NSF Engineering Research Center for Computer Integrated Surgical Systems and Technology

Medical Robotics and Computer-Integrated Interventional Systems:

Integrating Imaging, Intervention, and Informatics to Improve Patient Care

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WHITING SCHOOL OF ENGINEERING
THE JOHNS HOPKINS UNIVERSITY

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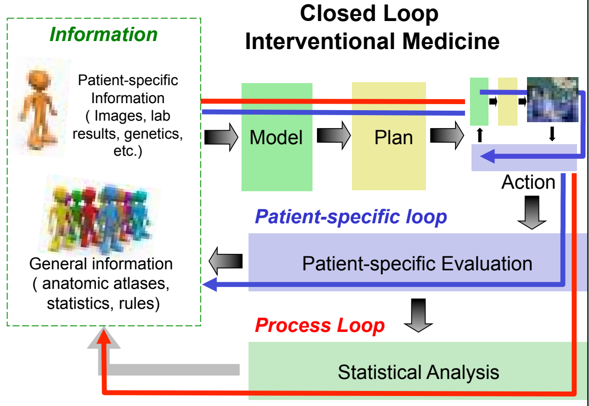
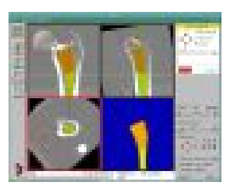
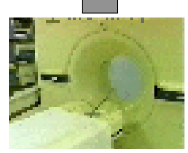
  - Siemens, Philips, Intuitive Surgical, General Electric, Acoustic MedSystems, Integrated Surgical Systems, Carl Zeiss Meditec, Alcon, and other Industry partners of the CISST ERC
  - Johns Hopkins University internal funds

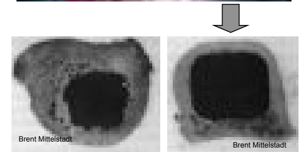
Closed Loop Interventional Medicine



Example: Robotic Joint Replacement Surgery



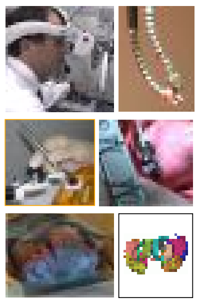




Manual Surgery   Robotic Surgery

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

Engineering Research Center for Computer Integrated Surgical Systems and Technology (CISST ERC)



The CISST ERC is developing a family of surgical systems that combine innovative algorithms, robotic devices, imaging systems, sensors, and human-machine interfaces to work cooperatively with surgeons in the planning and execution of surgical procedures.

Areas of Research

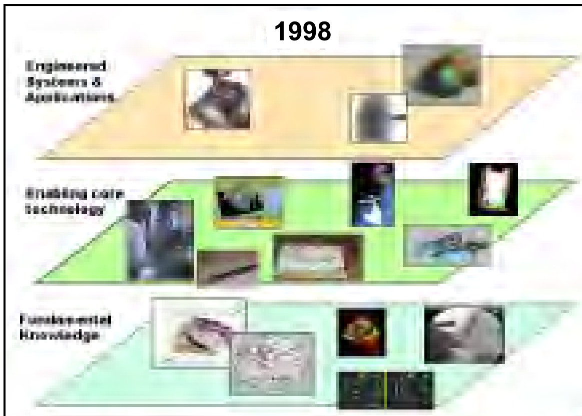
- Robotic surgical assistants
- Image-guided interventional systems
- Focused interdisciplinary research in algorithms, imaging, robotics, sensors, human-machine systems

Institutions & Funding

- Johns Hopkins, MIT, CMU, BWH, Harvard, Penn, Morgan State, Columbia
- Years 1-11: NSF = $32.7M; Total = ~$64.7M
  In-kind support = ~$13.9M

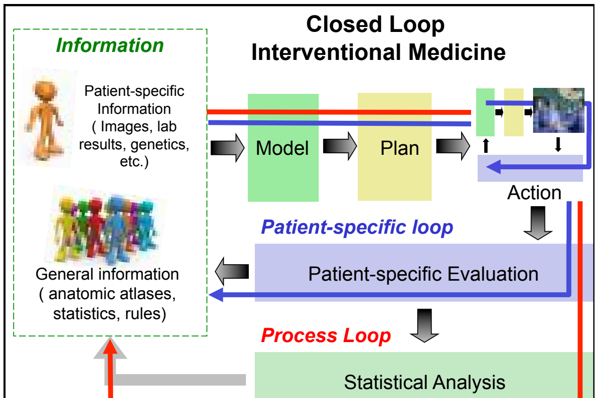
http://www.cisst.org

1998



2013

Closed Loop Interventional Medicine

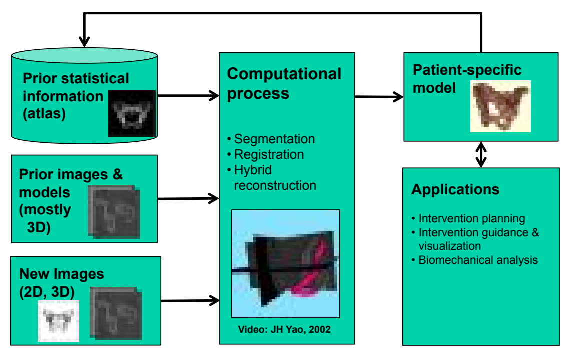


Patient-Specific Models for Interventions

- 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

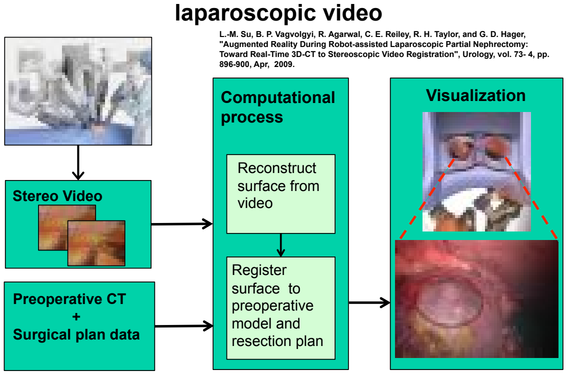
Video: Blake Lucas, "SpringLS…", *MICCAI 2011* & subsequent papers.
Data courtesy of Terry Peters and Eric Ford

Combining prior knowledge with online images



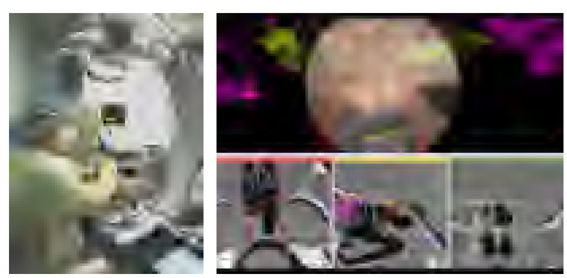
Intraoperative Overlay of CT model onto laparoscopic video

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.



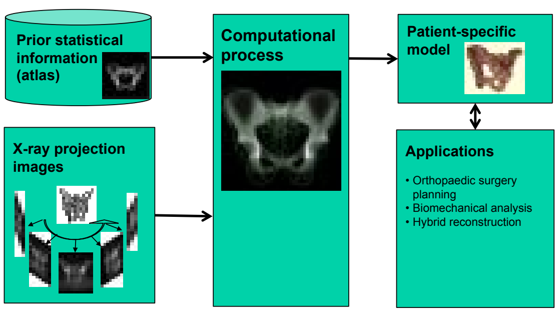
Information Overlay in Endoscopic Skull Base Surgery

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.

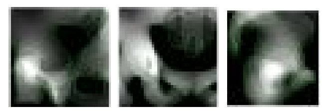
Deformable 2D/3D Registration to Statistical Atlas



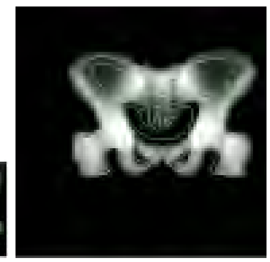
Examples: R. Taylor, J. Yao, O. Sadowsky, G. Chintalapani, O. Ahmad, …

2D/3D Registration – Hip Model

- Registration with truncated images
  - FOV: 160mm
  - Three views
- Avg surface registration accuracy: 2.15 mm



Atlas projections overlaid on DRR images after registration

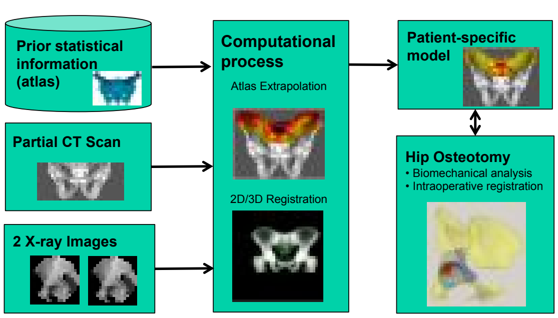


2D/3D deformable registration

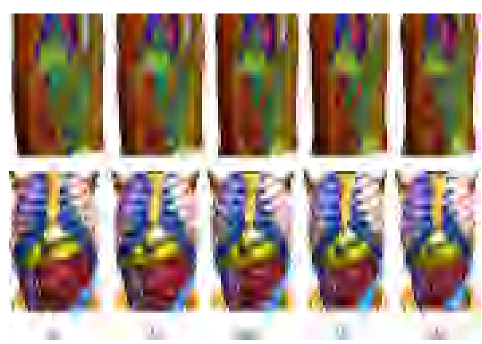
Chintalapani *et al.* CAOS 2009

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



Whole Body Atlasing



Blake Lucas, *Unifying Deformable Model Representations with New Geometric Data Structures*, Ph.D. Thesis in Computer Science, Johns Hopkins University, July 2012

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

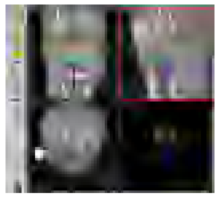
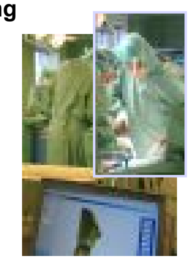
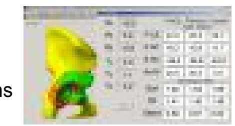


Photo: Integrated Surgical Systems

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

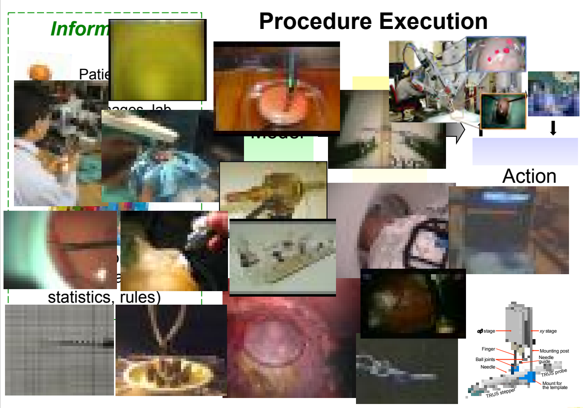
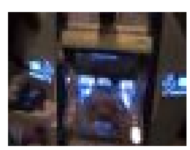
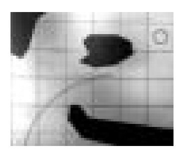


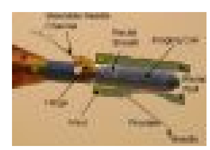
Image-guided needle placement



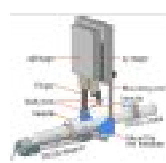
Masamune, Fichtinger, Iordachita, …



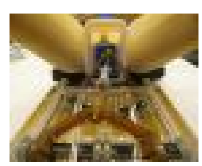
Okamura, Webster, …



Krieger, Fichtinger, Whitcomb, …



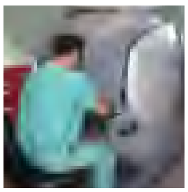
Fichtinger, Kazanzides,Burdette, Song …



Iordachita, Fischer, Hata…

Taylor, Masamune, Susil, Patriciu, Stoianovici,…

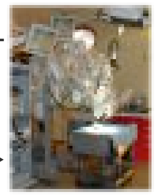
Information-enhanced robotic surgery



augmented reality displays imaging

safety barriers shared control "virtual fixtures"

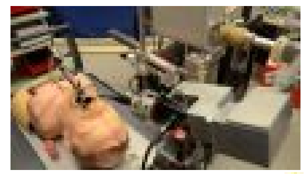
SAW



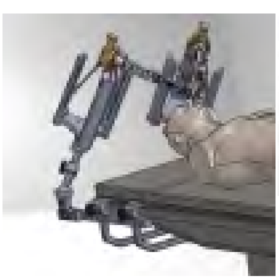
A Robotic Assistant for Trans-Oral Surgery: The Robotic Endo-Laryngeal Flexible (Robo-ELF) Scope

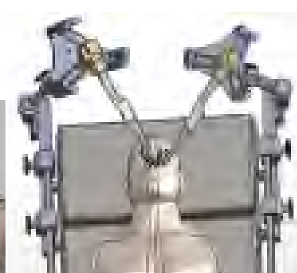
K. Olds, A. Hillel, E. Cha, J. Kriss, A. Nair, L. Akst, J. Richmon, R. Taylor

- **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





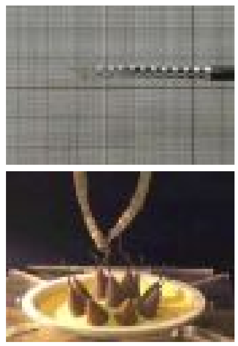
C. He, K. Olds, L. Akst, M. Ishii, W. Chien, I. Iordachita, and R. Taylor, "Evaluation, Optimization, and Verification of the Wrist Mechanism of a New Cooperatively Controlled Bimanual ENT Microsurgery Robot ", in *ASME 2012 International Mechanical Engineering Congress & Exposition*, Houston, Nov 9-15,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

New Robot for Head and Neck Surgery

C. He, K. Olds, I. Iordachita, and R. Taylor, "A New ENT Microsurgery Robot: Error Analysis and Implementation", in International Conference on Robots and Automation (ICRA), Karlsruhe, May 6-10, 2013.

Snake-like robot for minimally invasive surgery

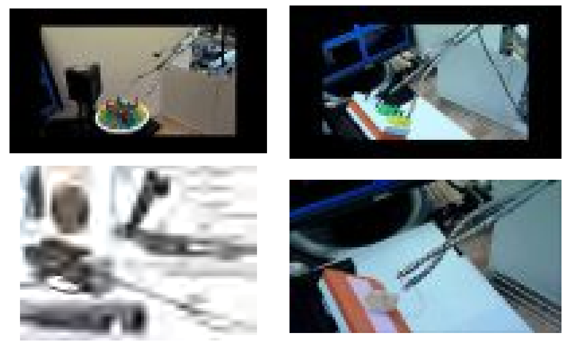
- **Goals**
  - Develop scalable robotic devices for high dexterity manipulation in confined spaces
  - Demonstrate in system for surgery in throat and upper airway
- **Approach**
  - "Snake-like" end effectors with flexible backbones and parallel actuation
  - Integrate into 2-handed teleoperator system 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.*

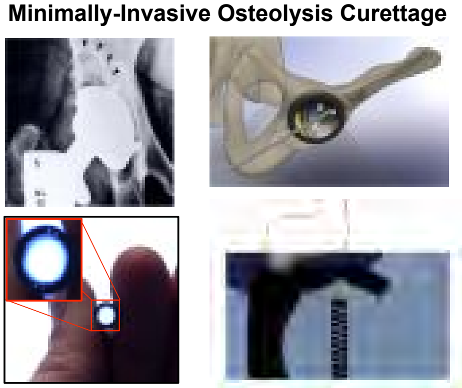
Single Port Access Surgery

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

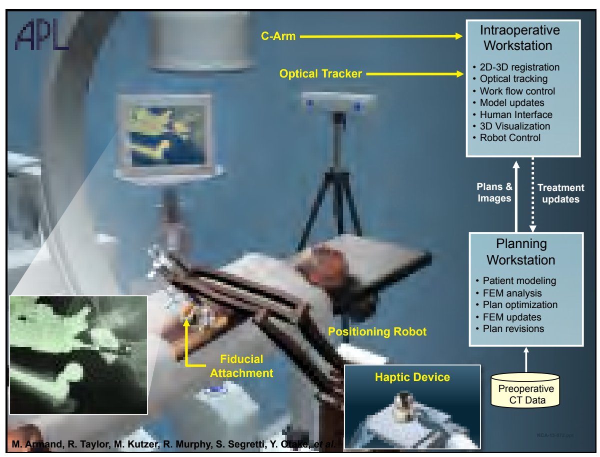


New technology finally allows true evaluation of the potential of single port access surgery. Systems raise new questions about control and telemanipulation infrastructure/cooperative control.

APL Minimally-Invasive Osteolysis Curettage

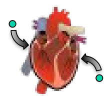


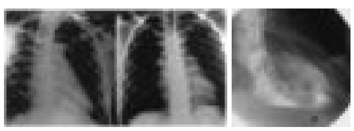
M. Armand, R. Taylor, M. Kutzer, R. Murphy, S. Segretti,, *et al.*

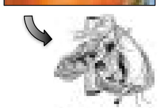


Foreign Bodies in the Heart

Causes	Symptoms	Conventional Treatment
Thrombi, Shrapnel	Cardiac Tamponade	Median Sternotomy
Iatrogenic	Hemorrhage	Cardiopulmonary Bypass
	Arrhythmia	
	Infection	
	Shock	
	Embolism	
	Valve Dysfunction	







(Actis Dato, 2003) (LeMaire, 1999)

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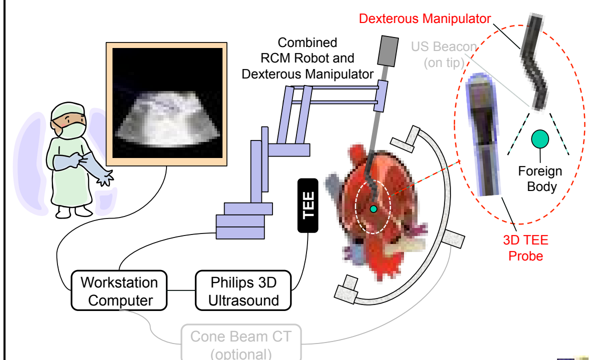
Beating Heart MIS with 3D US Guidance

Paul Thienphrapa, Aleksandra Popovic, Russell Taylor



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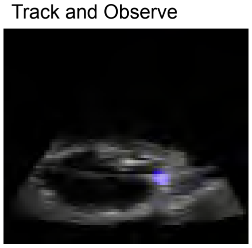
Beating Heart MIS with 3D US Guidance

Paul Thienphrapa, Aleksandra Popovic, Russell Taylor

Track and Observe



… then ambush

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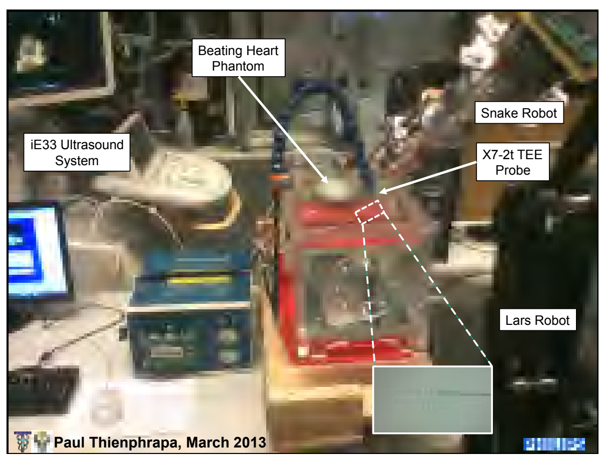
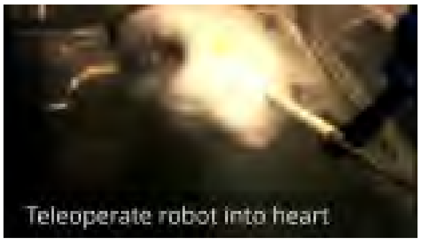


Experimental Procedure

1. Register robot to US images
2. Teleoperate robot to heart; Set RCM mode
3. Select foreign body in images
4. Track foreign body; Compute capture location
5. Guide robot for capture (automatic)



(4x speed)

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Thienphrapa *et al. 2013*

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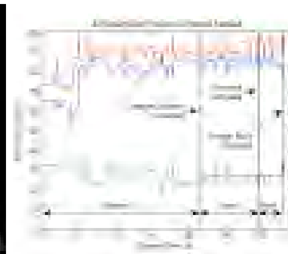
Retrieval Experiment Results



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Retrieval Experiment Results

- Success criterion: capture within 30 seconds
- Spatial probability
  - Success: 14/17 (82.4%)
  - Observation: 29.6 ± 6.9 sec
  - Waiting: 3.7 ± 2.0 sec
  - Total: 97.7 ± 21.6 sec
- Dwell time
  - Success: 5/5 (100%)
  - Observation: 54.3 ± 33.1 sec
  - Waiting: 2.2 ± 1.5 sec
  - Total: 124.5 ± 68.4 sec
- Failures
  - Reason: Motion changed after the capture location computed
  - Solution: Adaptive retry
- Large time variance possibly due to irregular motion
- Times of 2-3 minutes implies potential for improvement
- Visit frequency not tested

Thienphrapa *et al. 2013*

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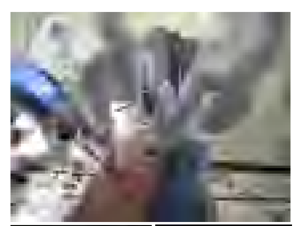
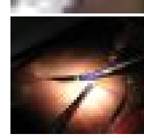
Robotically Assisted Laparoscopic Ultrasound

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

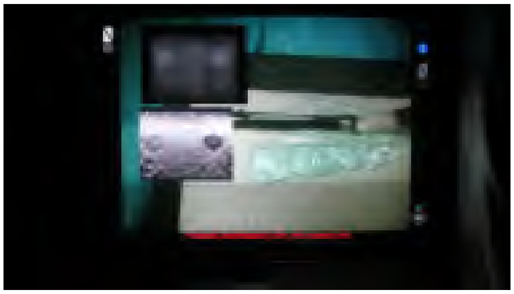




Research DaVinci Application – Not for Human Use

Engineering Research Center for Computer Integrated Surgical Systems and Technology

Ultrasound Elastography with DaVinci
(Boctor, Billings, Taylor)

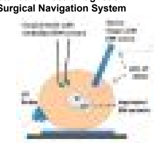


Human-robotic collaboration for in-vivo detection of tumors and monitoring of therapy

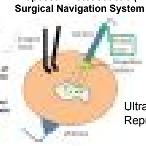
(Research DaVinci Application – Not for Human Use)

Direct 3D Ultrasound to Video Registration Using Photoacoustic Effect
A. Cheng, J. U. Kang, R. H. Taylor, E. M. Boctor
The Johns Hopkins University

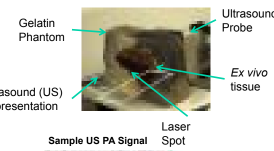
Standard Electromagnetic Surgical Navigation System



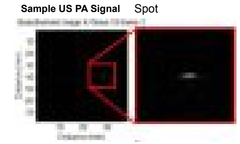
Proposed Photoacoustic (PA) Surgical Navigation System



Experimental Setup



Sample US PA Signal

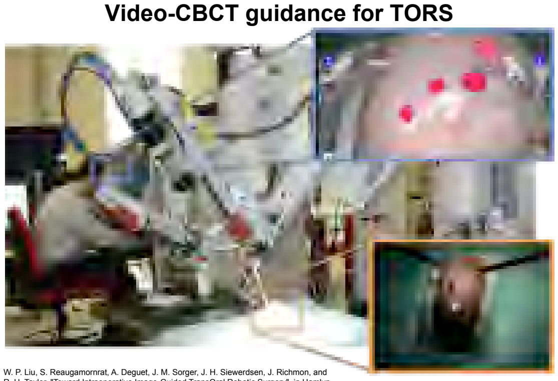


Advantages of PA system

- No wires
- No markers or sensors
- No Calibration Process
- Directly register video and 3D Ultrasound

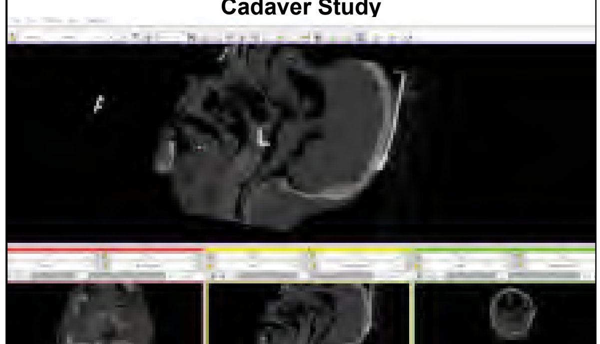
Literature shows registration errors of approximately 3mm
Our synthetic and *ex vivo* tissue phantom experiments show **submillimeter** errors!

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

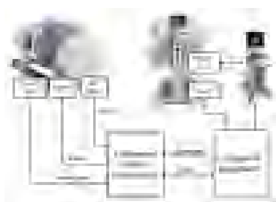
Cadaver Study



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

Research DaVinci Application – Not for Human Use

Robot-assisted prostate surgery using augmented reality with deformable models

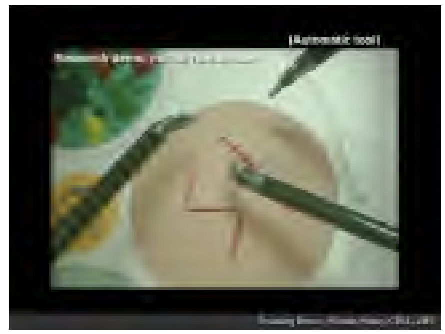


- Goal: Overlay deformed MRI image on da Vinci video to visualize critical neurovascular structures (uses intraoperative TRUS)
- Collaboration between JHU, Kitware, Blue Torch, U Penn Hospital
- Support: NIH R43 EB014074, Pistritto Research Fellowship

A. Enquobahrie, M. Kelly, A. Deguet, V. Shivaprabhu, E. Boctor , J. Stringham, P. Kazanzides, "Robot assisted prostate surgery using augmented reality with deformable models," *MICCAI Workshop on Systems & Architecture for CAI, Midas Journal*, Oct. 2012

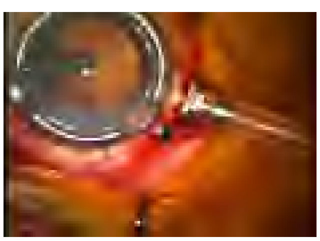
Example: Human-Machine Collaborative Surgery

Nicholas Padoy, Greg Hager (IROS 2011)

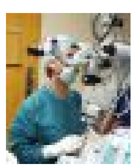


Research DaVinci Application – Not for Human Use

Vitreoretinal Microsurgery



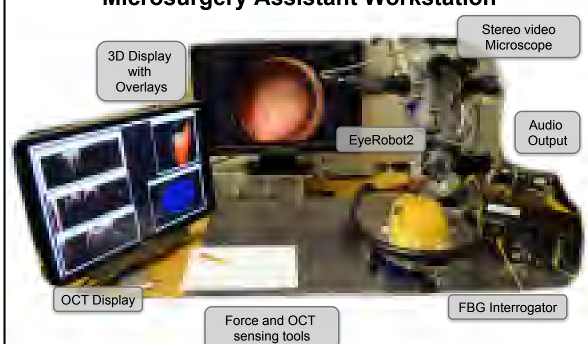
British Journal of Ophthalmology 2004 - Akifumi Ueno et al



www.eyemdlink.com

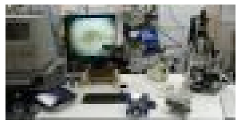
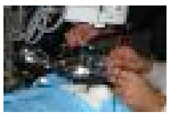
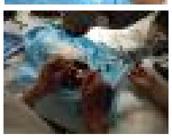
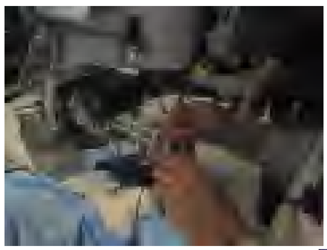
Alcon Vitreosurgery Instrument

Microsurgery Assistant Workstation

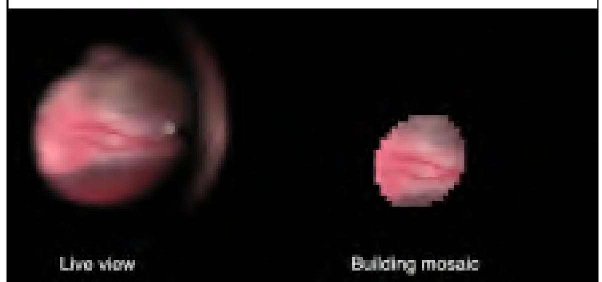


In-Vivo Experiments

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

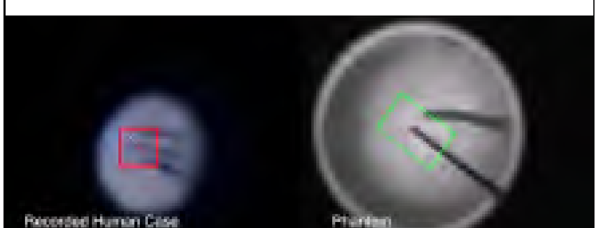





Retina Mosaicking, Annotation, and Registration



R. Richa, B. Vagvolgyi, R. Taylor, G. Hager, ***MICCAI 2012***,

Tool and Retina Tracking

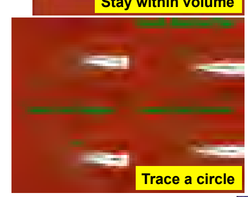


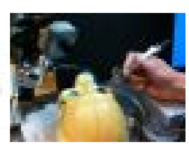
Balazs Vagvolgyi, Raphael Sznitman, Greg Hager, Rogerio Richa, Russ Taylor, *et al.*

MICRON active tremor cancellation device

Cameron Riviere, Robert McLaughlin, B. Becker *et al.* (CMU)

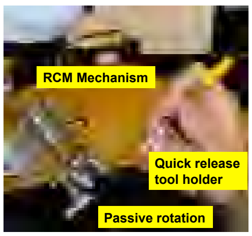
- Handheld device
- Sense tremulous motion
- Actively move to compensate
- BRP Research goals:
  - Incorporate "endpoint sensing" from vision & other sensors
  - Virtual fixtures
  - Improved device for eventual clinical use



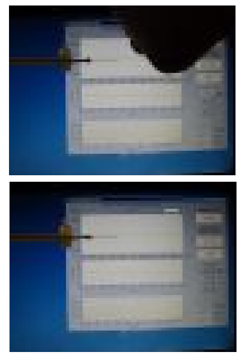
JHU Steady Hand "Eye Robot"

Russell Taylor, Iulian Iordachita, D. Gierlach, D. Roppenocker, *et al.*



- Highly precise robot
- Hands-on cooperative control or teleoperation
- Several generations in lab
- Precise, stable platform for developing "smart" surgical instruments and sensors
- Virtual fixtures and advanced control

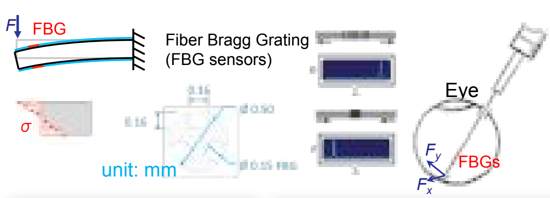
Force Sensing Surgical Instruments



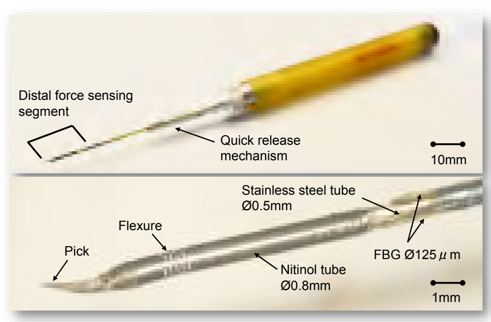
- Incorporate fiber optic force sensors into 0.5 mm diameter surgical tools
- 0.25 mN force sensitivity

Iordachita, Sun, Balicki, ..., Kang, Handa, Gehlbach, Taylor

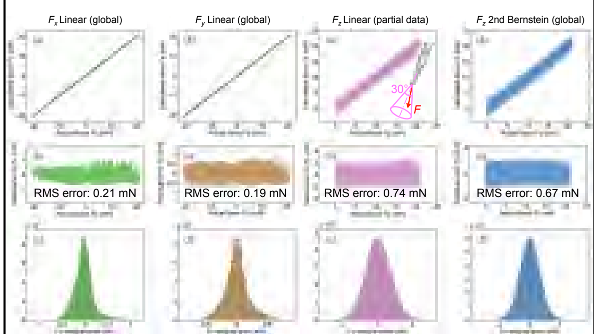
2-DOF Force Sensing Tools



3-DOF Force Sensing Pick Tool

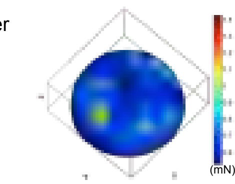


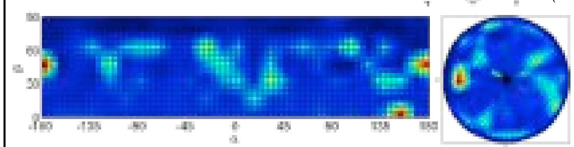
Calibration: Results



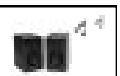
Calibration: F_z RMS Error

- Overall RMS error with 2nd order Bernstein polynomial: 0.67 mN
- Estimation performance in each force direction (total 168 poses)
  - 84.5% (142 poses) < 0.75 mN
  - 96.4% (162 poses) < 1 mN

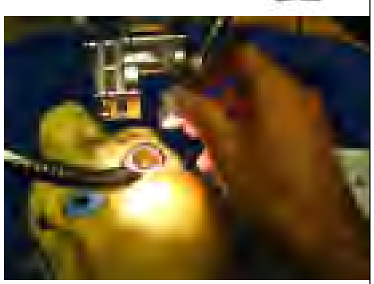




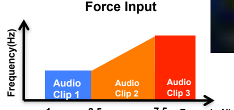
Use of Audio and Voice



- Voice commands and annotation
- Auditory sensory substitution

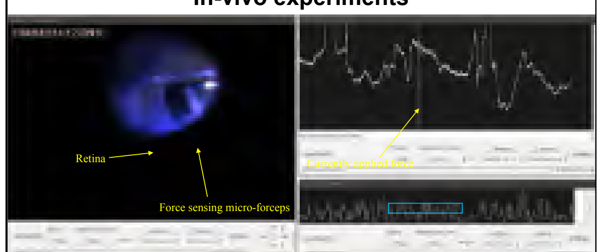


Example Audio Response to Force Input

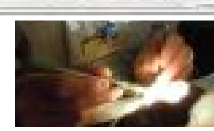


M. Balicki, *et al.*

In-vivo experiments



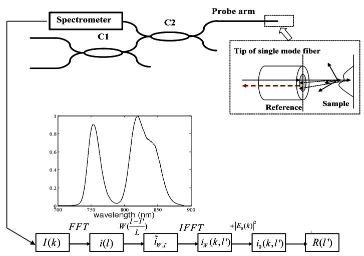
Xingchi He, Marcin Balicki, Jin U. Kang, Peter Gehlbach, James Handa, Russell Taylor, Iulian Iordachita "Force sensing micro-forceps with integrated fiber Bragg grating for vitreoretinal surgery", SPIE 2012

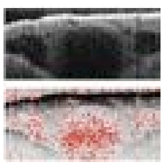


Imaging (OCT) Built Into 0.5mm Surgical Tool

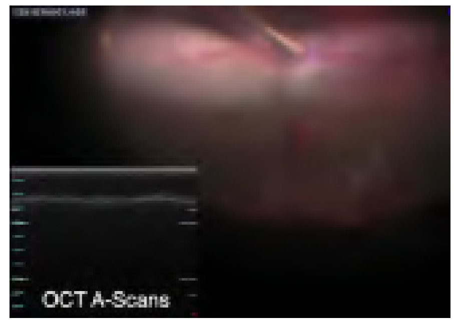
M. Balicki, J. Han, X. Liu, I. Iordachita, P. Gehlbach, J. Handa, R. Taylor, J. Kang.

- Fourier Domain Common Path OCT (FD CPOCT)
- Combined Superluminescent Diodes
- Functional and structural images





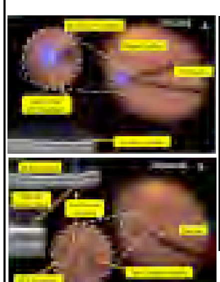
OCT of Rabbit Retina with Micron-held Probe



X. Liu, M. Balicki, C. Riviere, R. MacLaughlin, *et al.*

Engineering Research Center for Computer Integrated Surgical Systems and Technology

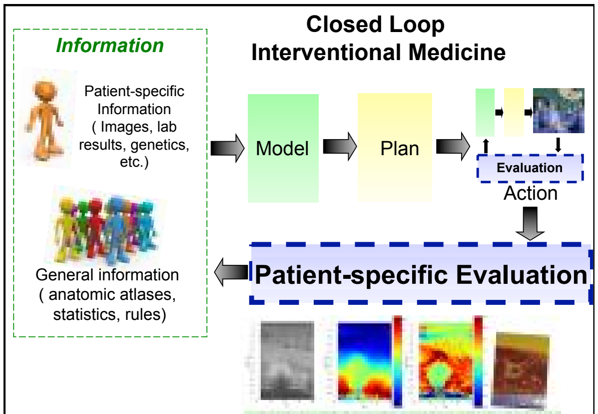
M-Scan



M. Balicki, R. Richa, B. Vagvolgyi, J. Handa, P. Gehlbach, J. Kang, P. Kazanzides, and R. Taylor, "Interactive OCT Annotation and Visualization System for Vitreoretinal Surgery", Medical Image Computing and Computer-Assisted Interventions (MICCAI), Nice, October, 2012

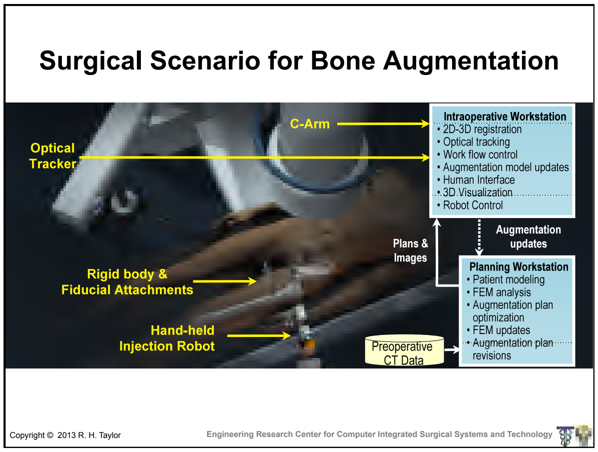
Engineering Research Center for Computer Integrated Surgical Systems and Technology

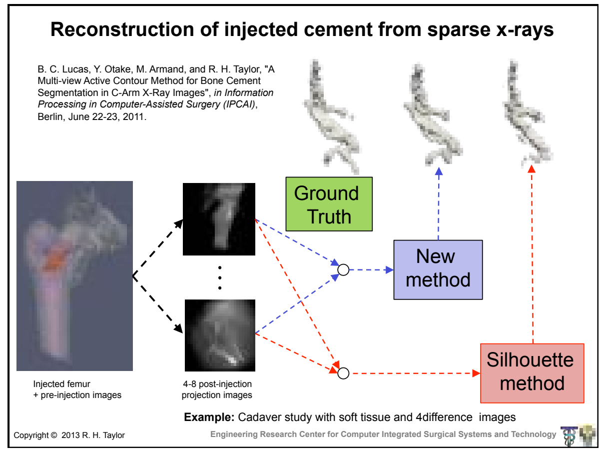
Closed Loop Interventional Medicine

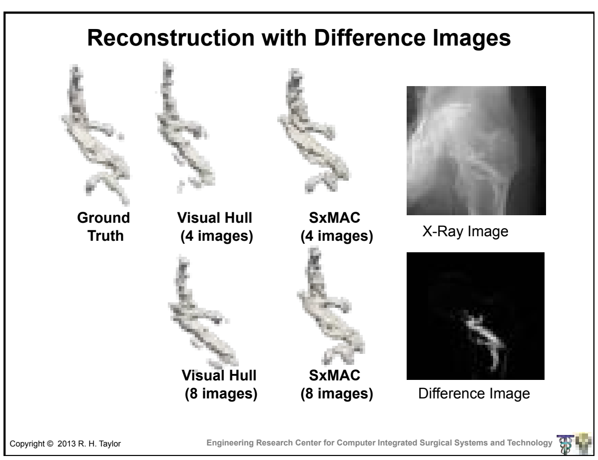


EUS images: E. Boctor

Engineering Research Center for Computer Integrated Surgical Systems and Technology


Surgical Scenario for Bone Augmentation
C-Arm
Optical Tracker
Rigid body & Fiducial Attachments
Hand-held Injection Robot
Intraoperative Workstation
• 2D-3D registration
• Optical tracking
• Work flow control
• Augmentation model updates
• Human Interface
• 3D Visualization
• Robot Control
Plans & Images
Augmentation updates
Planning Workstation
• Patient modeling
• FEM analysis
• Augmentation plan optimization
• FEM updates
• Augmentation plan revisions
Preoperative CT Data
Copyright © 2013 R. H. Taylor
Engineering Research Center for Computer Integrated Surgical Systems and Technology


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.
Ground Truth
New method
Silhouette method
Injected femur + pre-injection images
4-8 post-injection projection images
Example: Cadaver study with soft tissue and 4difference images
Copyright © 2013 R. H. Taylor
Engineering Research Center for Computer Integrated Surgical Systems and Technology


Reconstruction with Difference Images
Ground Truth
Visual Hull (4 images)
SxMAC (4 images)
X-Ray Image
Visual Hull (8 images)
SxMAC (8 images)
Difference Image
Copyright © 2013 R. H. Taylor
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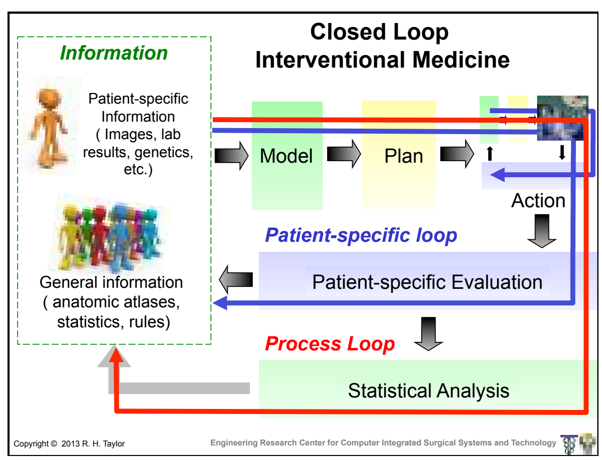
Closed Loop Interventional Medicine
Information
Patient-specific Information (Images, lab results, genetics, etc.)
General information (anatomic atlases, statistics, rules)
Model
Plan
Action
Patient-specific loop
Patient-specific Evaluation
Process Loop
Statistical Analysis
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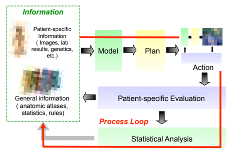
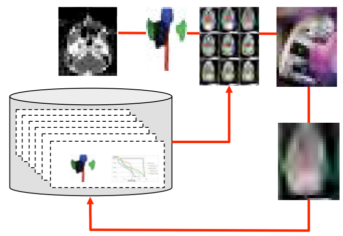
Information-Integrated Process Learning

- **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

Statistical process control for radiation therapy



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

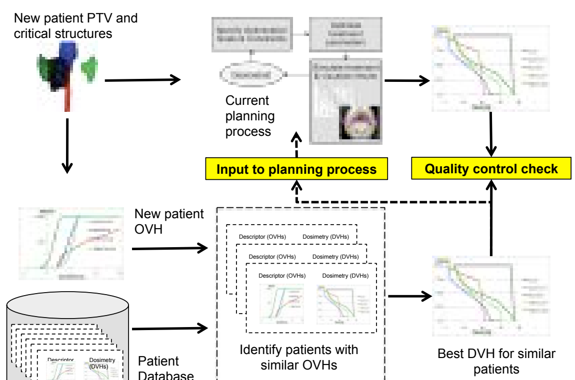
Team:

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

BME: R. Jacques

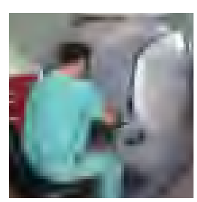
Rad. Oncology: T. McNutt, J. Wong, B. Wu, G. Sanguinetti (MD)

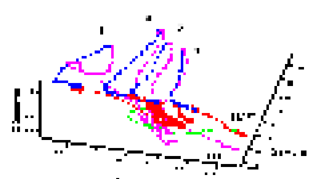
Support: Paul Maritz, Philips, JHU internal funds



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

"The language of surgery" Statistical learning of surgical gestures





Hager, *et al.*

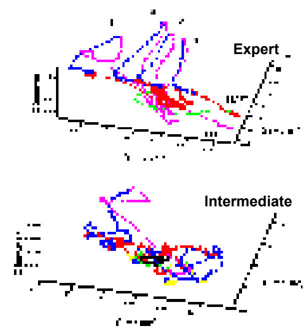
Applications Of Surgical Motion Models

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

G. Hager, *et al.*

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

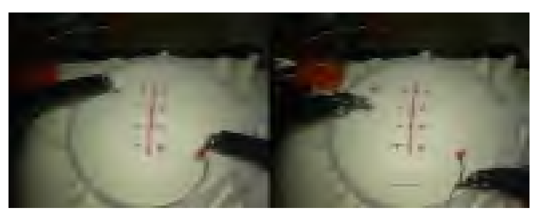


H. Lin, I. Shafran, T. Murphy, D. Yuh, A. Okamura, G. Hager (MICCAI 2005)

Expert-Expert

Hager, *et al.*

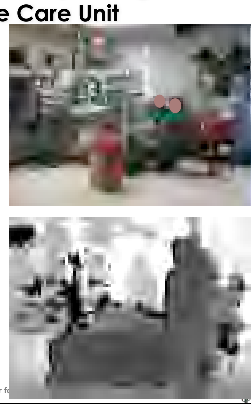
Expert-Novice



Hager, *et al.*

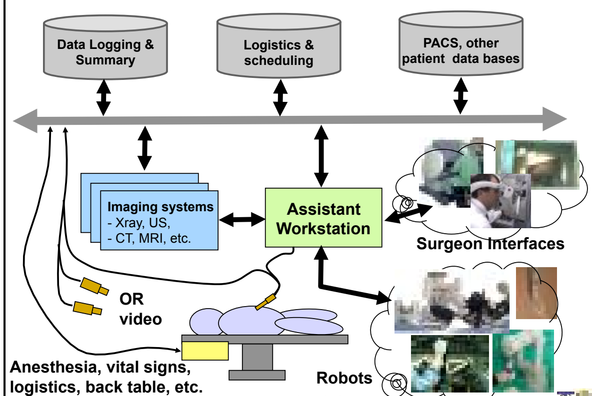
Towards Automated Activity Recognition in an Intensive Care Unit

ICUs are chaotic!
- •Hundreds of tasks
- •Dozens of staff
- •Cluttered environment



(Colin Lea, *et al.*)

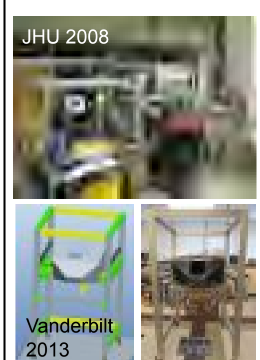
Information-Intensive Interventional Suite



Surgical Assistant Workstation

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

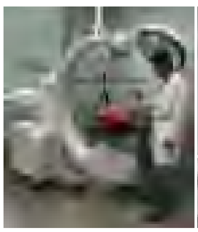
Use case: Da Vinci "Toolkits"



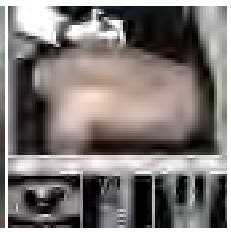
- Mechanical components from Da Vinci "classic" systems
- Donated by Intuitive Surgical to selected university labs
- Consortium to provide "open source" engineering and support
  - Software – JHU (CISST/SAW)
  - Controller electronics –JHU
  - Controller power/packaging – WPI

Cone-Beam CT-Guided Surgical Navigation

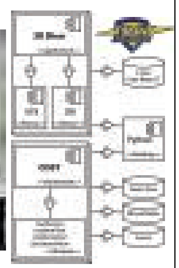
I-STAR Lab



C-arm Setup in the JHU Minimially Invasive Surgical Training and Innovation Center (MISTIC)



Integrated Tracking and Video Augmentation with the Claron MicronTracker



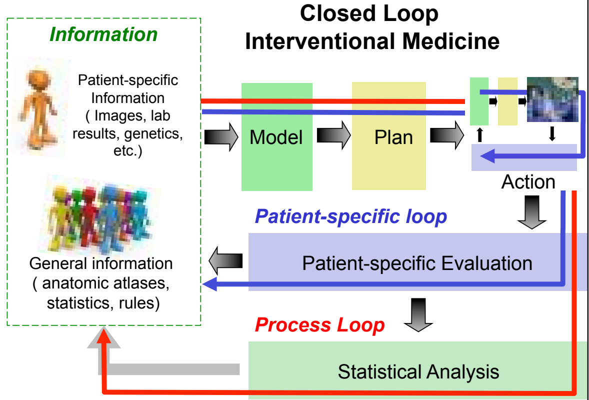
Open-Source Architecture for System Integration

Slide courtesy of J.H. Siewerdsen, Johns Hopkins University

SAW Beyond Surgery

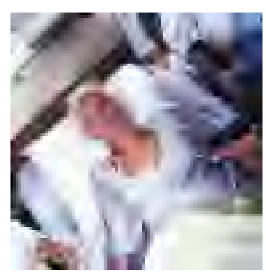
- SAW = Space Assistant Workstation?
- Perform “image-guided surgery” on satellites
  - CT/MRI Image → CAD Model
- Added challenge: time delay (5-10 seconds)
  - Virtual fixtures, semi-autonomous motions, shared control

Closed Loop Interventional Medicine



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