NSF Engineering Research Center
for Computer Integrated Surgical
Systems and Technology

Laboratory for Computational Sensing + Robotics

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

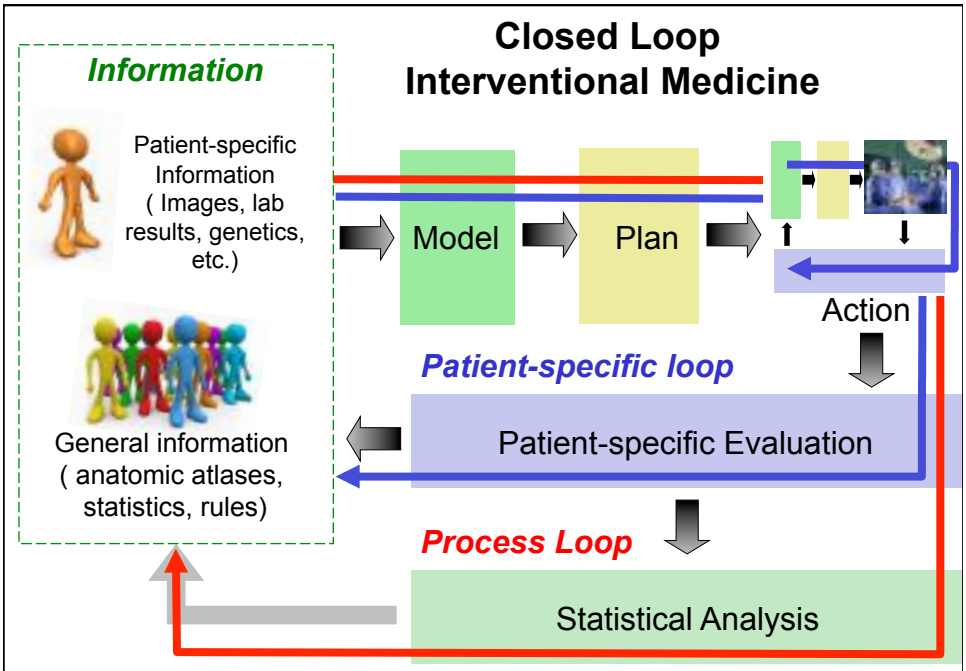
Acknowledgments

- This presentation reflects the contributions of **many** collaborators and colleagues from the CISST ERC and elsewhere. They are too many to name here, but their contributions are gratefully acknowledged.
- Partial funding or other support for the work presented likewise was provided by many sources, including
  - National Science Foundation, National Institutes of Health, Department of Defense, National Institute of Science and Technology
  - Siemens, Philips, Intuitive Surgical, General Electric, Acoustic MedSystems, Integrated Surgical Systems, Carl Zeiss Meditec, Alcon, and other Industry partners of the CISST ERC
  - Johns Hopkins University internal funds

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

Closed Loop Interventional Medicine



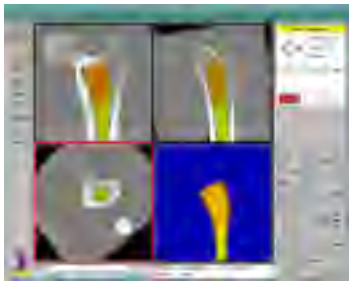
This Paradigm has not changed since Imhotep's day

27th Century BCE

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

21st Century CE

Example: Robotic Joint Replacement Surgery



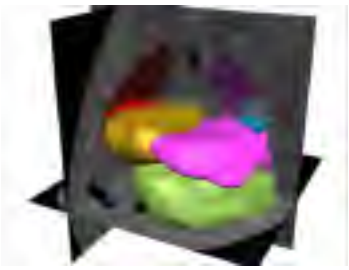
Manual Surgery

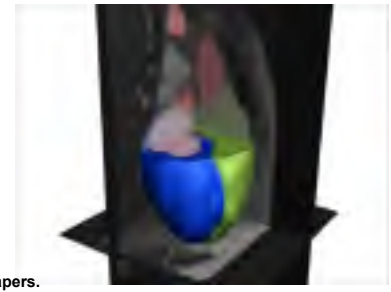
Robotic Surgery

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

Patient-Specific Models for Interventions

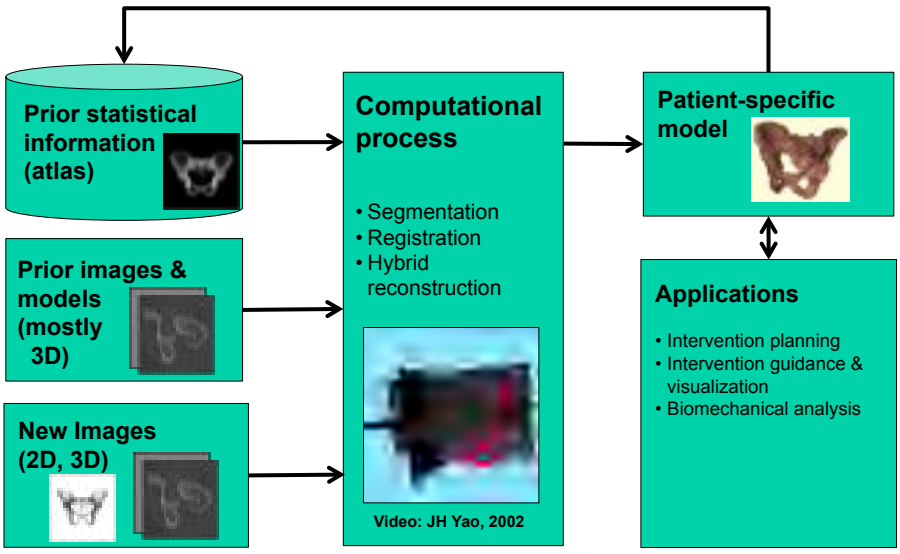
- Computationally efficient **representation of patient** enabling computer to assist in planning, guidance, control, and assessment of interventional procedures
- Generally focus on **anatomy**, but may sometimes include biology or other annotations
- Predominately derived from medical images and image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





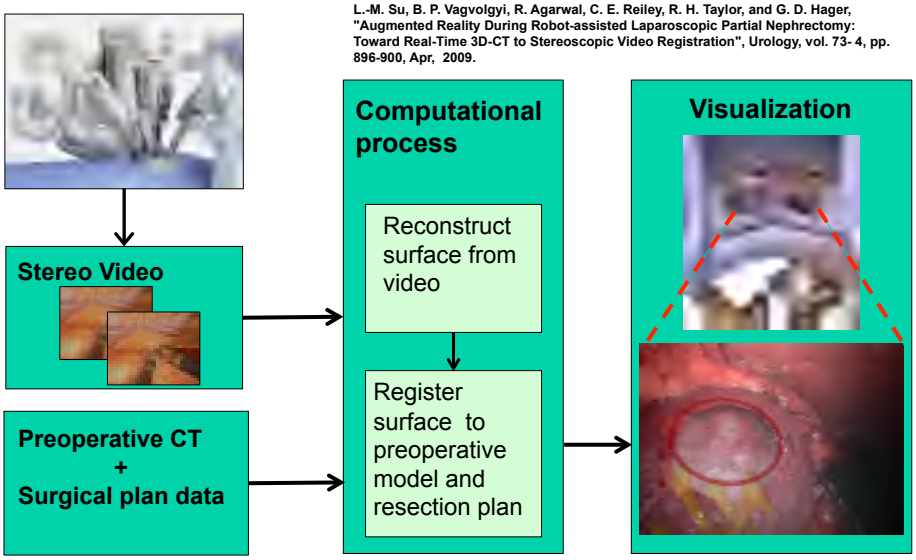
Video: Blake Lucas, "SpringLS…", *MICCAI 2011* & subsequent papers.
Data courtesy of Terry Peters and Eric Ford

Combining prior knowledge with online images



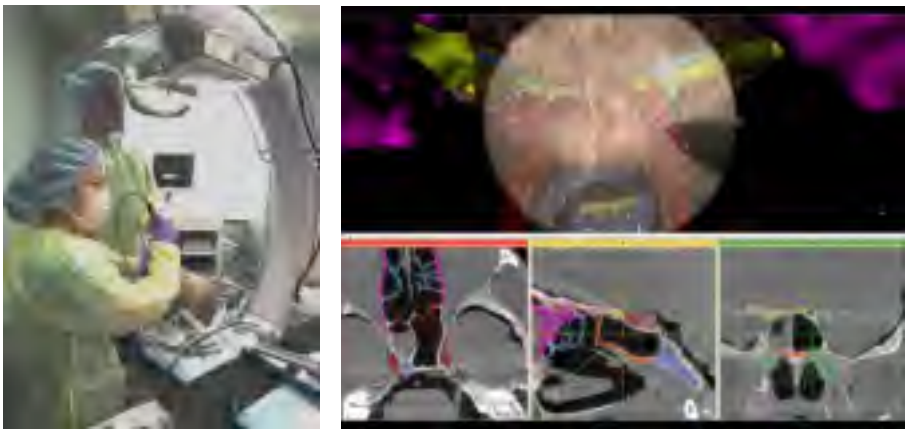
Intraoperative Overlay of CT model onto laparoscopic video

L.-M. Su, B. P. Vagvolgyi, R. Agarwal, C. E. Reiley, R. H. Taylor, and G. D. Hager, "Augmented Reality During Robot-assisted Laparoscopic Partial Nephrectomy: Toward Real-Time 3D-CT to Stereoscopic Video Registration", Urology, vol. 73- 4, pp. 896-900, Apr, 2009.



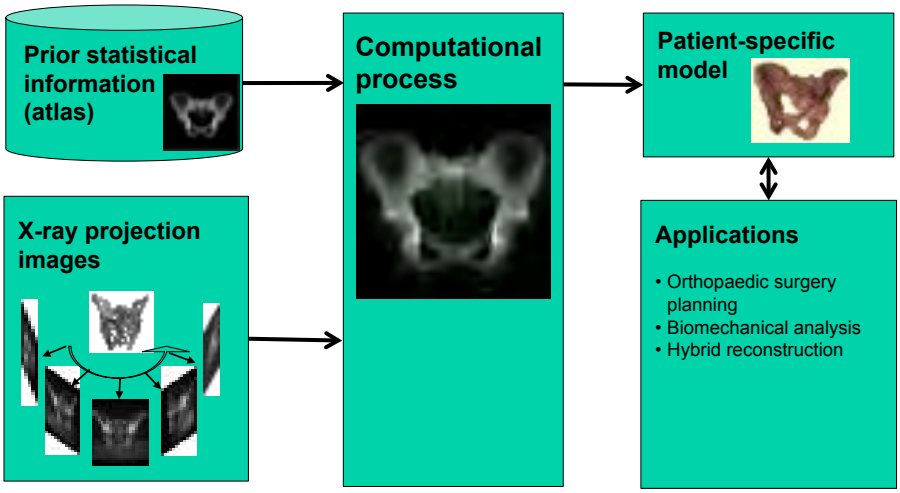
Information Overlay in Endoscopic Skull Base Surgery

Siewerdsen, Hager, Mirota, *et. al.*



- D. Mirota and T. R. Wang H, Ishii M, Gallia G, Hager G, "A System for Video-based Navigation for Endoscopic Endonasal Skull Base Surgery.", *IEEE Trans Med Imaging*, 2011. PMID 22113772.
- D. J. Mirota, A. Uneri, S. Schafer, S. Nithiananthan, D. D. Reh, G. L. Gallia, R. H. Taylor, G. D. Hager, and J. H. Siewerdsen, "High-accuracy 3D image-based registration of endoscopic video to C-arm cone-beam CT for image-guided skull base surgery", in *Medical Imaging 2011: Visualization, Image-Guided Procedures, and Modeling*, Orlando, 79640J-1 to 79640J-10, 2011.

Deformable 2D/3D Registration to Statistical Atlas



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

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

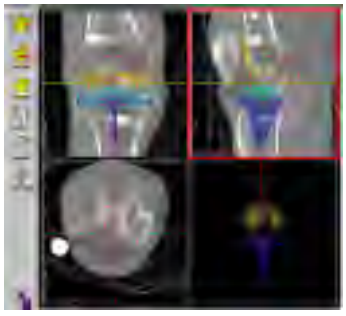
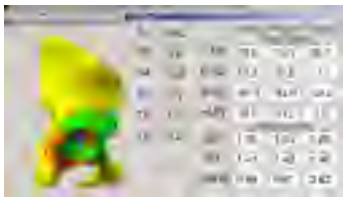


Photo: Integrated Surgical Systems

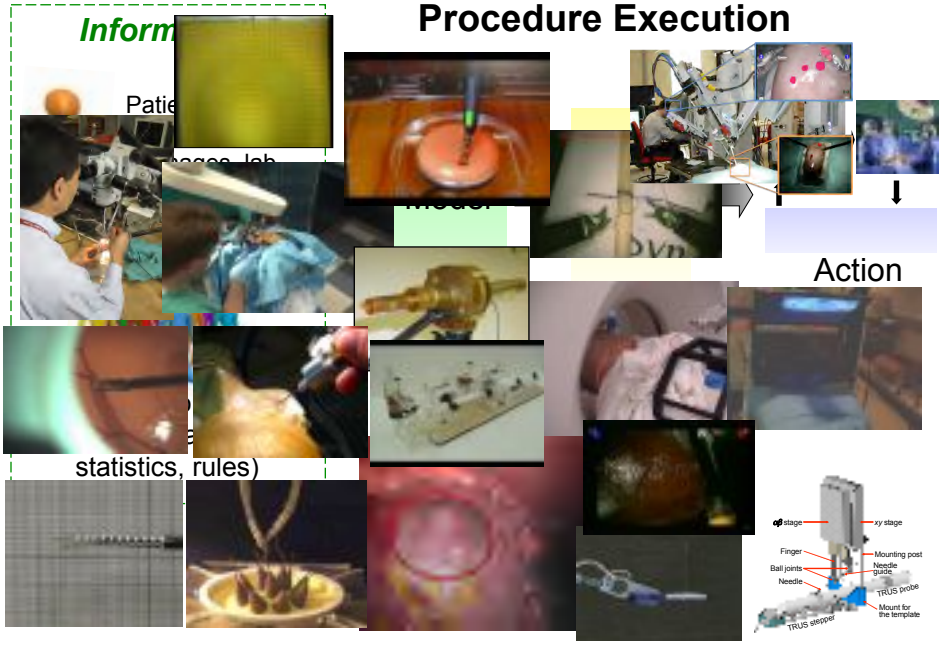
Procedure Planning

- **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

Taylor

Medtronic

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

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

G. Hager, B. Vagvolgyi , L-M. Su, *et al.*

Stoianovici, Taylor, Whitcomb, *et al.*

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

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

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

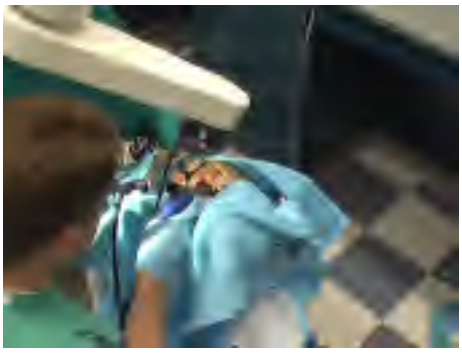
Taylor, Hager, Handa, Kazanzides, Kang, Iordachita, Gehlbach, *et al.*

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

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



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

Image-guided needle placement

Masamune, Fichtinger, Iordachita, …

Okamura, Webster, …

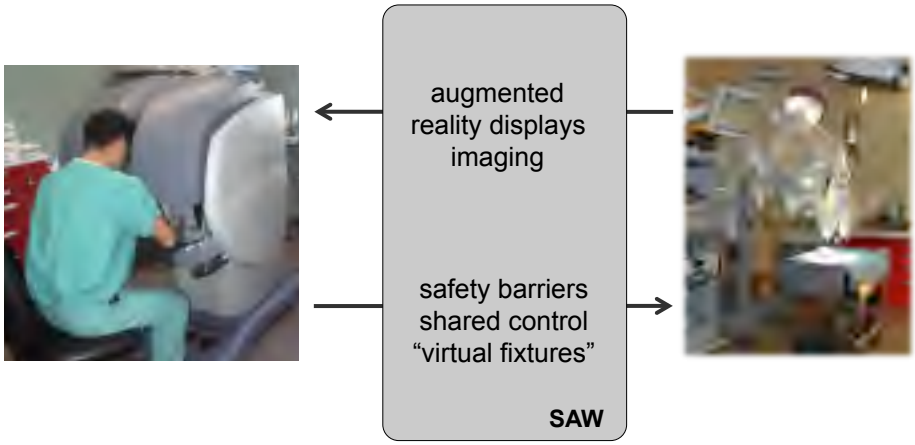
Krieger, Fichtinger, Whitcomb, …

Fichtinger, Kazanzides,Burdette, Song …

Iordachita, Fischer, Hata…

Taylor, Masamune, Susil, Patriciu, Stoianovici,…

Information-enhanced robotic surgery

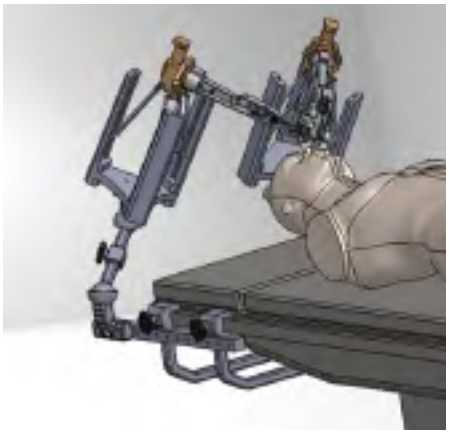


A Robotic Assistant for Trans-Oral Surgery: The Robotic Endo-Laryngeal Flexible (Robo-ELF) Scope

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

- **Goals**
  - Develop clinically usable robot for manipulating flexible endoscope in throat and airways
  - Permit bimanual surgery
  - Manipulation of ablation catheter
- **Approach**
  - Simple hardware for manipulating unmodified flexible scope
  - Simple joystick control
  - Platform for image guidance
- **Status**
  - In process of obtaining IRB approval for clinical use

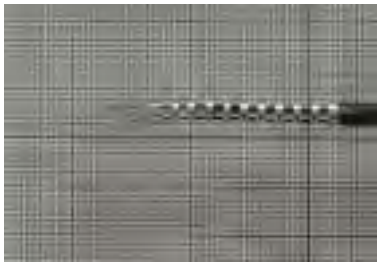
New Robot for Head and Neck Surgery



C. He, K. Olds, L. Akst, M. Ishii, W. Chien, I. Iordachita, and R. Taylor, "Evaluation, Optimization, and Verification of the Wrist Mechanism of a New Cooperatively Controlled Bimanual ENT Microsurgery Robot ", in *ASME 2012 International Mechanical Engineering Congress & Exposition*, Houston, Nov 9-15, 2012. p. 88460.

Snake-like robot for minimally invasive surgery

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



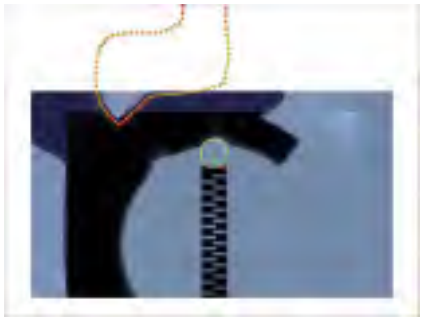
R. Taylor, N. Simaan, *et al.*

Single Port Access Surgery

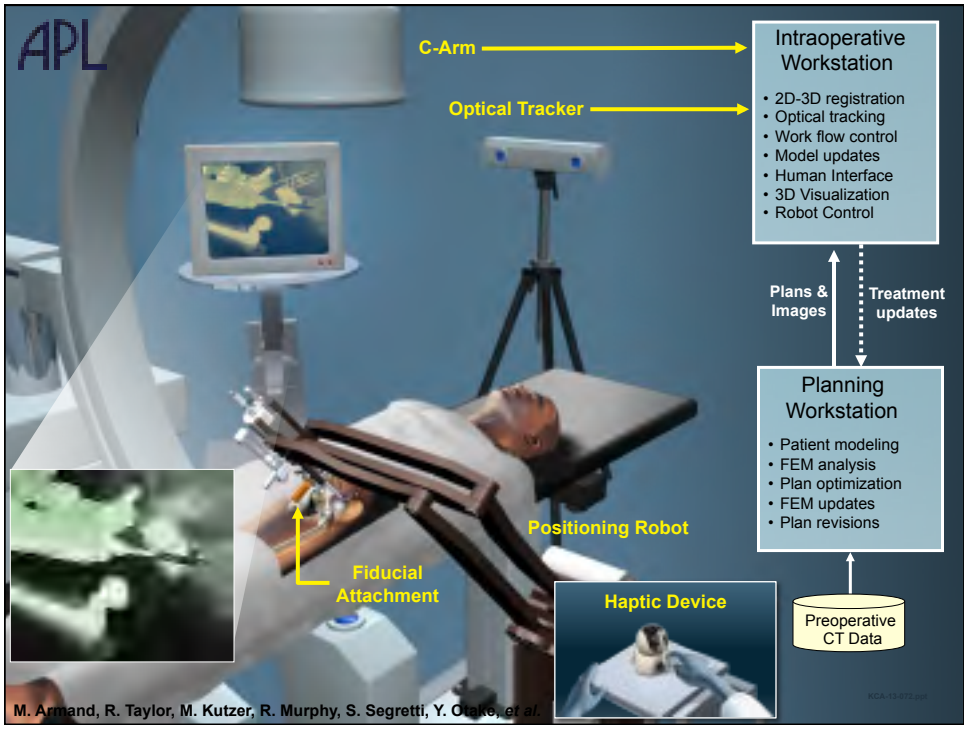
Nabil Simaan (Vanderbilt, Columbia), with P. Allen (Columbia), D. Fowler (Columbia)

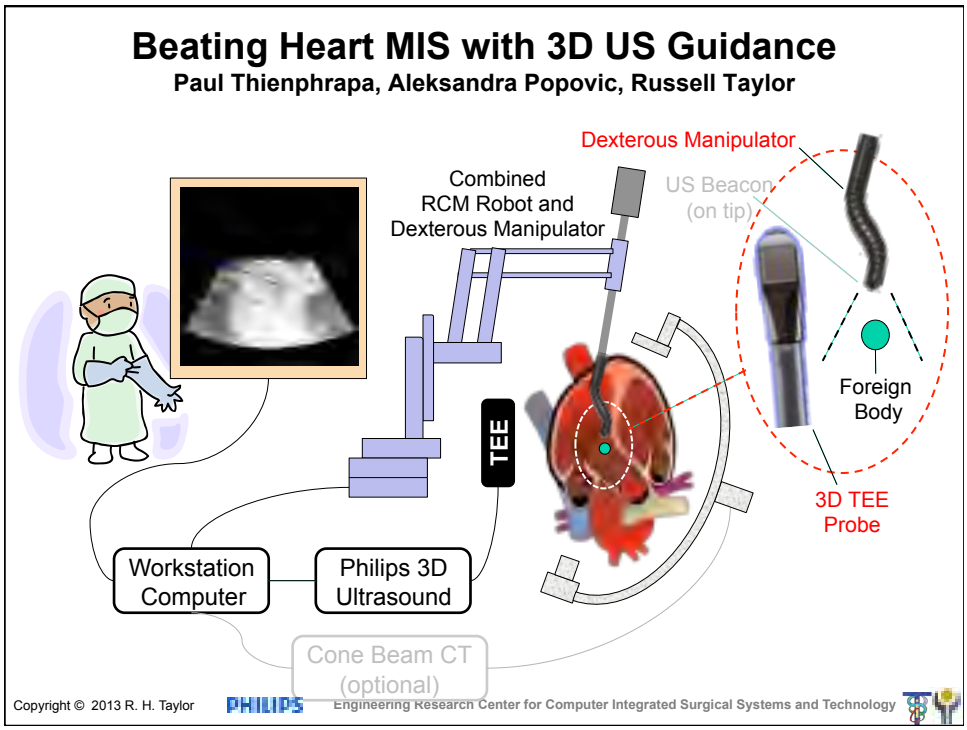
New technology finally allows true evaluation of the potential of single port access surgery. Systems raise new questions about control and telemanipulation infrastructure/cooperative control.

Minimally-Invasive Osteolysis Curettage



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

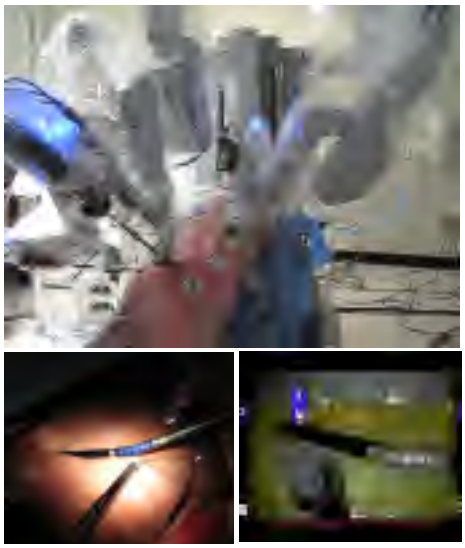

APL
C-Arm
Optical Tracker
Intraoperative Workstation
• 2D-3D registration
• Optical tracking
• Work flow control
• Model updates
• Human Interface
• 3D Visualization
• Robot Control
Plans & Images
Treatment updates
Planning Workstation
• Patient modeling
• FEM analysis
• Plan optimization
• FEM updates
• Plan revisions
Positioning Robot
Fiducial Attachment
Haptic Device
Preoperative CT Data
M. Armand, R. Taylor, M. Kutzer, R. Murphy, S. Segretti, Y. Otake, et al.


Beating Heart MIS with 3D US Guidance
Paul Thienphrapa, Aleksandra Popovic, Russell Taylor
Dexterous Manipulator
Combined RCM Robot and Dexterous Manipulator
US Beacon (on tip)
Foreign Body
TEE
3D TEE Probe
Workstation Computer
Philips 3D Ultrasound
Cone Beam CT (optional)
Copyright © 2013 R. H. Taylor
PHILIPS
Engineering Research Center for Computer Integrated Surgical Systems and Technology

Robotically Assisted Laparoscopic Ultrasound

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

- NIH STTR between CISST ERC and Intuitive Surgical
- Goals
  - Develop dexterous laparoscopic ultrasound instrumentation and software interfaces for DaVinci surgical robot
  - Produce integrated system for LUS-enhanced robotic surgery
  - Evaluate effectiveness of prototype system for liver surgery
- Approach
  - Custom DaVinci-S LUS tool
  - Software built on JHU/ISI "SAW" interface
- Status
  - Evaluation of prototype by surgeons



Research DaVinci Application – Not for Human Use

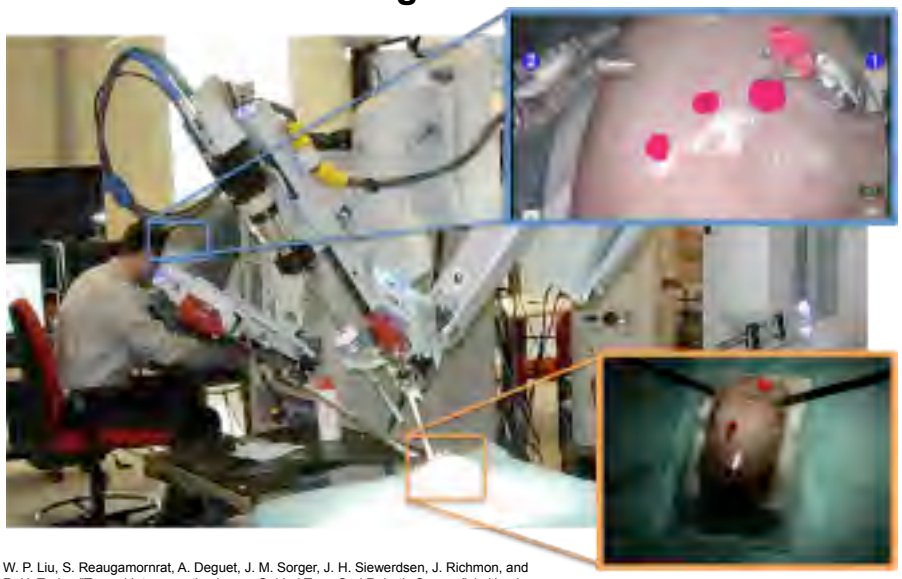
Ultrasound Elastography with DaVinci

(Boctor, Billings, Taylor)

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

(Research DaVinci Application – Not for Human Use)

Video-CBCT guidance for TORS



W. P. Liu, S. Reaugamornrat, A. Deguet, J. M. Sorger, J. H. Siewerdsen, J. Richmon, and R. H. Taylor, "Toward Intraoperative Image-Guided TransOral Robotic Surgery", in Hamlyn Symposium on Medical Robotics, London, July 1-2, 2012

Example: Human-Machine Collaborative Surgery

Nicholas Padoy, Greg Hager (IROS 2011)

Research DaVinci Application – Not for Human Use

Dynamic Augmented Reality for Sensory Substitution in Robot-Assisted Surgical Systems

A. Okamura, T. Yamomoto *et al.*

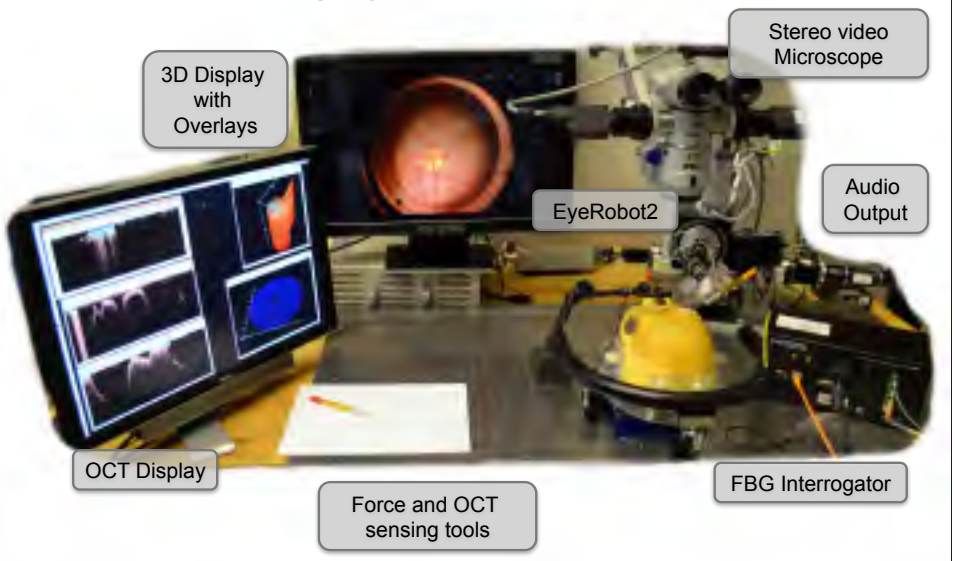
Vitreoretinal Microsurgery

British Journal of Ophthalmology 2004 - Akifumi Ueno et al

www.eyemdlink.com

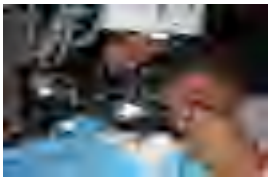
Alcon Vitreosurgery Instrument

Microsurgery Assistant Workstation



In-Vivo Experiments

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



Closed Loop Interventional Medicine

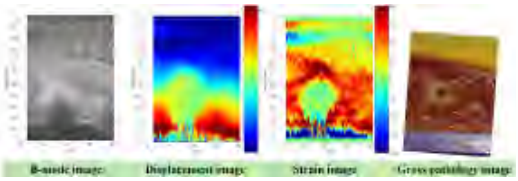
Information

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

General information (anatomic atlases, statistics, rules)

Model → Plan → Action → Evaluation

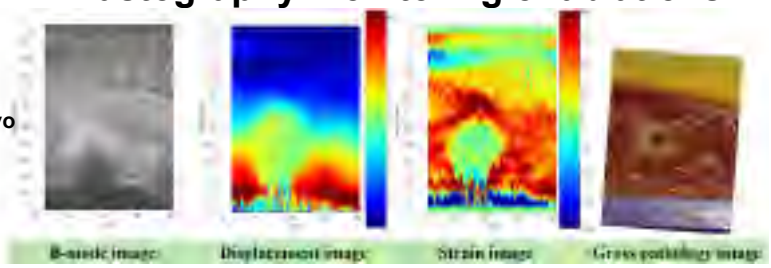
Patient-specific Evaluation

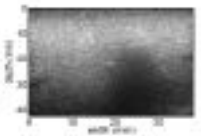
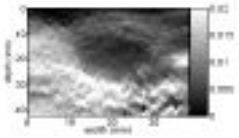
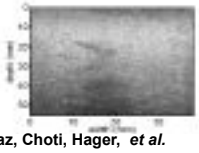
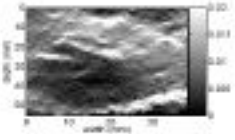
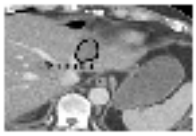


EUS images: E. Boctor

Elastography monitoring of ablations

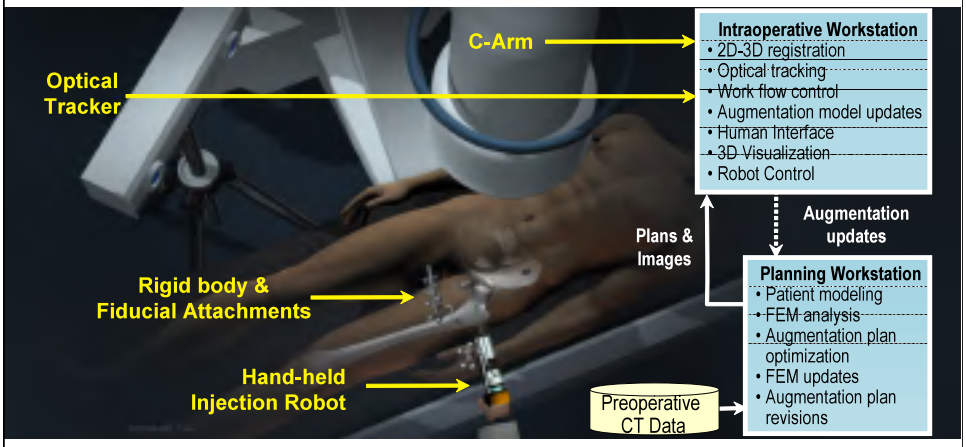
Ex vivo



	ultrasound	elasticity	post-operation CT
patient 1			
patient 2			

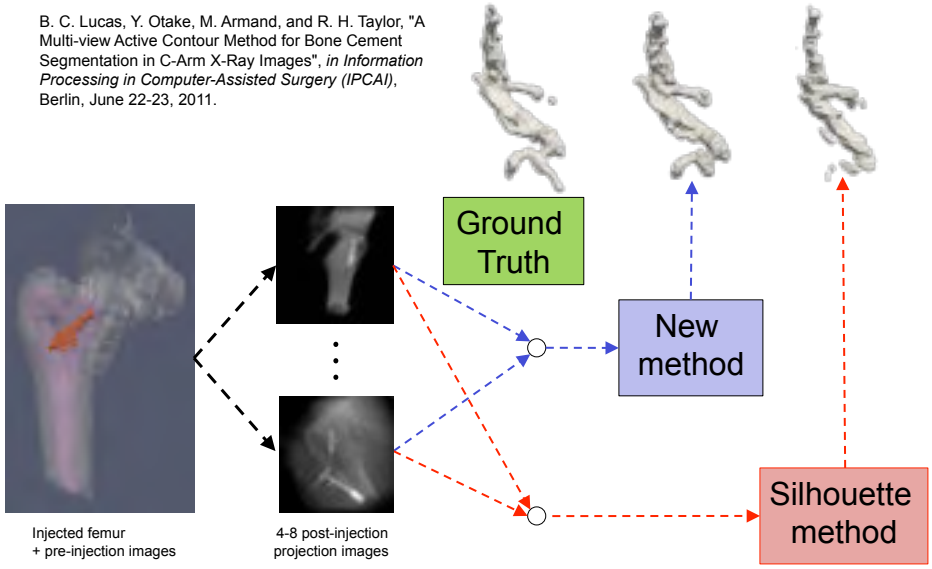
Credit: Boctor, Rivaz, Choti, Hager, *et al.*

Surgical Scenario for Bone Augmentation



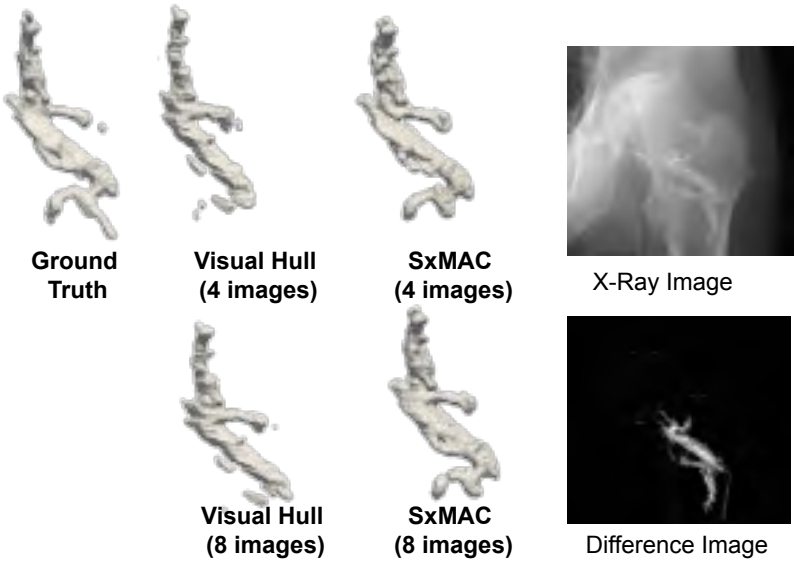
Reconstruction of injected cement from sparse x-rays

B. C. Lucas, Y. Otake, M. Armand, and R. H. Taylor, "A Multi-view Active Contour Method for Bone Cement Segmentation in C-Arm X-Ray Images", *in Information Processing in Computer-Assisted Surgery (IPCAI)*, Berlin, June 22-23, 2011.

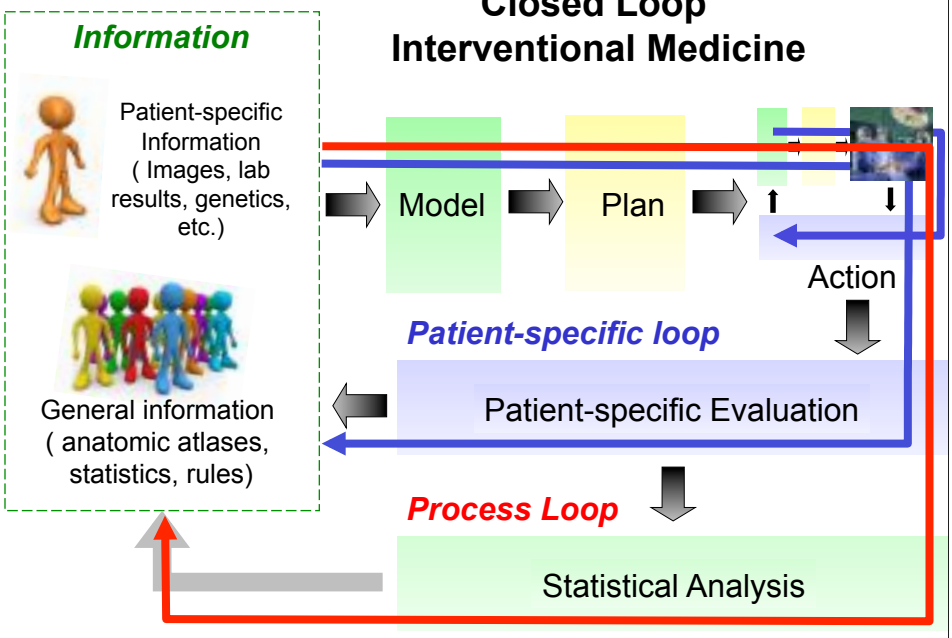


Example: Cadaver study with soft tissue and 4difference images

Reconstruction with Difference Images

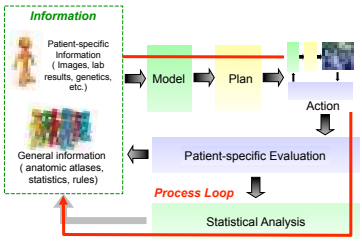


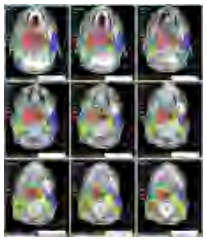
Closed Loop Interventional Medicine



Information-Integrated Process Learning

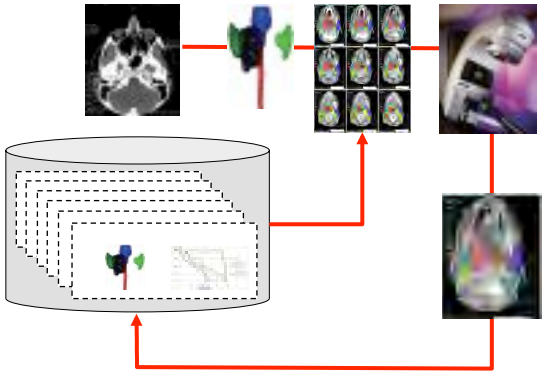
- **Key idea**
  - Medical robots and CAI systems inherently generate data and promote consistency
  - Eventually, outcomes are known
  - Combine this information over many patients to improve treatment plans / processes
- **Issues / Themes**
  - Very large data bases combining heterogeneous data
  -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





Credit: Todd McNutt

Statistical process control for radiation therapy



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

Team:

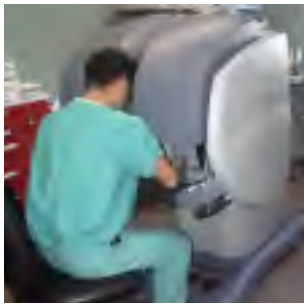
CS: R. Taylor, M. Kazhdan, P. Simari, A. King

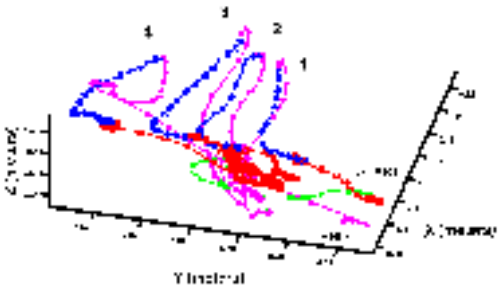
BME: R. Jacques

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

Support: Paul Maritz, Philips, JHU internal funds

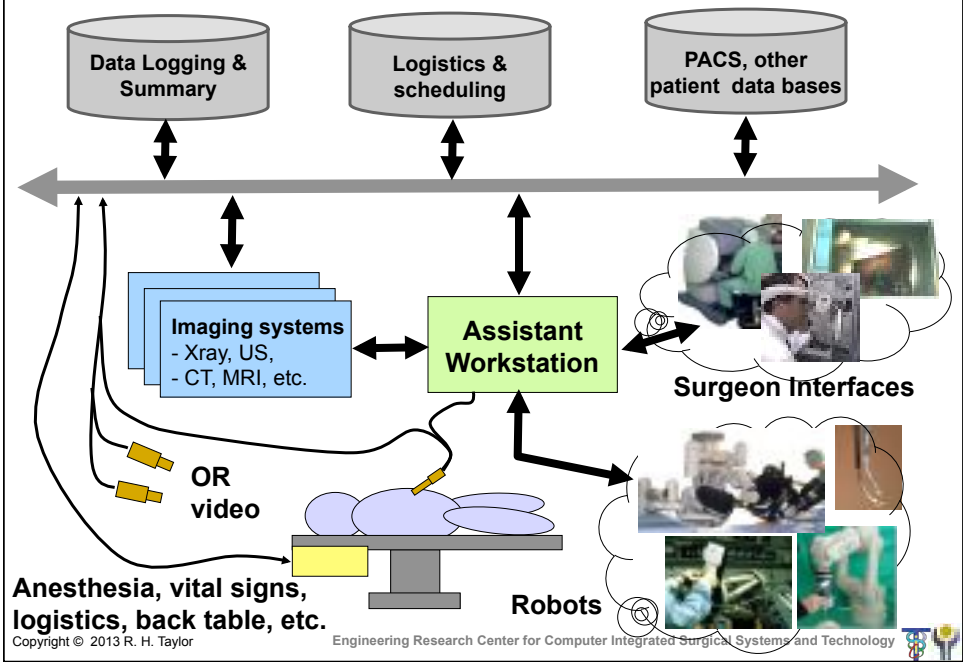
"The language of surgery"
Statistical learning of surgical gestures



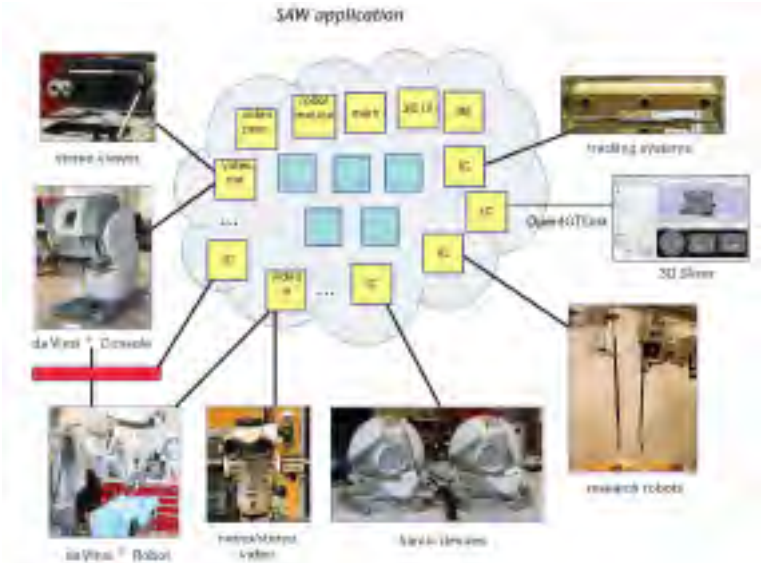


Hager, *et al.*

Information-Intensive Interventional Suite



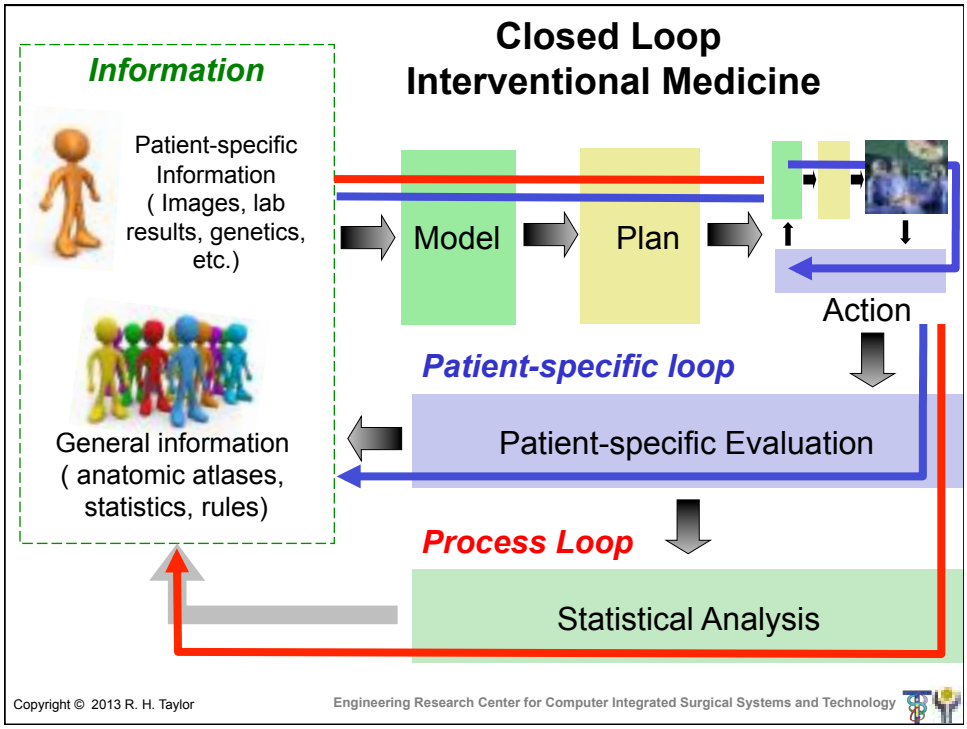
Surgical Assistant Workstation



Balazs Vagvolgyi, Simon P. DiMaio, Anton Deguet, Peter Kazanzides, Rajesh Kumar, Christopher Hasser, Russell H. Taylor

Use case: Da Vinci "Toolkits"

- 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
  - Controller power/packaging – WPI



General working model

Use clinical applications to provide focus & key problems

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

Some current areas include

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

Funding models

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

The real bottom line: patient care

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

Discussion