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.
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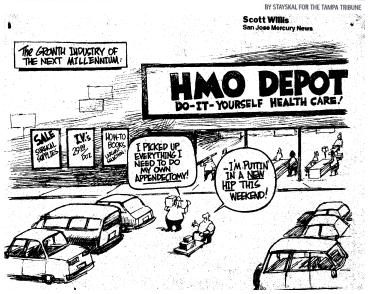

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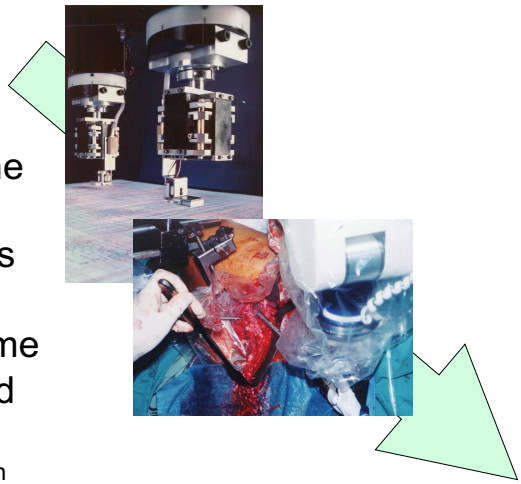
Motivating Insight

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



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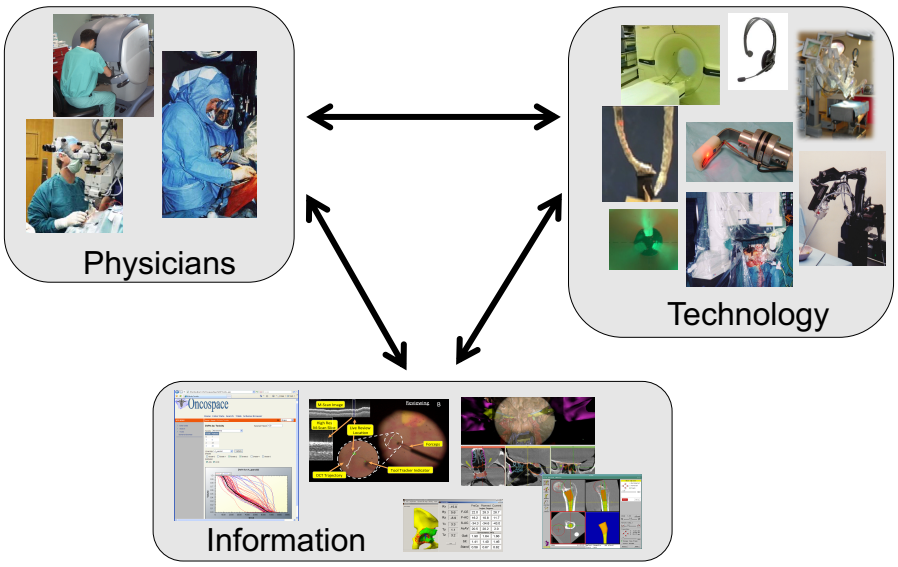
Goal: Human-machine partnership to fundamentally improve interventional medicine



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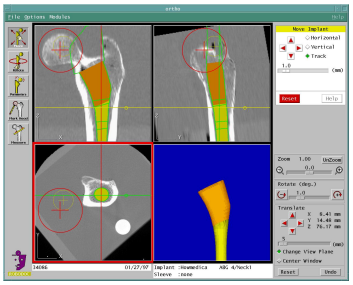
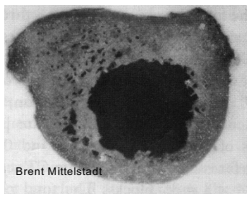
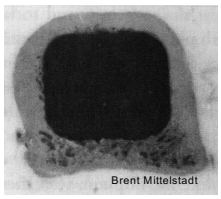
Over 25 years ago: Robotic Joint Replacement Surgery







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

Manual Surgery

Robotic Surgery

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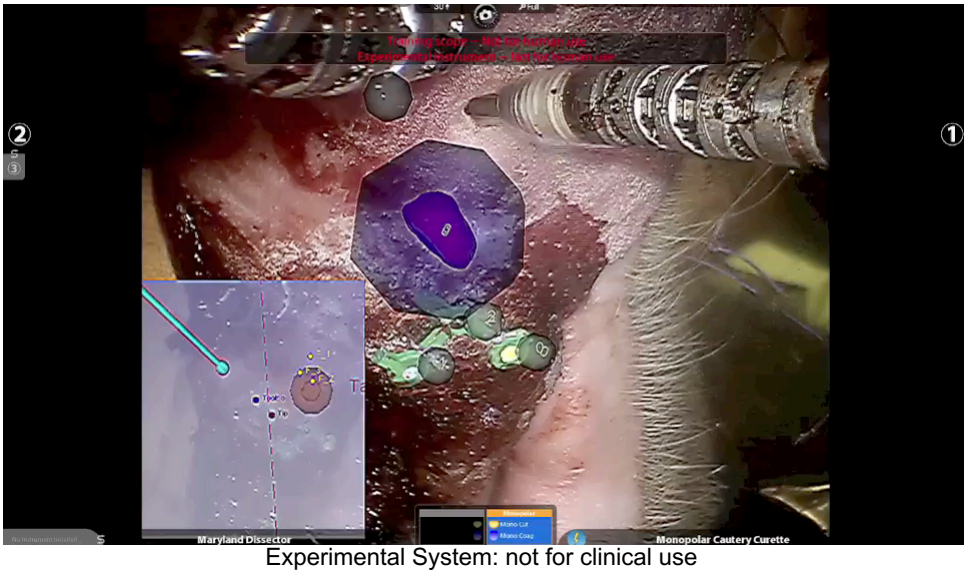
Emerging: Information-Augmented Robotic Surgery

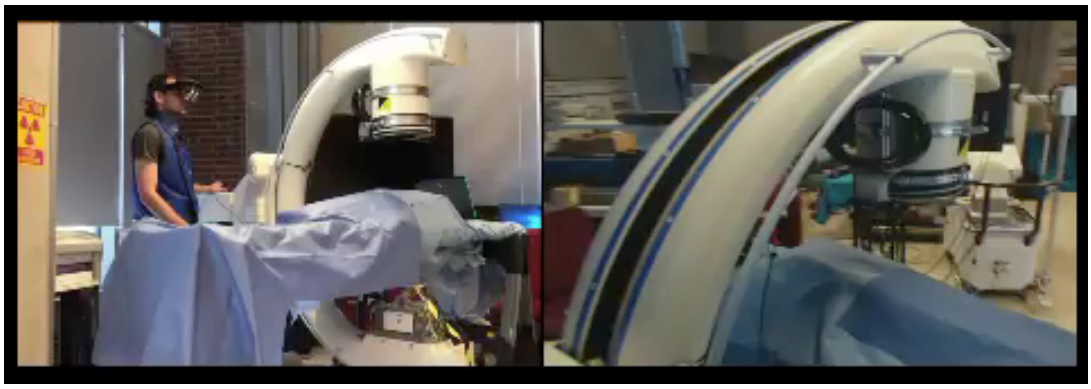
W. P. Liu, S. Reaugamornrat, A. Deguet, J. M. Sorger, J. H. Siewerdsen, J. Richmon, R. H. Taylor



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" To appear in *2018 AE-CAI MICCAI workshop*.

* Joint first authors

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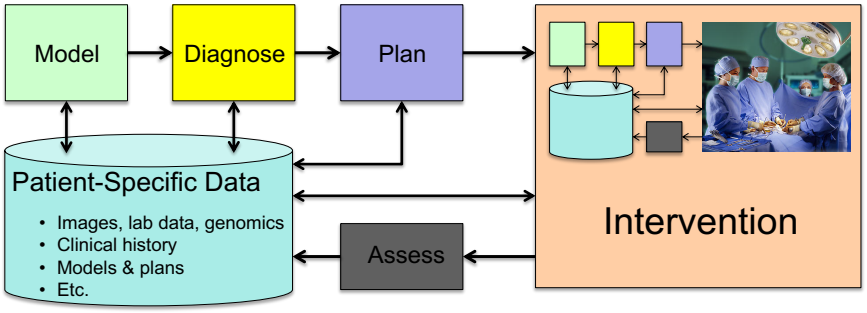
Computer-Integrated Interventional Medicine



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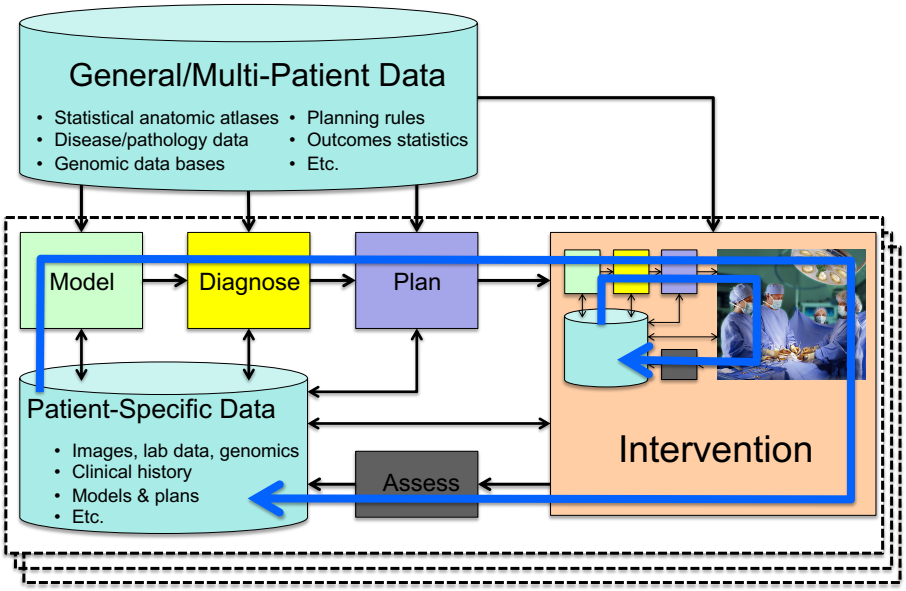
Computer-Integrated Interventional Medicine



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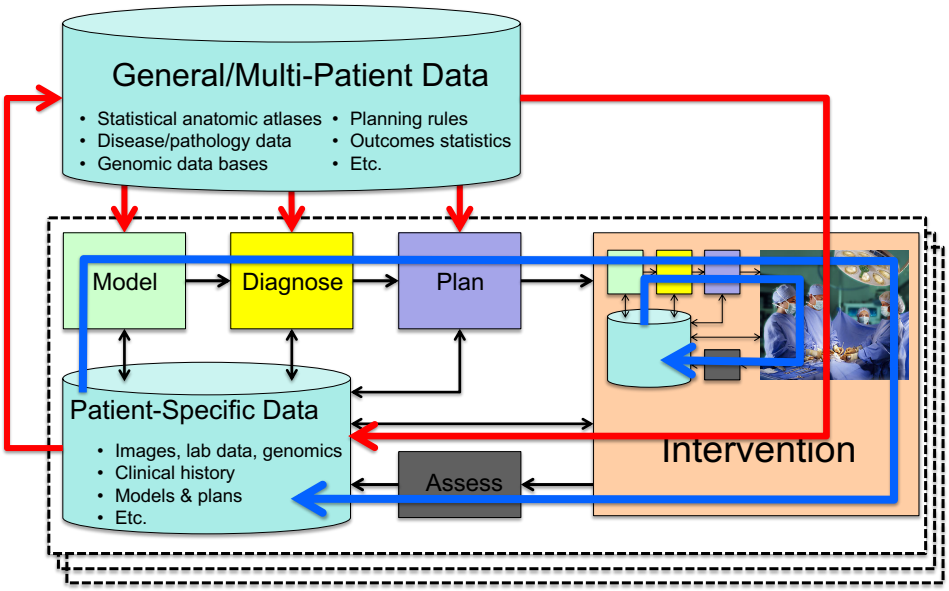
Computer-Integrated Interventional Medicine



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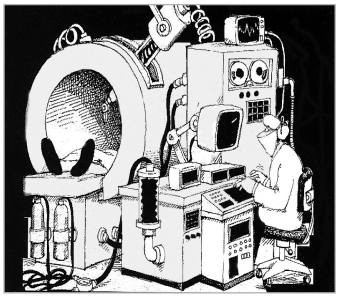
This Paradigm has not changed since Imhotep's day

27th Century BCE

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



21st Century CE

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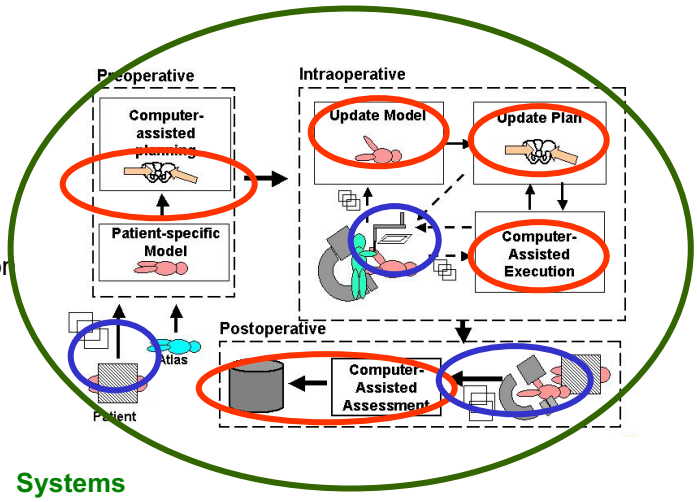
Multidisciplinary Integration is Crucial

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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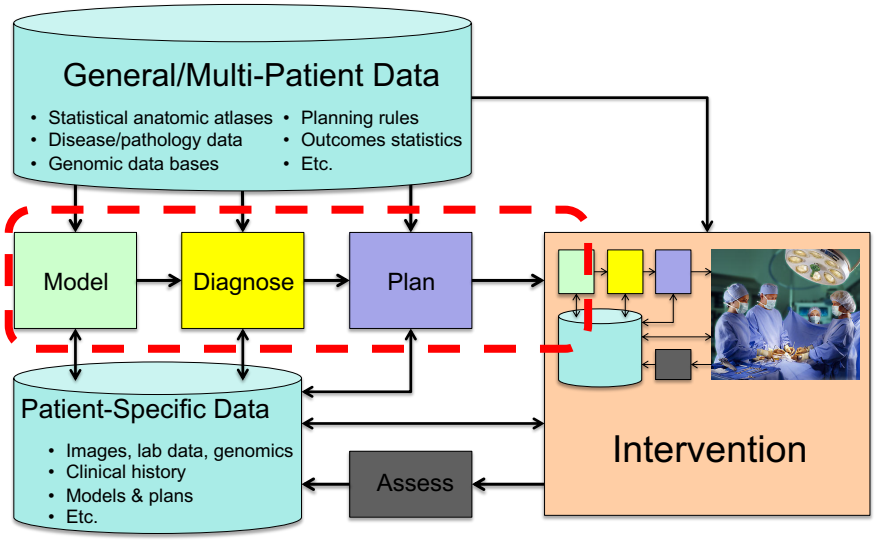
Image-based modeling & analysis



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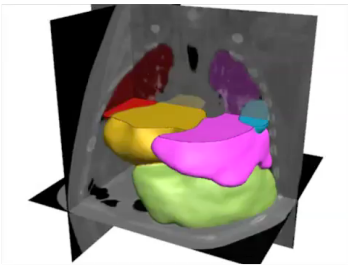
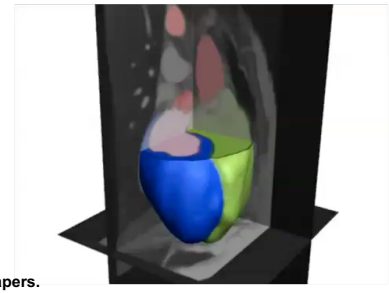
Patient-Specific Models for Interventions

- 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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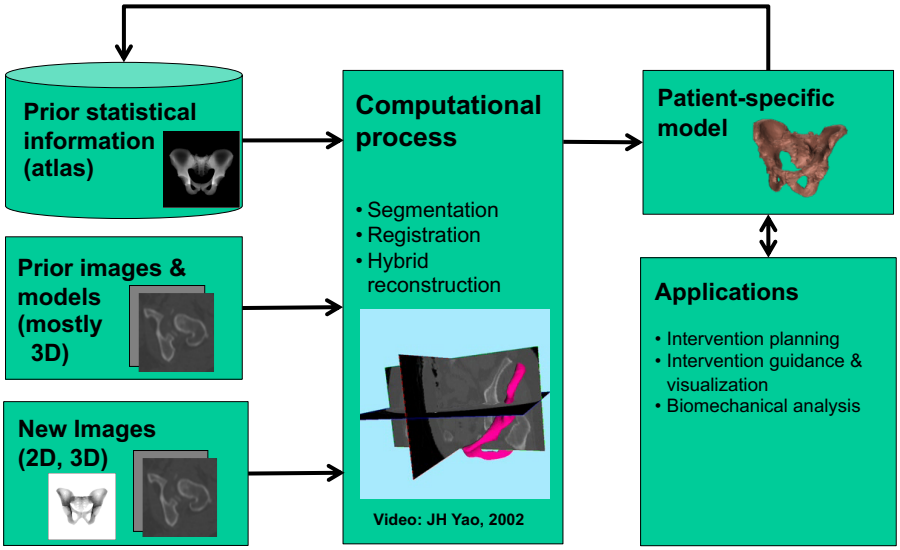
Combining prior knowledge with online images



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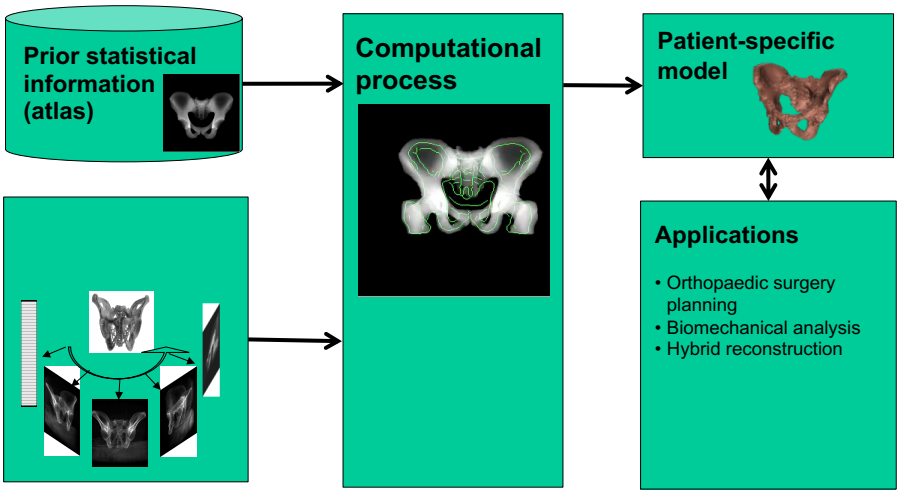
Deformable 2D/3D Registration to Statistical Atlas



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

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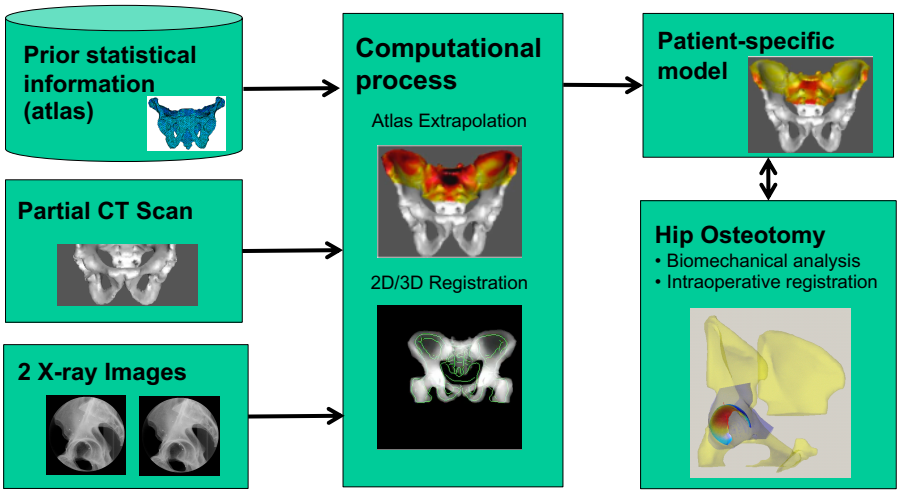
Model Completion, Given Partial CT + X-rays

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



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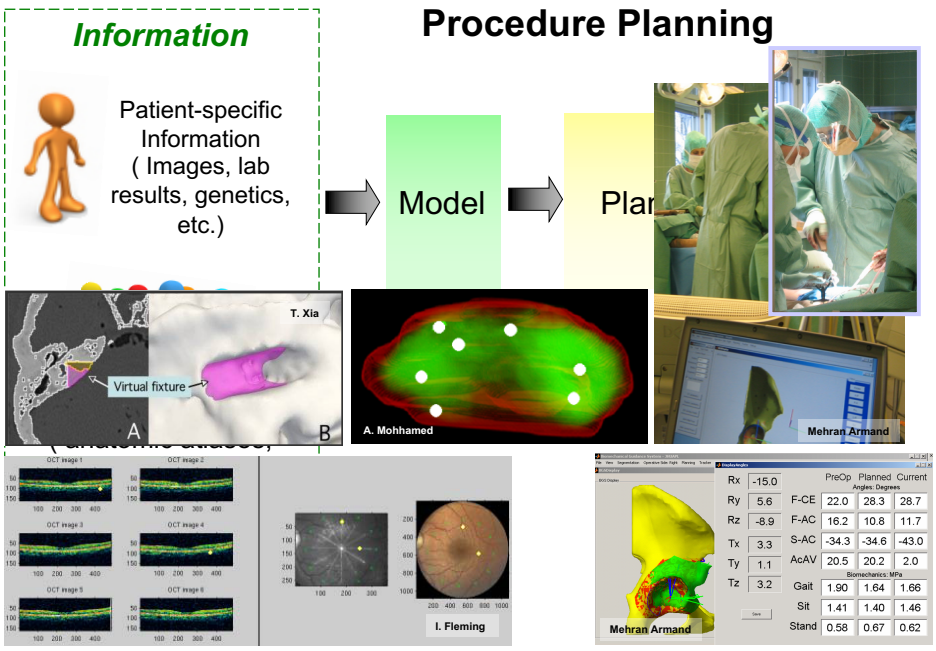
Procedure Planning



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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

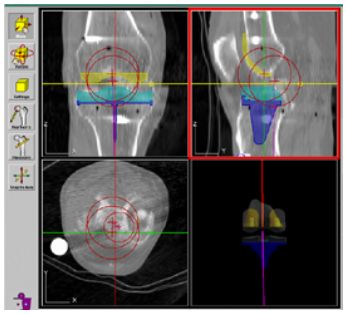
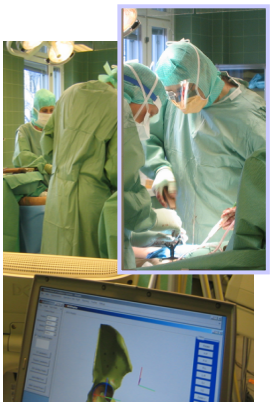
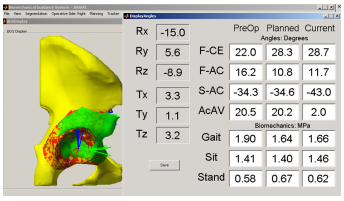


Photo: Integrated Surgical Systems

Procedure Planning

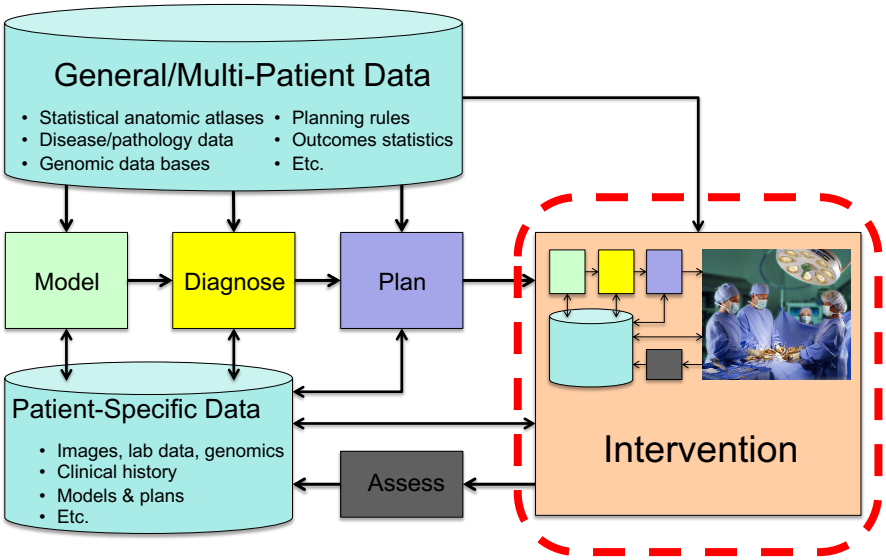
- **Typical outputs**
  - Target positions (seeds, biopsies, ablation sites, etc.)
  - Tool paths
  - Desired geometric relationships
  - Key-frame visualizations
  - Images, models & control parameters
- **Emerging themes**
  - Atlas-based planning
  - Statistical process control & integration of outcomes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





Photos: Mehran Armand

Procedure Execution



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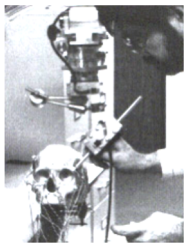
Procedure Execution

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

Medtronic



Taylor

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

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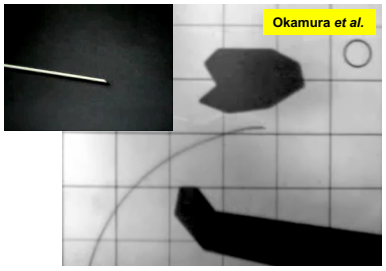

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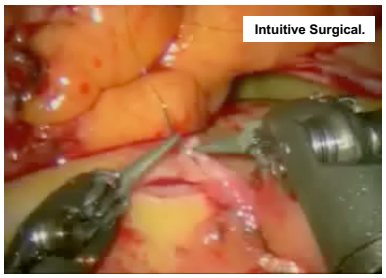

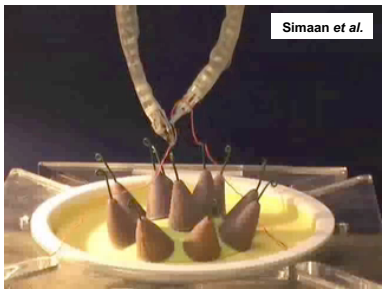

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Taylor, Hager, Handa, Kazanzides, Kang, Iordachita, Gehlbach, *et al.*

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Procedure Execution

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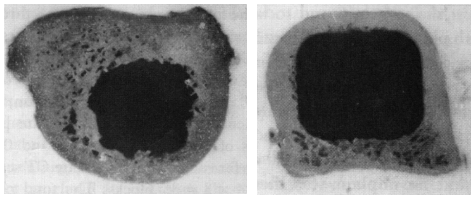

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Procedure Execution

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  - and safer

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

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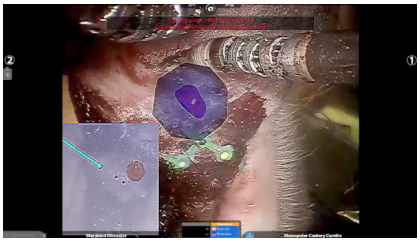
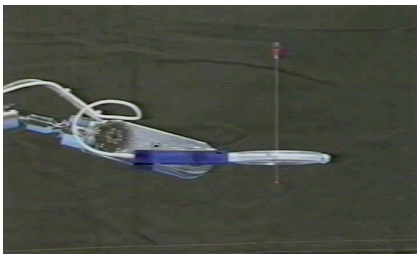
Procedure Execution

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



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



Stoianovici, Taylor, Whictomb, *et al.*

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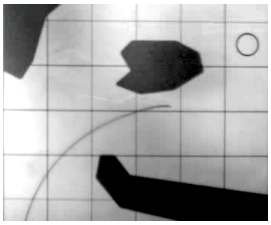
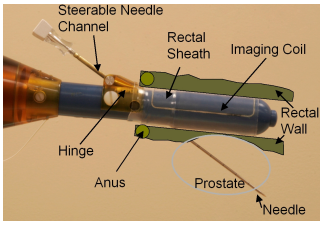
Image-guided needle placement

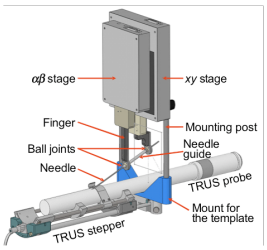
Masamune, Fichtinger, Iordachita, …



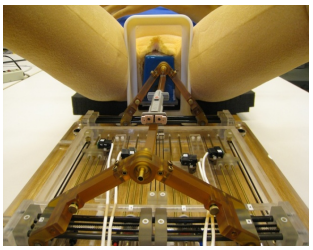
Okamura, Webster, …



Krieger, Fichtinger, Whitcomb, …



Fichtinger, Kazanzides,Burdette, Song …



Iordachita, Fischer, Hata…

Taylor, Masamune, Susil, Patriciu, Stoianovici,…

Information-enhanced robotic surgery

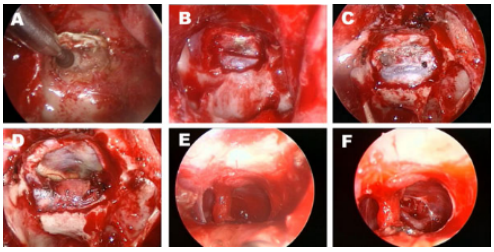
augmented reality displays imaging

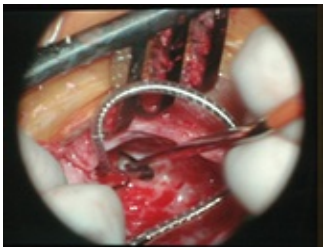
safety barriers shared control "virtual fixtures"

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



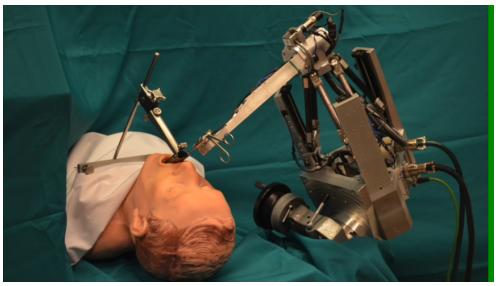


The Robotic ENT Microsurgery System (REMS)

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

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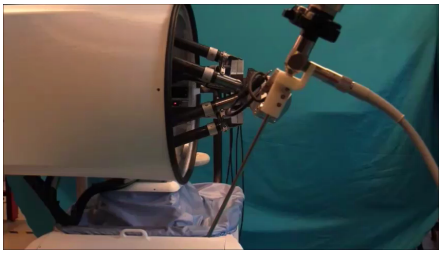
GALEN ROBOTICS

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

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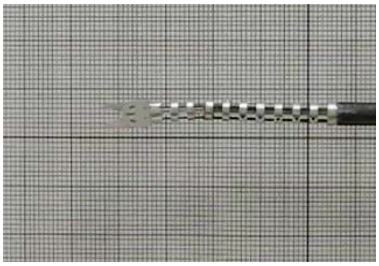
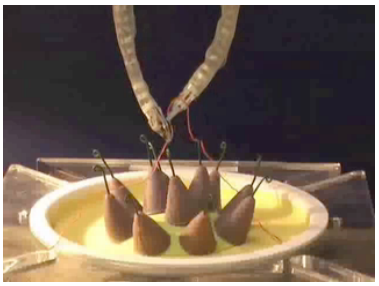
Snake-like robot for minimally invasive surgery

- **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

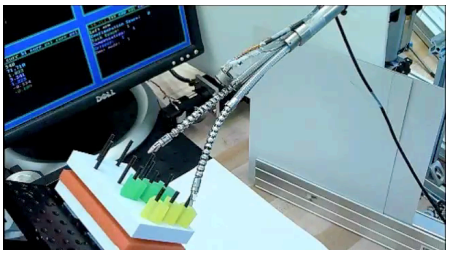


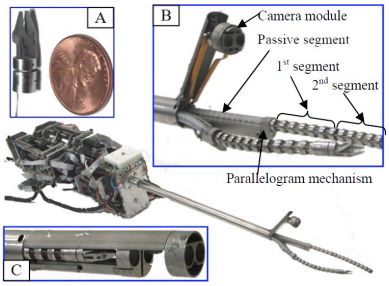


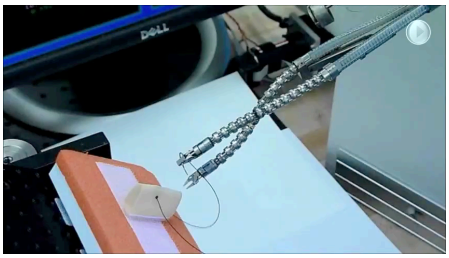
R. Taylor, N. Simaan, *et al.*

Single Port Access Surgery

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

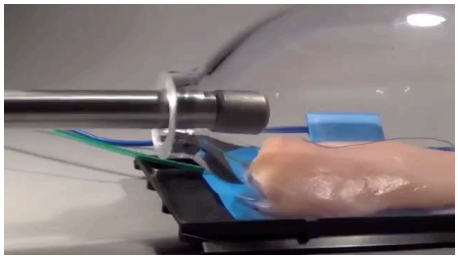


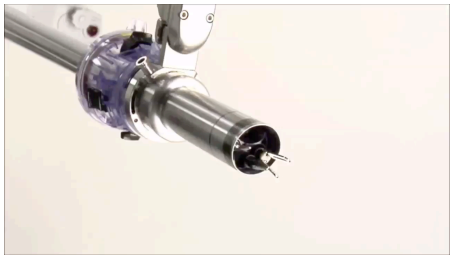




New technology finally allows true evaluation of the potential of single port access surgery. Systems raise new questions about control and telemanipulation infrastructure/cooperative control.

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

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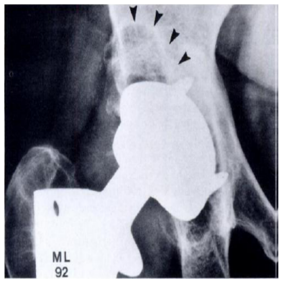
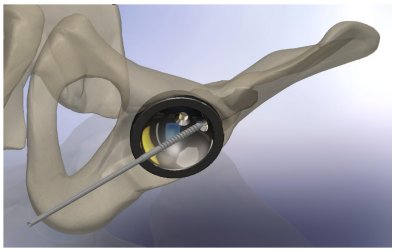
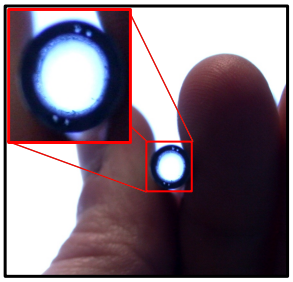
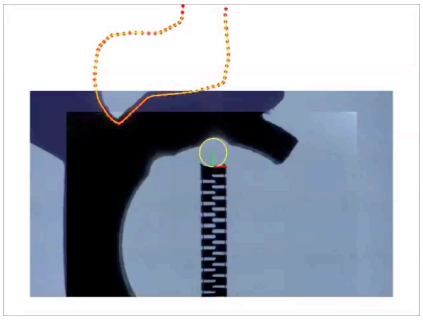
Minimally-Invasive Osteolysis Curettage









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

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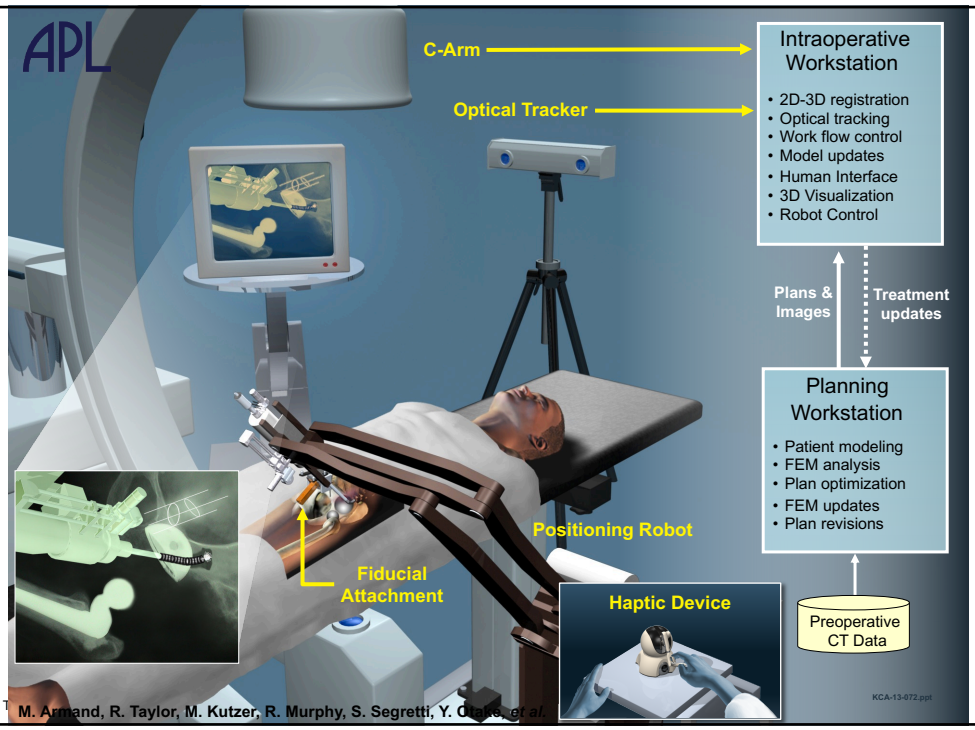

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M. Armand, R. Taylor, M. Kutzer, R. Murphy, S. Segretti, Y. O[illegible], *et al.*

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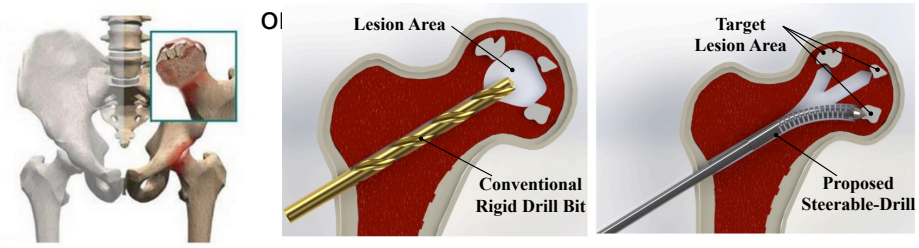
Curved Drilling of the Femoral Head

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*

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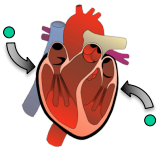
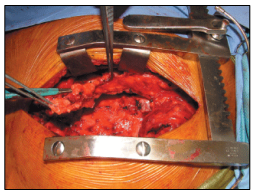
Foreign Bodies in the Heart

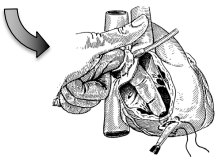
Causes
Thrombi, Shrapnel
Iatrogenic

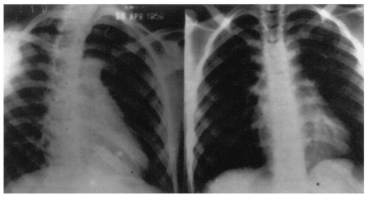


Symptoms
Cardiac Tamponade
Hemorrhage
Arrhythmia
Infection
Shock
Embolism
Valve Dysfunction

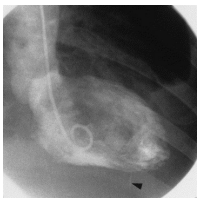
Conventional Treatment
Median Sternotomy
Cardiopulmonary Bypass







(Actis Dato, 2003)



(LeMaire, 1999)

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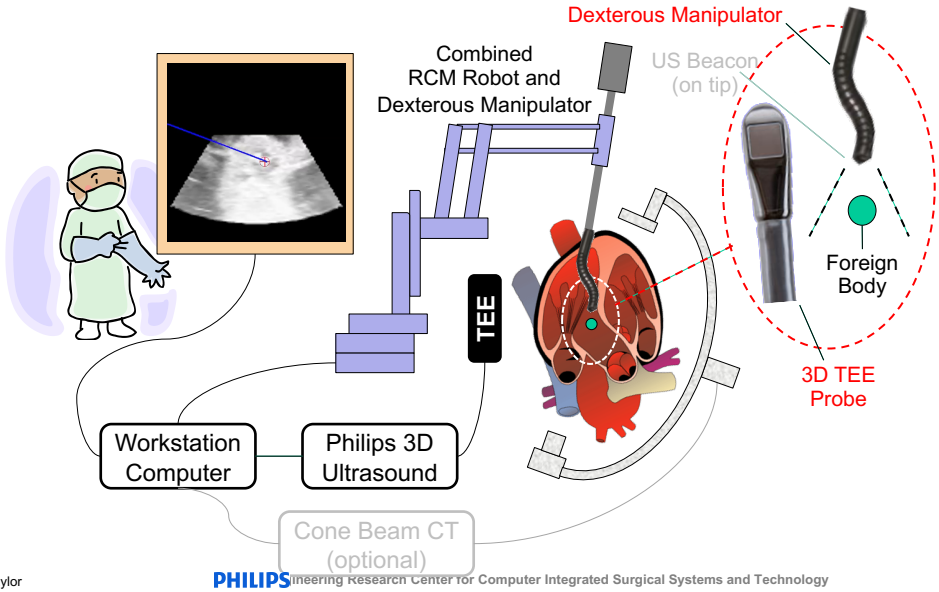
Beating Heart MIS with 3D US Guidance

Paul Thienphrapa, Aleksandra Popovic, Russell Taylor



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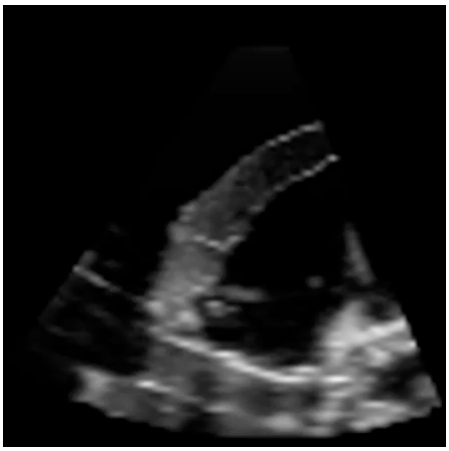
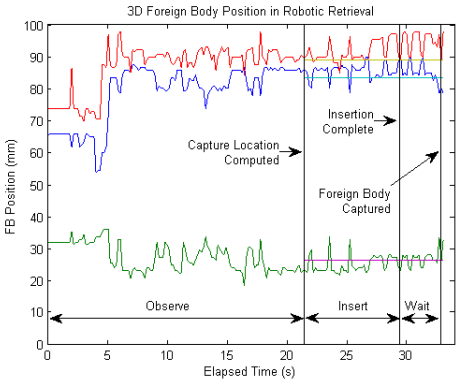
Retrieval Experiment Results





PHILIPS

Thienphrapa *et al. 2013*

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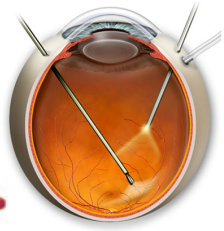
Vitreoretinal Microsurgery

British Journal of Ophthalmology 2004 - Akifumi Ueno et al



www.eyemdlink.com

Alcon Vitreosurgery Instrument

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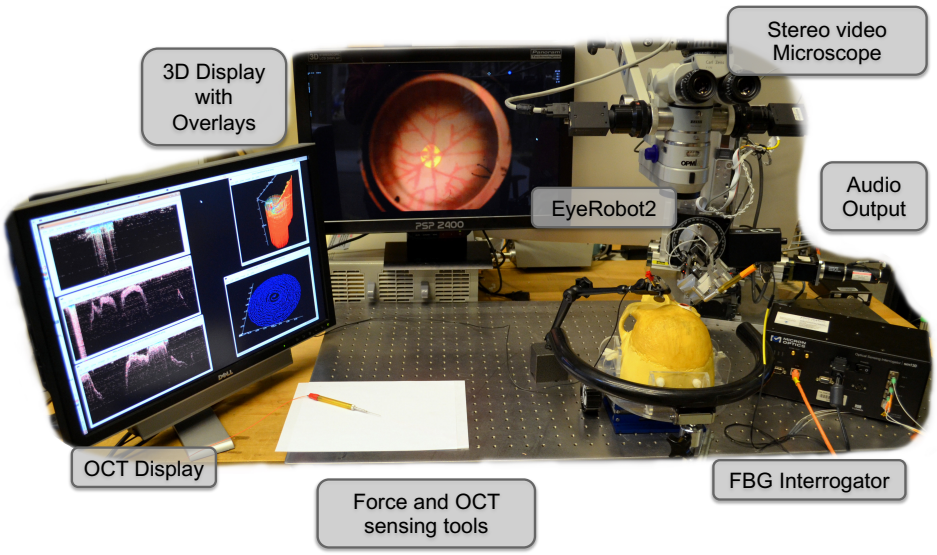
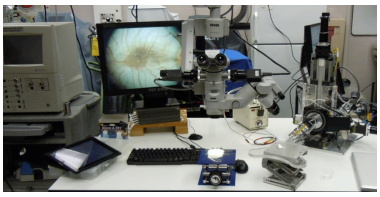
Microsurgery Assistant Workstation

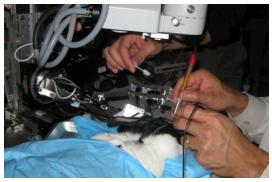


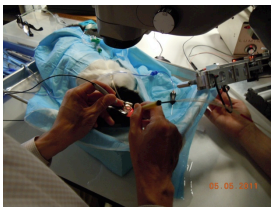
66

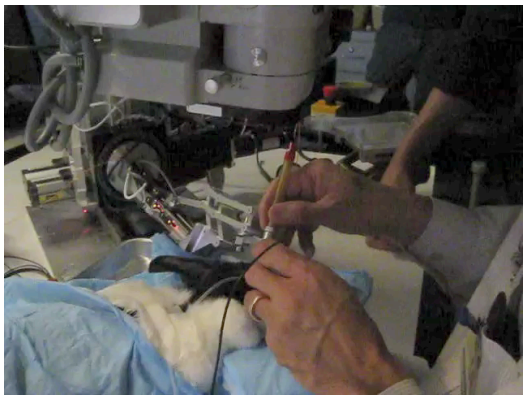
In-Vivo Experiments

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









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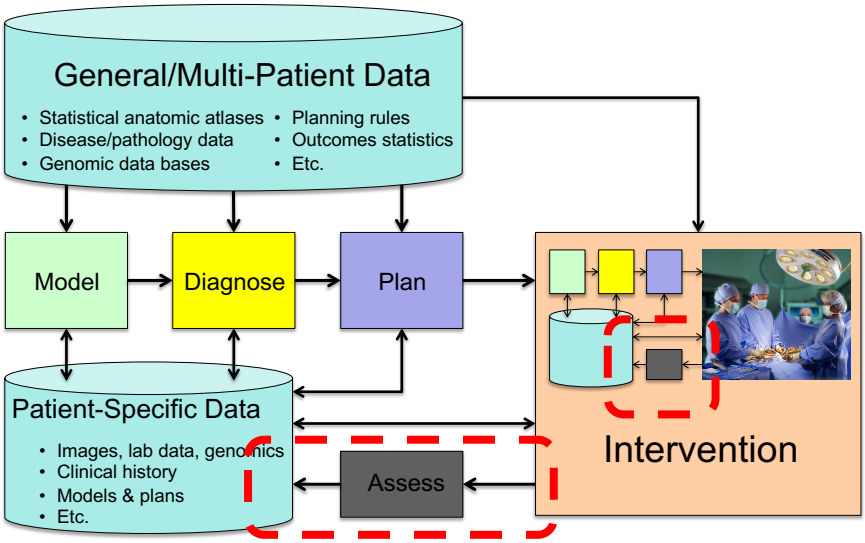
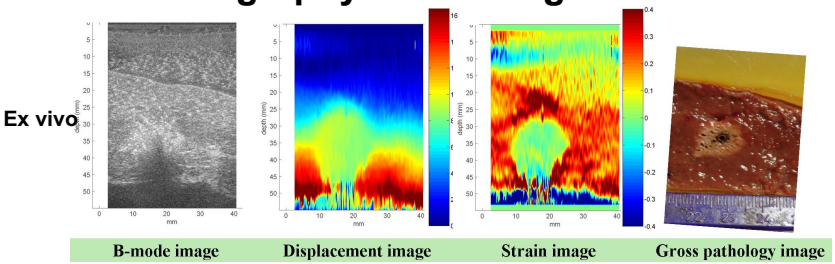
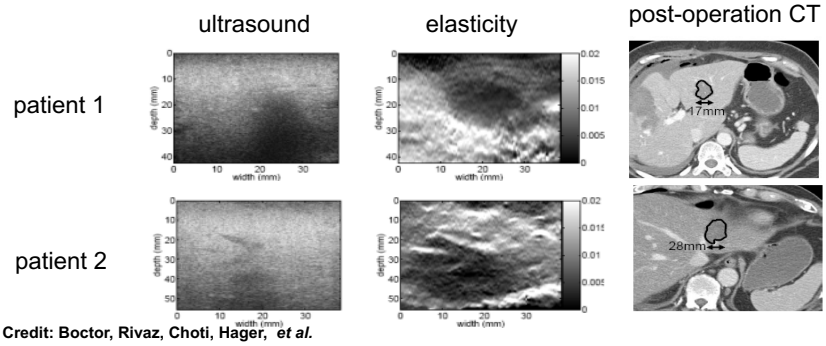
Patient-specific assessment and feedback



68

Elastography monitoring of ablations





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

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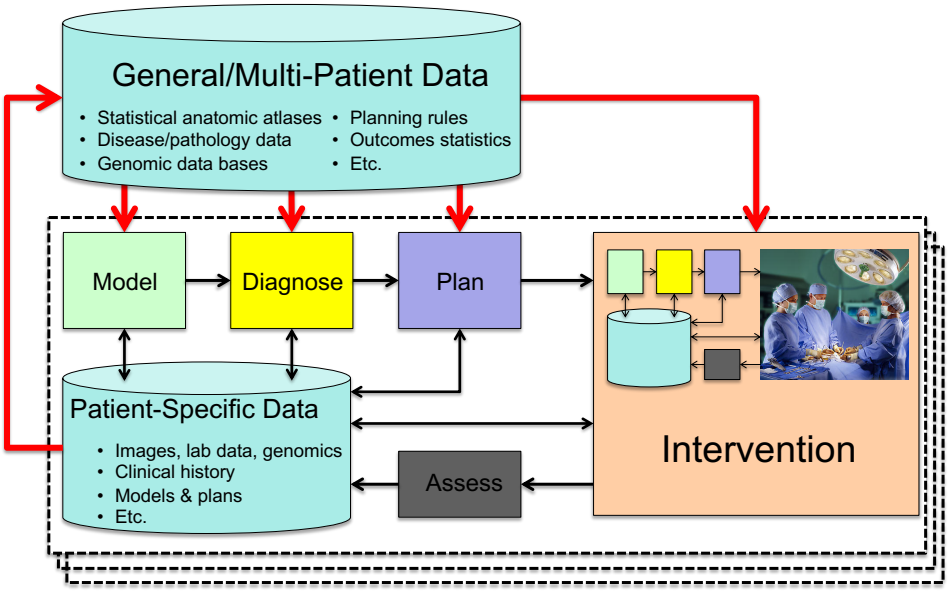
Statistical Analysis and Decision Support



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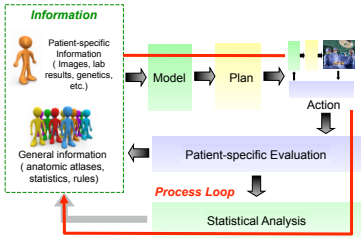
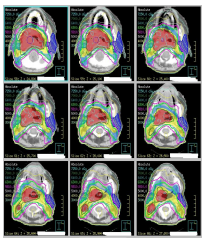
Information-Integrated Process Learning

- **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

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Outer/Population Loop

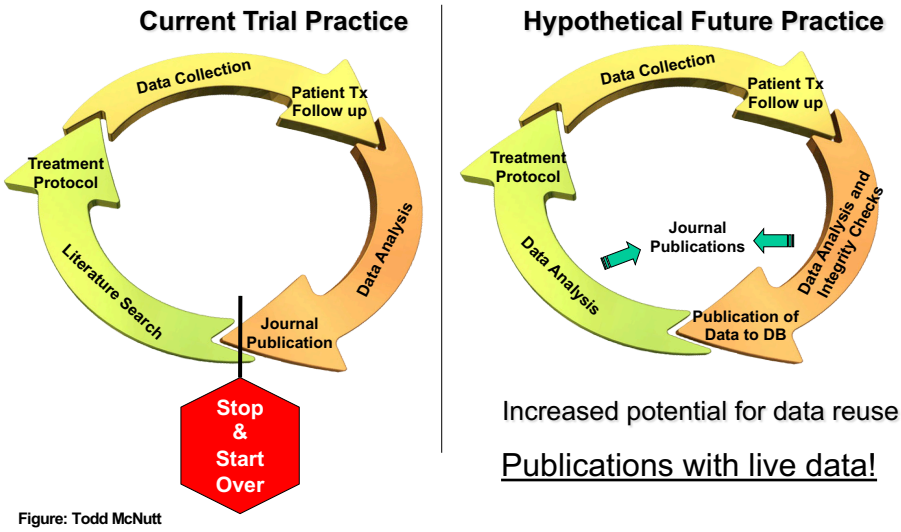

Figure: Todd McNutt

Increased potential for data reuse

Publications with live data!

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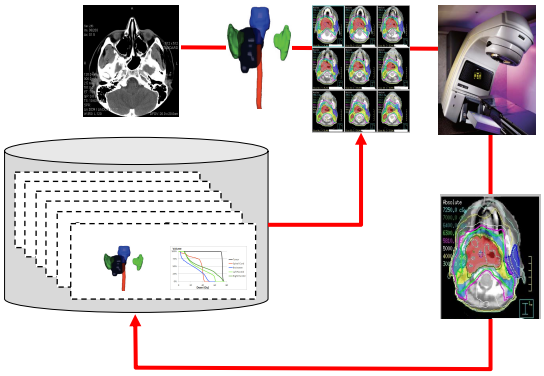
Statistical process control for radiation therapy



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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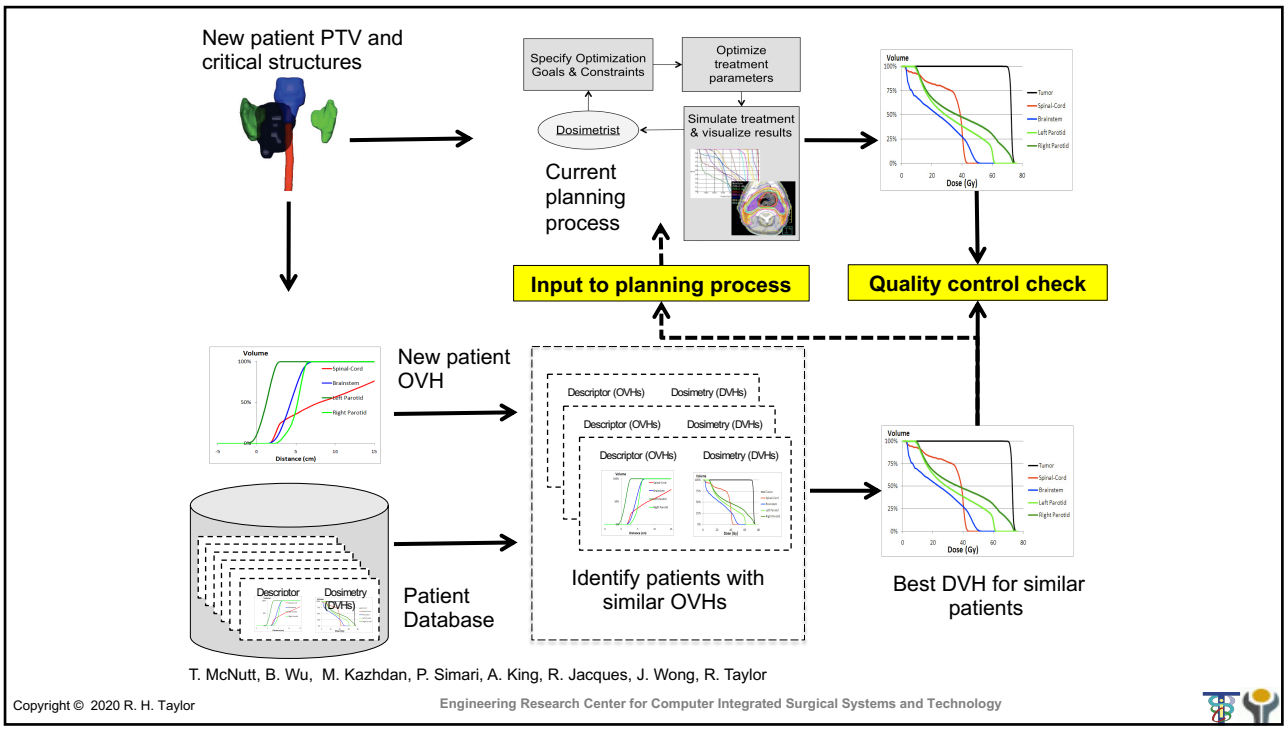

T. McNutt, B. Wu, M. Kazhdan, P. Simari, A. King, R. Jacques, J. Wong, R. Taylor

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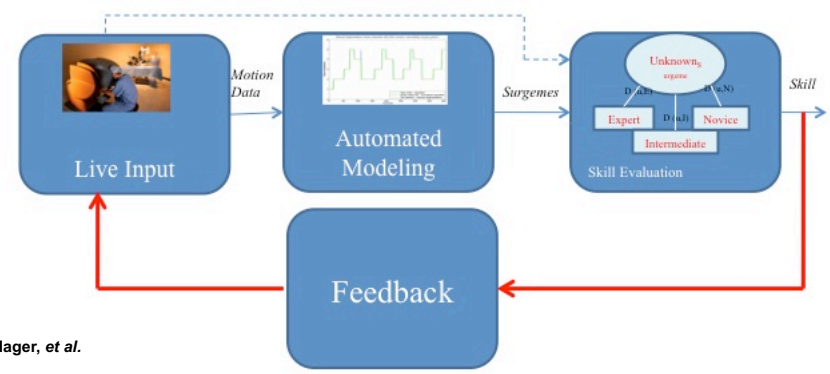
Applications Of Surgical Motion Models

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



G. Hager, *et al.*

Computational Sensing + Robotics

ERC | CISST

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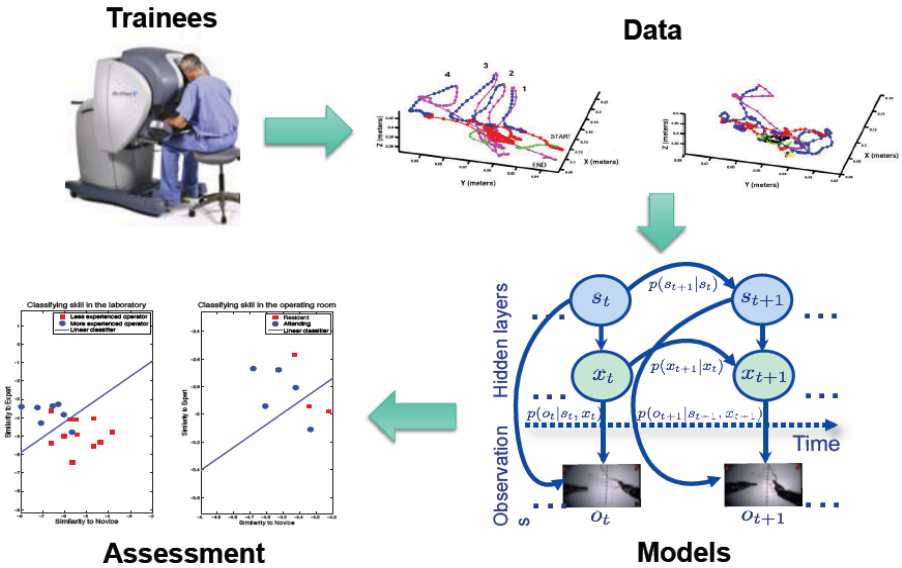
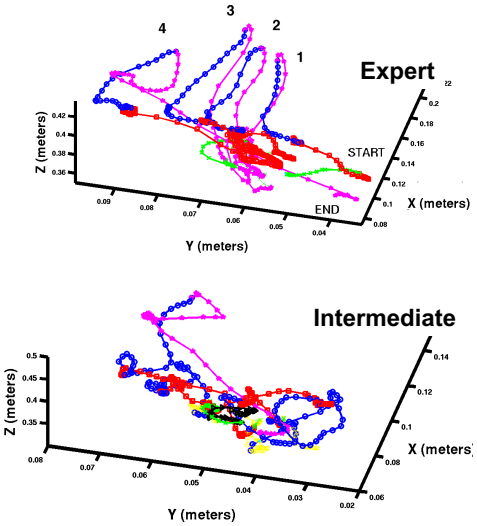
The Language of Surgery

Hager, Khudanpur, Vidal + Chen, Lee, Ishii



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

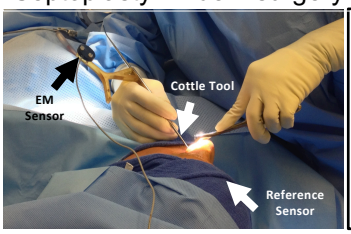
- Goals:
  - Automatic recognition of different surgical motions
  - Comparison of skill level differences between surgeons
- Method
  - Extract features from position and velocity traces
  - Linear discriminant analysis with probabilistic Bayesian classifier

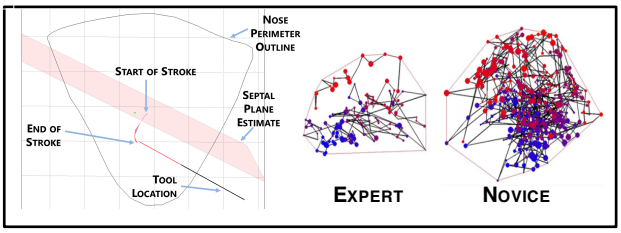


H. Lin, I. Shafran, T. Murphy, D. Yuh, A. Okamura, G. Hager (MICCAI 2005)

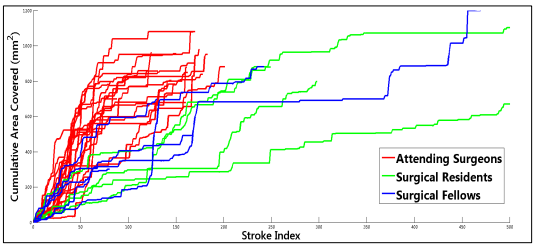
Unstructured surgeries: Discovering “teachable” tactics

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.

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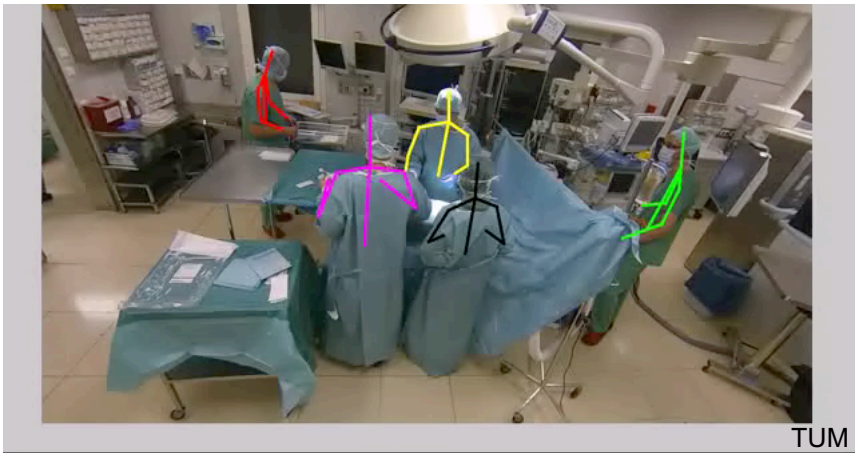
OR Workflow Observation and Analysis

N. Navab *et al.*



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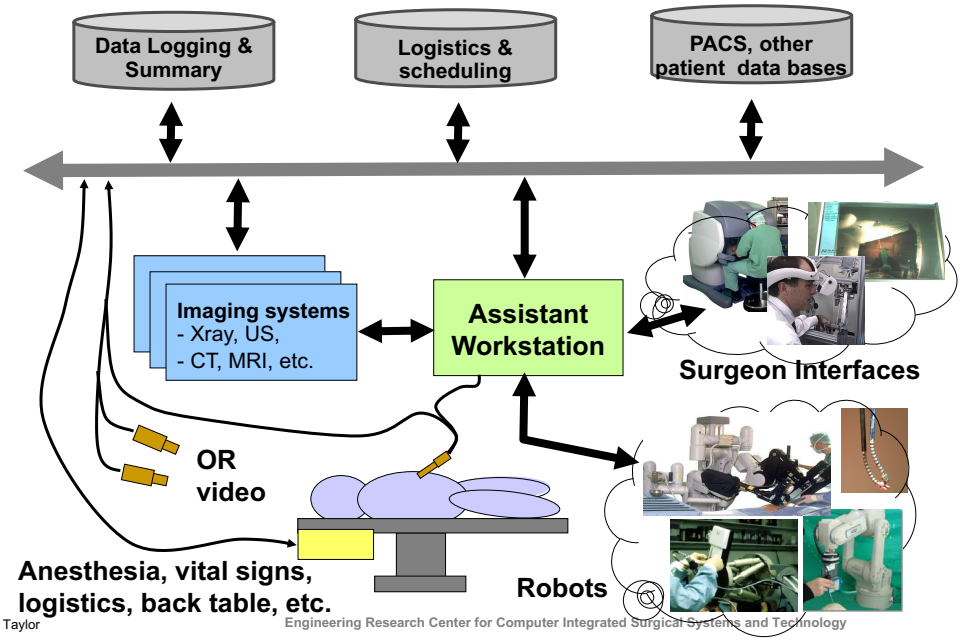
Information-Intensive Interventional Suite



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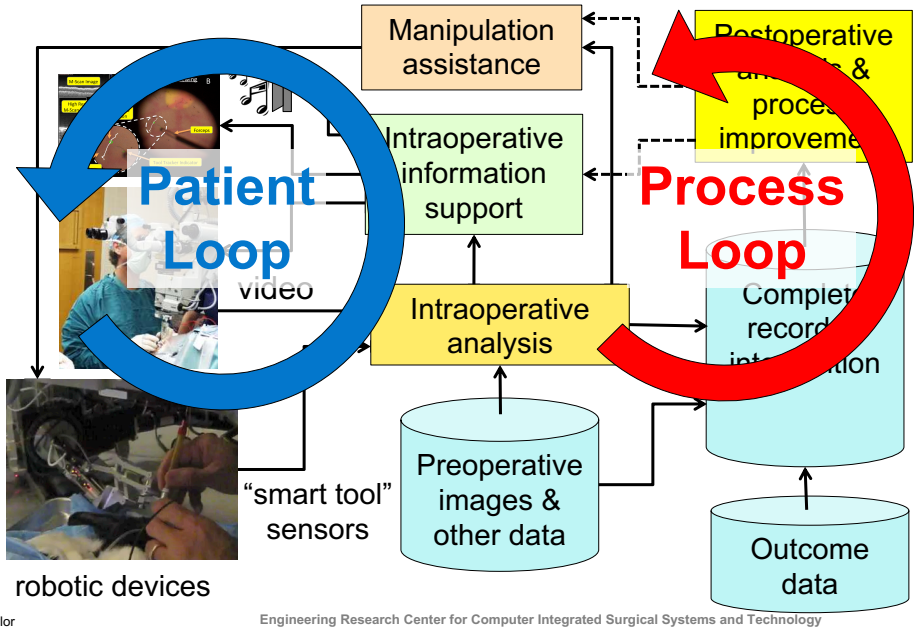
The computer-integrated operating room



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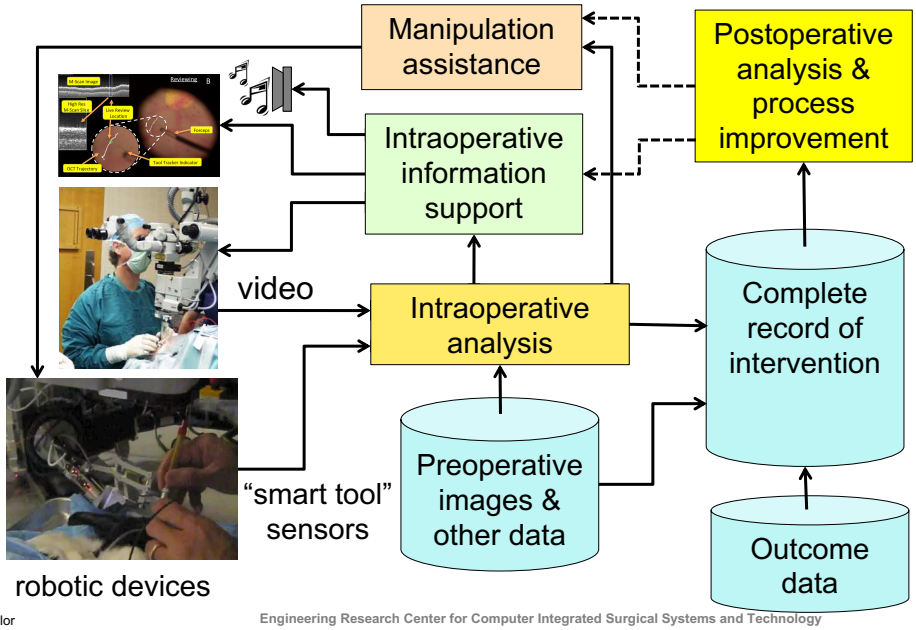
The computer-integrated operating room



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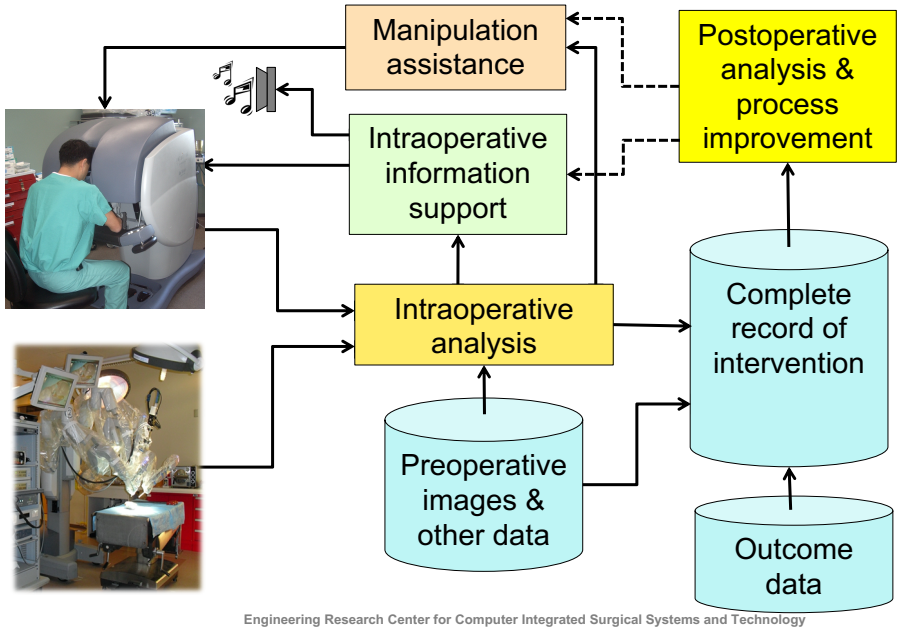
The computer-integrated operating room



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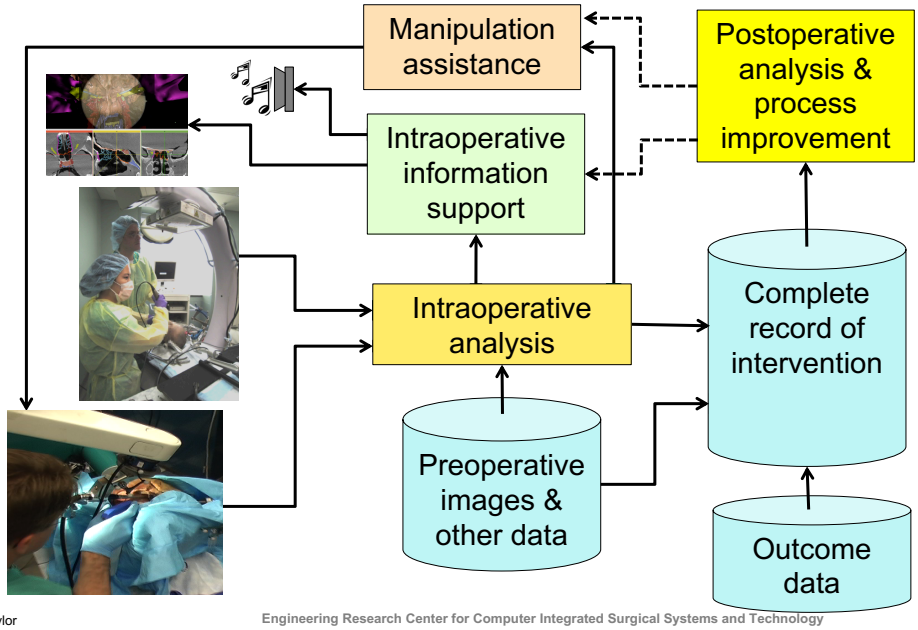
The computer-integrated operating room



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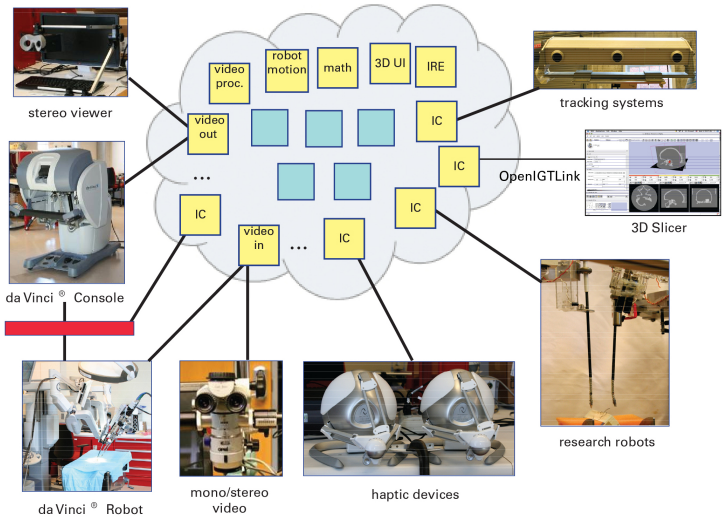
cisst libraries and Surgical Assistant Workstation

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



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

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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/**

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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)

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The real bottom line: patient care

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

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Discussion

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