some portion of these royalties. Also, Dr. Taylor is a paid consultant to and owns equity in Galen Robotics, Inc. These arrangements have been reviewed and approved by JHU in accordance with its conflict of interest policy.
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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**
- **Disclosures:** 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 Intuitive Surgical, Varian Medical Systems, Philips Nuclear Medicine, Virtuoso Technologies, Galen Robotics and other corporate entities. Prof. Taylor and the University are entitled to royalty distributions related to this technology, and Dr. Taylor has received or may receive some portion of these royalties. Also, Dr. Taylor is a paid consultant to and owns equity in Galen Robotics, Inc. These arrangements have been reviewed and approved by JHU in accordance with its conflict of interest policy

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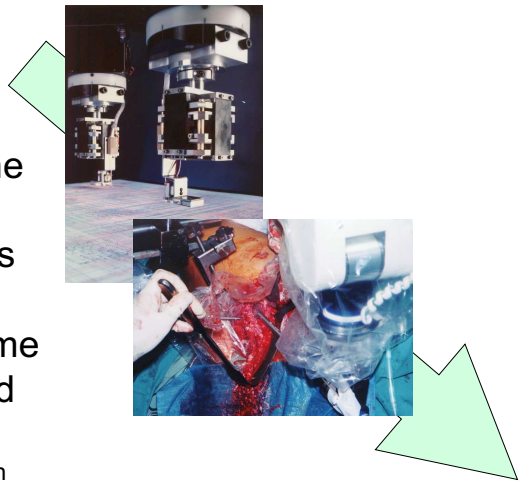
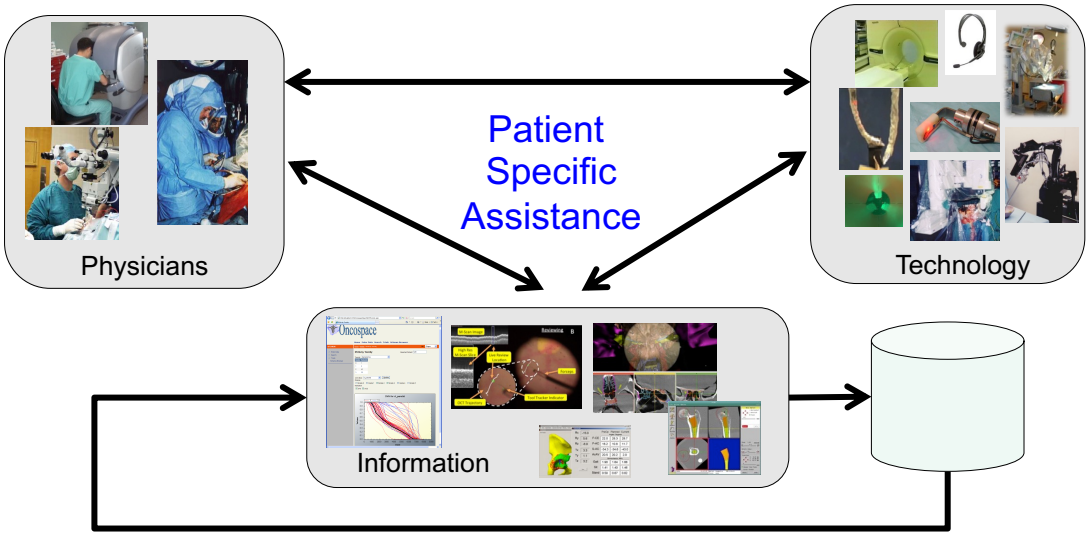
Motivating Insight

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



4

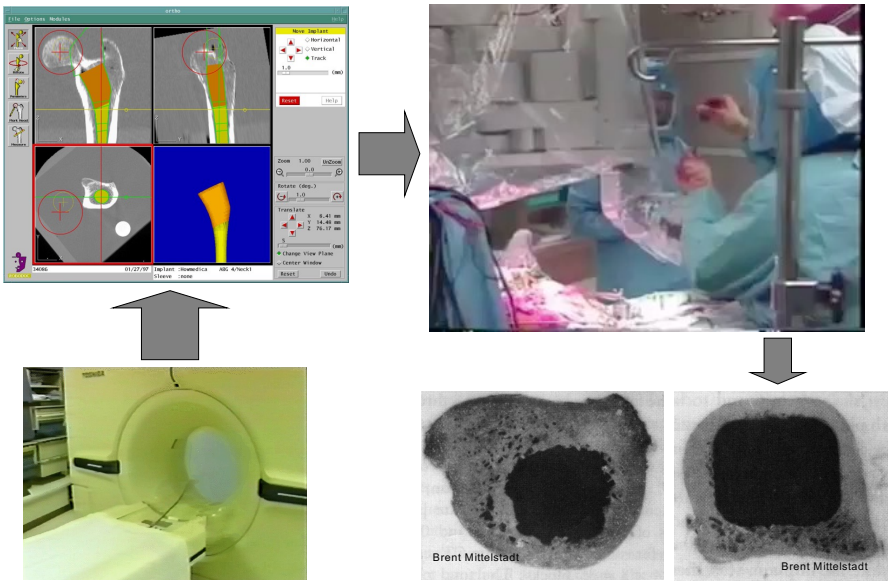
Human-machine partnership to fundamentally improve interventional medicine



Statistical Process Improvement

5

Over 30 years ago: Robotic Joint Replacement Surgery



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

Manual Surgery

Robotic Surgery

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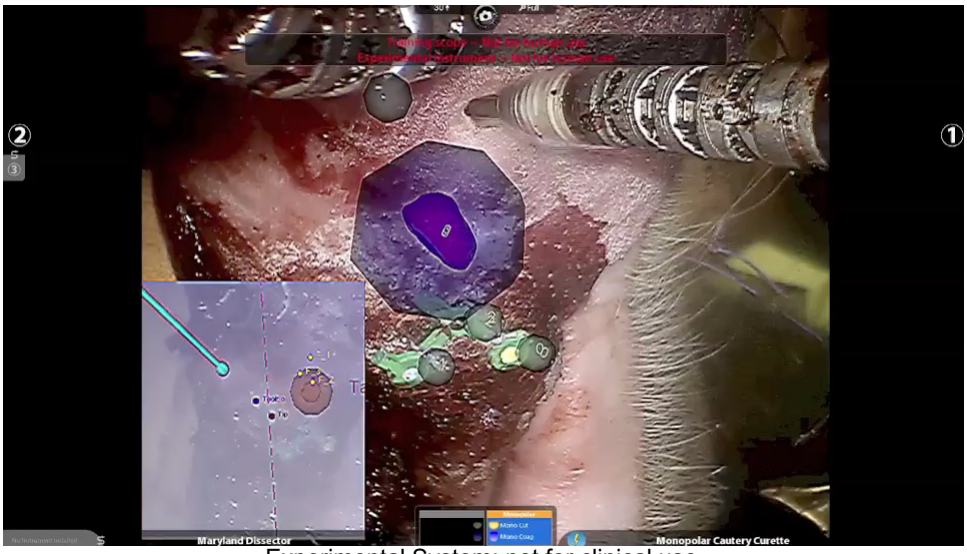
Emerging: Information-Augmented Robotic Surgery

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



Experimental System: not for clinical use

7

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” *2018 AE-CAI MICCAI workshop*.

* Joint first authors

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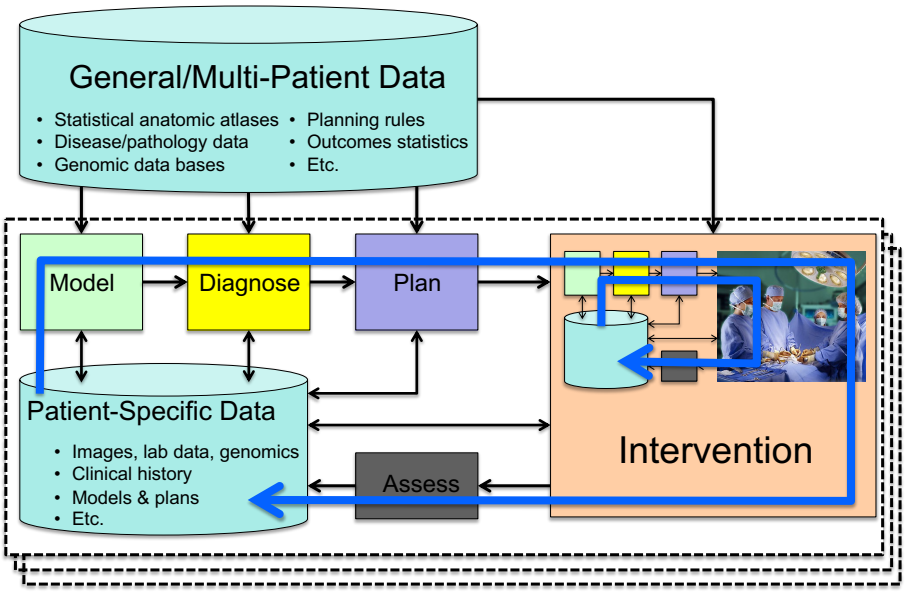
Computer-Integrated Interventional Medicine



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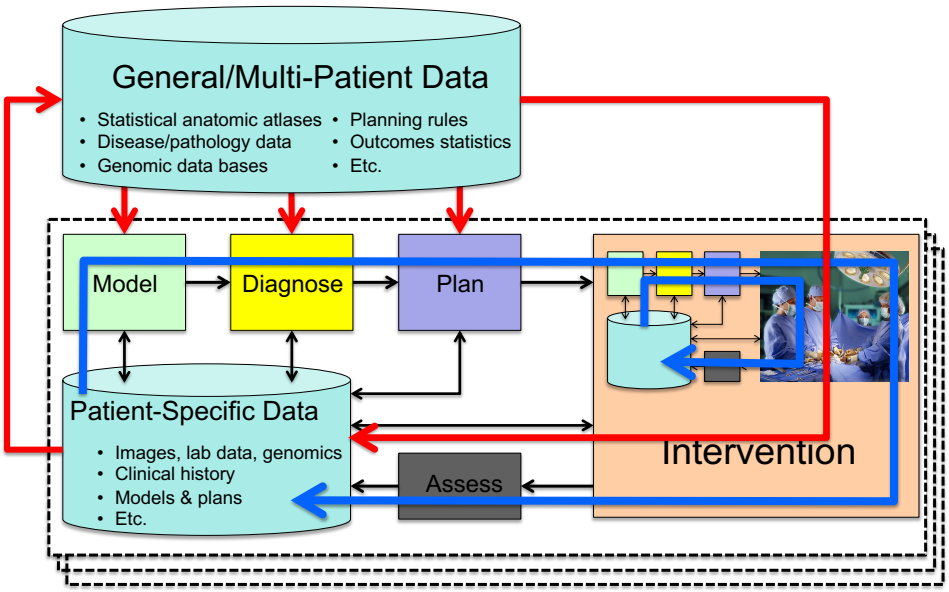
Computer-Integrated Interventional Medicine



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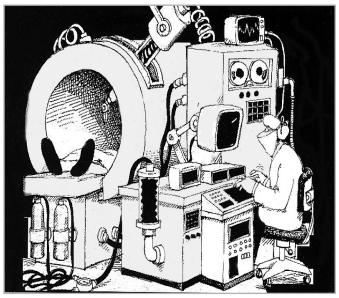
This Paradigm has not changed since Imhotep's day

27th Century BCE

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



21st Century CE

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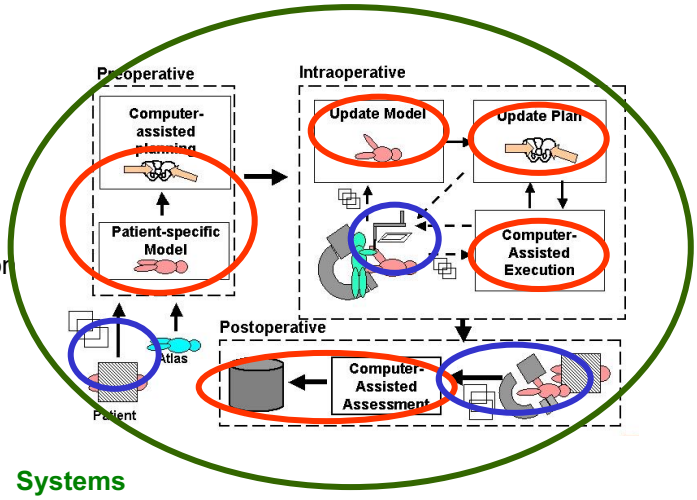
Multidisciplinary Integration is Crucial

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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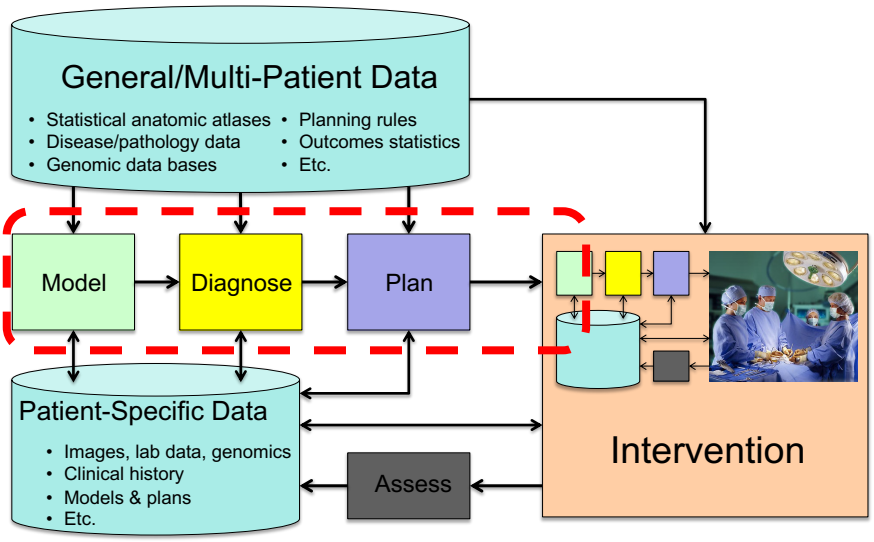
Image-based modeling & analysis



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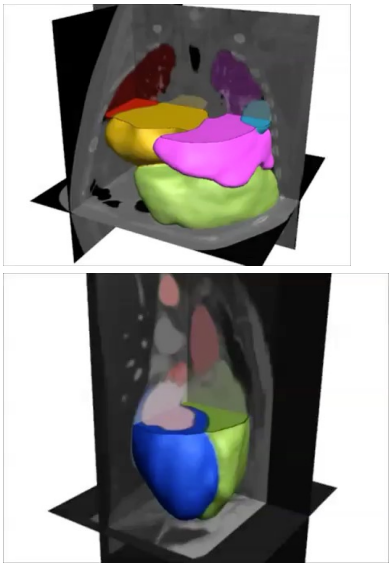
Patient-Specific Models for Interventions

- 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
- 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

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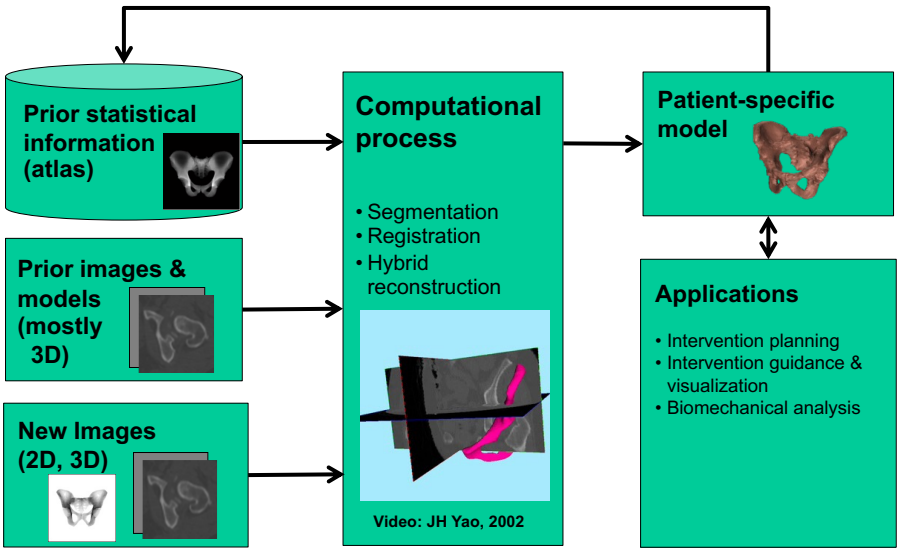
Combining prior knowledge with online images



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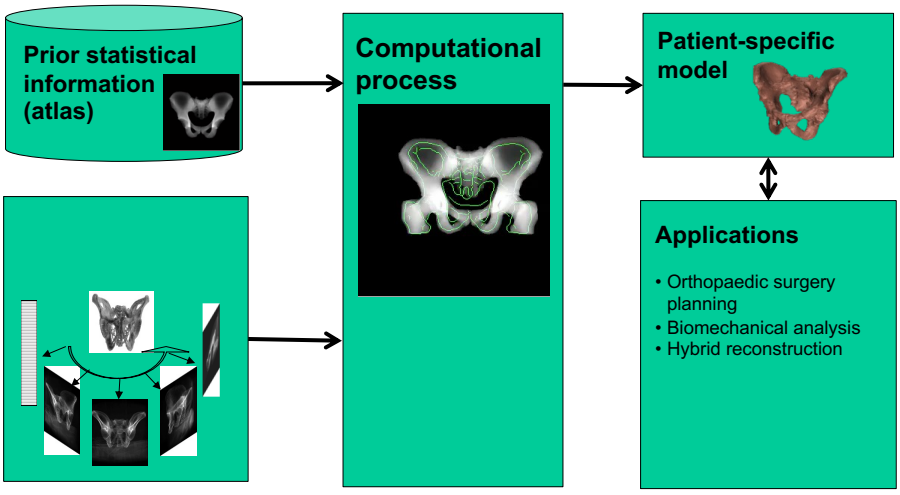
Deformable 2D/3D Registration to Statistical Atlas



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

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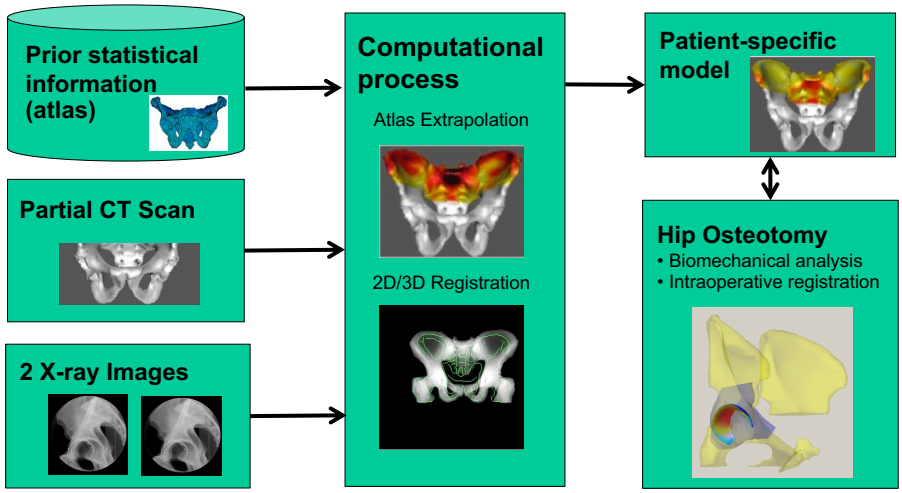
Model Completion, Given Partial CT + X-rays

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



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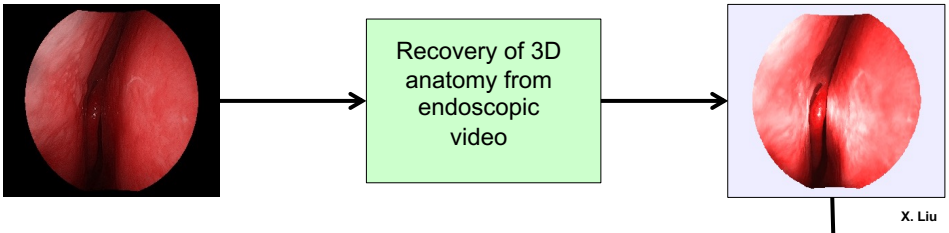
A "smart" sinus endoscopy assistant



- Dense point cloud recovery from untracked monocular endoscope video
- Registration to preoperative CT or statistical model
- Intraoperative navigation and surgical assistance

R. Taylor, A. Sinha, S. Leonard, X. Liu, G, Hager, M. Ishii, *et al.*

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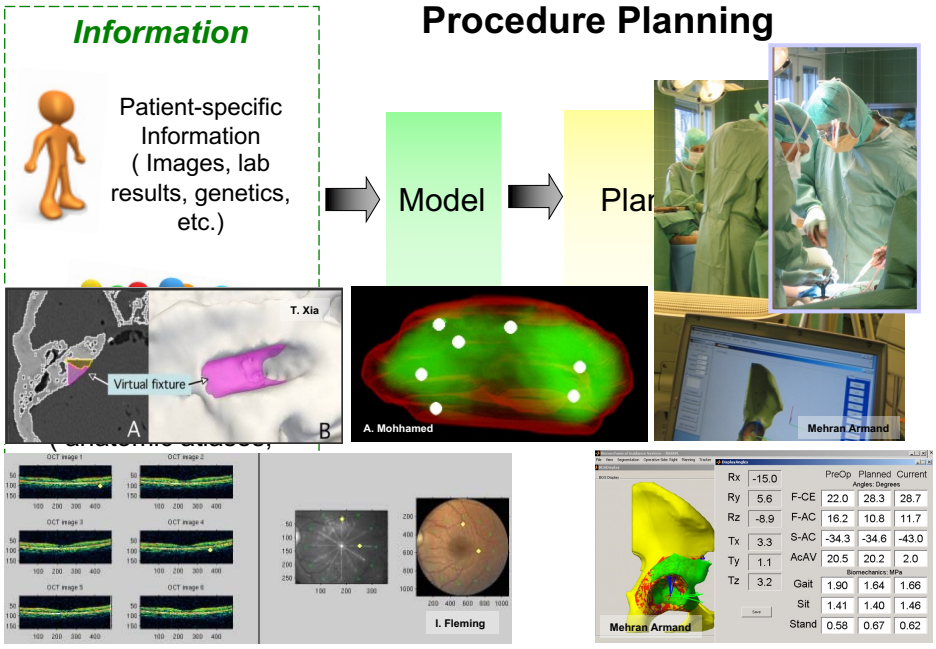
Procedure Planning



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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

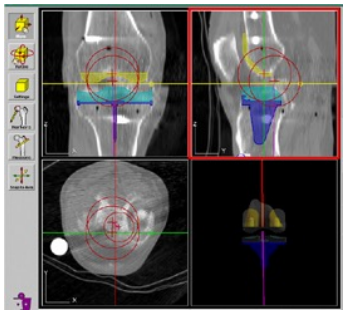

Photo: Integrated Surgical Systems

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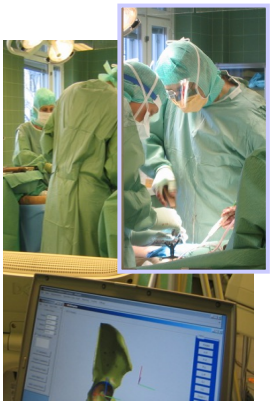
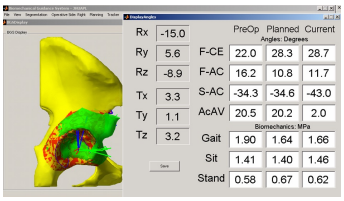
Procedure Planning

- **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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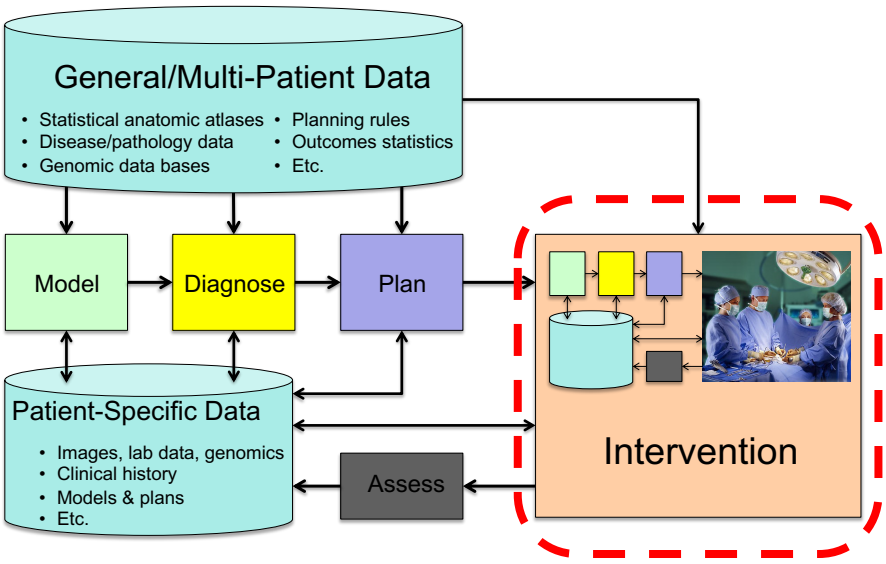
Procedure Execution

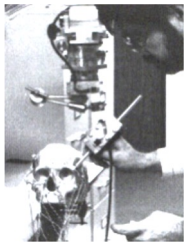


30

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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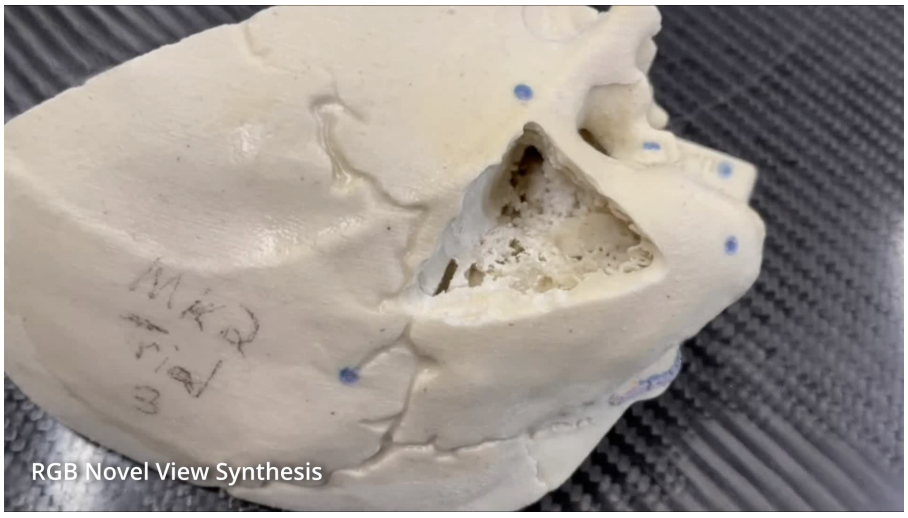
Video-based reconstruction and overlay in skull base surgery



Zhaoshuo Li, Thomas Müller, Alex Evans, Russell H Taylor, Mathias Unberath, Ming-Yu Liu, Chen-Hsuan Lin, "Neuralangelo: High-Fidelity Neural Surface Reconstruction", *CVPR 2023*

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Procedure Execution

- Highly procedure-specific
- Don't always have a robot
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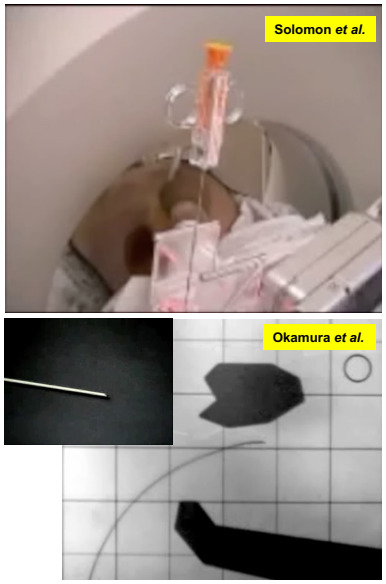

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Procedure Execution

- Highly procedure-specific
- Don't always have a robot
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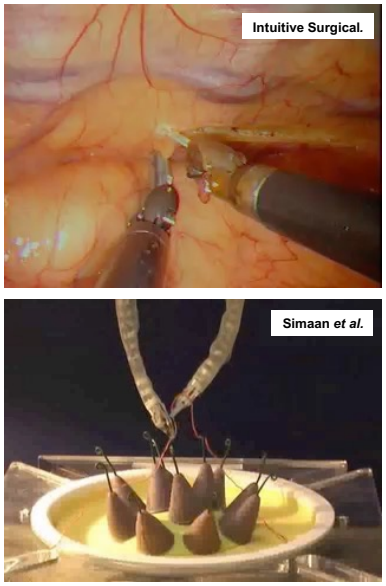

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Procedure Execution

- 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

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

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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,
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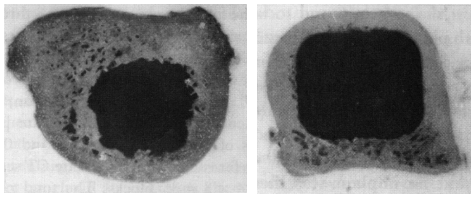
  - and safer



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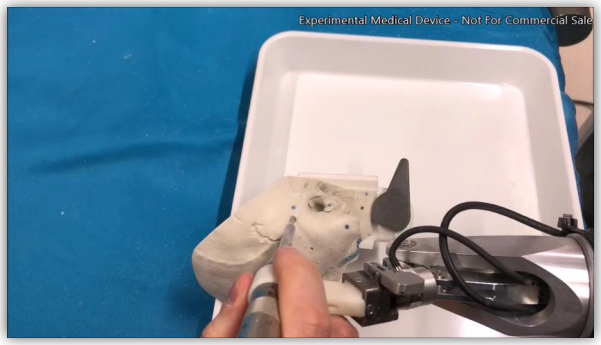
Procedure Execution

GALEN ROBOTICS

- 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



Francis X. Creighton, Christopher R. Razavi, Paul R. Wilkening, Rui Yin, Nicholas Lamaison, Russell H. Taylor, John P. Carey, "Image-Guided Mastoidectomy with the Robotic ENT Microsurgery System (REMS)", *AAO Conference*, October 7, 2018.

Disclosure: Under a license agreement between Galen Robotics, Inc. and the Johns Hopkins University, Dr. Taylor and the University are entitled to royalty distributions on technology related to technology described in the study discussed in this publication. Dr. Taylor also is a paid consultant to and owns equity in Galen Robotics, Inc. This arrangement has been reviewed and approved by the Johns Hopkins University in accordance with its conflict-of-interest policies.

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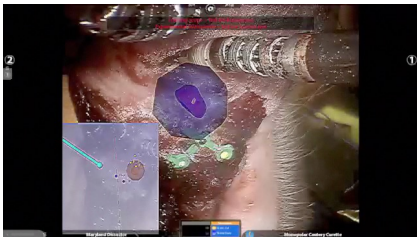
Procedure Execution

- **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



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

I. Iordachits, R. Taylor, *et al*

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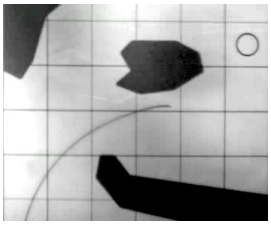
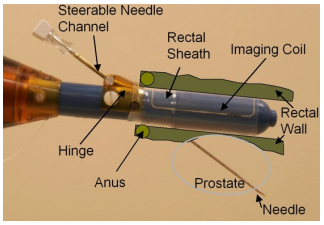
Image-guided needle placement

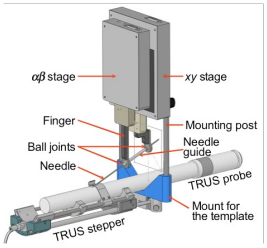
Masamune, Fichtinger, Iordachita, …



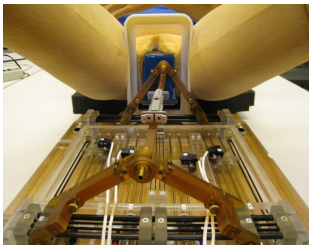
Okamura, Webster, …



Krieger, Fichtinger, Whitcomb, …



Fichtinger, Kazanzides,Burdette, Song …



Iordachita, Fischer, Hata…

Taylor, Masamune, Susil, Patriciu, Stoianovici,…

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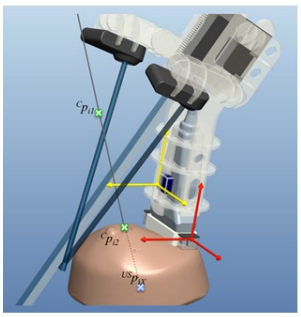
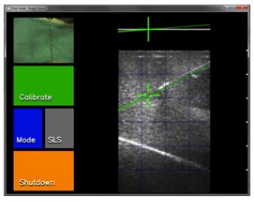
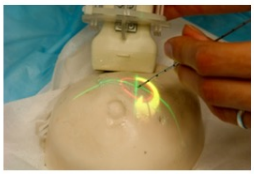
Example: Ultrasound-guided needle placement

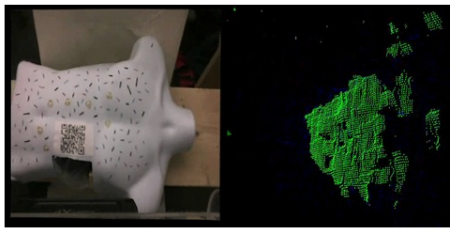




Traditional ultrasound screen AND on-screen guidance overlay



As well as on-patient projection



Real-time multi-modal fusion

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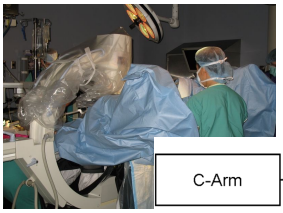
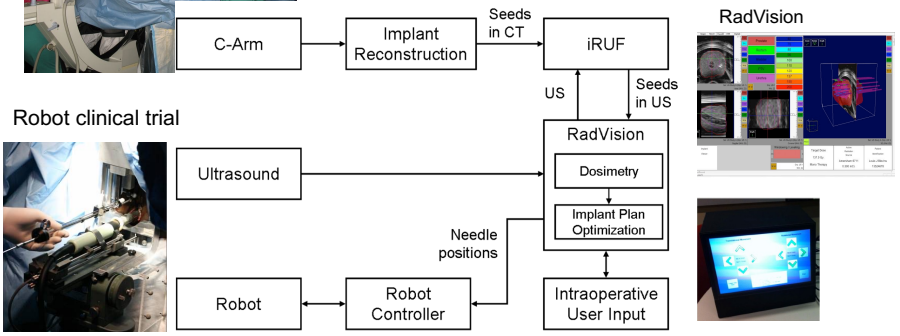
TRUS Robot for Prostate Brachytherapy

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)



RadVision

Robot clinical trial

Prototype sterile touchscreen: Digital Dash

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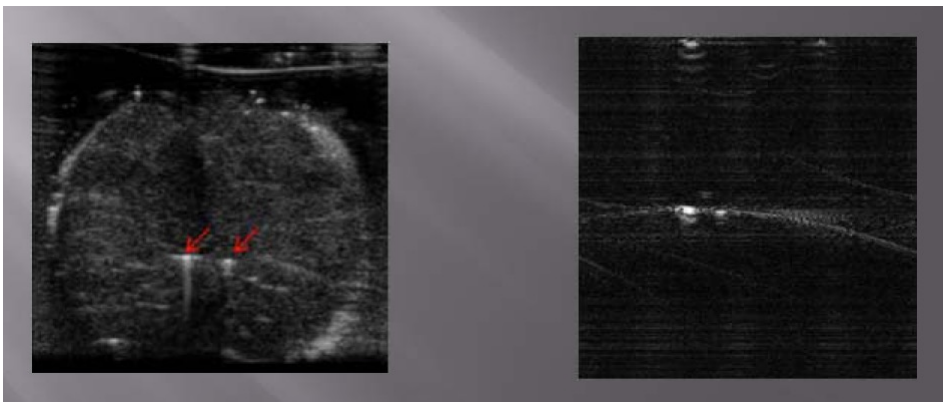
Prostate brachytherapy seed localization using combined photoacoustic and ultrasound imaging Boctor/Kang/Prince (JHU), Burdette (AMS)



B-mode PA-mode

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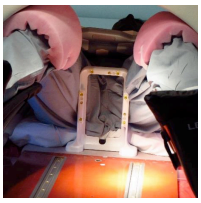
MRI-guided Surgical Manipulator for Transperineal Prostate Interventions - Clinical Workflow

Patient ready on scanner table

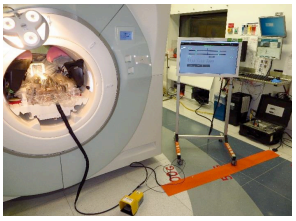


Z-frame in position

Drape robot, attach needle guide

Slide in robot until hit Z-frame

Lock robot in place

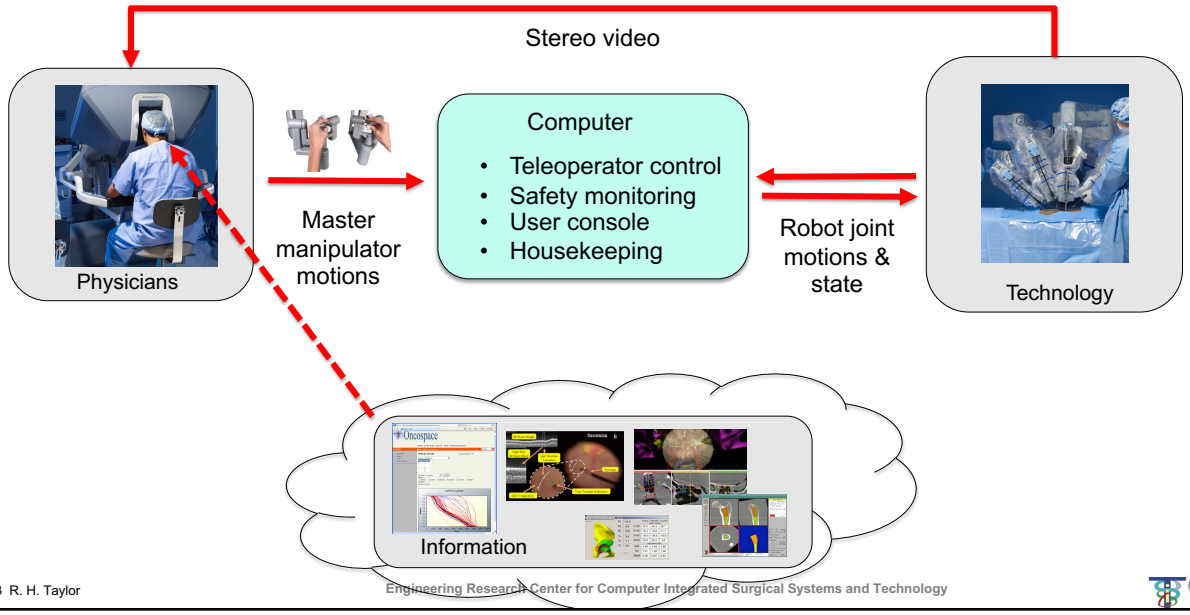


Robot ready for targeting

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

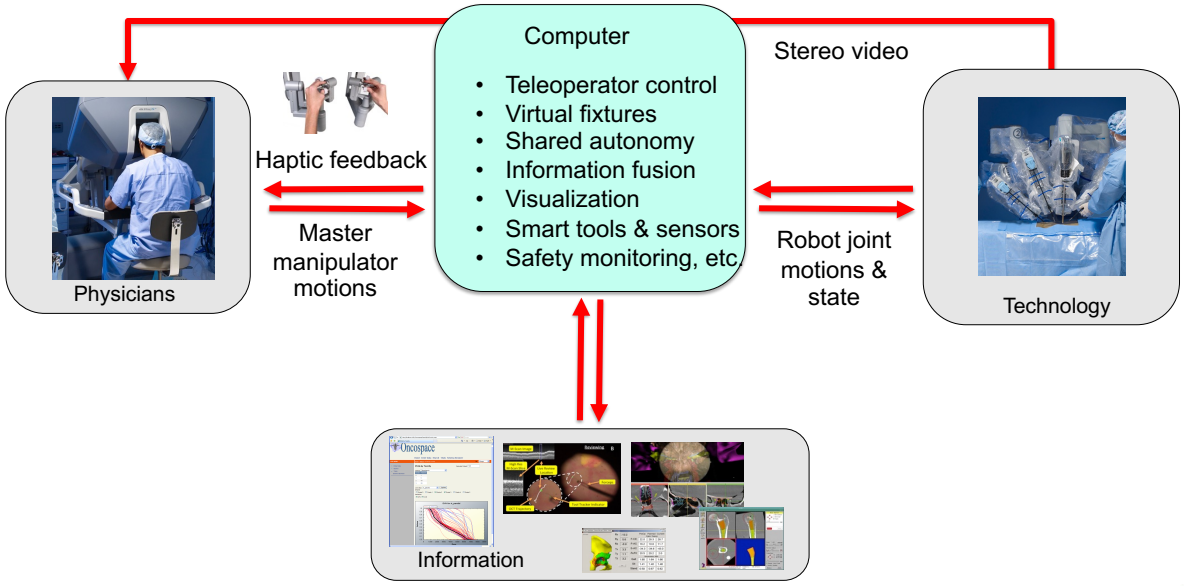
44

Current dominant paradigm for interactive surgery



45

Emerging paradigm (shared autonomy & assistant modes)

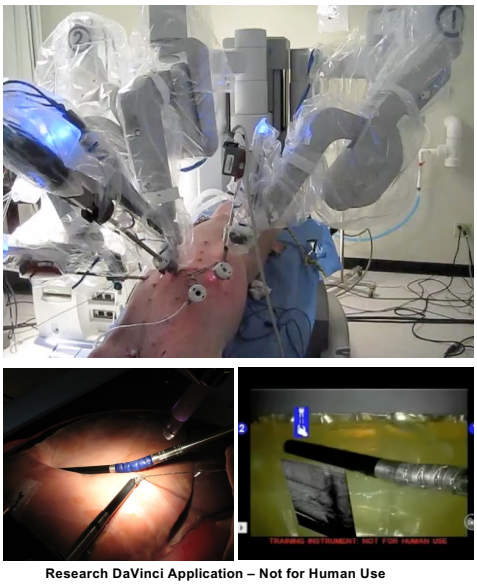


46

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

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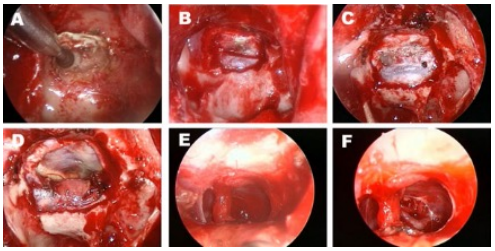
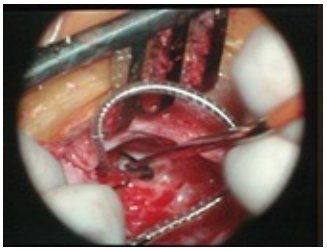
Example: Challenges in Precise Minimally Invasive Head-and Neck Surgery

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





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The Robotic ENT Microsurgery System (REMS)

User interface:

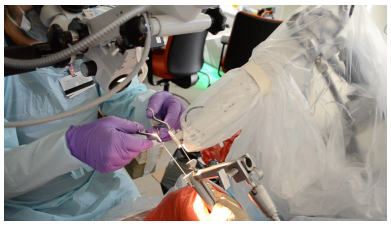
- Hands-on control, surgeon “in the game”
- Foot pedal-controlled gain

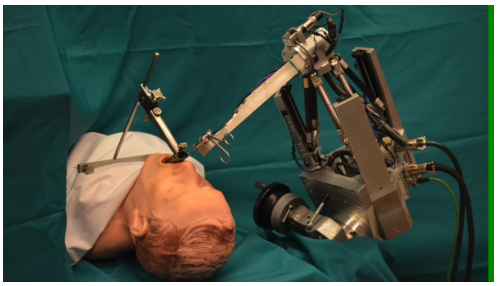
Technical specs:

- 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.

55

Cadaver Study: Sinus Surgery with Virtual Fixtures

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

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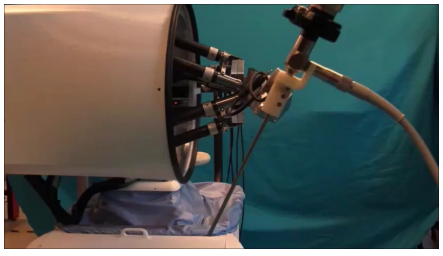
GALEN ROBOTICS

The Galen Platform

Technology:

- Custom 5-DOF architecture
- "Steady Hand" cooperative control
- Hand tremor cancellation
- Virtual fixtures



Ease of Use:

- Same footprint as a person
- Accommodates standard instruments
- Minimal change to existing surgical workflow

Broad Applications:

- ENT, spine, brain, trauma, ….

Disclosure: Under a license agreement between Galen Robotics, Inc. and the Johns Hopkins University, Dr. Taylor and the University are entitled to royalty distributions on technology related to technology described in the study discussed in this publication. Dr. Taylor also is a paid consultant to and owns equity in Galen Robotics, Inc. This arrangement has been reviewed and approved by the Johns Hopkins University in accordance with its conflict-of-interest policies.

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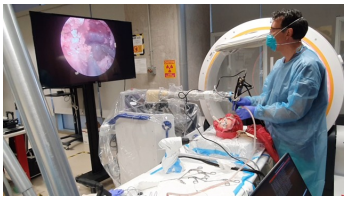
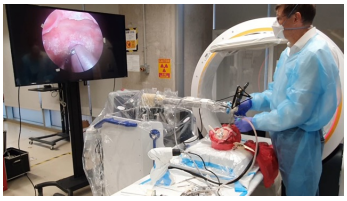
Robotic otologic surgery

Robotic laryngeal surgery

Robotic sinus surgery



Robotic endoscopic endonasal skull base surgery



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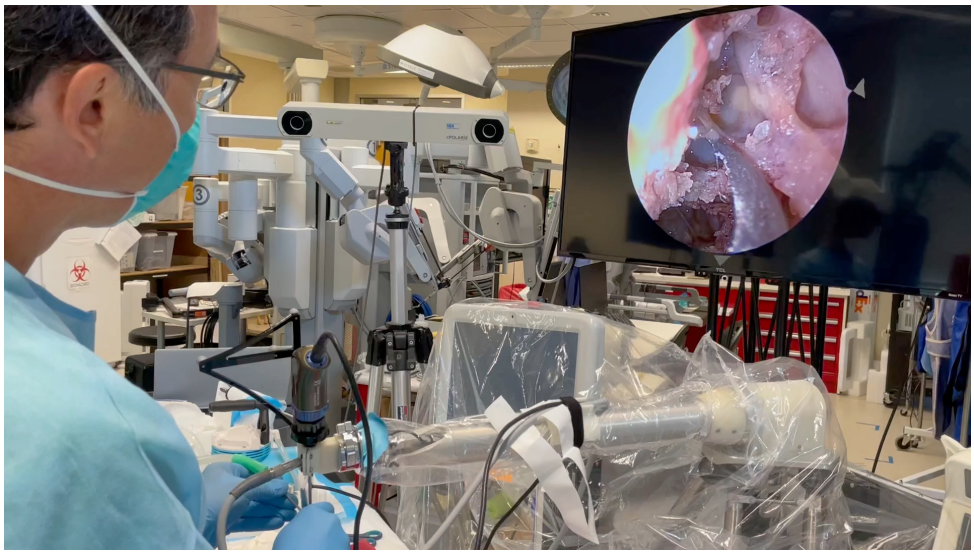
GALEN ROBOTICS

Recent Cadaver Study with Galen Robot



M. Ishii, M. Sahu, R. Taylor

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Robotic Sinus Surgery

M. Sahu, J. Porras, M. Ishii, R. Taylor

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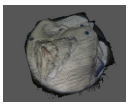
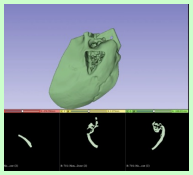
A "smart" skull base surgical assistant


Stereo Video


3D Point Cloud


Patient CT

Registered
and updated
real time
model
Tool tracking



Assistance Modes & Virtual fixtures
Navigation
Advanced Visualization
Learning & Training

Max Li, Russ Taylor, Mathias Unberath, Francis Creighton,

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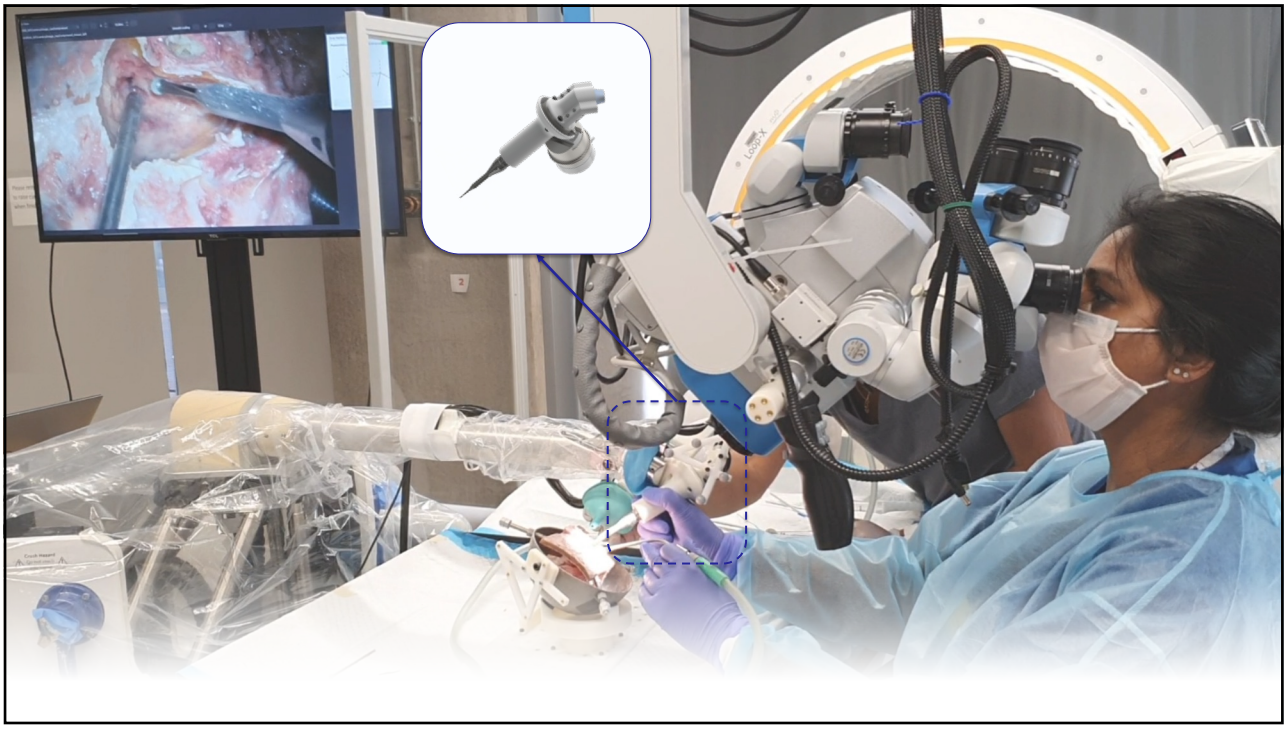

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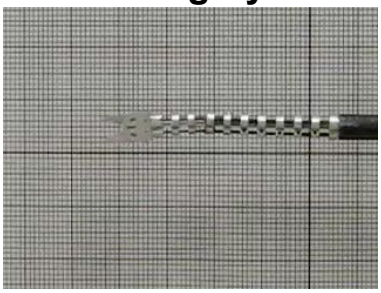
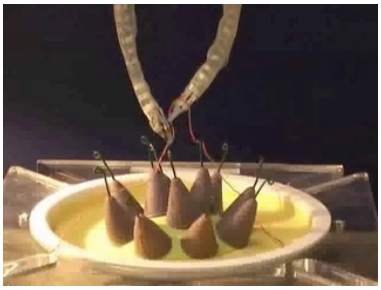
Snake-like robot for minimally invasive surgery

- **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.*

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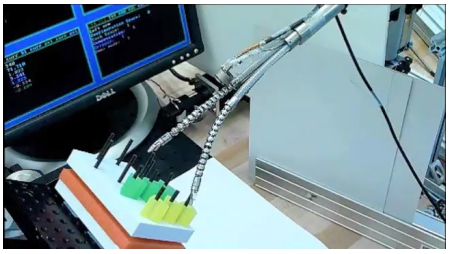
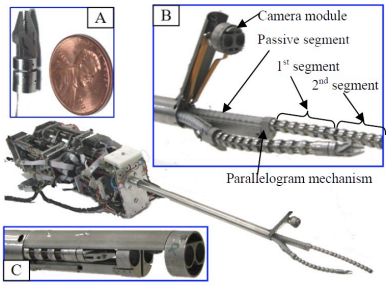
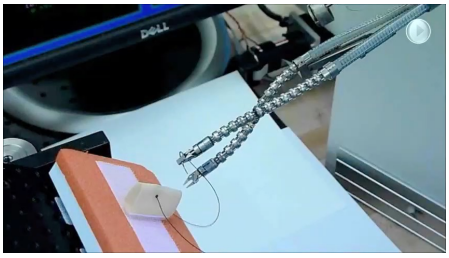
Single Port Access Surgery

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.

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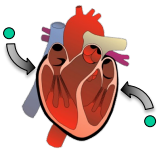
Foreign Bodies in the Heart

Causes

Thrombi, Shrapnel
Iatrogenic

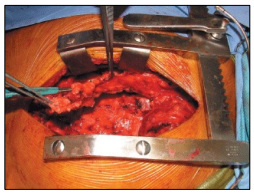


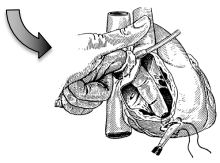
Symptoms

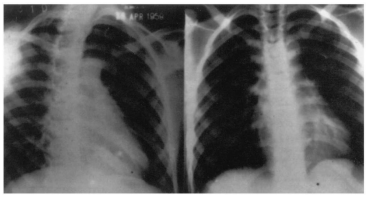
Cardiac Tamponade
Hemorrhage
Arrhythmia
Infection
Shock
Embolism
Valve Dysfunction

Conventional Treatment

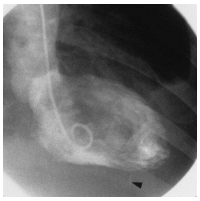
Median Sternotomy
Cardiopulmonary Bypass







(Actis Dato, 2003)



(LeMaire, 1999)

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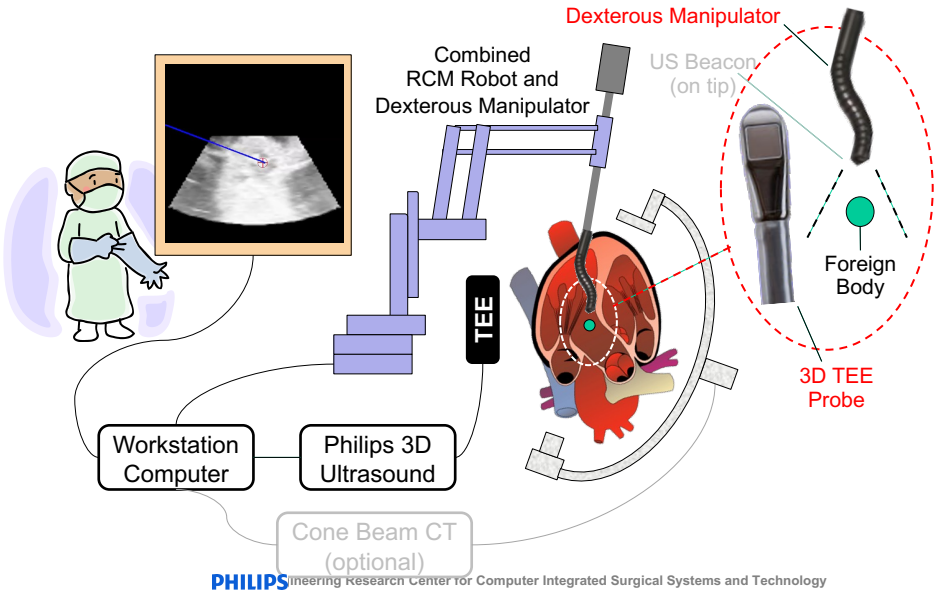
Beating Heart MIS with 3D US Guidance

Paul Thienphrapa, Aleksandra Popovic, Russell Taylor



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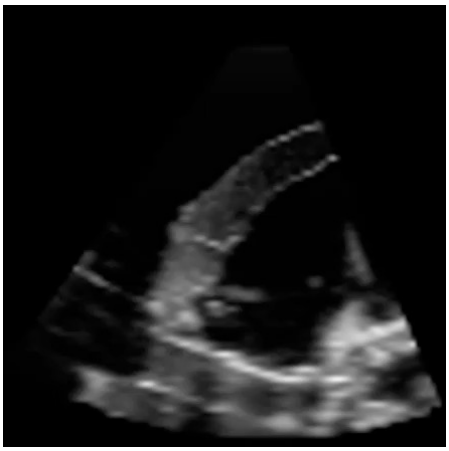
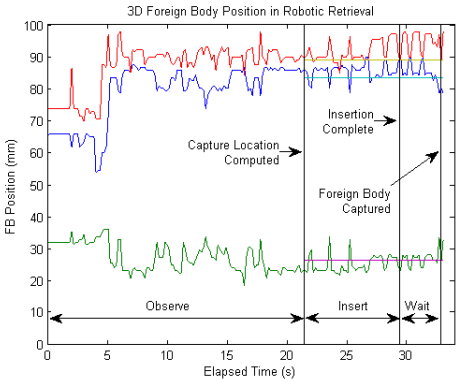
Retrieval Experiment Results





PHILIPS

Thienphrapa *et al. 2013*

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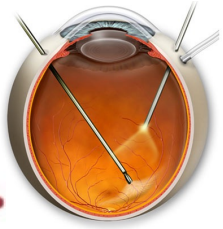
Vitreoretinal Microsurgery

British Journal of Ophthalmology 2004 - Akifumi Ueno et al



www.eyemdlink.com

Alcon Vitreosurgery Instrument

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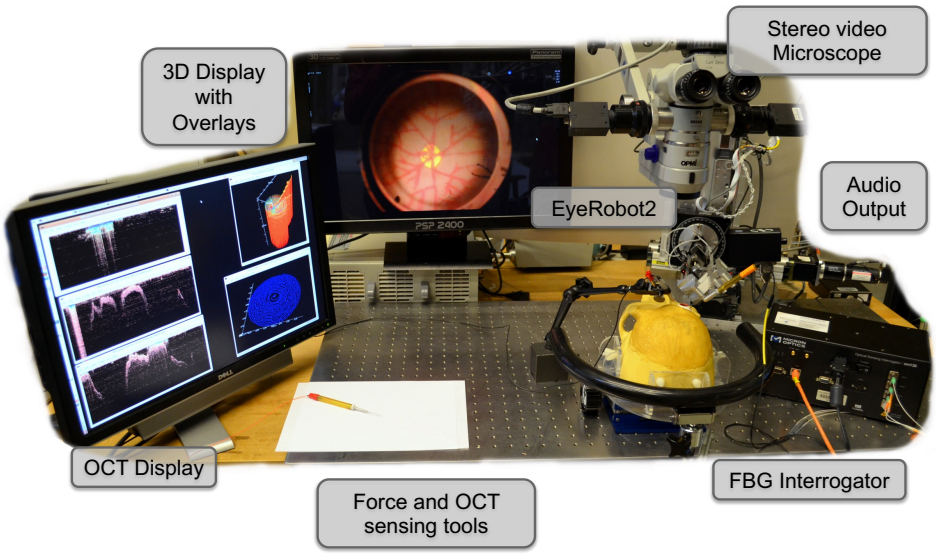
Microsurgery Assistant Workstation



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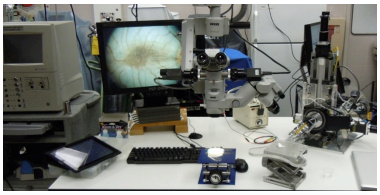
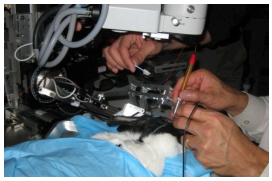
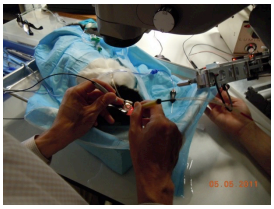
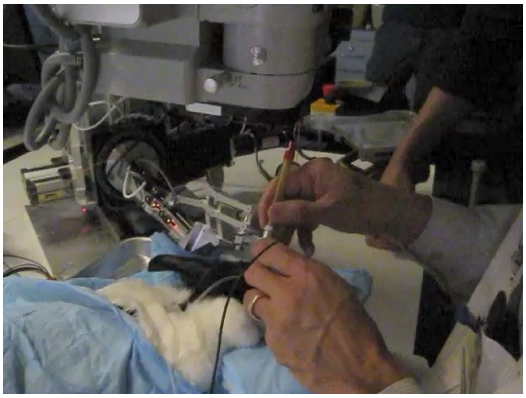
In-Vivo Experiments

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

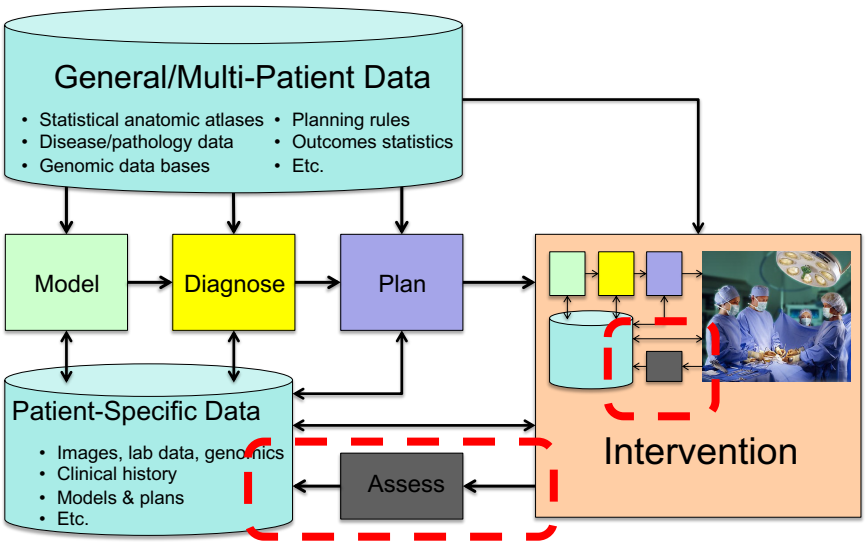




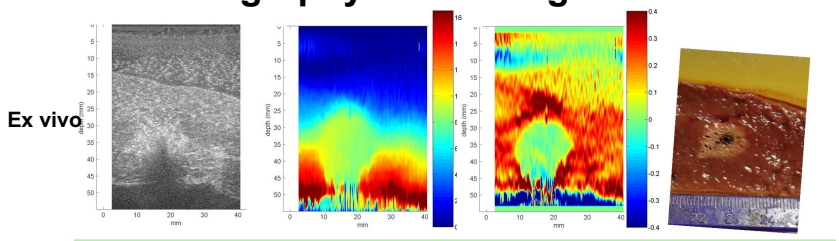


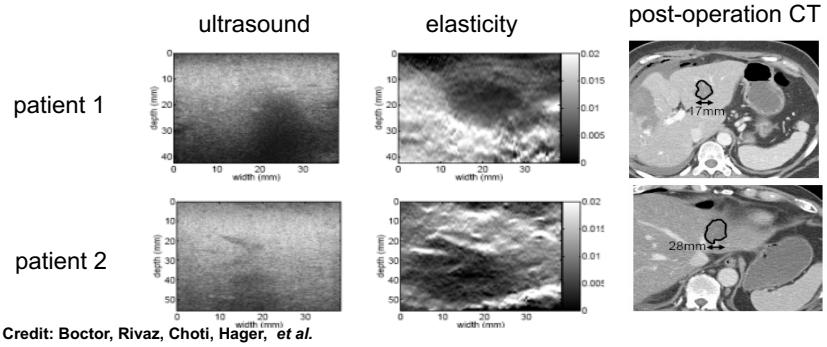


Patient-specific assessment and feedback



Elastography monitoring of ablations





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

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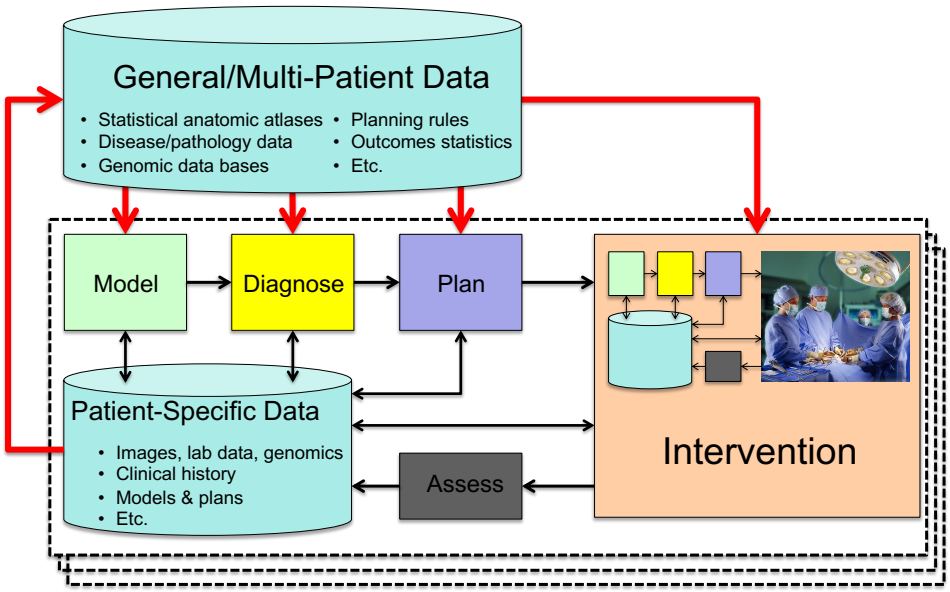
Statistical Analysis and Decision Support



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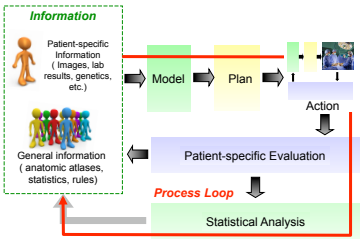
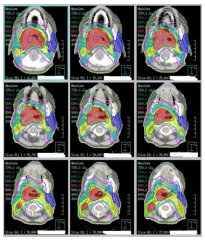
Information-Integrated Process Learning

- **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

Current Trial Practice

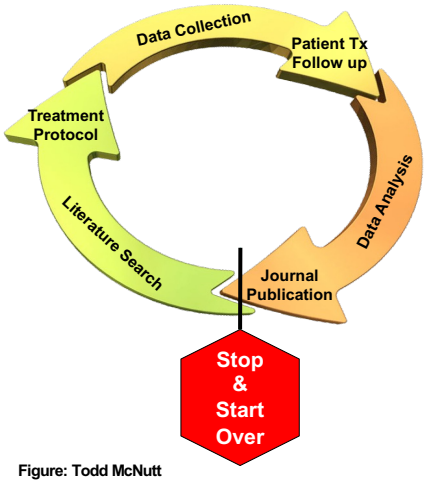
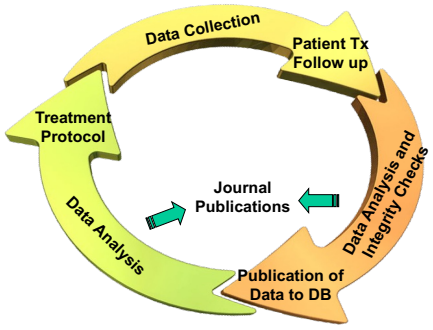


Figure: Todd McNutt

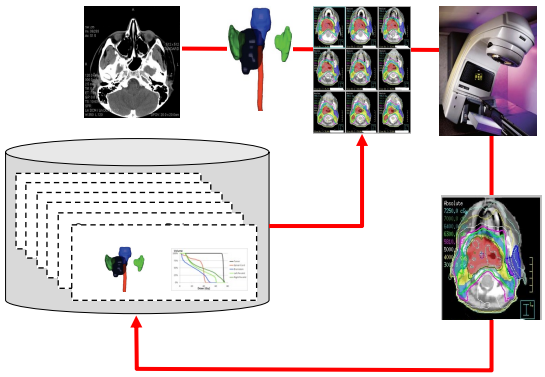
Hypothetical Future Practice



Increased potential for data reuse

Publications with live data!

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

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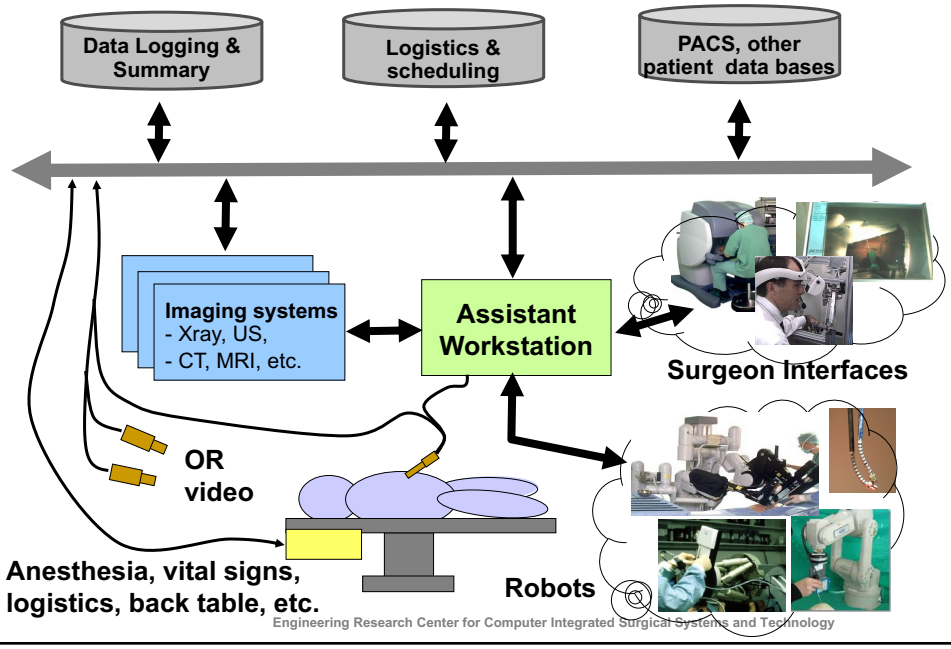
Information-Intensive Interventional Suite



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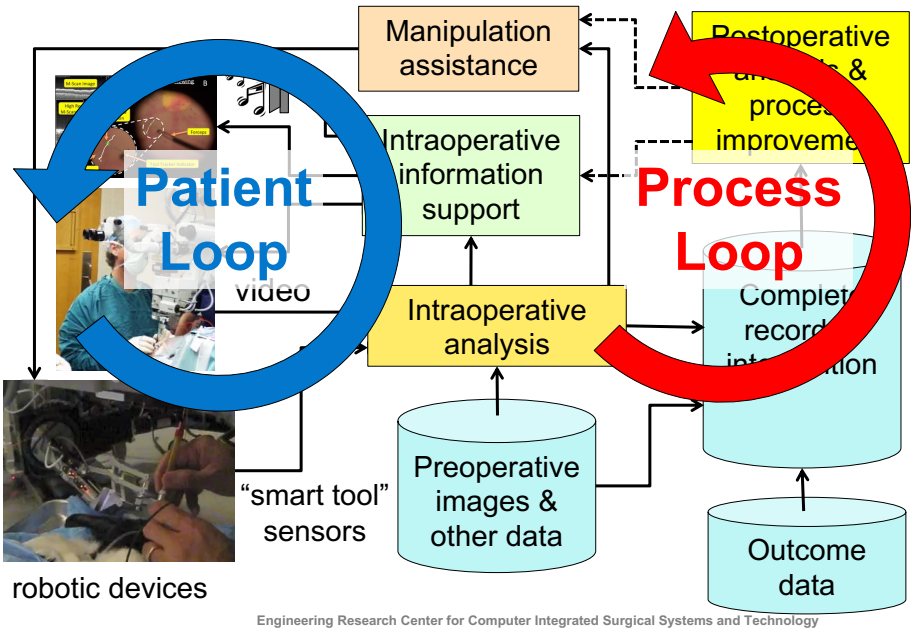
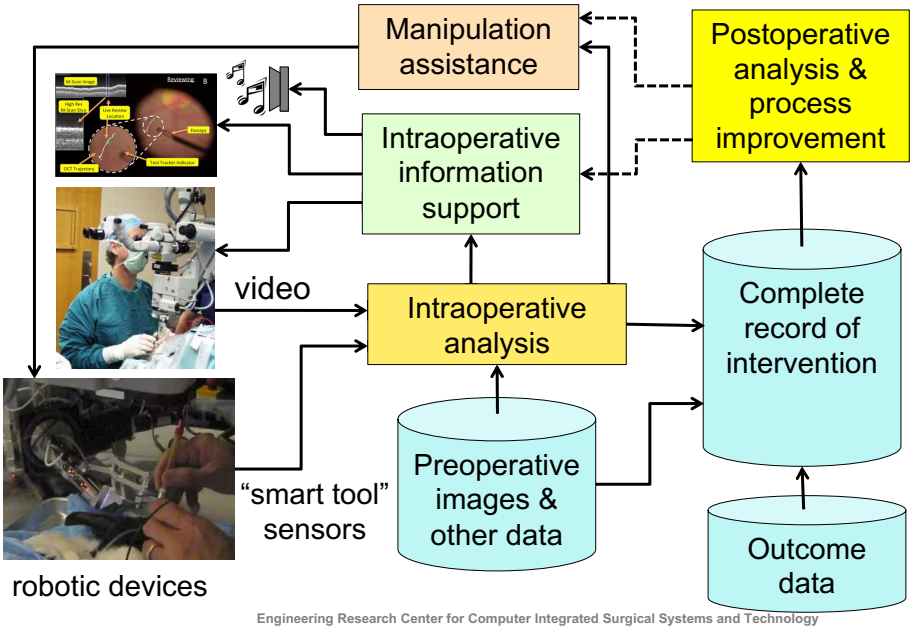
The computer-integrated operating room



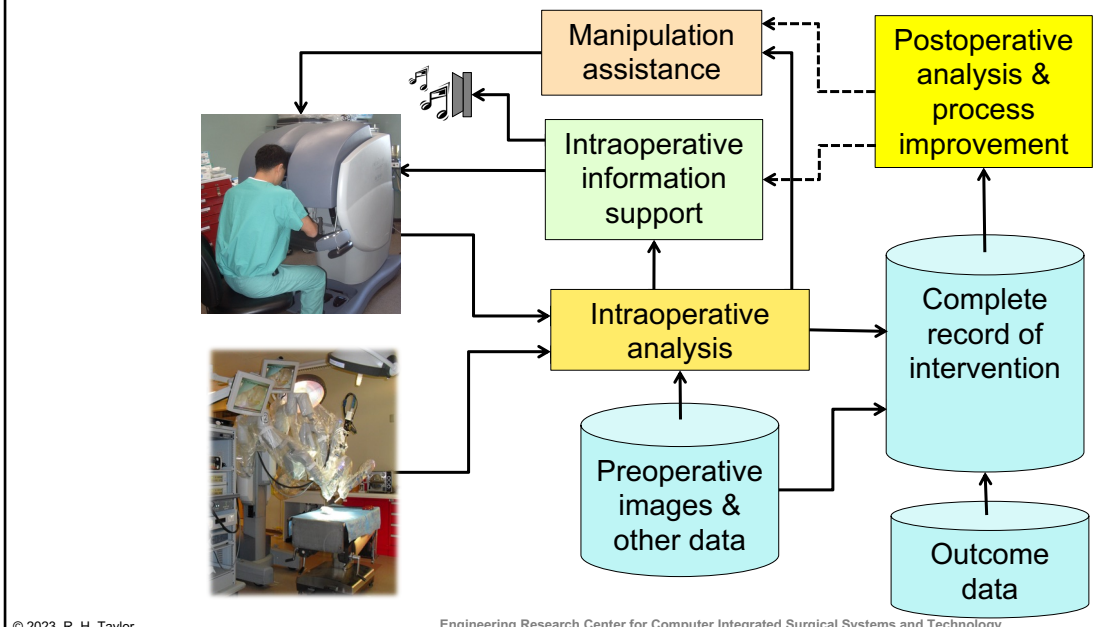
104

The computer-integrated operating room



105

The computer-integrated operating room



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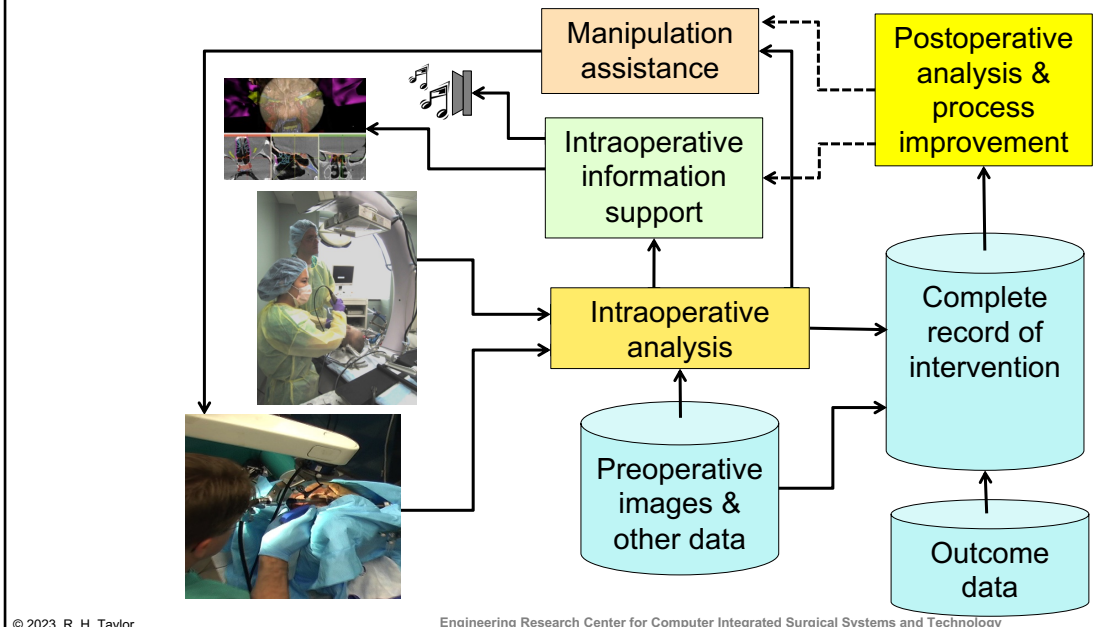
The computer-integrated operating room



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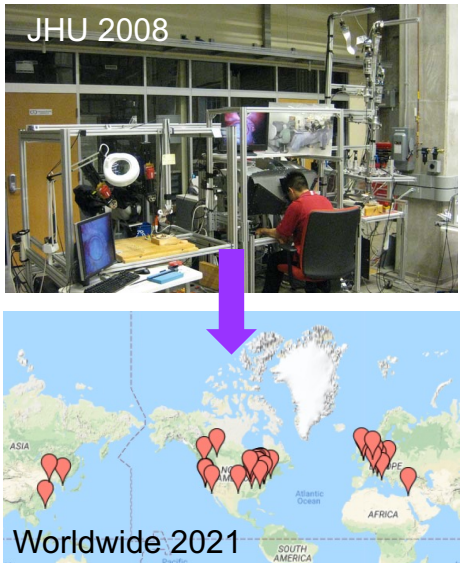
Use Case: da Vinci Research Kit



- Mechanical components from da Vinci "classic" systems
- Donated by Intuitive Surgical to selected academic 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
- Systems at over 30 universities around the world
- **https://www.intuitive-foundation.org/dvrk/**

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

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