Autonomy and Semi-Autonomous Behavior in Surgical Robot Systems

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Disclosures & Acknowledgments

- **This is the work of many people**
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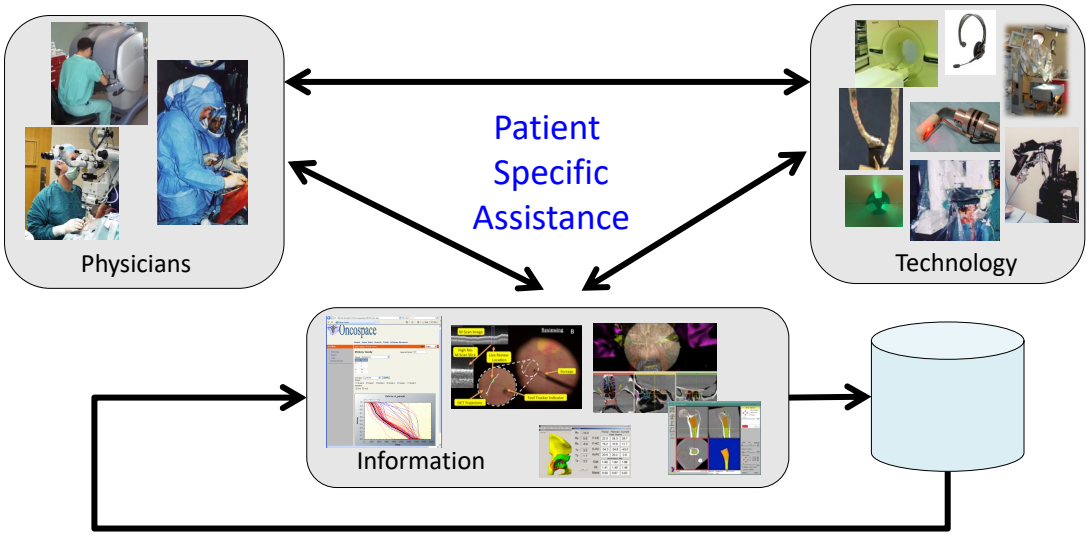
Human-machine partnership to fundamentally improve interventional medicine



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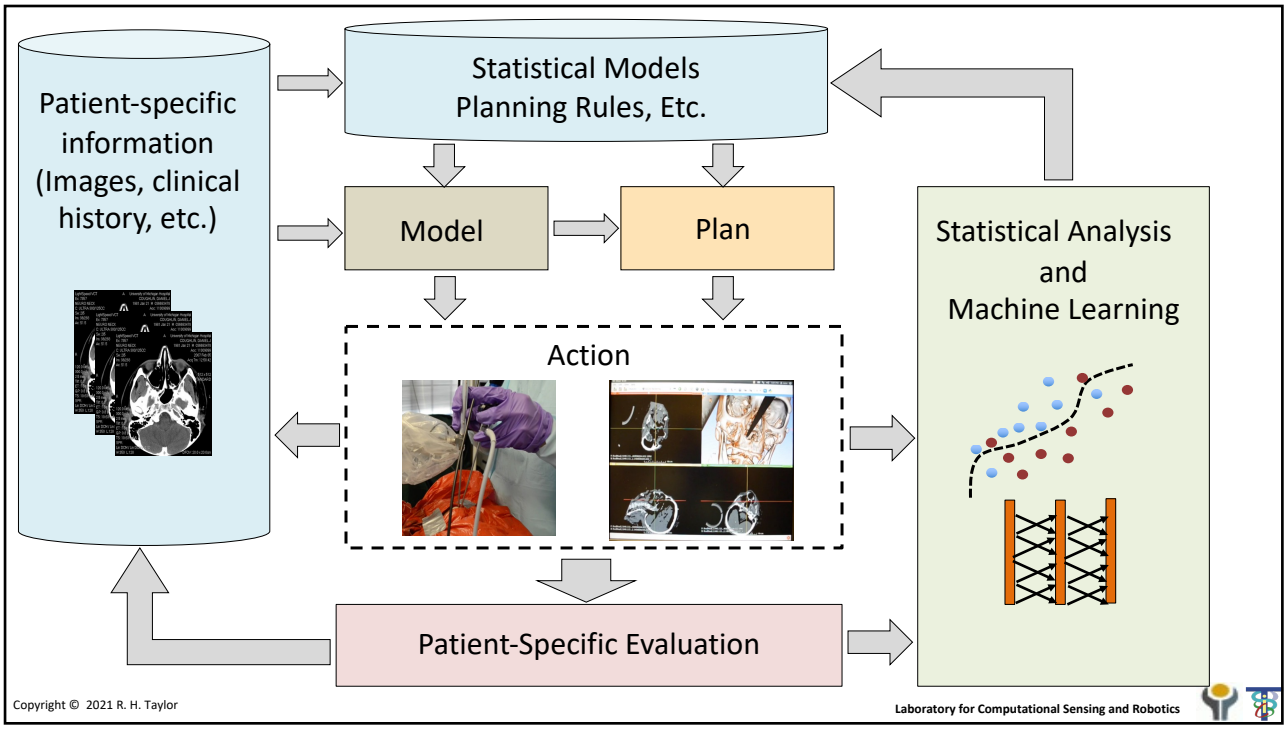

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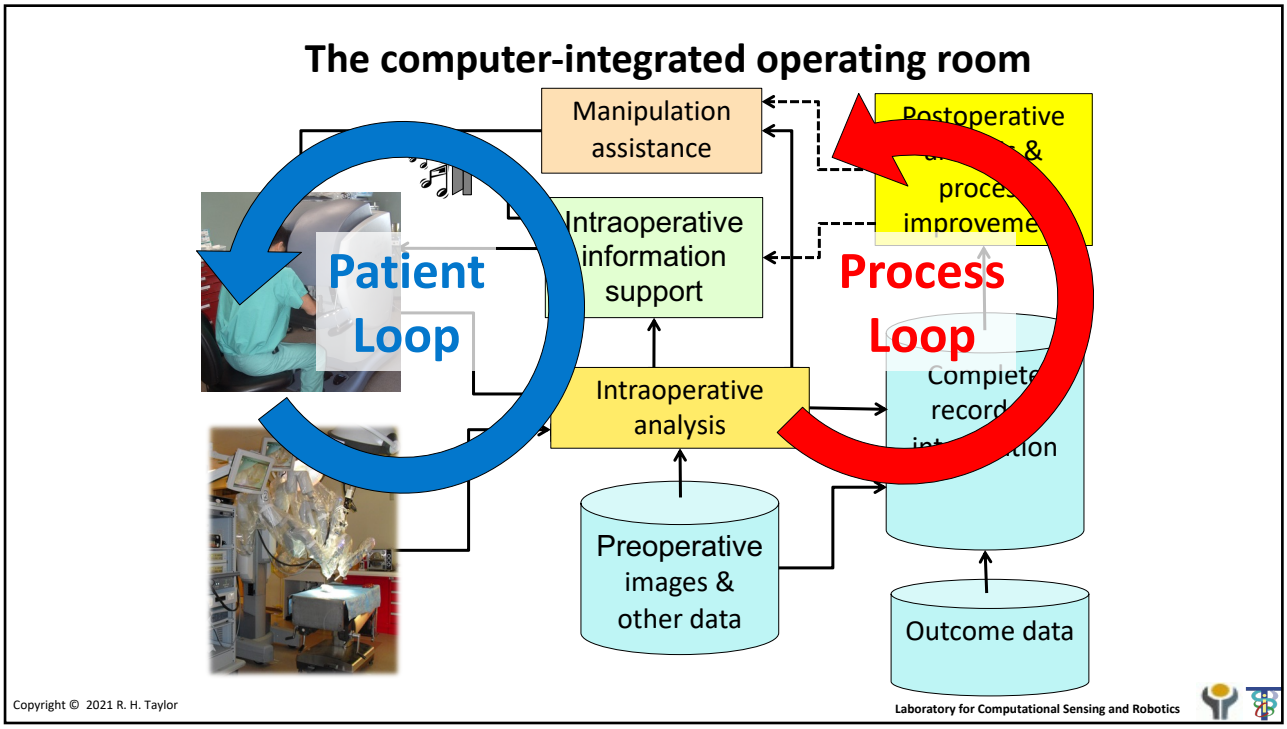
The computer-integrated operating room
Manipulation assistance
Intraoperative information support
Intraoperative analysis
Preoperative images & other data
Outcome data
Patient Loop
Process Loop
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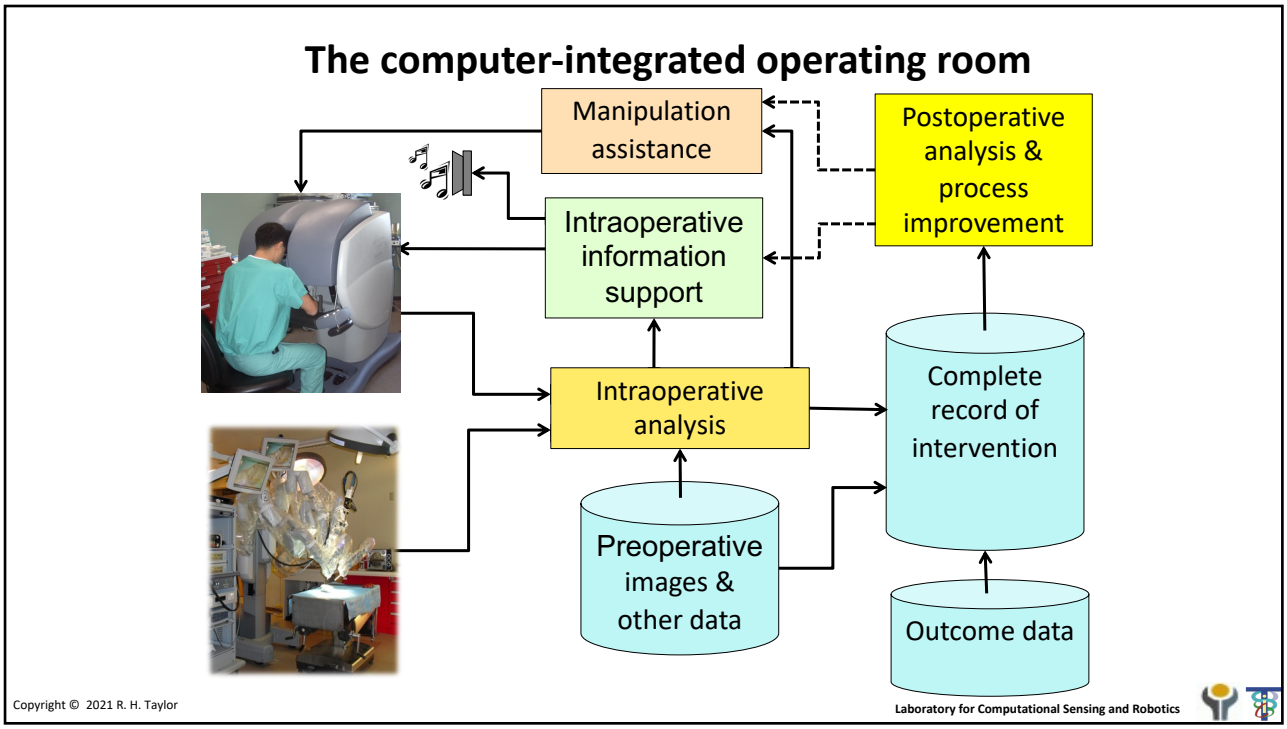
The computer-integrated operating room
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Postoperative analysis & process improvement
Complete record of intervention
Outcome data
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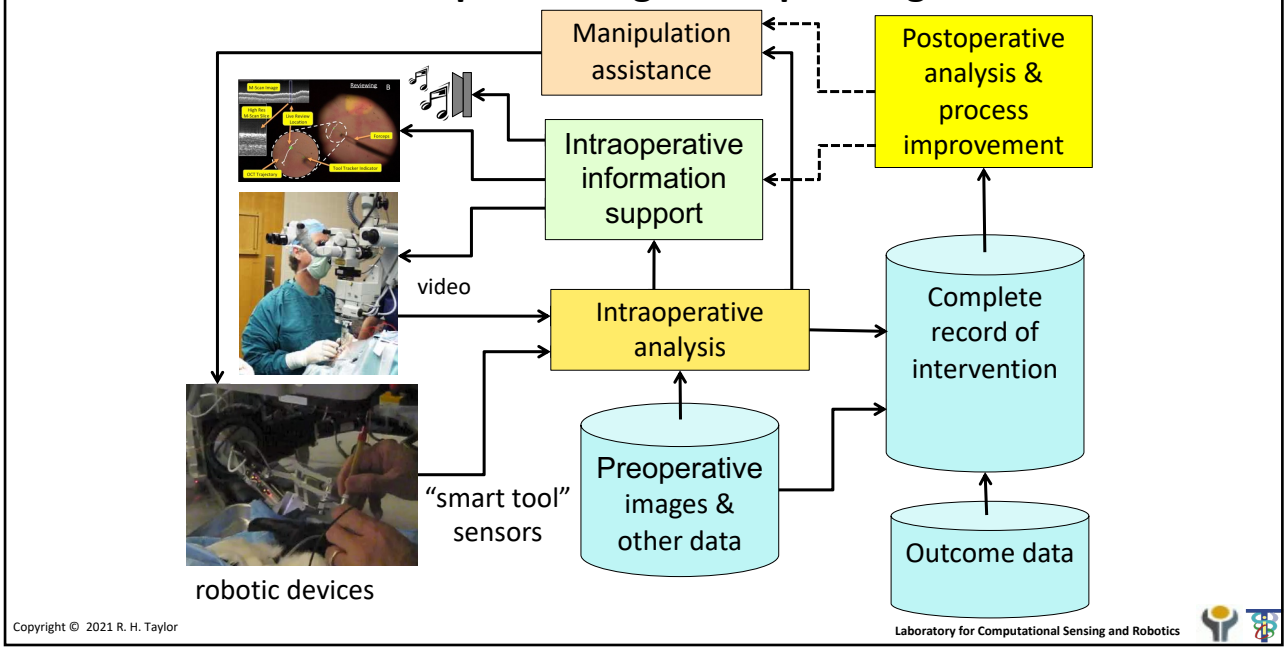
The computer-integrated operating room



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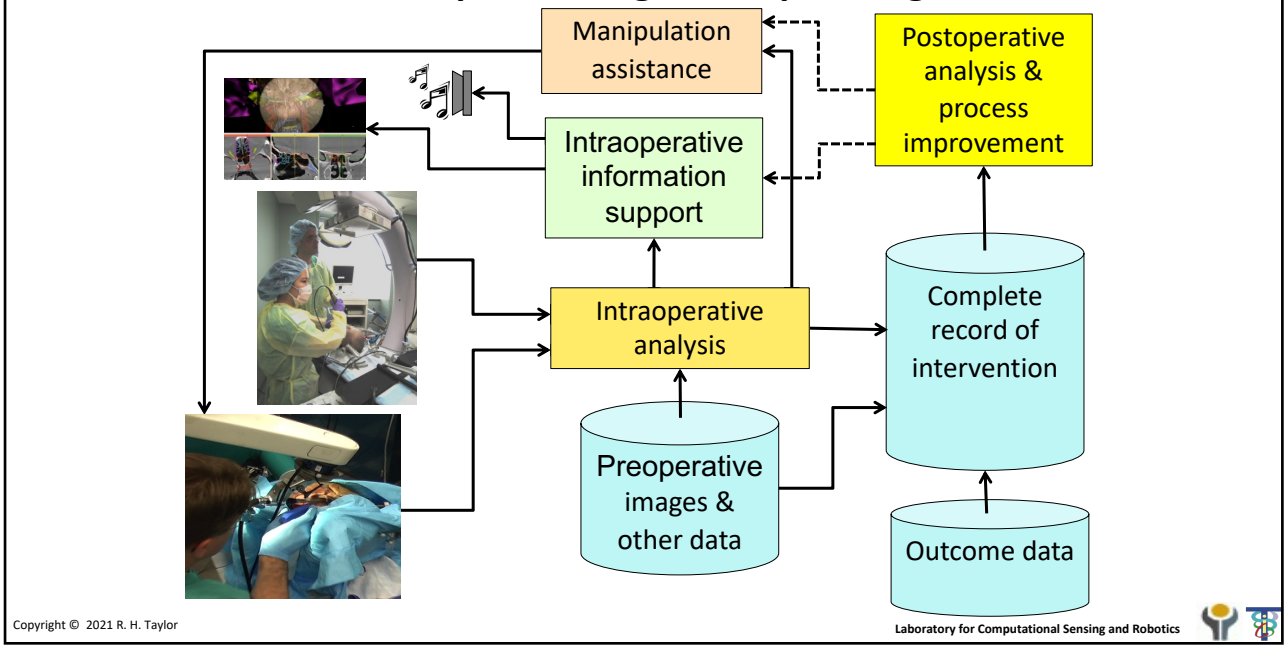
The computer-integrated operating room



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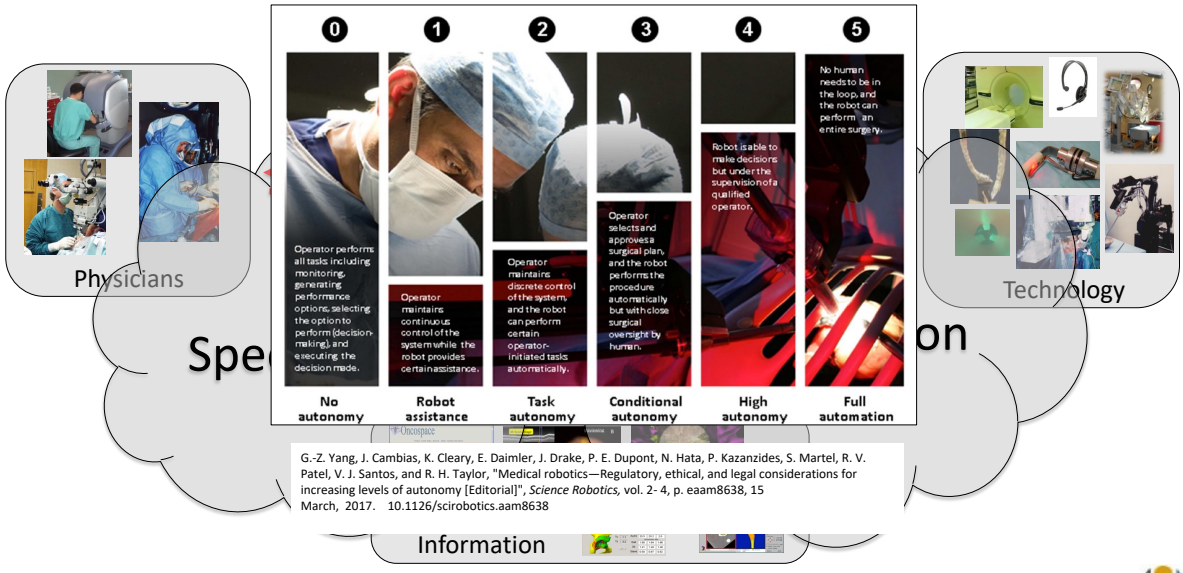
The key issue: mediating between human intention and action



G.-Z. Yang, J. Cambias, K. Cleary, E. Daimler, J. Drake, P. E. Dupont, N. Hata, P. Kazanzides, S. Martel, R. V. Patel, V. J. Santos, and R. H. Taylor, "Medical robotics—Regulatory, ethical, and legal considerations for increasing levels of autonomy [Editorial]", *Science Robotics,* vol. 2- 4, p. eaam8638, 15 March, 2017. 10.1126/scirobotics.aam8638

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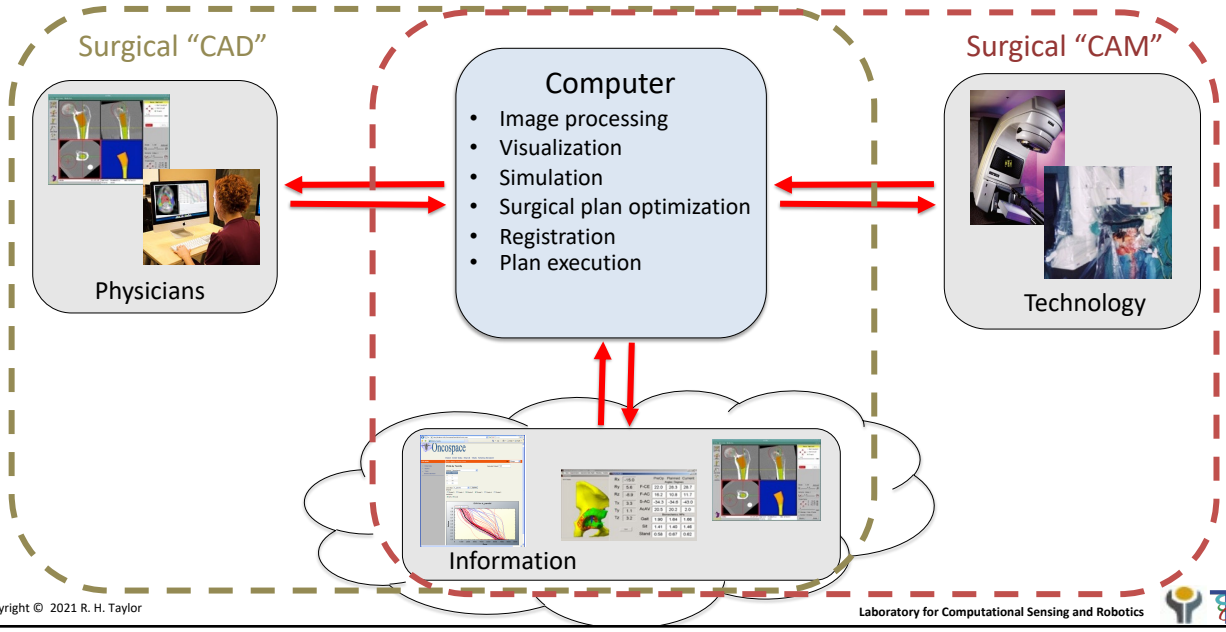
Surgical "CAD/CAM"



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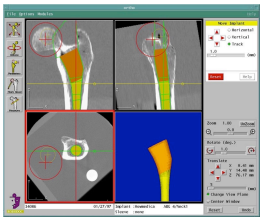
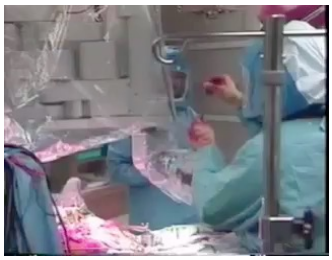
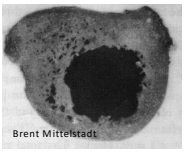
Robotic Joint Replacement Surgery

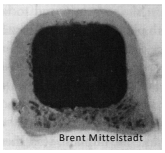


Taylor, Kazanzides, Paul, Mittelstadt, *et al.*





Manual Surgery



Robotic Surgery

Planning:

- Initially interactive graphics with CT images
- Subsequently
  - Automate segmentation
  - Statistics based planning

Execution

- Combination of hand guiding and autonomous machining bones
- Initially mechanical location of fiducials for registration
- Subsequently
  - ICP-based registration
  - Image-based registration

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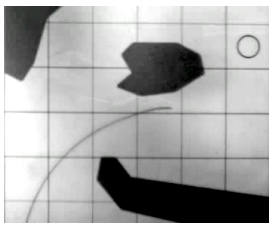
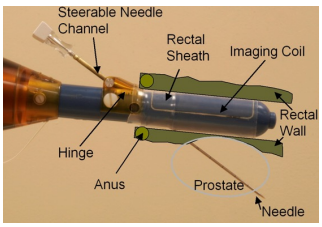
Image-guided needle placement

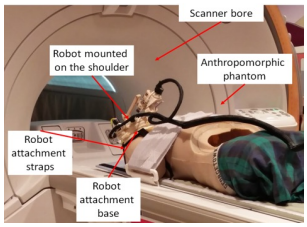
Masamune, Fichtinger, Iordachita, …



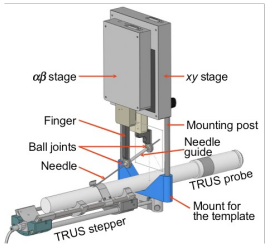
Okamura, Webster, …



Krieger, Fichtinger, Whitcomb, …

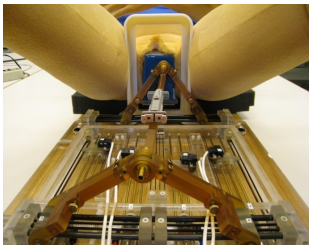


Monfaredi, Sharma, Kim, Iordachita, Cleary



Fichtinger, Kazanzides,Burdette, Song …

Taylor, Masamune, Susil, Patriciu, Stoianovici,…



Iordachita, Fischer, Hata…

Iordachita, Fischer, Hata…

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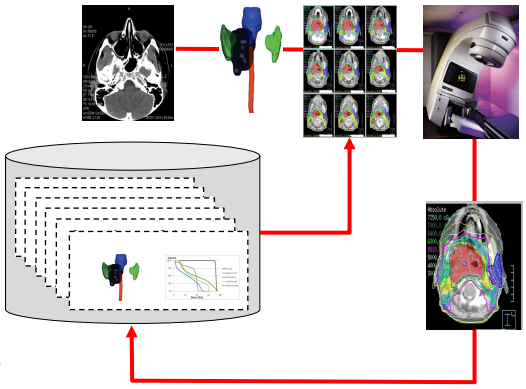
Example: External Beam Radiation Therapy Systems

- "Robotic" systems since at least 1980s
- Task Specification
  - Planning of radiation pattern from CT
  - Typically human-machine process involving optimization + simulation
- Task Execution
  - Very careful and accurate machine calibration & verification
  - Registration to patient
  - Machine delivers beams of radiation from multiple angles
- Challenges/Opportunities
  - Adaptation to patient changes/motion
  - Experience-based planning to optimize outcomes
  - The "usual" (system integrity, etc.)



JHU Faculty: Todd McNutt, Russell Taylor, Mischa Kazhdan, Ilya Shpitser, Sauleh Siddiqui

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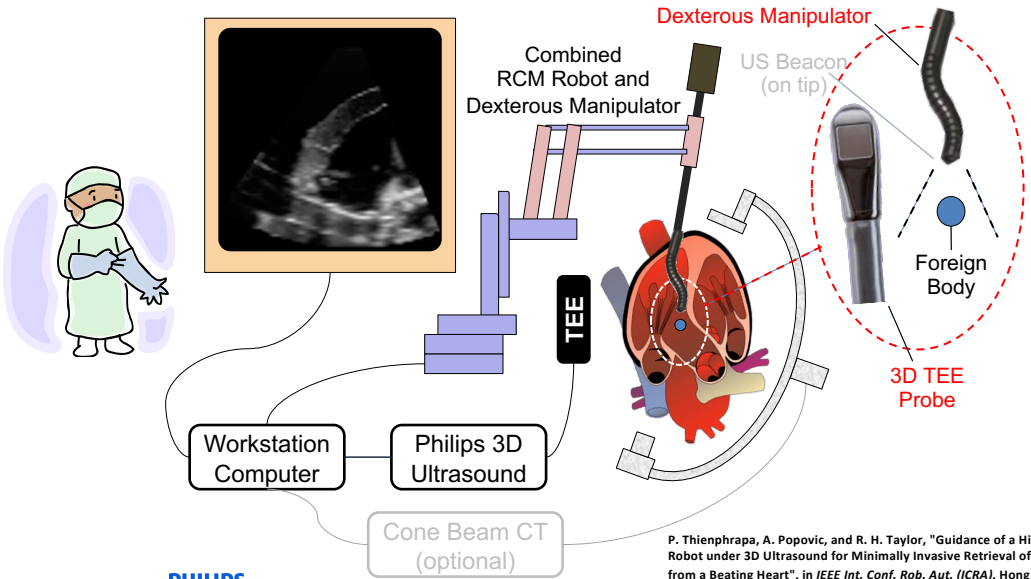
Beating Heart MIS with 3D US Guidance

Paul Thienphrapa, Aleksandra Popovic, Russell Taylor



P. Thienphrapa, A. Popovic, and R. H. Taylor, "Guidance of a High Dexterity Robot under 3D Ultrasound for Minimally Invasive Retrieval of Foreign Bodies from a Beating Heart", in *IEEE Int. Conf. Rob. Aut. (ICRA)*, Hong Kong, May 31-Jun 6, 2014. pp. 4869-4874.

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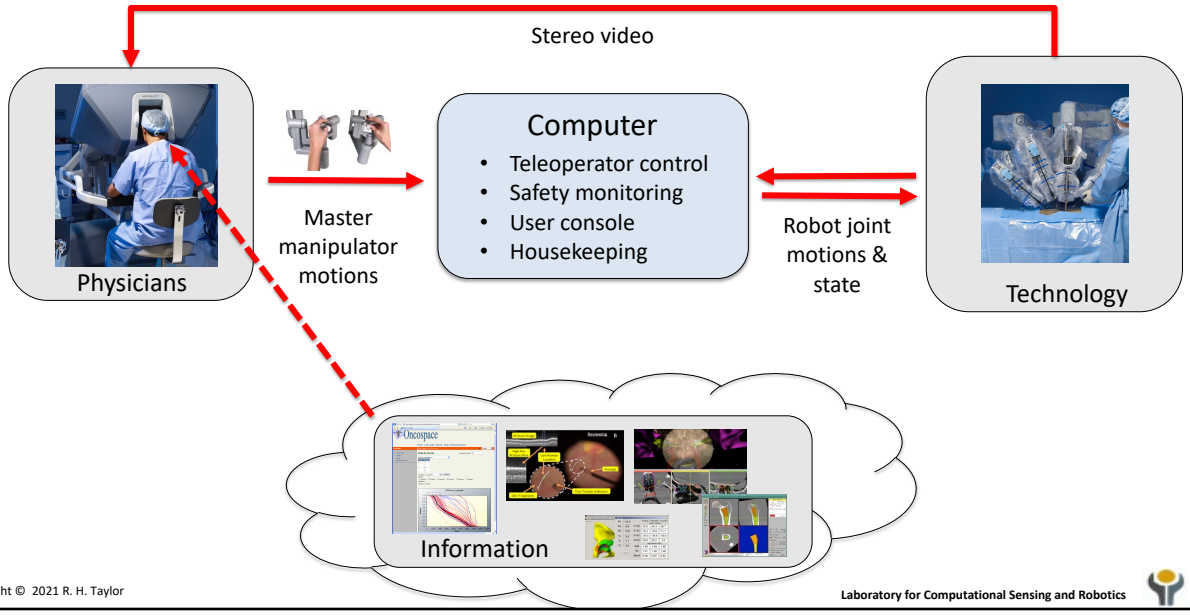
Current dominant paradigm for interactive surgery



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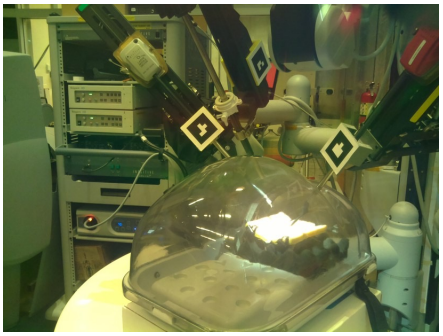
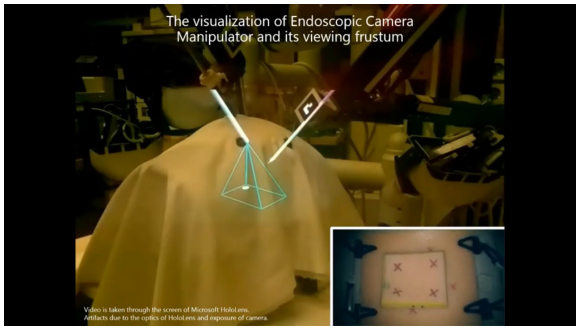
Augmented Reality: da Vinci Patient-Side Assistant

L. Qian, A. Deguet, Z. Wang, Y. Liu, P. Kazanzides



Setup with transparent abdominal phantom



View through HMD (HoloLens)

L. Qian, A. Deguet, P. Kazanzides, "ARssist: Augmented Reality on a Head-Mounted Display for the First Assistant in Robotic Surgery", *IET Healthcare Technology Letters*, Oct. 2018

L. Qian, A. Deguet, Z. Wang, Y. Liu, P. Kazanzides, "Augmented Reality Assisted Instrument Insertion and Tool Manipulation for the First Assistant in Robotic Surgery", *IEEE ICRA*, May 2019.

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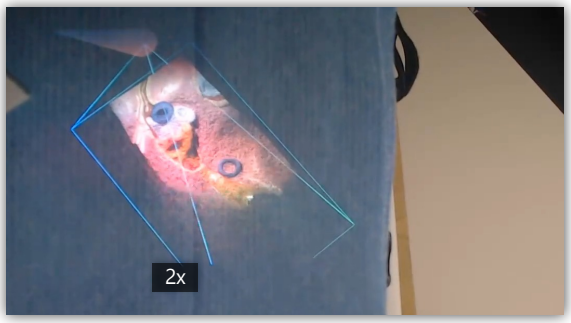
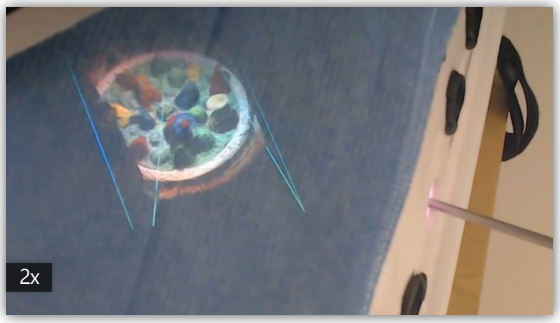
Augmented Reality: Laparoscopic Guidance

L. Qian, X. Zhang, A. Deguet, P. Kazanzides





L. Qian, X. Zhang, A. Deguet, P. Kazanzides. "ARAMIS: Augmented Reality Assistance for Minimally Invasive Surgery Using a Head-Mounted Display." *MICCAI* 2019.

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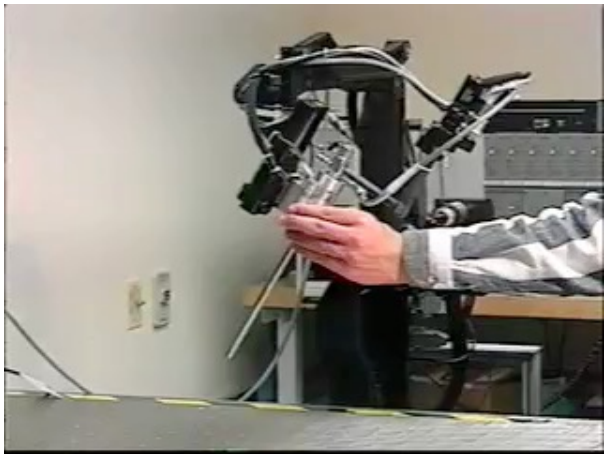
Steady Hand Manipulation

Robodoc Canine Surgery, 1990



LARS Robot in IBM Lab, *ca.* 1993

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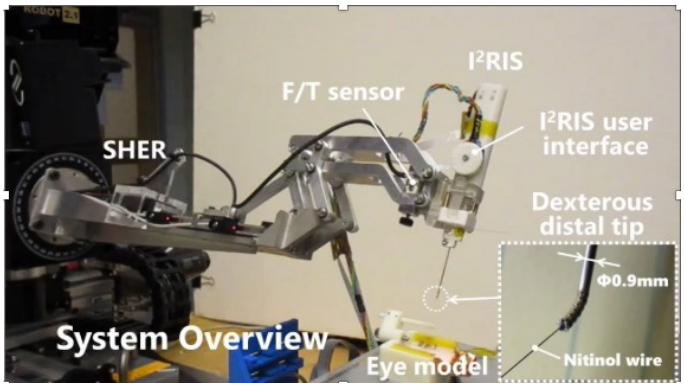
An Integrated High-dexterity Cooperative Robotic Assistant for Intraocular Micromanipulation

Makoto Jinno
School of Science and Engineering, Kokushikan University, Japan
Gang Li, Niravkumar Patel and Iulian Iordachita
WSE, LCSR, Johns Hopkins University, USA

- This system comprises an improved integrated robotic intraocular snake (I²RIS) and the Steady-Hand Eye Robot (SHER).
- Two user interfaces (joystick and tactile switch) for the I²RIS were developed and evaluated.
- The usability experiments using eye models indicated high-dexterity for either user interface.



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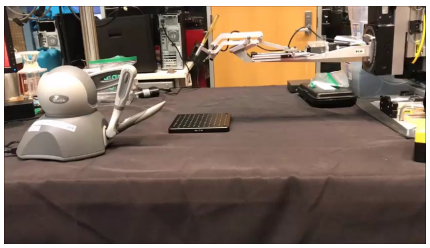
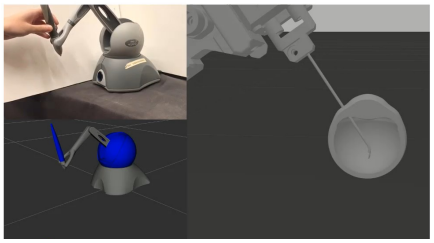
Teleoperation control of snake robot attached to eye robot

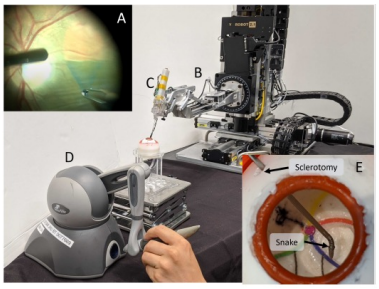
A. Ebrahimi, M. Jinno, I. Iordachita, *et al.*





Envisioned high dexterity intraocular manipulator:

(A)Epiretinal membrane peeling
(B) Steady Hand Eye Robot
(C) Integrated robotic intraocular snake robot
(D) Phantom Omni
(E) Distal snake-like tool-end inside eye phantom



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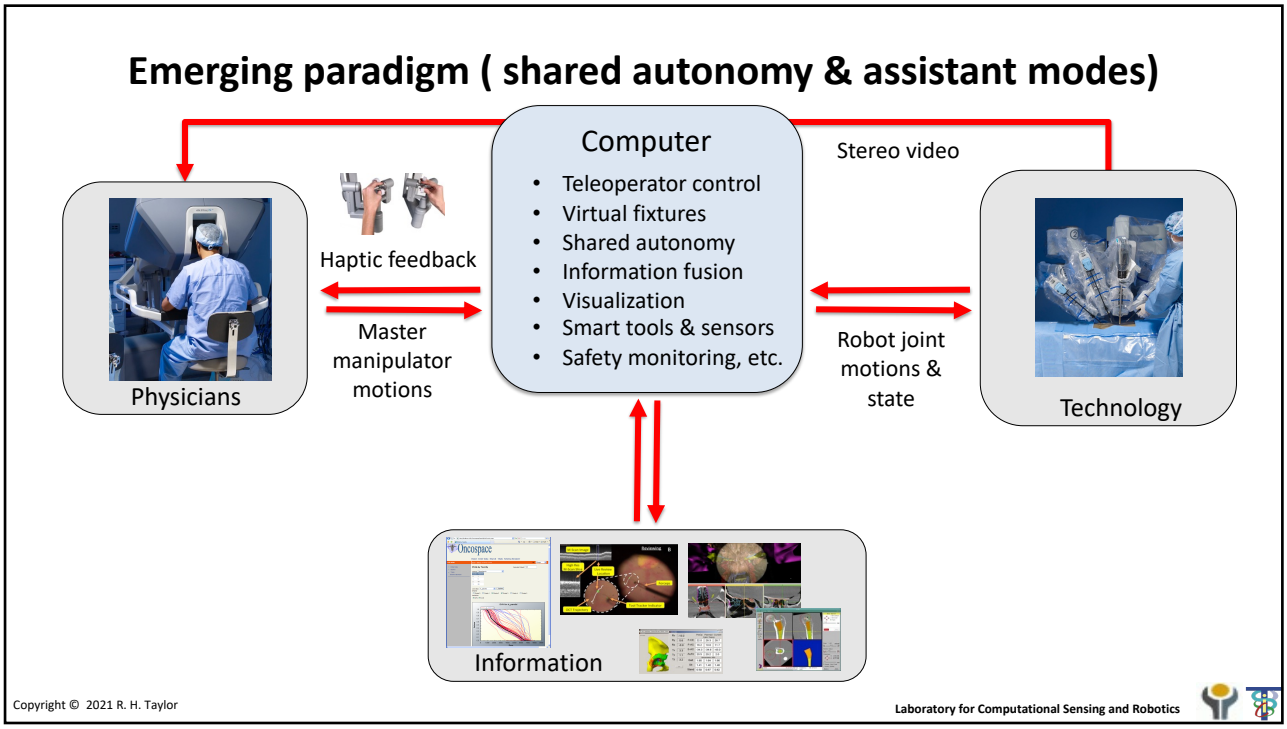
Emerging paradigm (shared autonomy & assistant modes)
Computer
• Teleoperator control
• Virtual fixtures
• Shared autonomy
• Information fusion
• Visualization
• Smart tools & sensors
• Safety monitoring, etc.
Stereo video
Haptic feedback
Master manipulator motions
Robot joint motions & state
Physicians
Technology
Information
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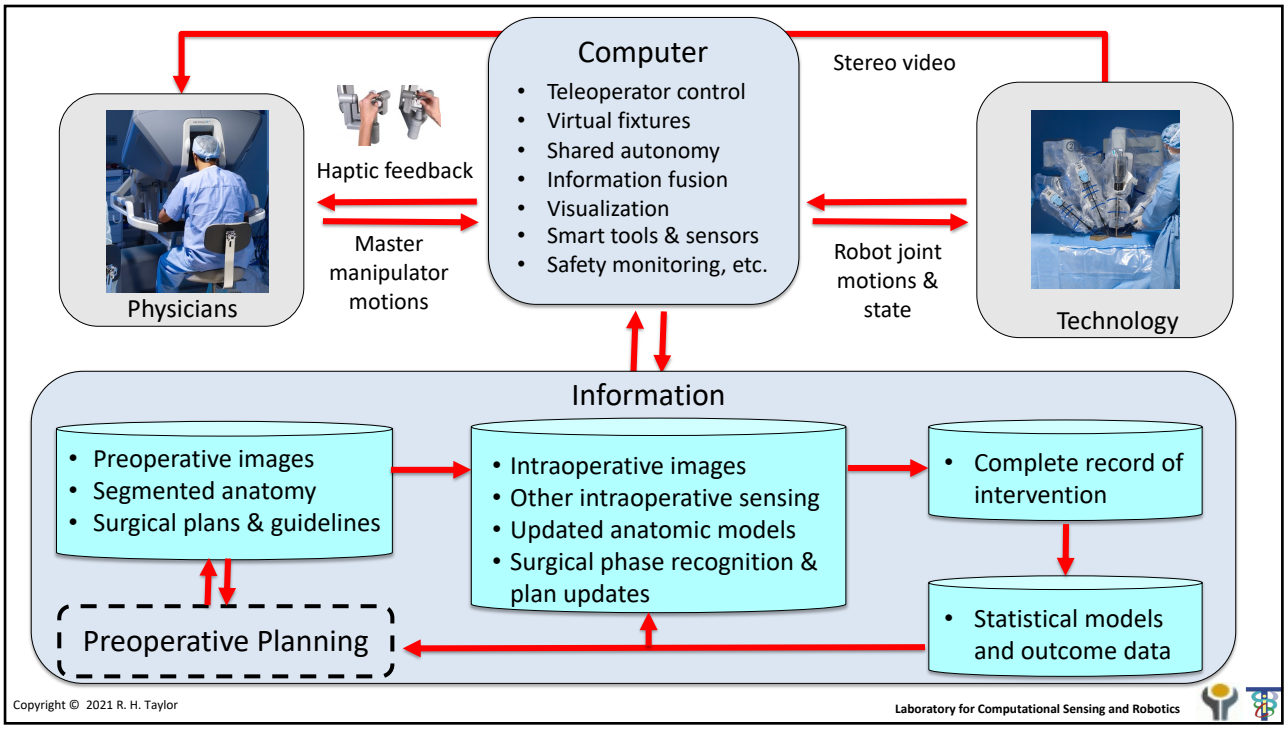
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• Preoperative images
• Segmented anatomy
• Surgical plans & guidelines
• Intraoperative images
• Other intraoperative sensing
• Updated anatomic models
• Surgical phase recognition & plan updates
• Complete record of intervention
• Statistical models and outcome data
Preoperative Planning
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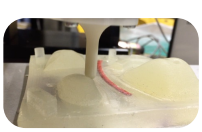
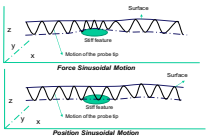
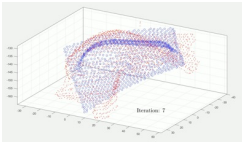
Complementary Situational Awareness in a Robotic Surgical Assistant







Technology

Surgeon

Teleop, Palpation

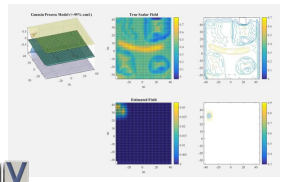
Manipulation

Stiffness and surface information, Display

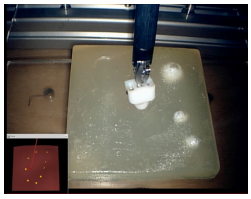
Visualization

Guidance

VFs , Surface Modelling, Registration, Haptics



Information



NSF NRI 1327566: JHU, CMU, Vanderbilt

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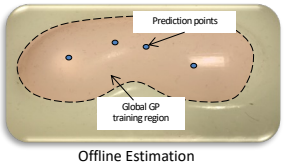
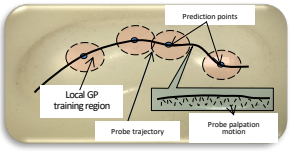
Continuous Stiffness and Geometry Update

Preetham Chalasani, Russell Taylor



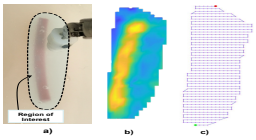
Offline Estimation

Chalasani et. al, ICRA 2016

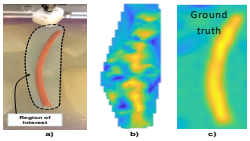


Online Estimation

Chalasani et. al, RAL 2018



Results from automated Sinusoidal palpation



Teleoperated palpation w. superimposed motion

Automated Sinusoidal Palpation

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Semi-Autonomous Palpation Example

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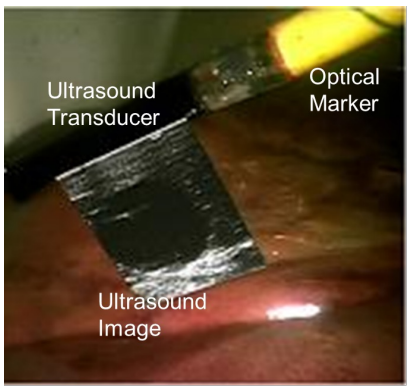
ULTRASOUND PALPATION

Seth Billings, Nishikant Deshmuk, Hyun-Jae Kang, Russ Taylor, Emad Boctor (2011)



Leven J. et al., "DaVinci Canvas: A Telerobotic Surgical System with Integrated, Robot-Assisted, Laparoscopic Ultrasound Capability". MICCAI 2005, 811-818

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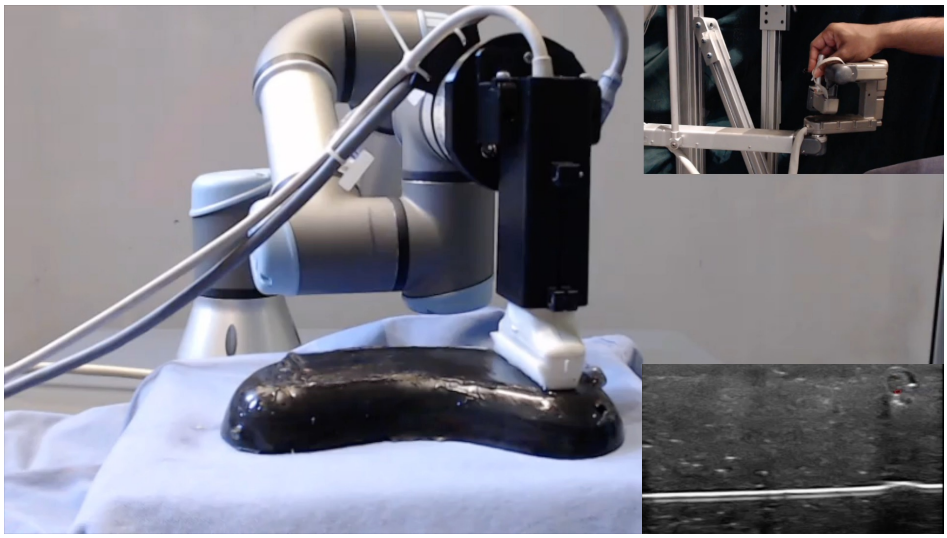
ULTRASOUND PALPATION



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Cadaver Study: Sinus Surgery with Virtual Fixtures

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

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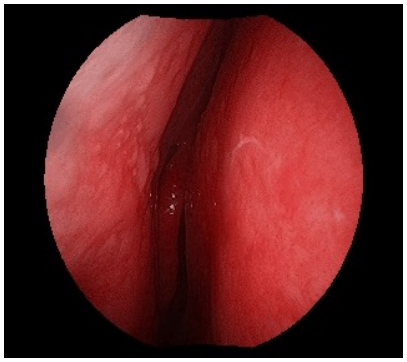
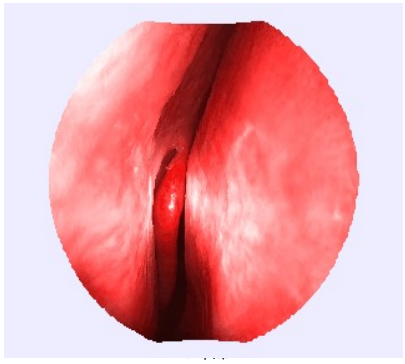
3D airway reconstruction during nasal endoscopic procedures without external tracking devices

Xingtong Liu





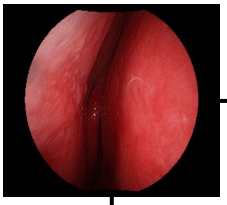
Monoscopic Endoscope Video

Dense Point Cloud Reconstruction

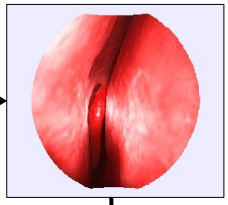
X. Liu, A. Sinha, M. Unbareth, M. Ishii, G. D. Hager, R. H. Taylor, and A. Reiter, "Self-Supervised Learning for Dense Depth Estimation in Monocular Endoscopy", (best paper) in MICCAI Computer Assisted and Robotic Endoscopy (CARE), Grenada, Spain, September 16, 2018.

44

A "smart" sinus endoscopy assistant



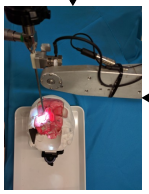
Structure from Motion

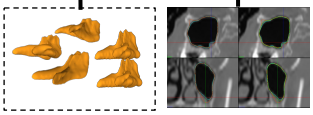


Tool Tracking

Navigation
Quantitative endoscopy
Assistance Modes
Learning & Training

Registration



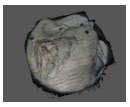


49

A "smart" skull base surgical assistant

Zhaoshuo Li

Stereo Video

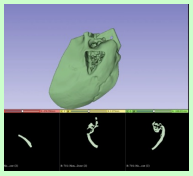


3D Point Cloud

Patient CT

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

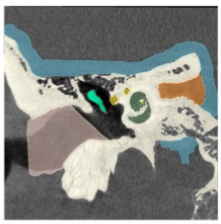
Registered and updated real time model
Tool tracking

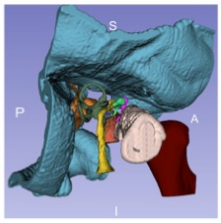


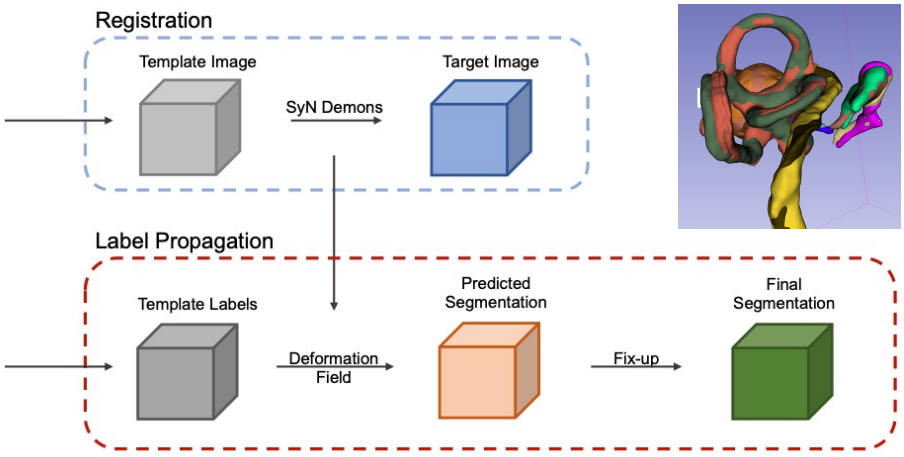
Assistance Modes & Virtual fixtures
Navigation
Advanced Visualization
Learning & Training

50

Automated Segmentation of Temporal Bone Structures







Andy Ding, Alex Lu, Francis Creighton, Russ Taylor

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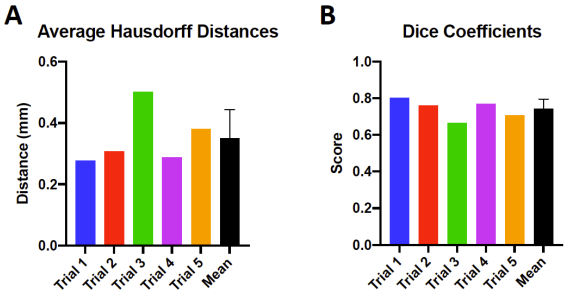
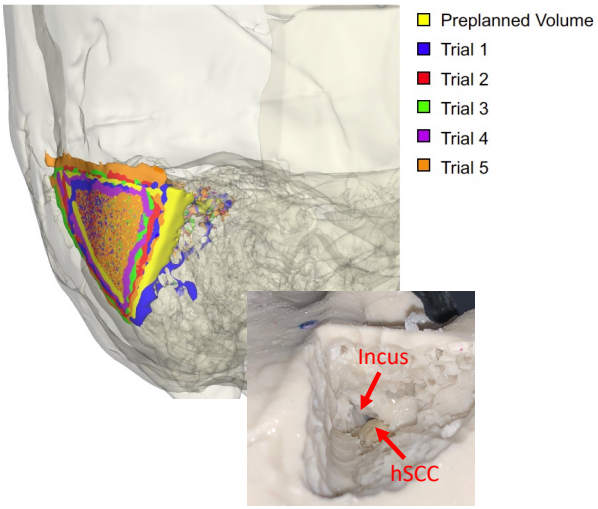
Results

- Mean time to completion: 221 +/- 35 seconds (3.6 min)
- Average Hausdorff Distance ~0.3mm





Andy Ding, Alex Lu, Francis Creighton, Russ Taylor

Laboratory for Computational Sensing and Robotics

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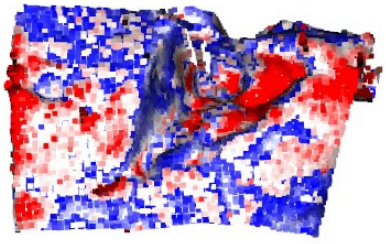
Registration Result

	Inlier RMSE	# of Correspondence
Direct generalization	1.152 mm	6946
Self supervision	1.147 mm	6928



Zhaoshuo (Max Li), Mathias Unberath, Russell Taylor, *et al.*

Laboratory for Computational Sensing and Robotics

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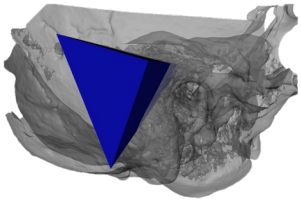
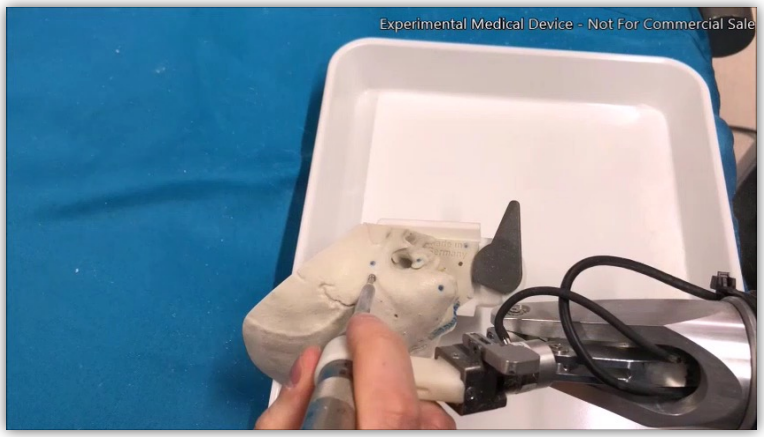
Virtual Fixtures for Mastoidectomy

GALEN ROBOTICS

- 5 identical phantoms
- 3 plane virtual fixture planned from CT
- Engineer with no surgical training
- Robot enforces constraints
- Results assessed using postoperative CT





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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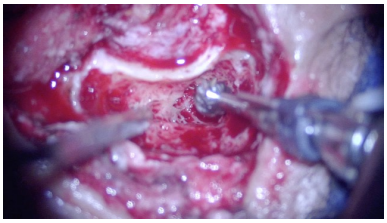
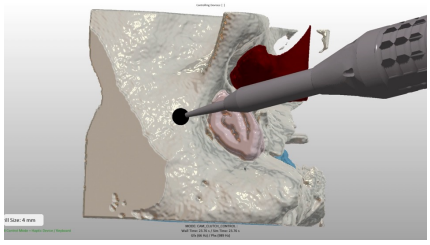
Complementary Situational Awareness



Context
Situational Awareness



Actual Surgical State

Simulated Surgical State

Slide Credit: Zhaoshuo Li, Russell Taylor
Simulation video: Adnan Munawar

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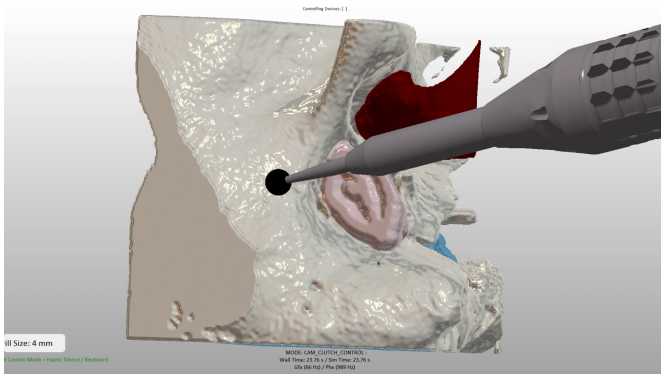
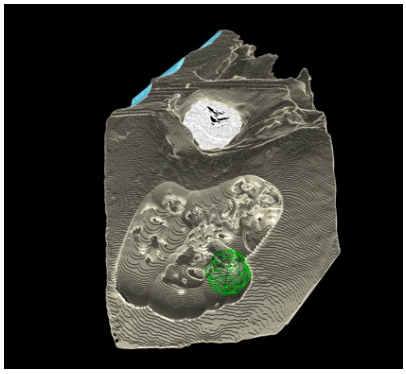
Virtual Reality for Synergistic Surgical Training and Data Generation





- Simulator for training otology and lateral skullbase surgeons
- Data for transfer learning for stereo

Adnan Munawar, Francis Creighton, Mathias Unberath, Zhaoshuo (Max Li), Russell Taylor, *et al.*

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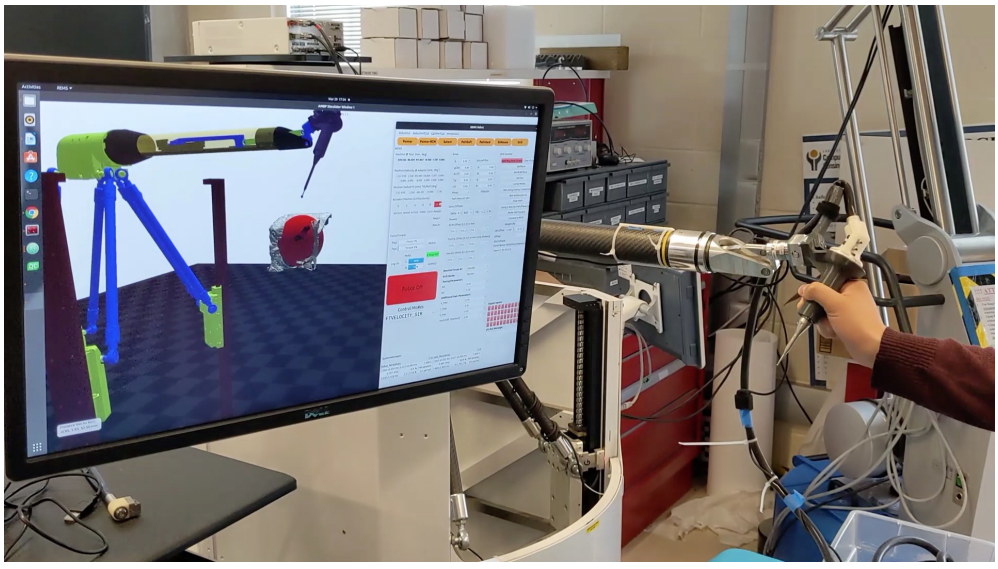
Complementary Situational Awareness



Video: Tommy Liang, Mike Fan, Jintan Zhang, Adnan Munawar

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Co-robotic Ultrasound Imaging

Emad Boctor, R. Taylor, *et al.*

Wrist flexion and "pinch" grip

Trunk and neck twist

Trunk flexion

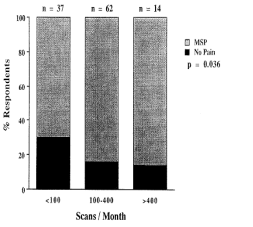

Figure 3 Bar graphs comparing the prevalence of musculoskeletal pains (*MSP*) with the average number of echo studies performed each month. The number of scans are subdivided due to the wide range of responses. Ninety percent of sonographers performing over 100 scans/month had MSP ($p = 0.036$ for both categories).

Challenges on ultrasound imaging:

- Limited image quality and field of view
- Limited reproducibility
- High user dependency
- Work related musculoskeletal pain (MSP) affect 63 - 91% of sonographers

Robotic Ultrasound Solution

Smith A. C., et al., J Am Soc Echocardiog, 1997. Coffin C., Reports in Medical Imaging, 2014.

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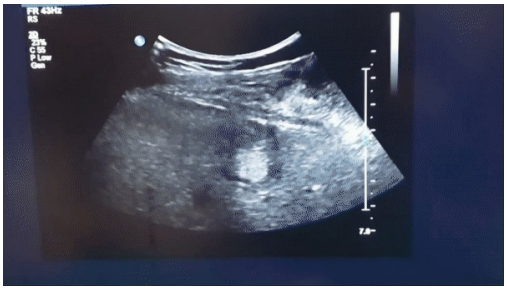
Image-based automated tracking of lesion to stabilize view in biopsy

- **Robotic arm:**
  - force control, accuracy, repeatability
- **Co-robotic ultrasound**

In a biopsy procedure, **physiological motions** of the target is another problem to solve.

"Hand-over-hand control"



Respiratory motion

T. Xie, M. Shahbazi, Y. Wu, R. H. Taylor, and E. M. Boctor, "Stabilized ultrasound imaging of a moving object using 2D B-mode images and convolutional neural network", in *Proc.SPIE*, 2020 https://doi.org/10.1117/12.2550198 10.1117/12.2550198.

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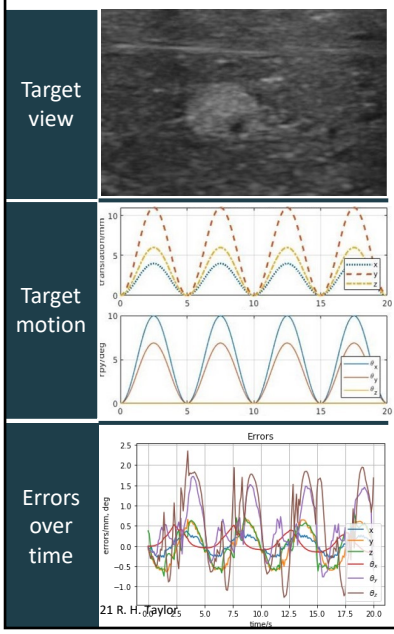
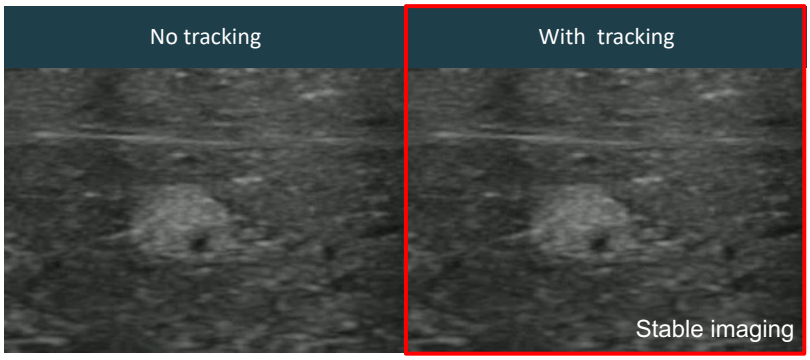
Image-based automated tracking of lesion to stabilize view in biopsy



- **Target motion:**
  - 4, 11 and 6 mm along axial, lateral and elevational axes
  - 10 and 6 degree about x and y axes (w/o in-plane rotation)
- **Error:**
  - Translations: less than 0.7 mm
  - Rotations: less than 2 degree
- No fine tuning. Same linear probe used for CNN training.



T. Xie, M. Shahbazi, Y. Wu, R. H. Taylor, and E. M. Boctor, "Stabilized ultrasound imaging of a moving object using 2D B-mode images and convolutional neural network", in *Proc.SPIE*, 2020 https://doi.org/10.1117/12.2550198 10.1117/12.2550198.

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More Details

SPIE. MEDICAL IMAGING

MUSiiC Research Laboratory

Stabilized Ultrasound Imaging of a Moving Object Using 2D B-mode Images and a Convolutional Neural Network

Tian Xie [a], Mahya Shahbazi [a], Yixuan Wu [b], Russell H. Taylor [a, b], Emad Boctor [a, b, c]

[a] Laboratory for Computational Sensing and Robotics, Johns Hopkins University
[b] Department of Computer Science, Johns Hopkins University
[c] Russell H. Morgan Department of Radiology and Radiological Science, Johns Hopkins Medical Institutes

JOHNS HOPKINS UNIVERSITY
JOHNS HOPKINS SCHOOL of MEDICINE

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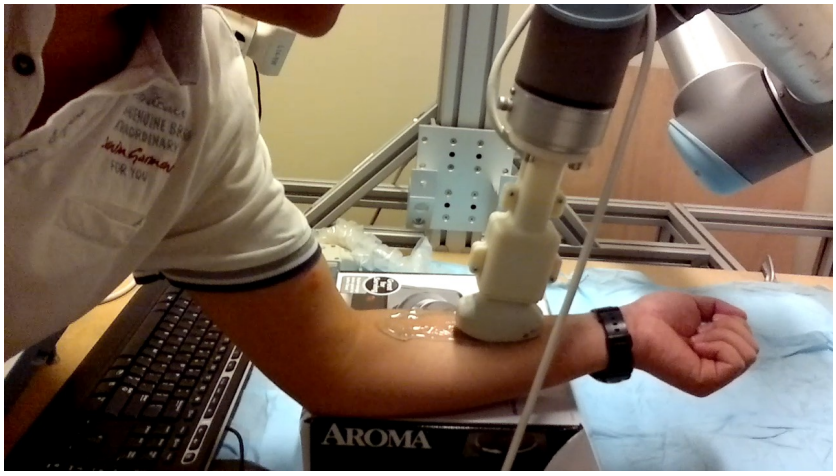
Synthetic-Tracked Aperture Ultrasound (STrAtUS) Imaging Using Robotic Guidance

Emad Boctor, *et al.*



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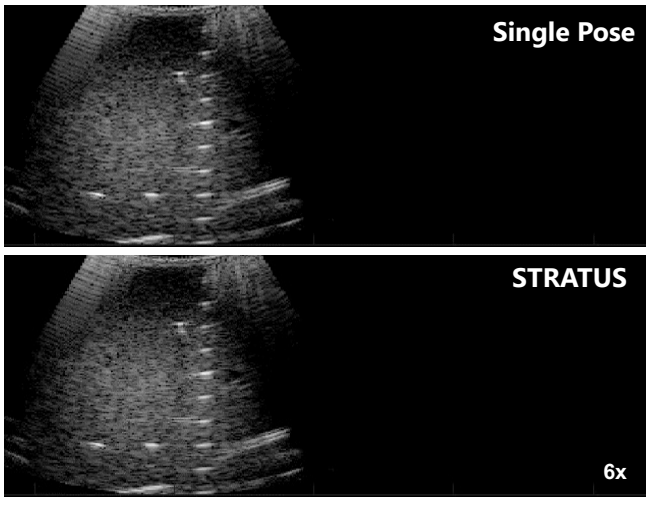
Synthetic-Tracked Aperture Ultrasound (STrAtUS) Imaging Using Robotic Guidance & Virtual Fixtures

Emad Boctor, *et al.*



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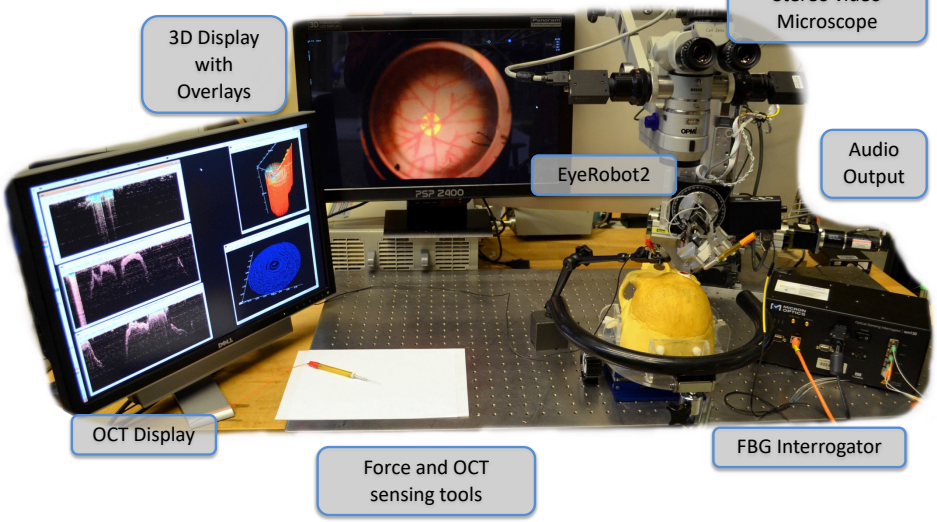
Microsurgery Assistant Workstation



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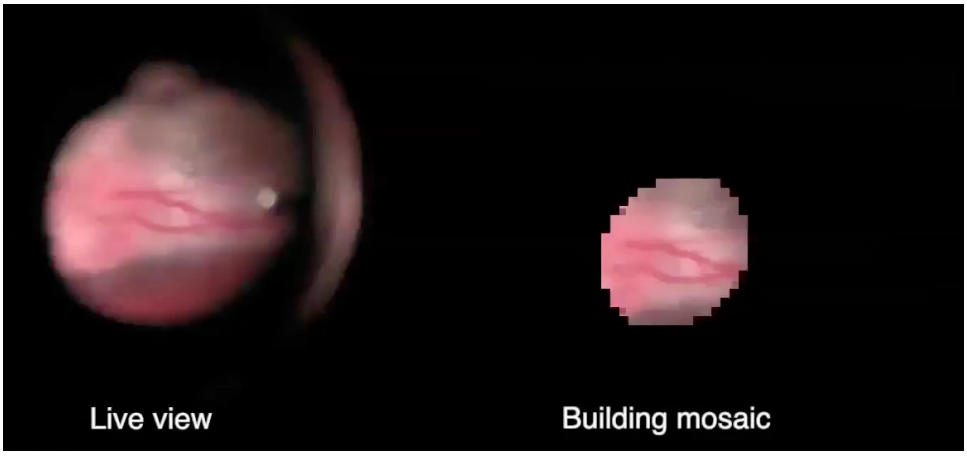
Retina Mosaicking, Annotation, and Registration



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

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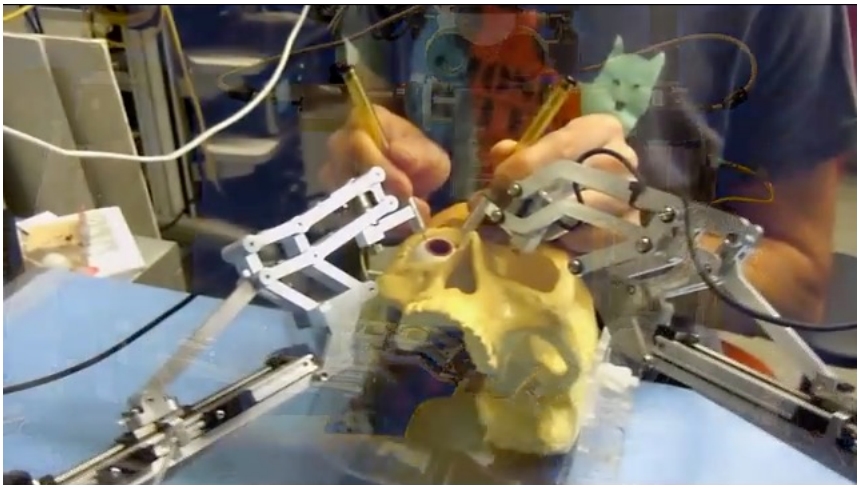
Bilateral Robot-Assisted Retinal Surgery

Iulian Iordachita, *et al.*



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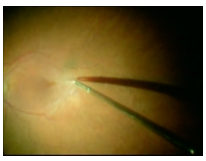
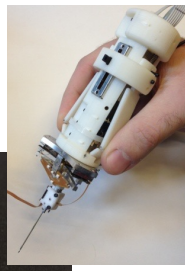
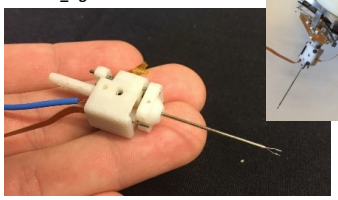
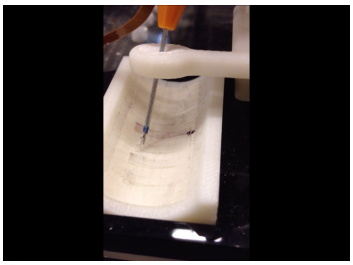


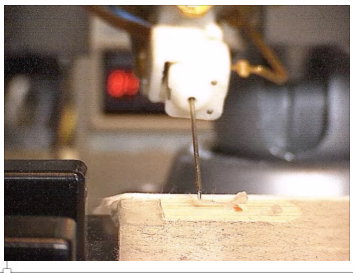
Example: Force-limited Retinal Membrane Peeling

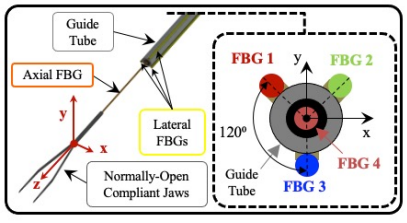
https://www.youtube.com/watch?v=JCpZ255_YVI&feature=emb_logo

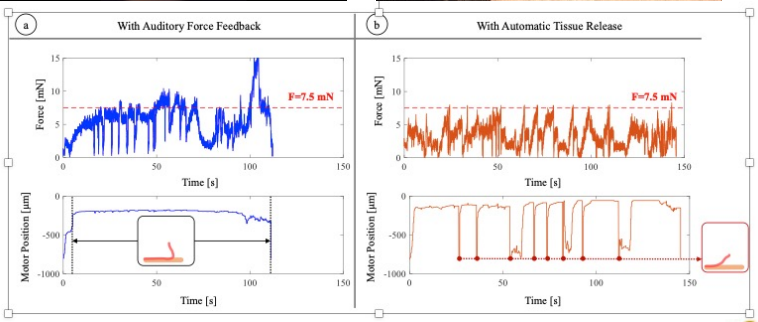












Berc Gonenc, I. Iordachita, *et al.*

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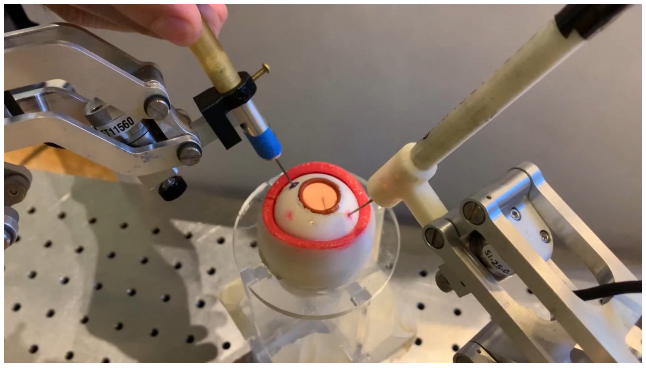
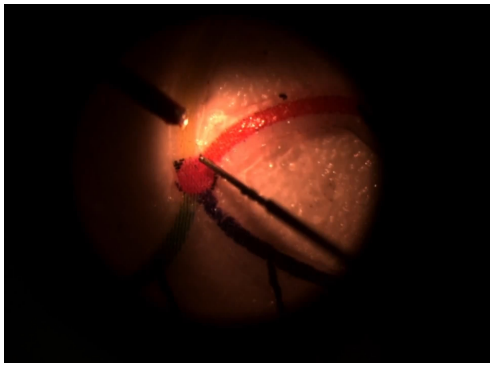
Automatic Light Pipe Actuating System in Bilateral Surgery

Automatic light pipe actuation



Microscope view



Changyan He, et al. *IEEE Trans. on Mechatronics*, 2020

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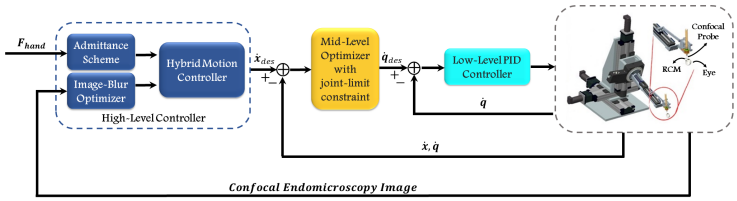
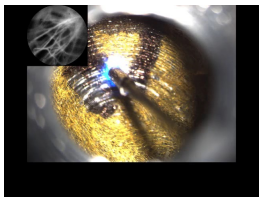
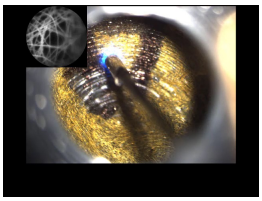
Robot-assisted confocal endoscopic imaging for retinal surgery



Simple hand guiding with robot (5 DoF)





Hybrid control:

- Hand-guided lateral motion
- Image-based depth/focus control

Z. Li, M. Shahbazi, M. Patel, P. Chalasani, E. O'Sullivan, H. Zhang, K. Vyas, A. Deguet, P. Gehlbach, I. Iordachita, G. Z. Yang, R. H. Taylor, "A Comparison of Cooperative vs. Teleoperated Robot-Assisted Frameworks for Confocal Endomicroscopy Scanning of the Retina", *IEEE TMRB*, in submission.

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Intelligent Medical Robotic Systems and Equipment Lab

Smart Autonomous Surgery

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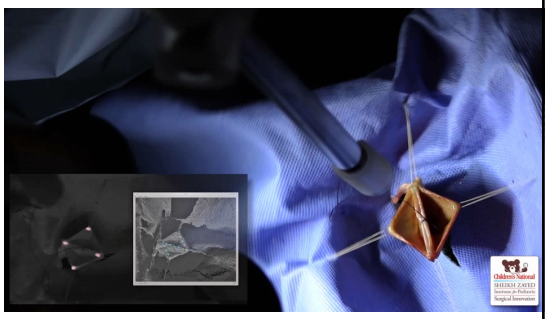
Example: End-to-End Small Bowel Anastomosis

- Smart Tool Autonomous Robot designed for suturing tasks
- Task Specification
  - Near-infrared fluorescent (NIRF) markers used to delimit the task and tracked in NIR images
  - Plan is computed and updated based on the realtime 3D coordinates of the markers
- Execution
  - Registration of plan to robot
  - Robot executes the anastomosis plan:
    - Use force sensing to detect the tissue and tension the suture
  - Before executing each stitch, the system requires approval of surgeon
  - Assistant manages loose thread and folds the bowel at midpoint
- Challenges/Opportunities
  - Tested 2nd "assistant arm to replace human assistance
  - Developing 3D/NIRF endoscope
  - Tested NIRF stay sutures to replace NIRF markers
  - Laparoscopic anastomosis



JHU Faculty: Simon Leonard
UMD Faculty: Axel Krieger

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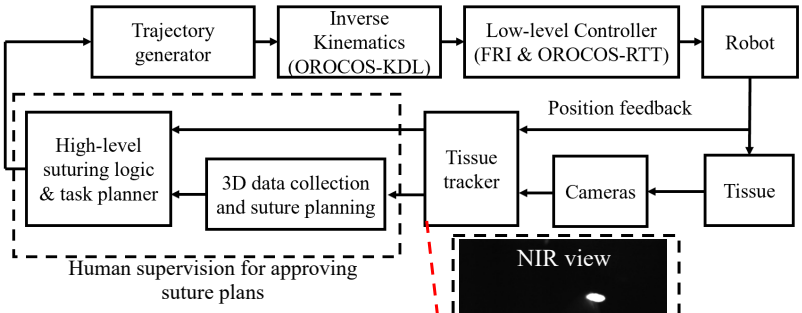
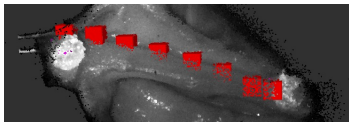
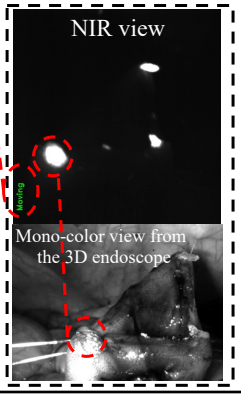
Intelligent Medical Robotic Systems and Equipment Lab





Suture planning is done at the end of breathing cycle to reduce 3D model inaccuracy caused by tissue's motion. Robot is controlled under a remote center of motion (RCM) and motions are synced with breathing and the planned sutures.



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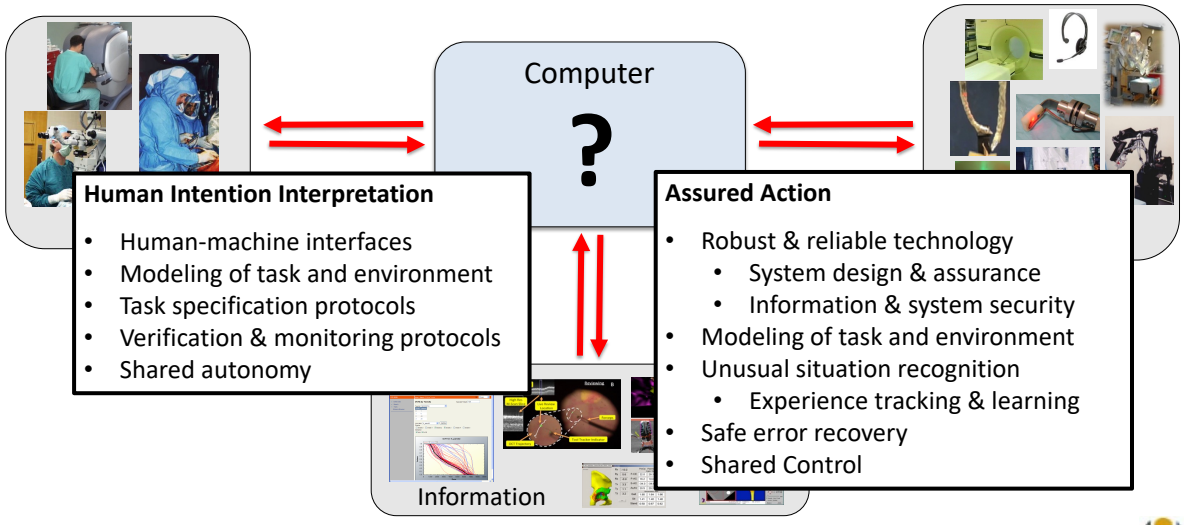
The key issue: mediating between human intention and action



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Information and machine "intelligence" are the crucial links