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

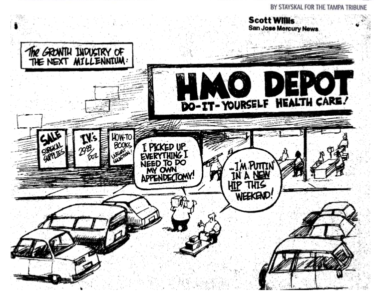
rht@jhu.edu

WHITING
SCHOOL OF
ENGINEERING
THE JOHNS HOPKINS UNIVERSITY

Acknowledgments

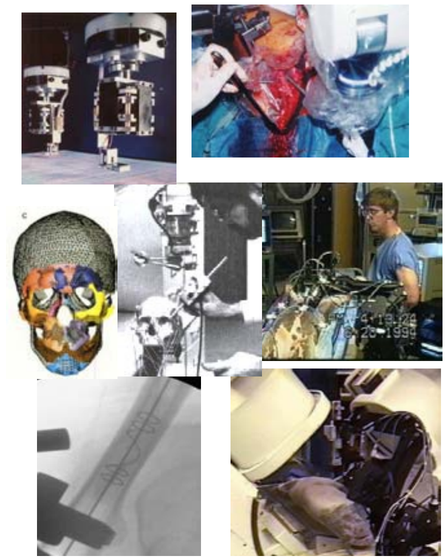
- **This is the work of many people**
- Some of the work reported in this presentation was supported by fellowship grants from Intuitive Surgical and Philips Research North America to Johns Hopkins graduate students and by equipment loans from Intuitive Surgical, Think Surgical, Philips, Kuka, and Carl 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.
- Much of this work has been funded by Government research grants, including NSF grants EEC9731478 and IIS0099770 and NIH grants R01-EB016703, R01-EB007969, R01-CA127144, R42-RR019159, and R21-EB0045457; by Industry Research Contracts, including from Think Surgical and Galen Robotics; by gifts to Johns Hopkins University from John C. Malone, Richard Swirnow and Paul Maritz; and by Johns Hopkins University internal funds.

BY STAYSKAL FOR THE TAMPA TRIBUNE



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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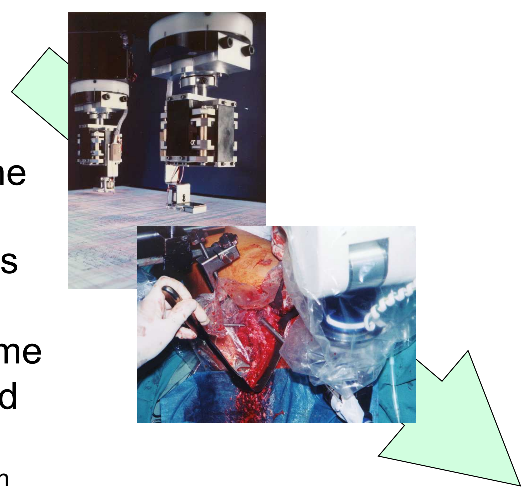
3

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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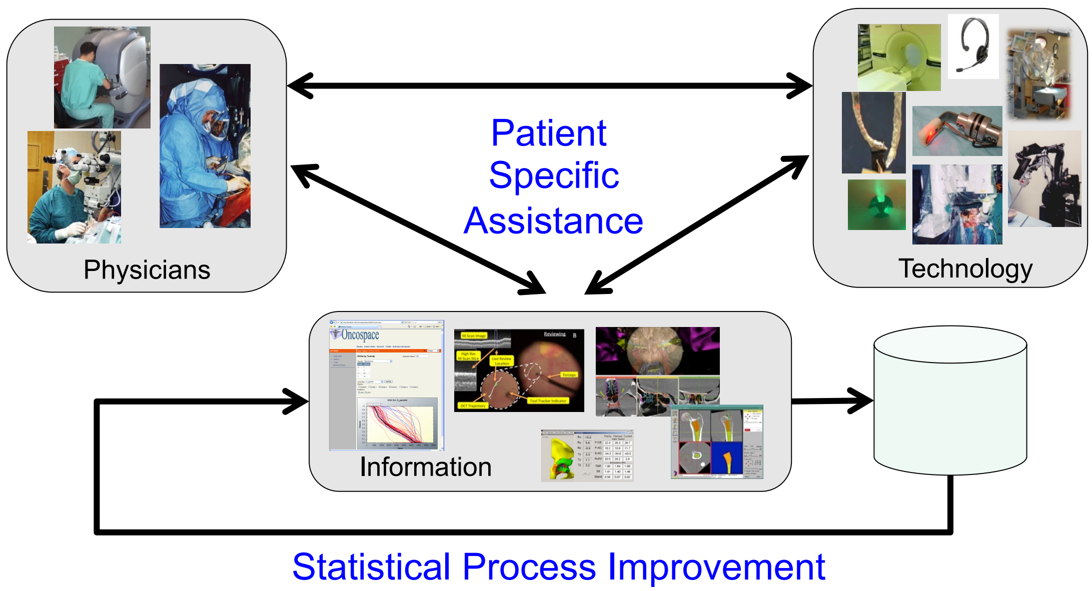
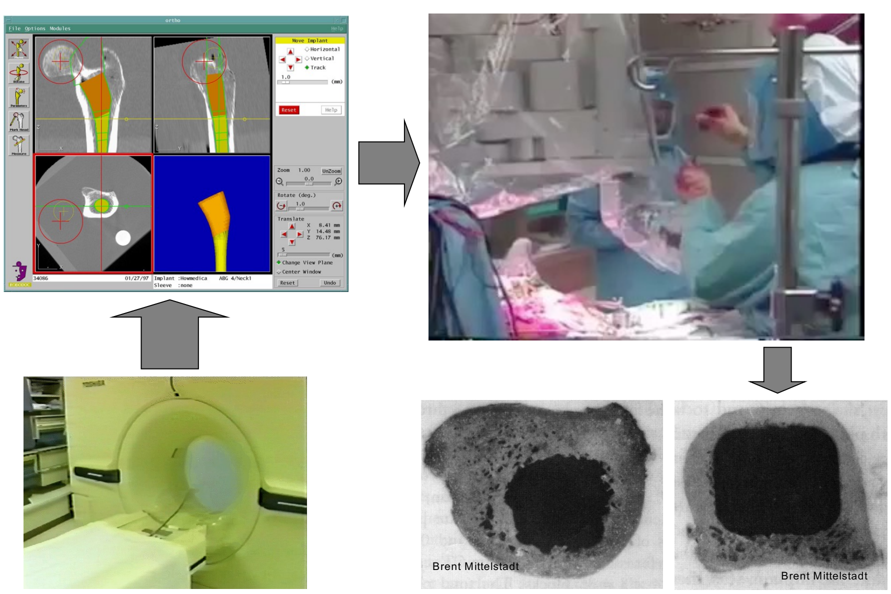
Human-machine partnership to fundamentally improve interventional medicine



Over 25 years ago: Robotic Joint Replacement Surgery



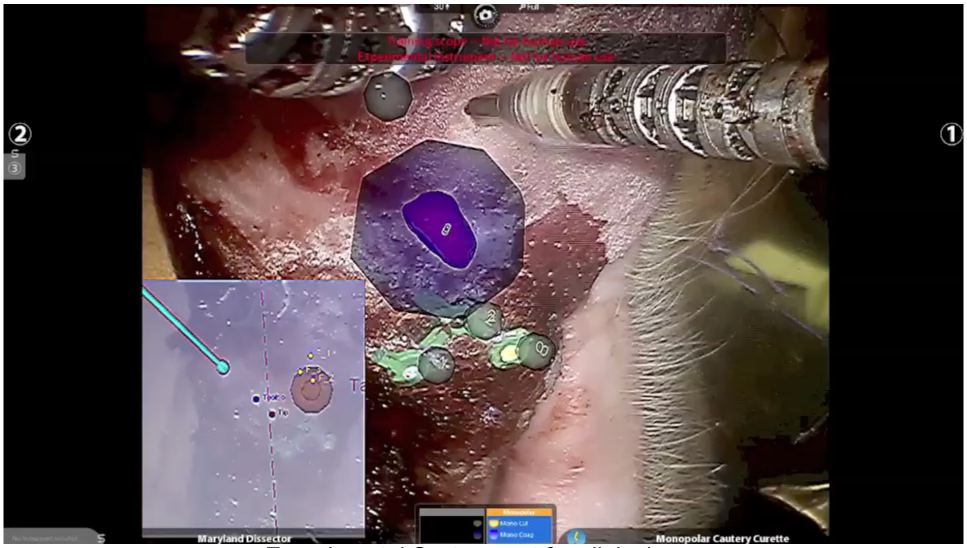
Manual Surgery

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

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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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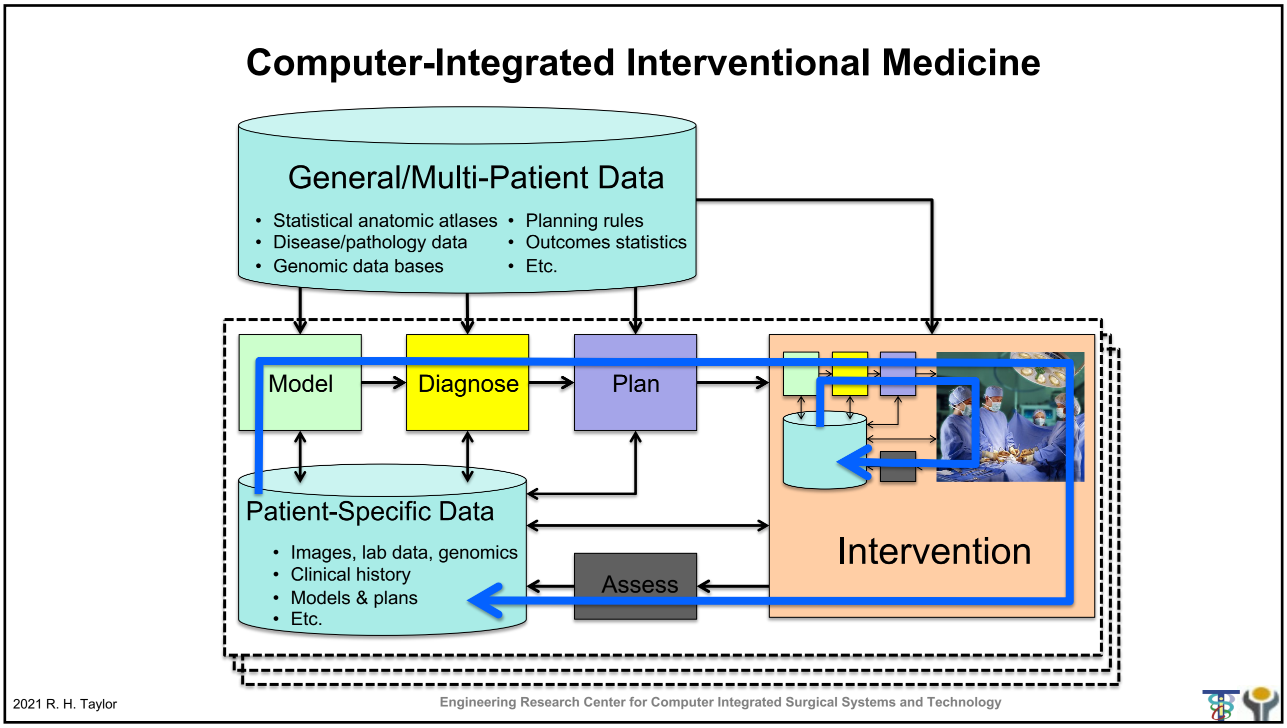
8


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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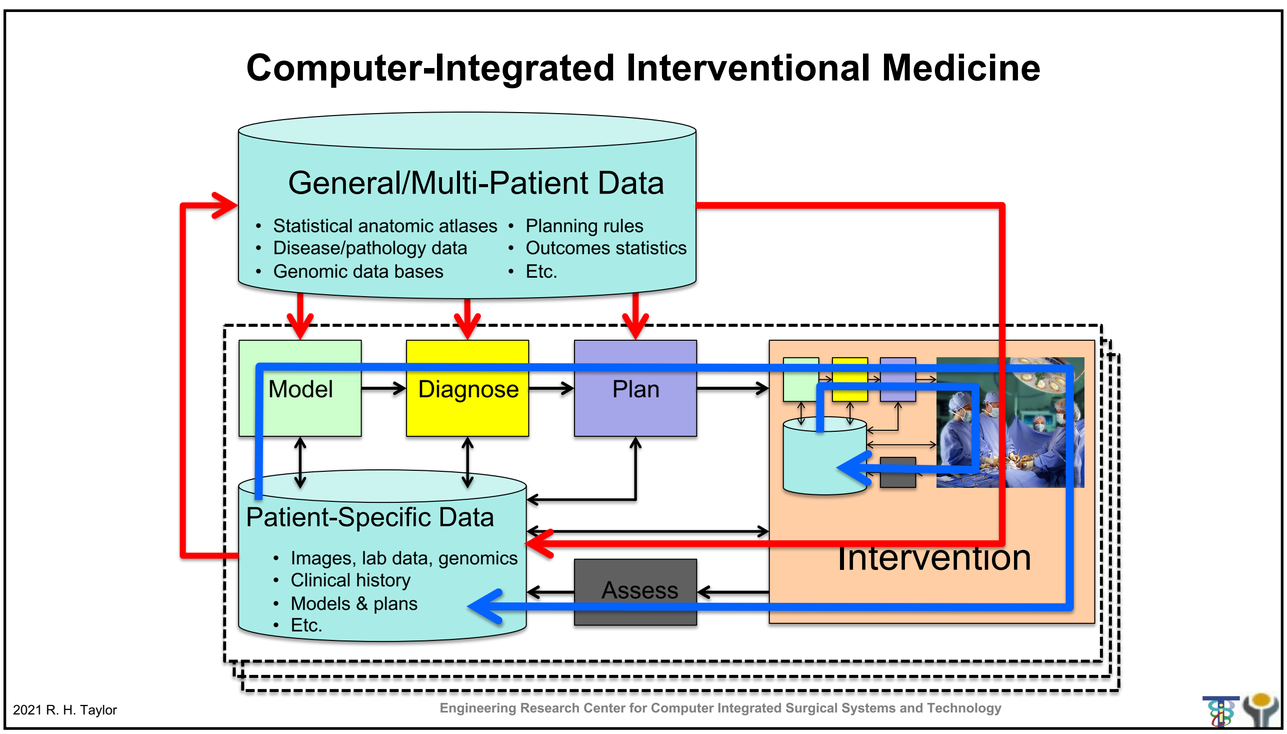
12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Assess
Intervention
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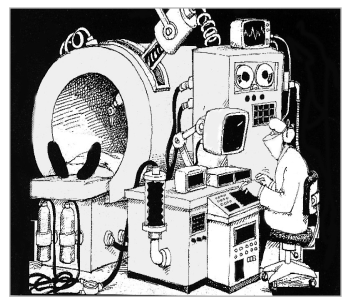
13

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



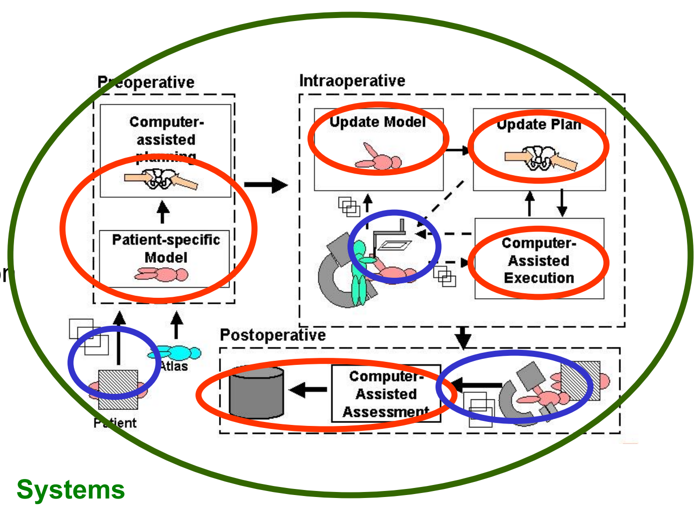
21st Century CE

14

Multidisciplinary Integration is Crucial

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

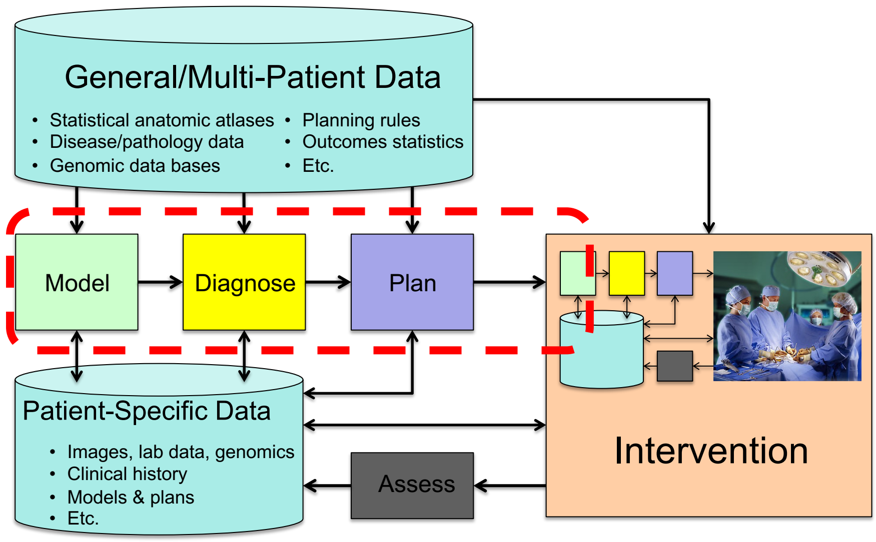
Interface Technology
- Sensing
- Robotics
- Human-machine interfaces



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

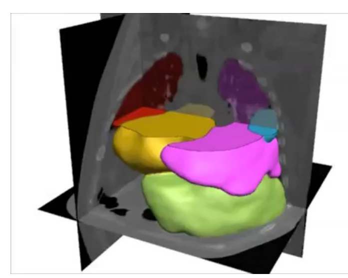
15

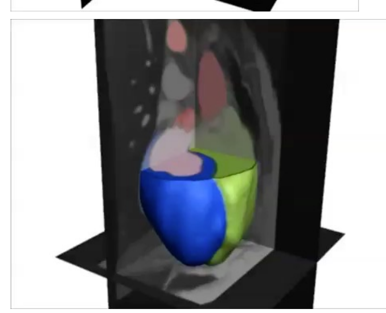
Image-based modeling & analysis



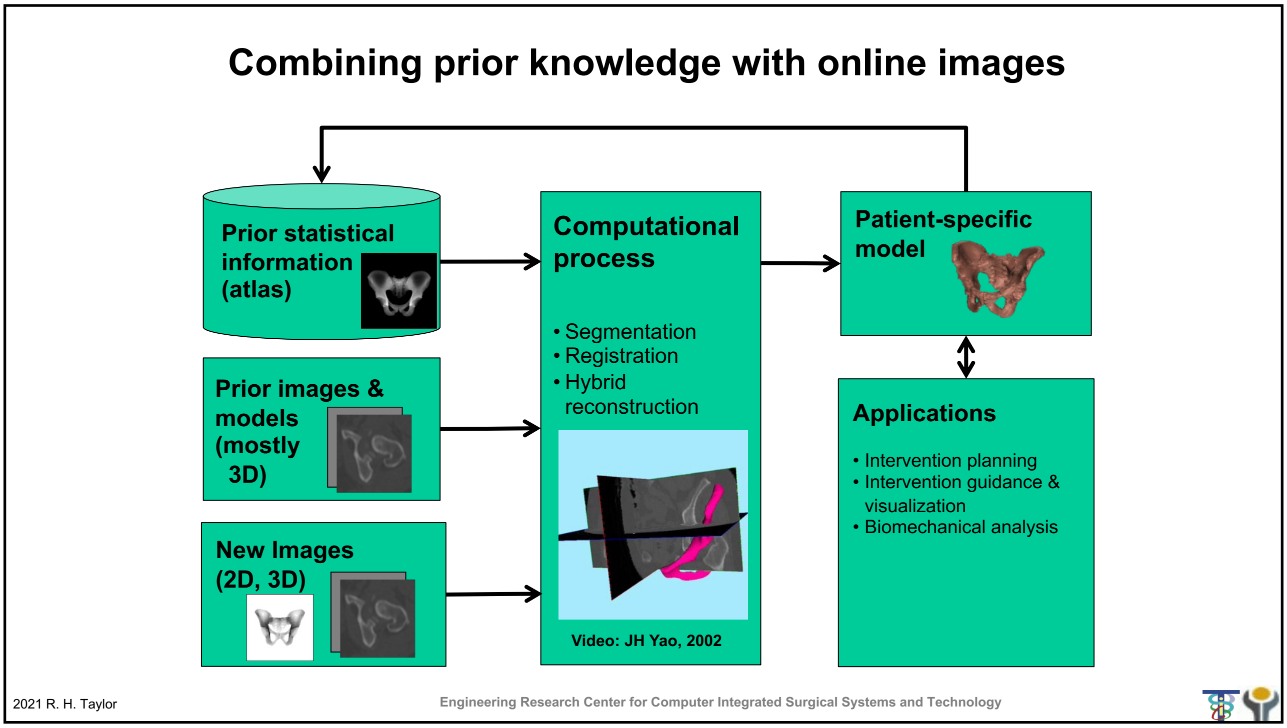
Patient-Specific Models for Interventions

- 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
Prior statistical information (atlas)
Prior images & models (mostly 3D)
New Images (2D, 3D)
Computational process
• Segmentation
• Registration
• Hybrid reconstruction
Video: JH Yao, 2002
Patient-specific model
Applications
• Intervention planning
• Intervention guidance & visualization
• Biomechanical analysis
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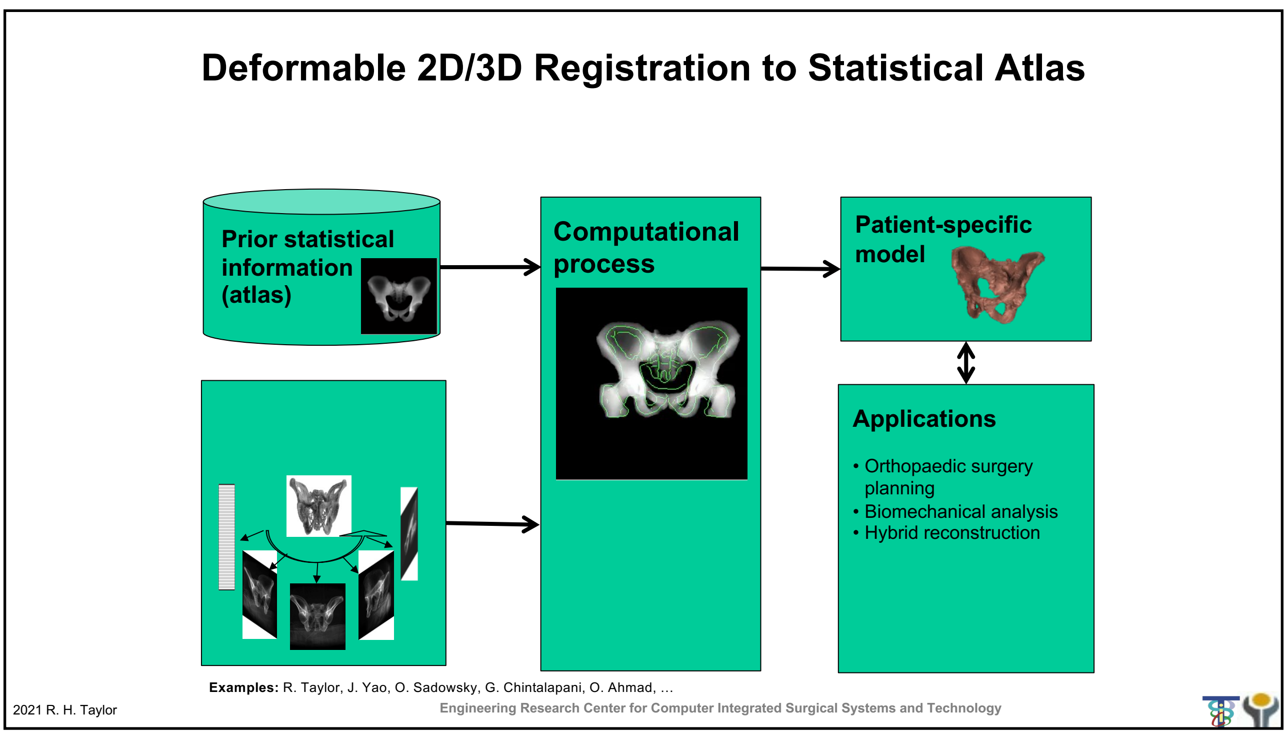
19


Deformable 2D/3D Registration to Statistical Atlas
Prior statistical information (atlas)
Computational process
Patient-specific model
Applications
• Orthopaedic surgery planning
• Biomechanical analysis
• Hybrid reconstruction
Examples: R. Taylor, J. Yao, O. Sadowsky, G. Chintalapani, O. Ahmad, …
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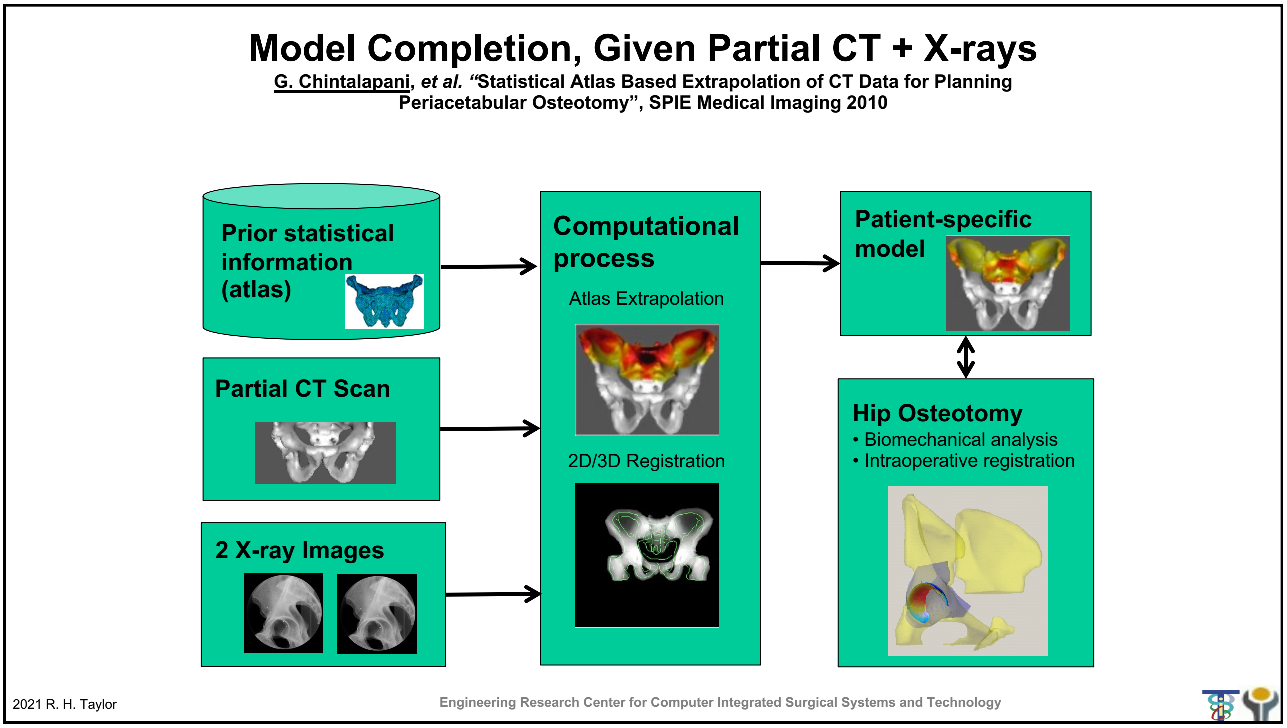
20


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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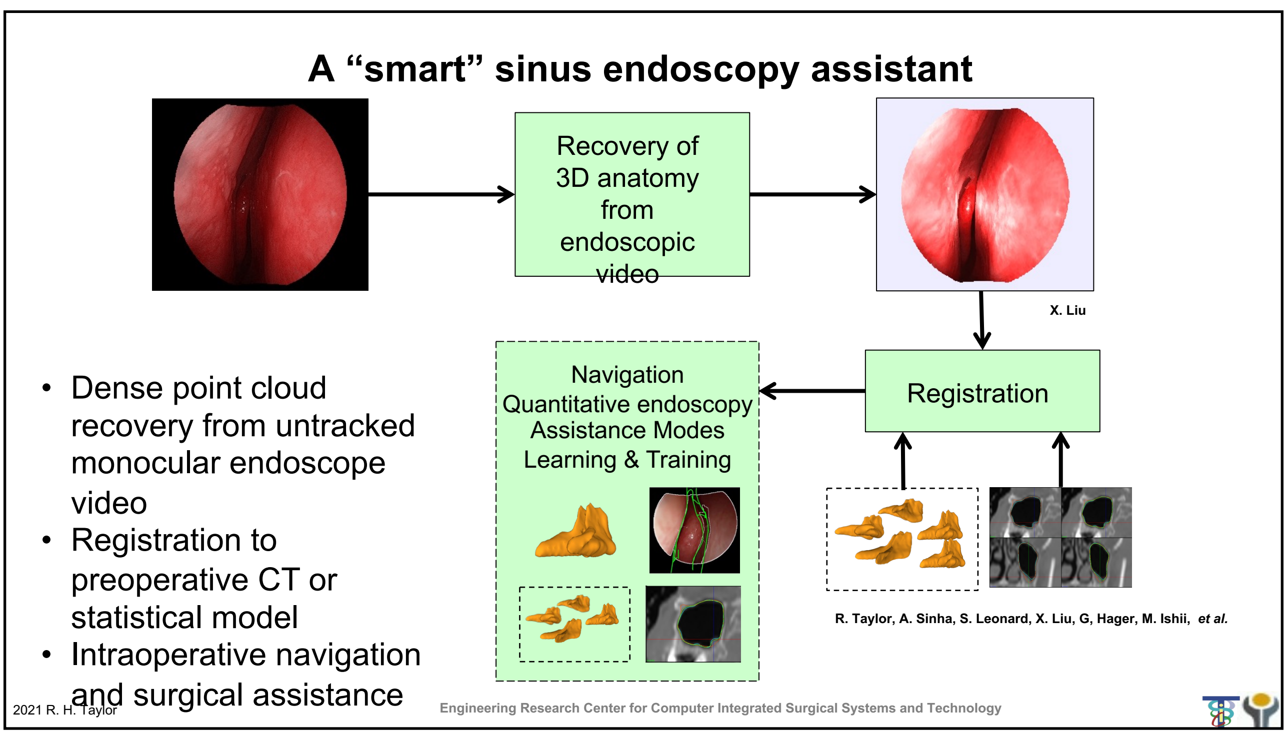
23


A "smart" sinus endoscopy assistant
Recovery of 3D anatomy from endoscopic video
X. Liu
Registration
Navigation
Quantitative endoscopy
Assistance Modes
Learning & Training
• 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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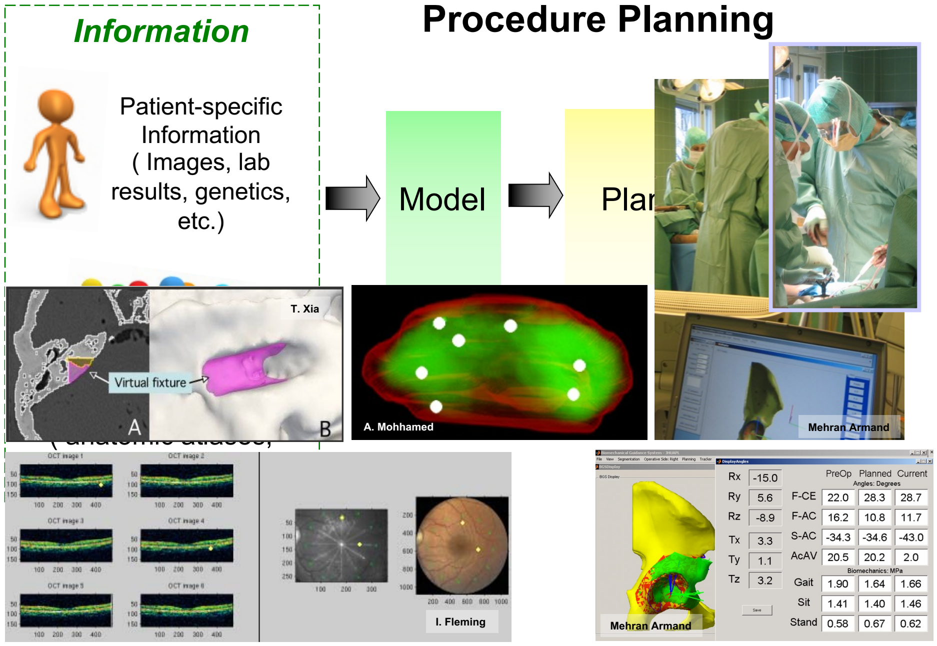
26

Procedure Planning



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

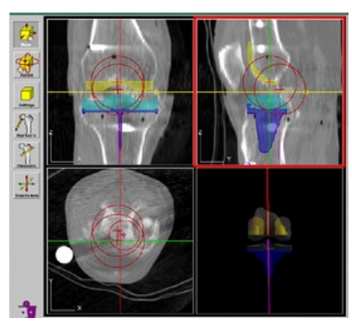
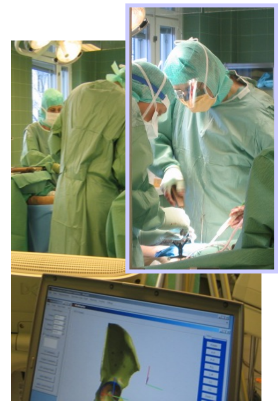
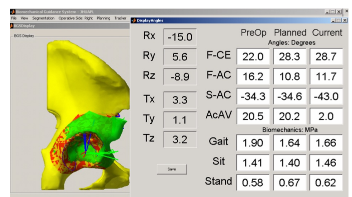


Photo: Integrated Surgical Systems

Procedure Planning

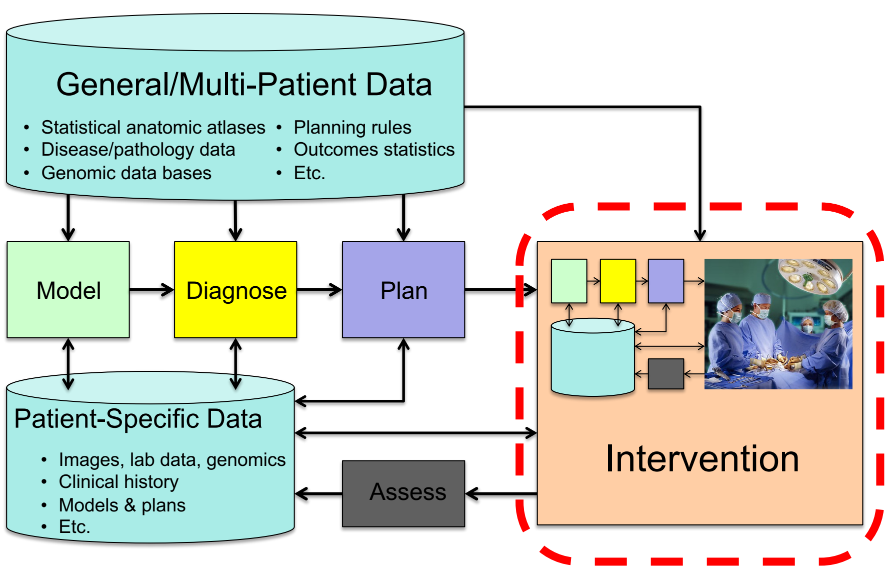
- **Typical outputs**
  - Target positions (seeds, biopsies, ablation sites, etc.)
  - Tool paths
  - Desired geometric relationships
  - Key-frame visualizations
  - Images, models & control parameters
- **Emerging themes**
  - Atlas-based planning
  - Statistical process control & integration of outcomes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





Photos: Mehran Armand

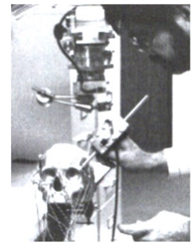
Procedure Execution



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, …

31

Procedure Execution

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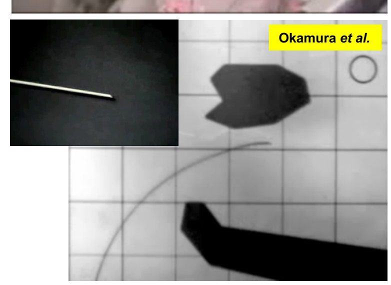

32

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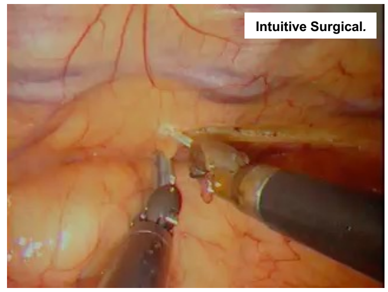

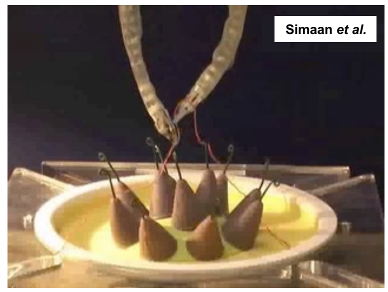

33

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

34

Procedure Execution

- Highly procedure-specific
- Don't always have a robot
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  - Image Overlay
- **But robots can transcend human limitations**
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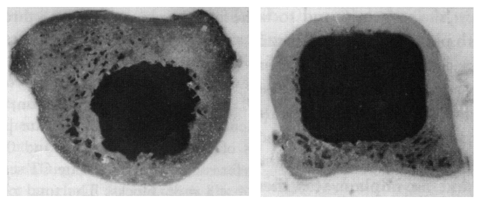

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Procedure Execution

GALEN ROBOTICS

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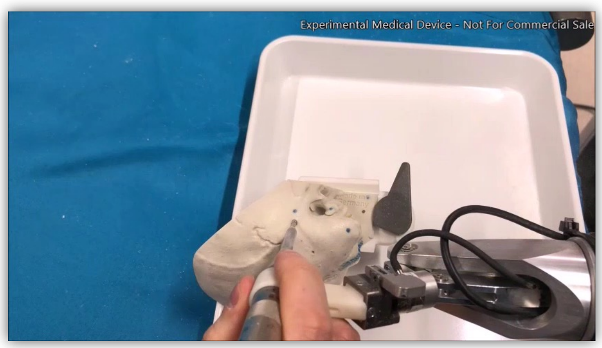

Francis X. Creighton, Christopher R. Razavi, Paul R. Wilkening, Rui Yin, Nicholas Lamaison, Russell H. Taylor, John P. Carey, "Image-Guided Mastoidectomy with the Robotic ENT Microsurgery System (REMS)", *AAO Conference*, October 7, 2018.

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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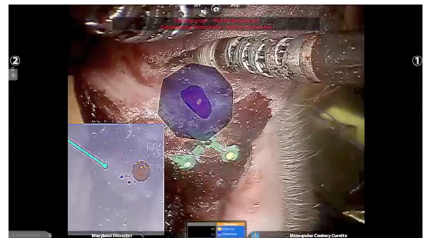
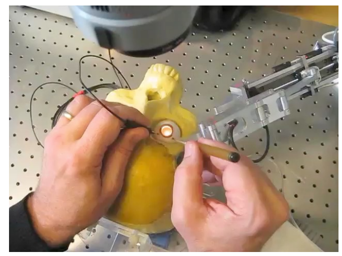
Procedure Execution

- **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



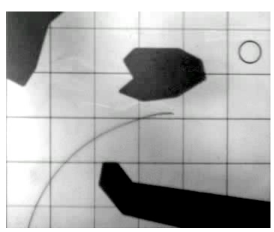
W. Liu, J. Sorger, J. Richmon, R. Taylor, *et al*



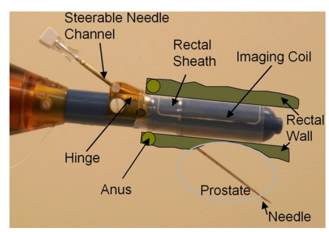
I. Iordachits, R. Taylor, *et al*

Image-guided needle placement

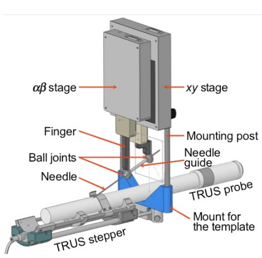
Masamune, Fichtinger, Iordachita, …



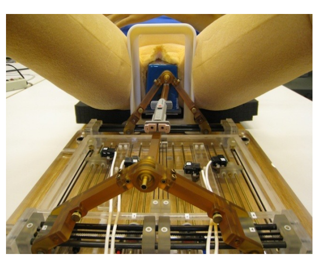
Okamura, Webster, …



Krieger, Fichtinger, Whitcomb, …



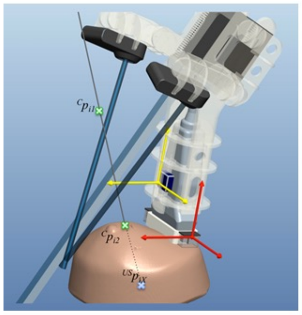
Fichtinger, Kazanzides,Burdette, Song …

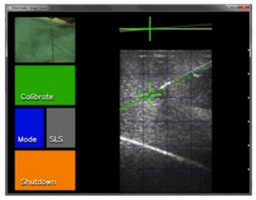


Iordachita, Fischer, Hata…

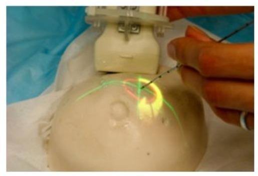
Taylor, Masamune, Susil, Patriciu, Stoianovici,…

Example: Ultrasound-guided needle placement

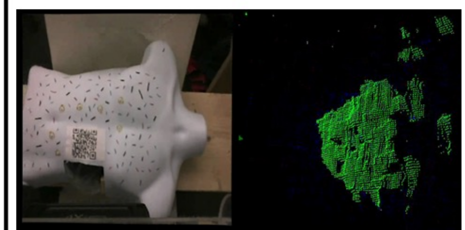




Traditional ultrasound screen AND on-screen guidance overlay



As well as on-patient projection



Real-time multi-modal fusion

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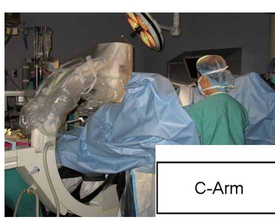
39

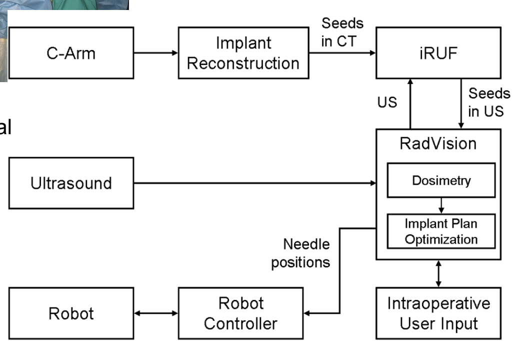
TRUS Robot for Prostate Brachytherapy

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

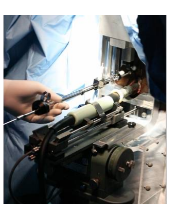


<u>Current efforts</u>:

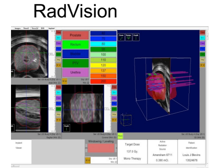
- Integration with RadVision / RUF project
- Needle quick-release mechanism
- Intraoperative user interface (sterile touchscreen)



Robot clinical trial



RadVision



Prototype sterile touchscreen: Digital Dash

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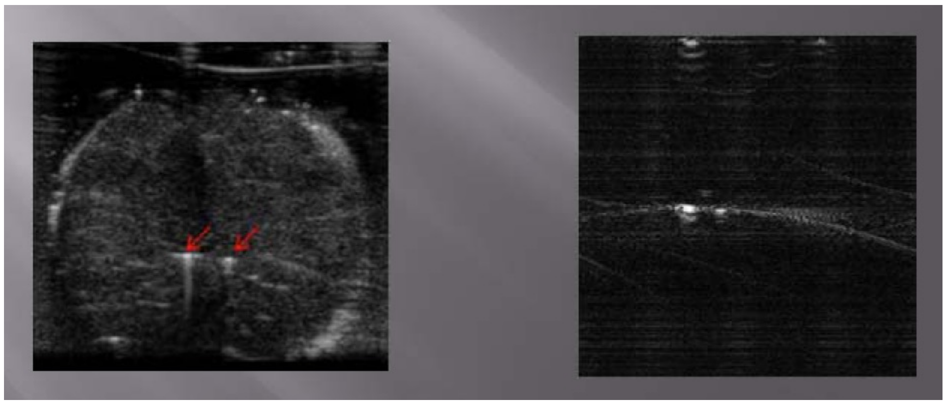
40

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

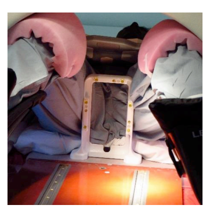


B-mode PA-mode

41

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

Patient ready on scanner table

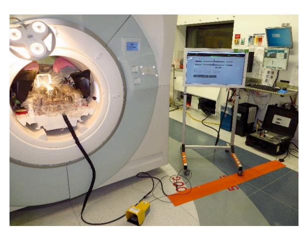


Z-frame in position

Drape robot, attach needle guide

Slide in robot until hit Z-frame

Lock robot in place

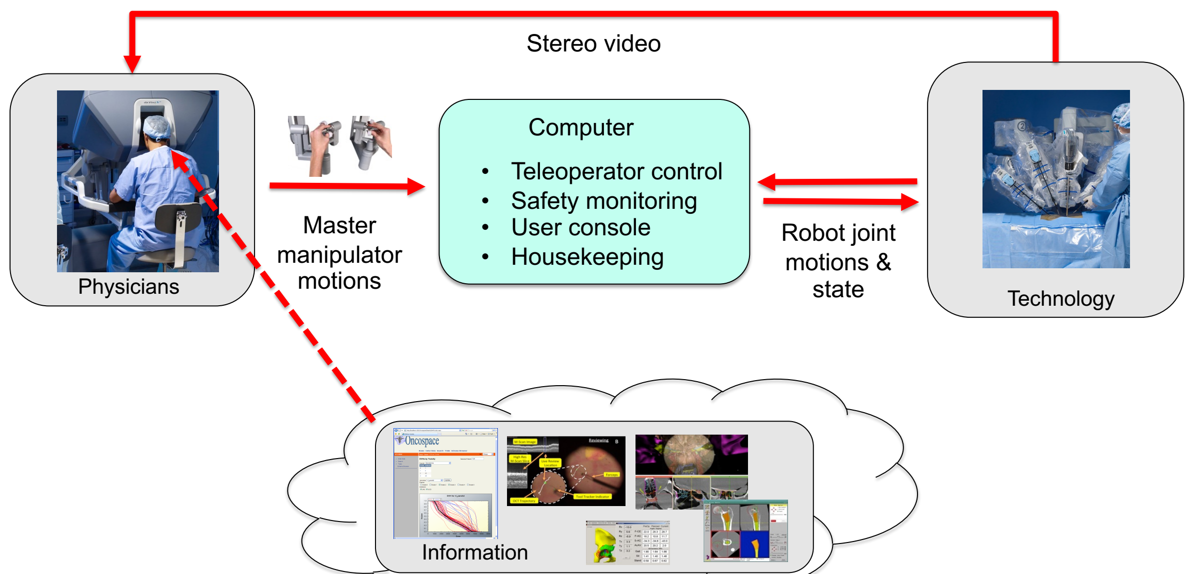


Robot ready for targeting

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

42

Current dominant paradigm for interactive surgery



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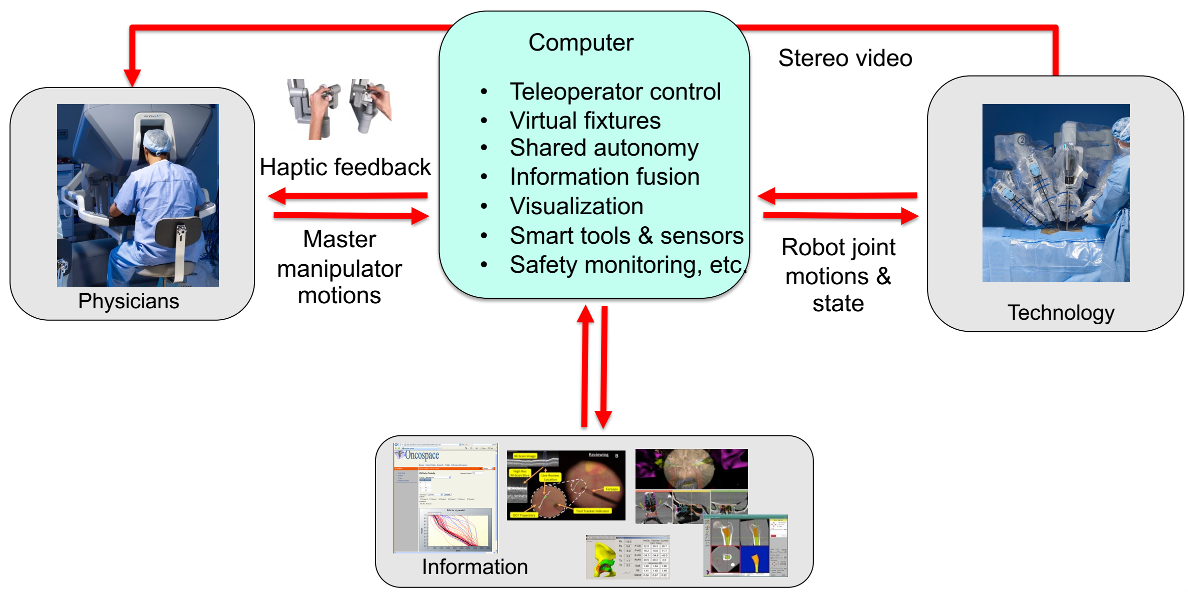
43

Emerging paradigm (shared autonomy & assistant modes)



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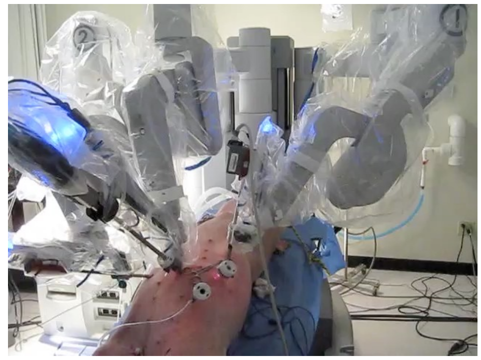
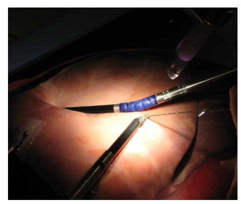
44

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

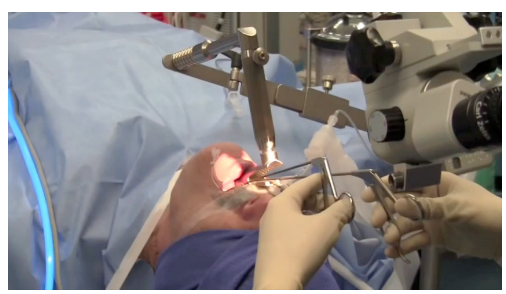


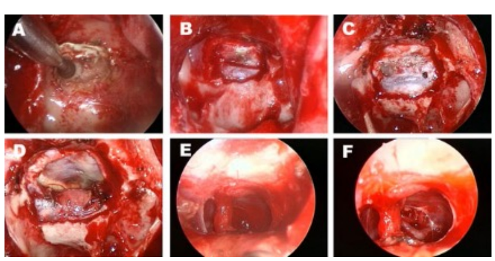


Research DaVinci Application – Not for Human Use

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



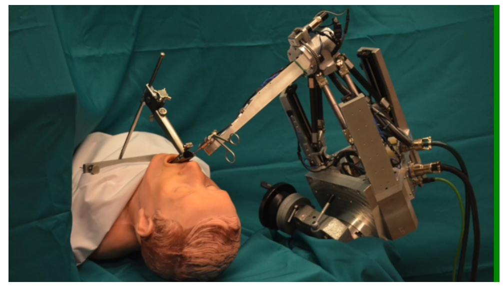


The Robotic ENT Microsurgery System (REMS)

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.

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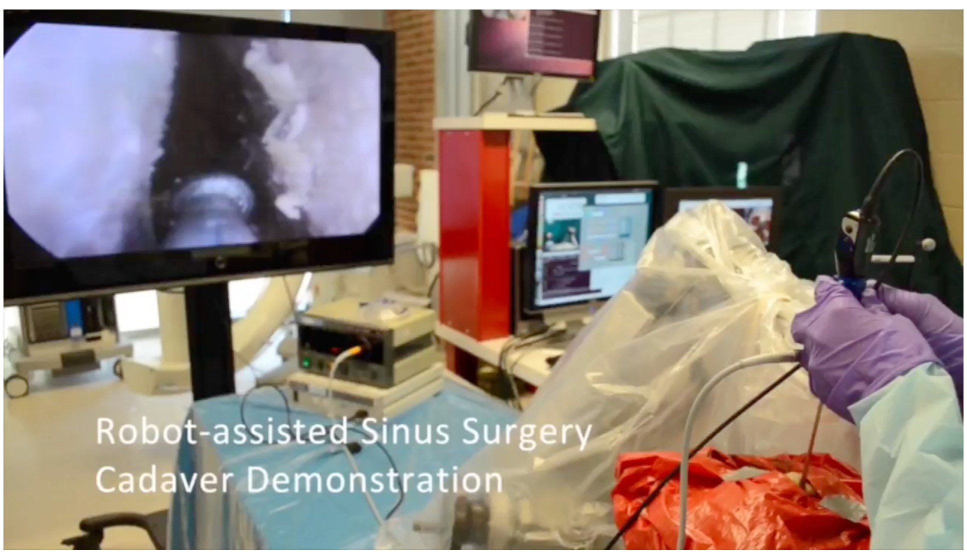
53

Cadaver Study: Sinus Surgery with Virtual Fixtures



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

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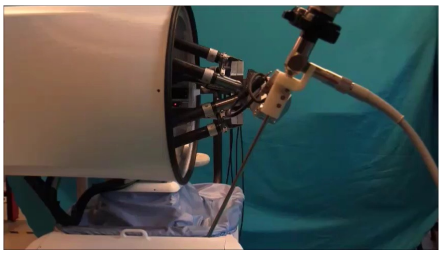
55

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

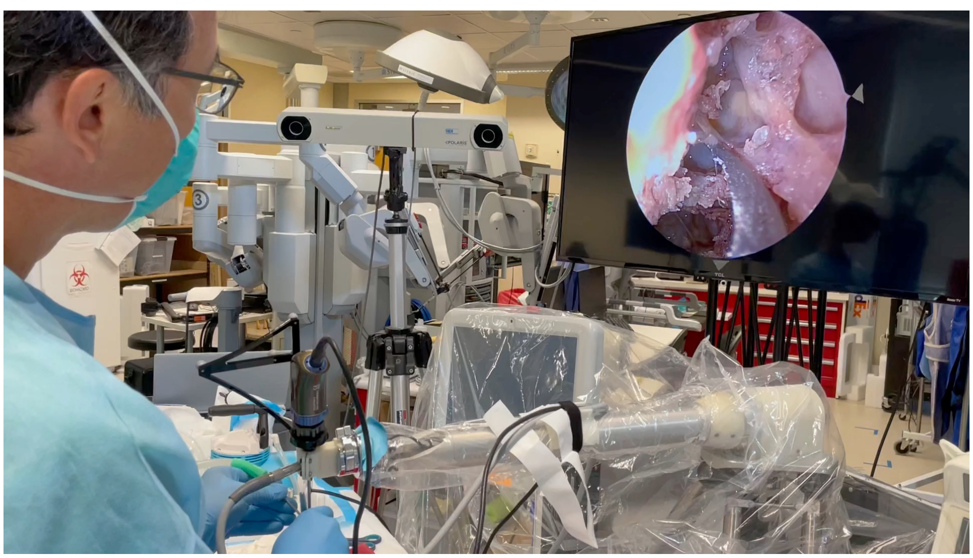
Broad Applications:
- ENT, spine, brain, trauma, ….

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.

56

GALEN ROBOTICS

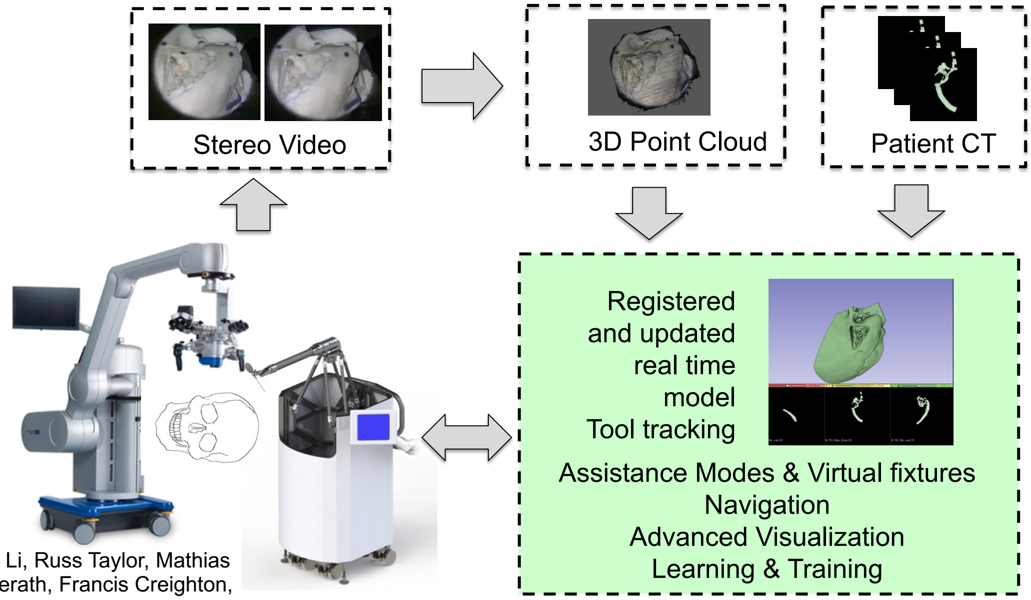
Recent Cadaver Study with Galen Robot



M. Ishii, M. Sahu, R. Taylor

57

A “smart” skull base surgical assistant

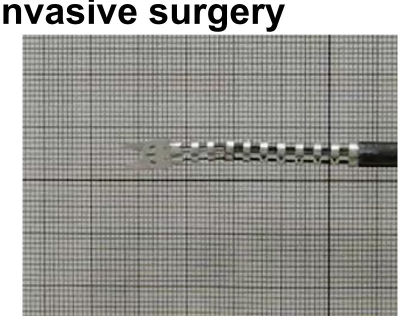


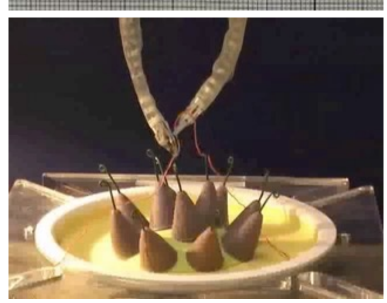
Max Li, Russ Taylor, Mathias Unberath, Francis Creighton,

58

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



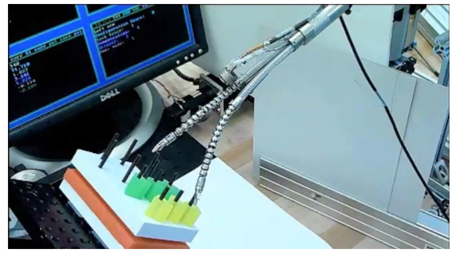
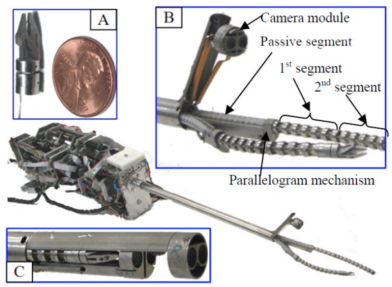


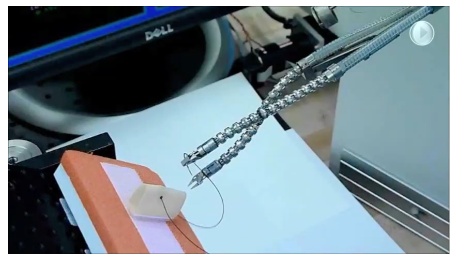
R. Taylor, N. Simaan, *et al.*

59

Single Port Access Surgery

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

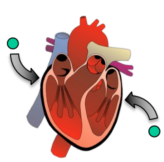






New technology finally allows true evaluation of the potential of single port access surgery. Systems raise new questions about control and telemanipulation infrastructure/cooperative control.

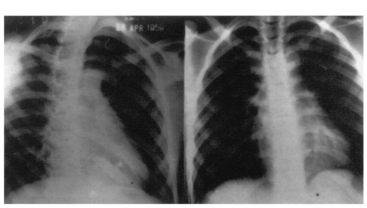
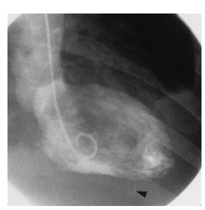
Foreign Bodies in the Heart

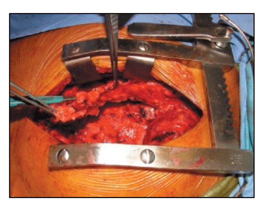
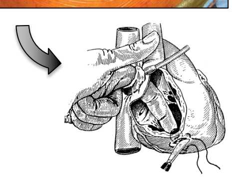
Causes
Thrombi, Shrapnel
Iatrogenic



Symptoms
Cardiac Tamponade
Hemorrhage
Arrhythmia
Infection
Shock
Embolism
Valve Dysfunction

Conventional Treatment
Median Sternotomy
Cardiopulmonary Bypass

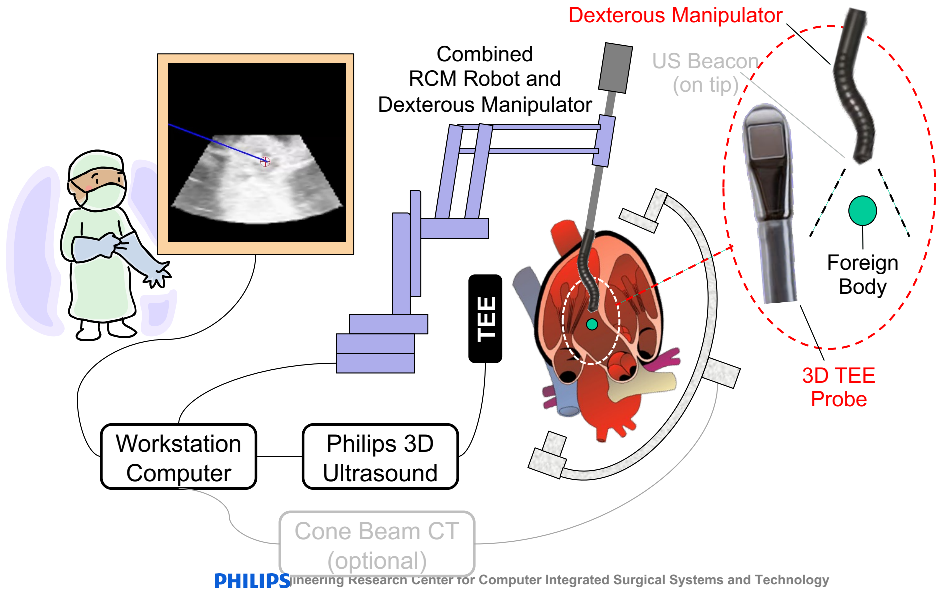



(Actis Dato, 2003)

(LeMaire, 1999)

Beating Heart MIS with 3D US Guidance

Paul Thienphrapa, Aleksandra Popovic, Russell Taylor



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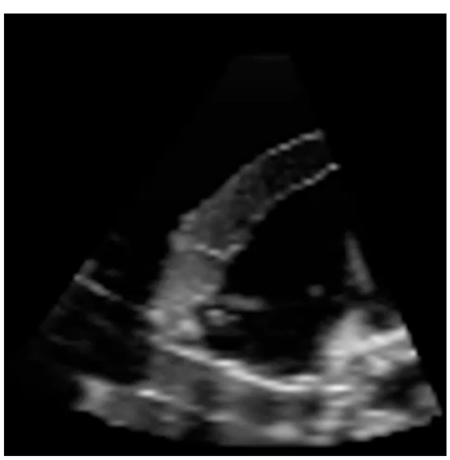
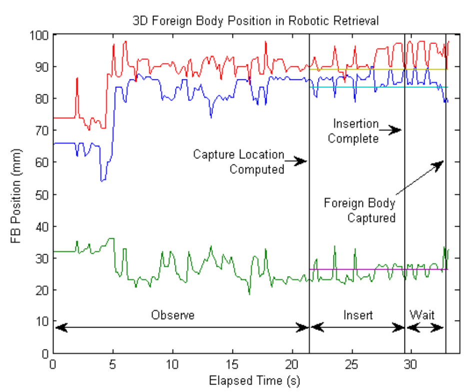
68

Retrieval Experiment Results





PHILIPS

Thienphrapa *et al.* 2013

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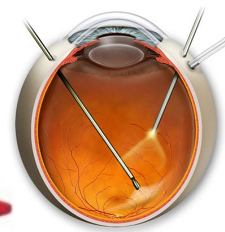
70

Vitreoretinal Microsurgery

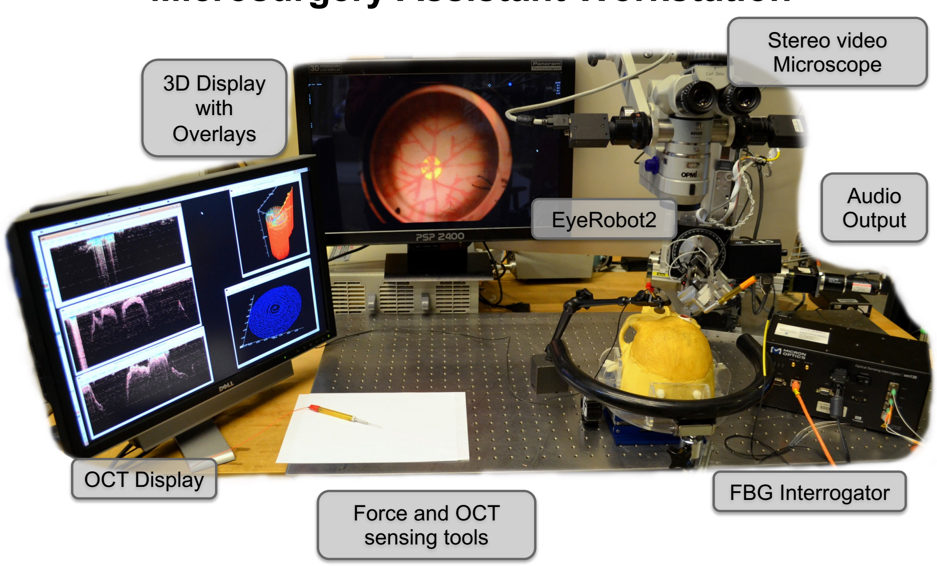
British Journal of Ophthalmology 2004 - Akifumi Ueno et al



www.eyemdlink.com

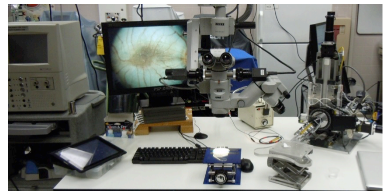
Alcon Vitreosurgery Instrument

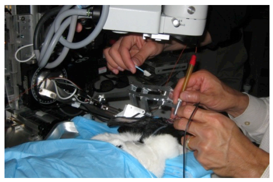
Microsurgery Assistant Workstation

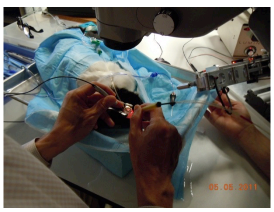


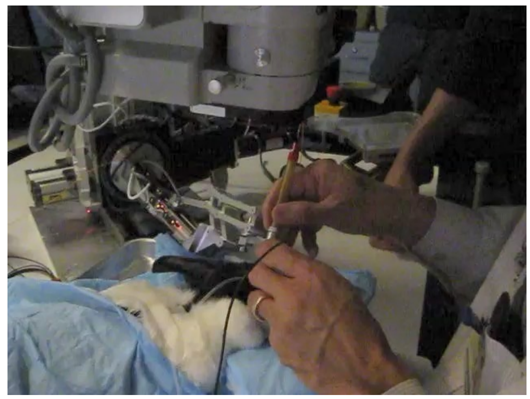
In-Vivo Experiments

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









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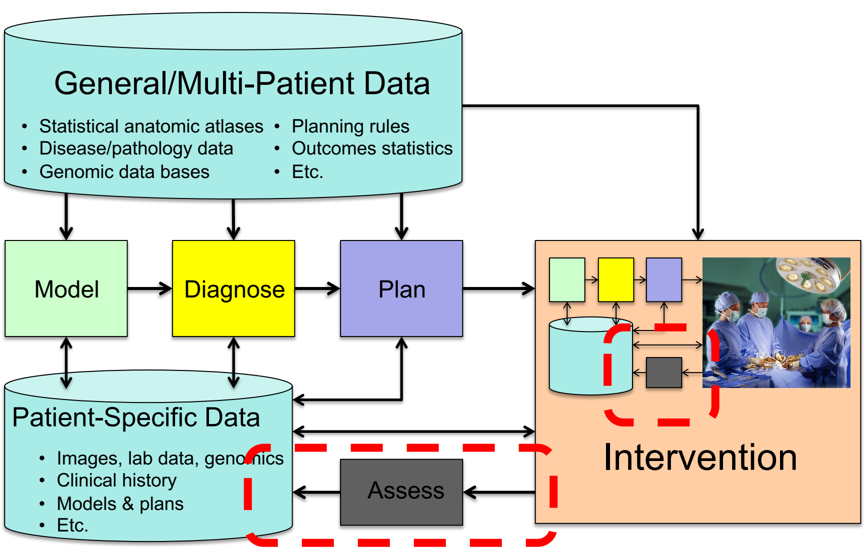
74

Patient-specific assessment and feedback



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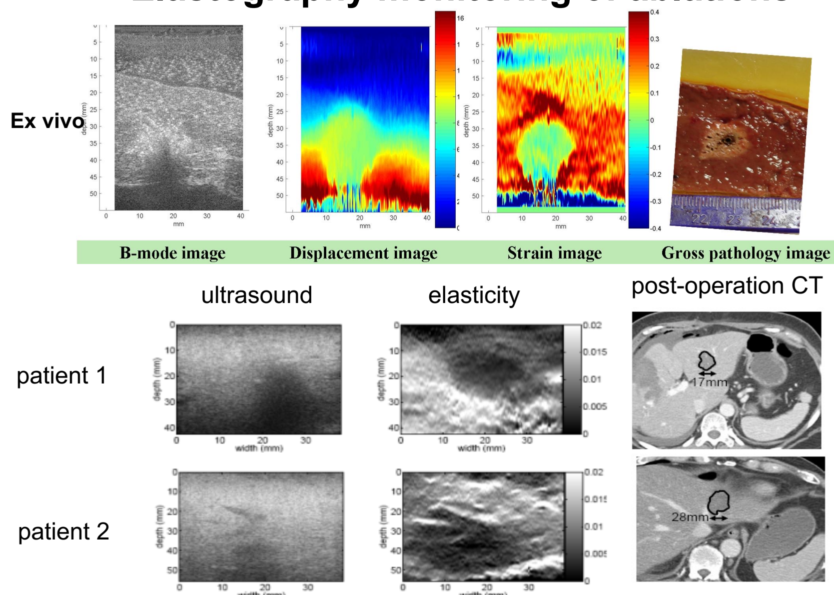
75

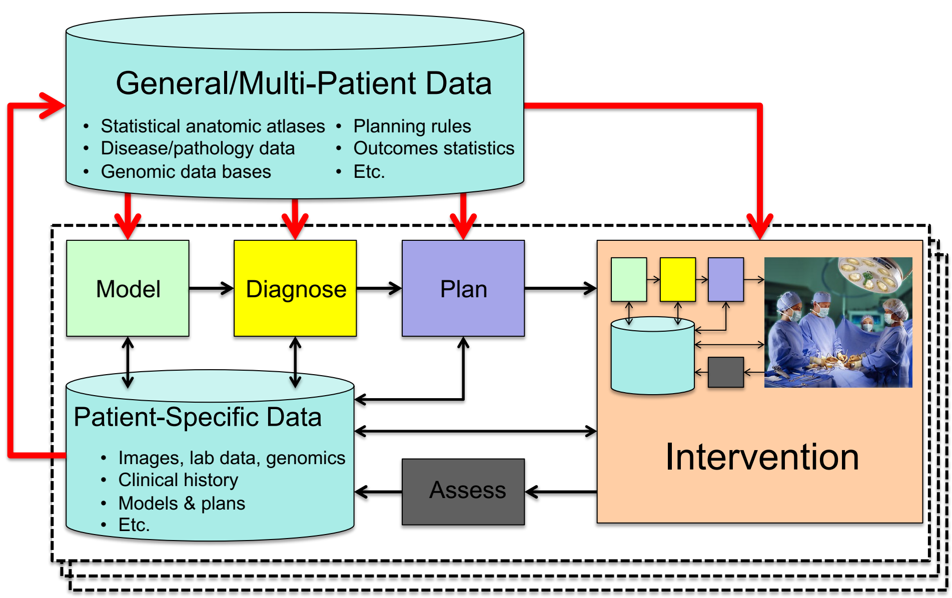
Elastography monitoring of ablations



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

76

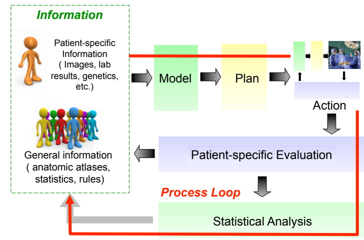
Statistical Analysis and Decision Support

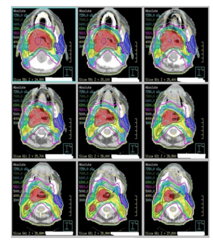


82

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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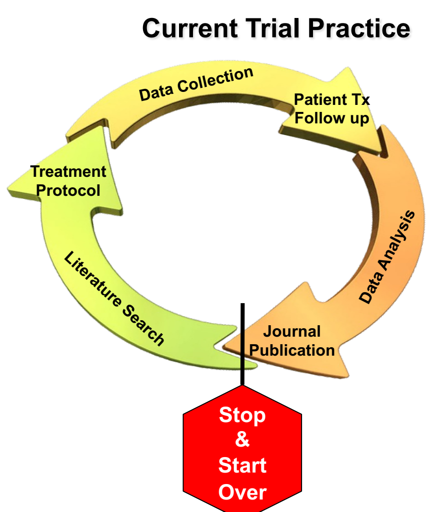
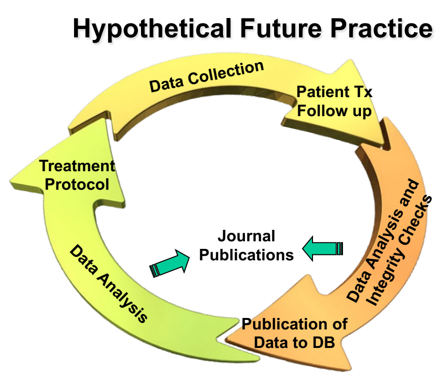
83

Outer/Population Loop





Increased potential for data reuse

<u>Publications with live data!</u>

Figure: Todd McNutt

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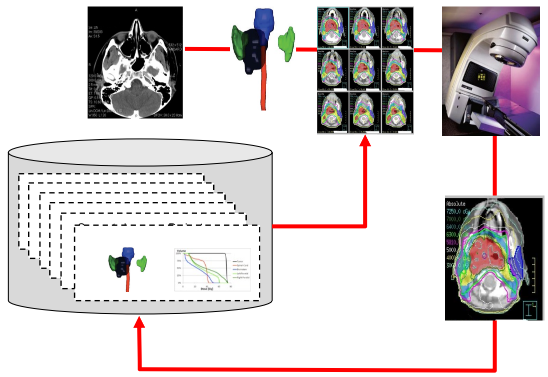
84

Statistical process control for radiation therapy



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

Team:

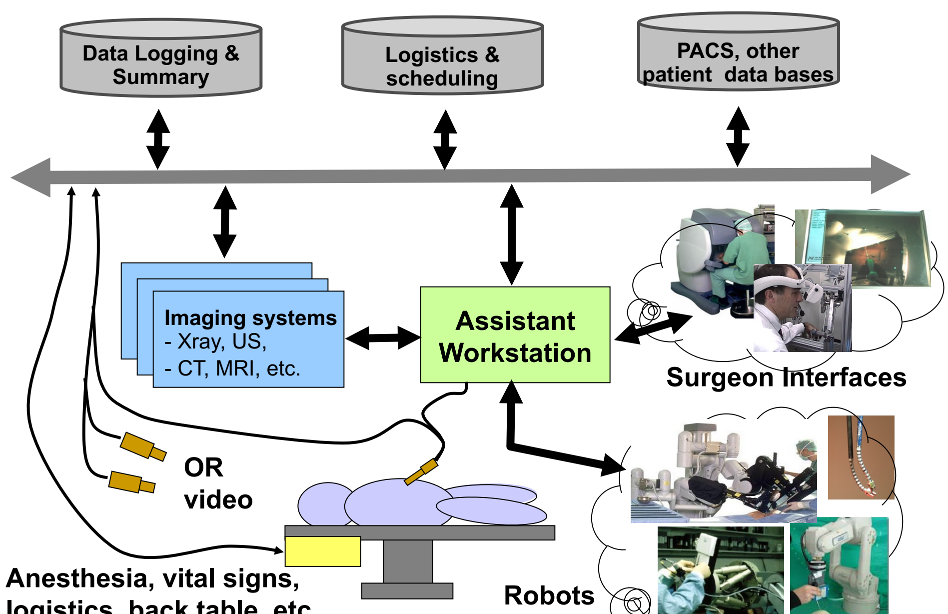
CS: R. Taylor, M. Kazhdan, P. Simari, A. King

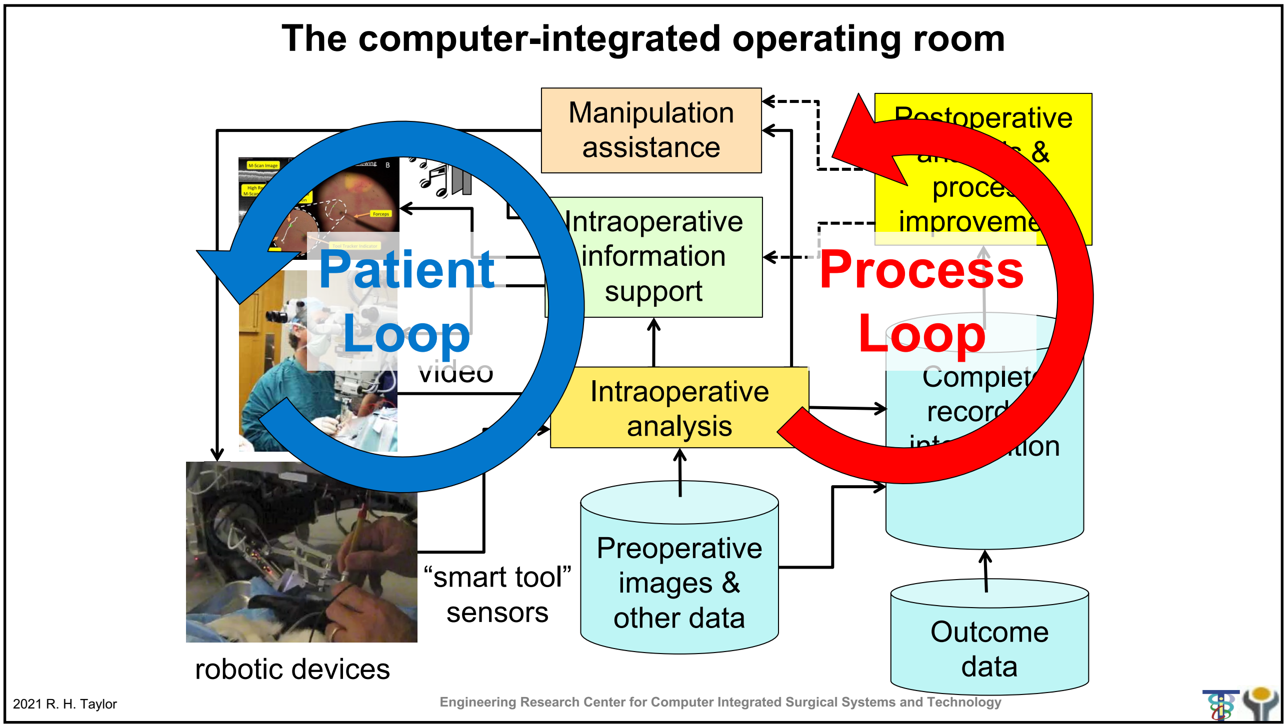
BME: R. Jacques

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

Support: Paul Maritz, Philips, JHU internal funds

Information-Intensive Interventional Suite




The computer-integrated operating room
Manipulation assistance
Intraoperative information support
Intraoperative analysis
Preoperative images & other data
Outcome data
video
"smart tool" sensors
robotic devices
Patient Loop
Process Loop
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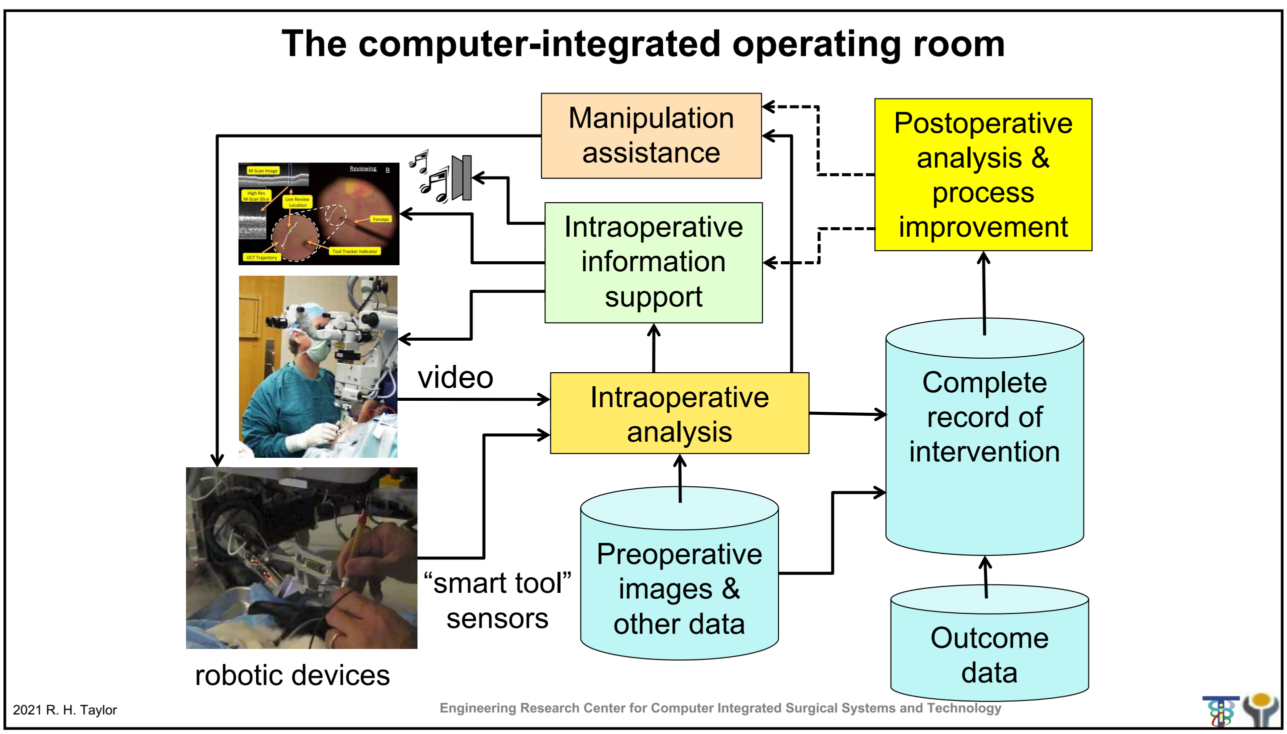
99


The computer-integrated operating room
Manipulation assistance
Postoperative analysis & process improvement
Intraoperative information support
Intraoperative analysis
Complete record of intervention
Preoperative images & other data
Outcome data
video
"smart tool" sensors
robotic devices
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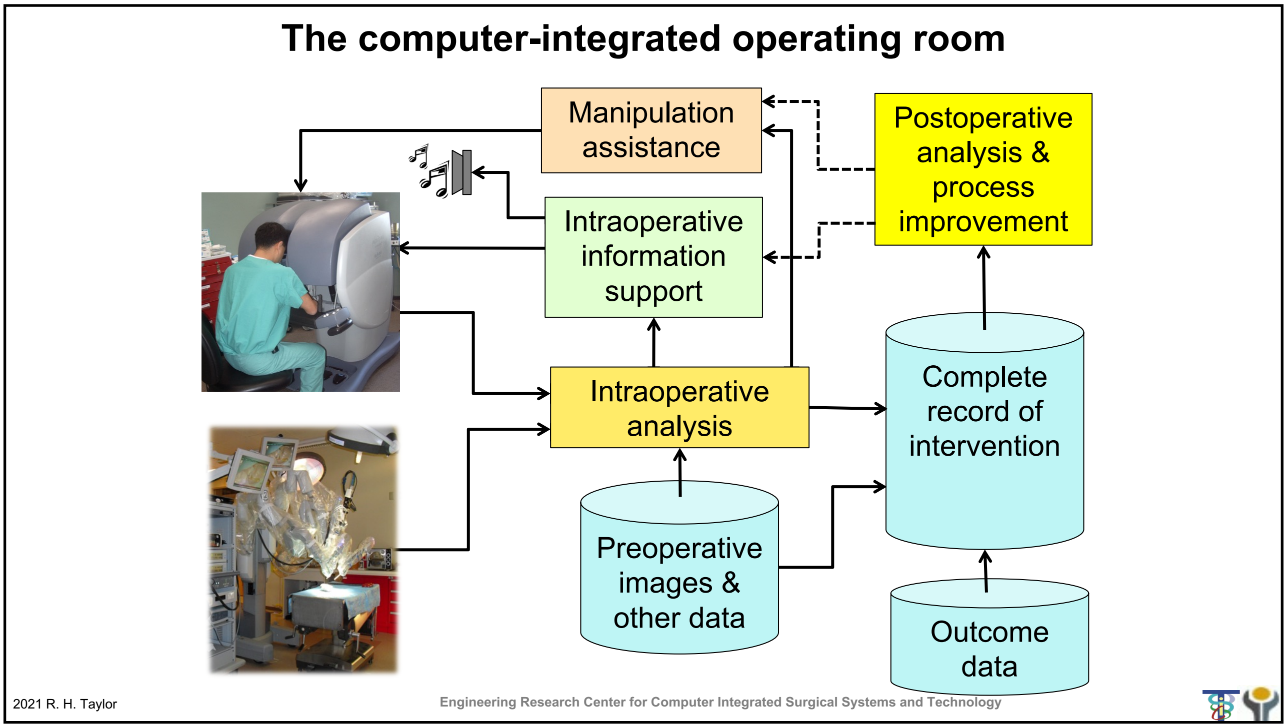
100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Outcome data
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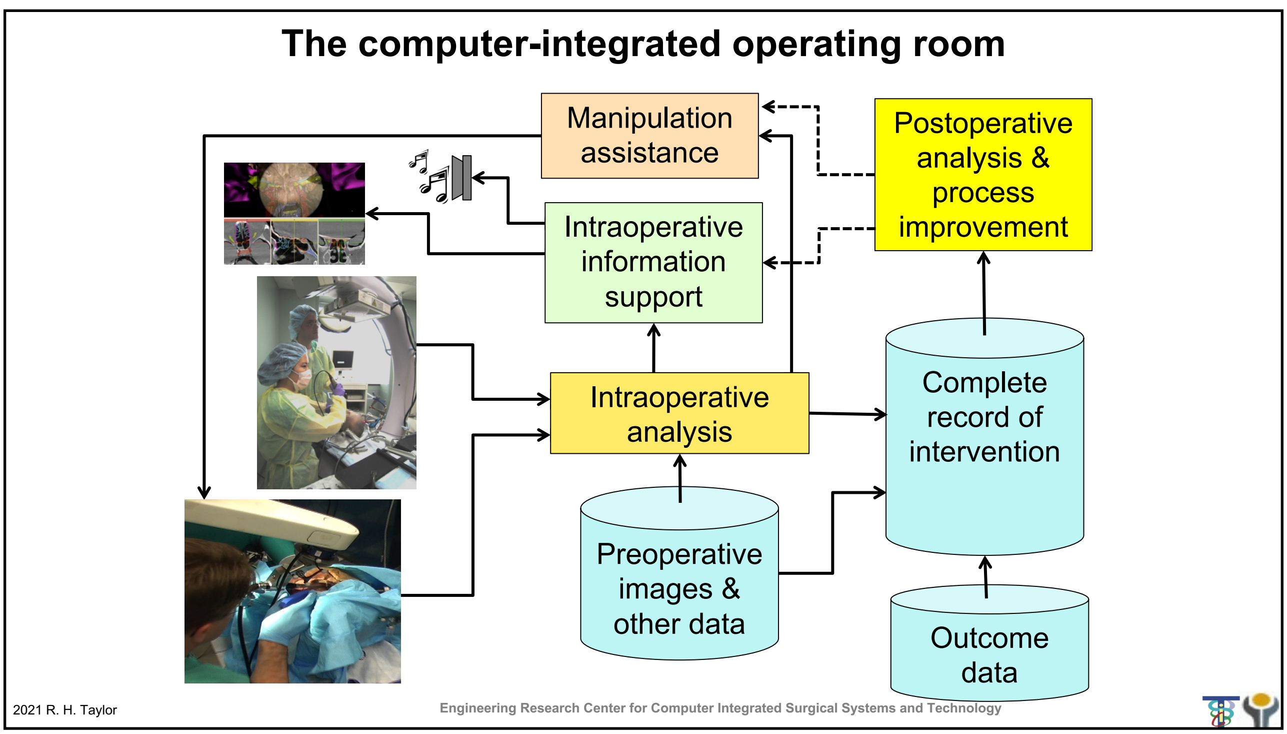
101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Manipulation assistance
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Intraoperative analysis
Postoperative analysis & process improvement
Complete record of intervention
Preoperative images & other data
Outcome data
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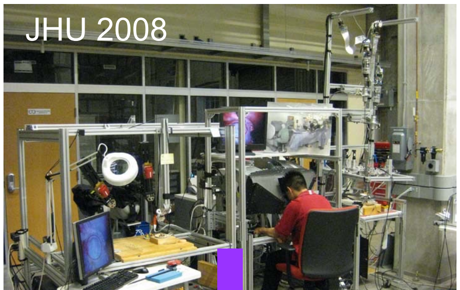
102

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
- 45 systems now deployed around the world
- **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

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107