



Autonomy and Semi-Autonomous Behavior in Surgical Robot Systems

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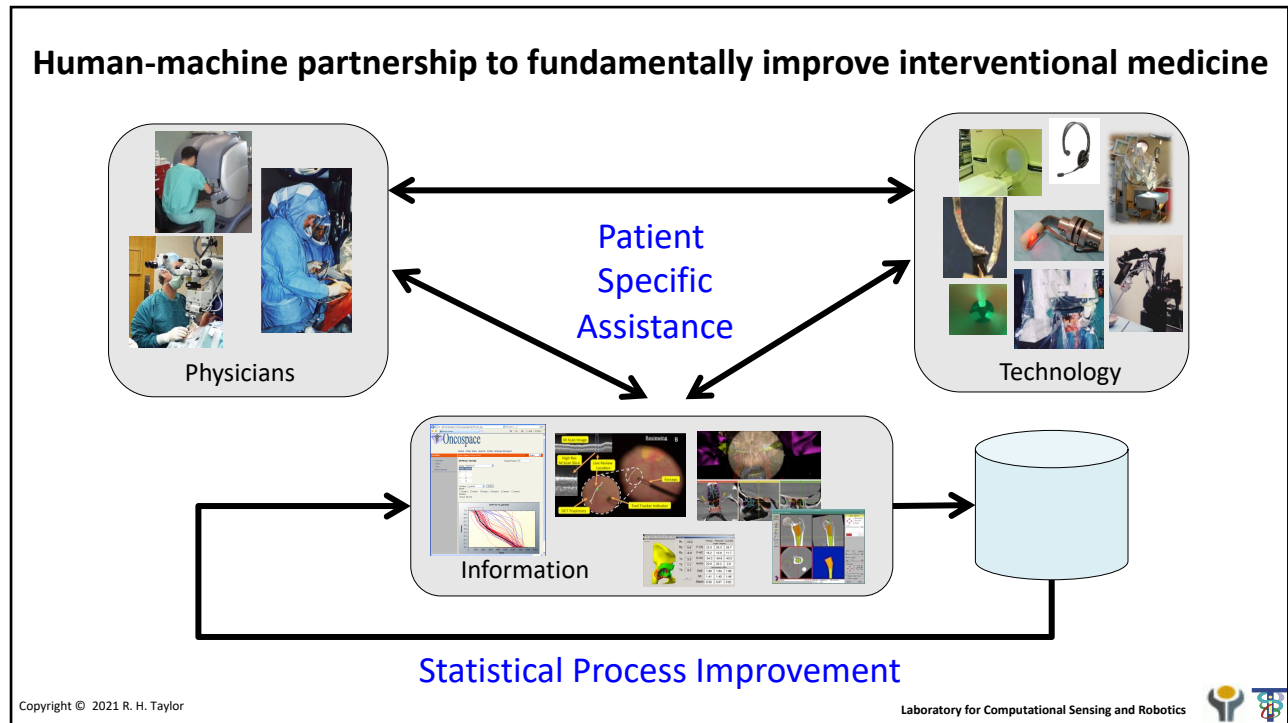
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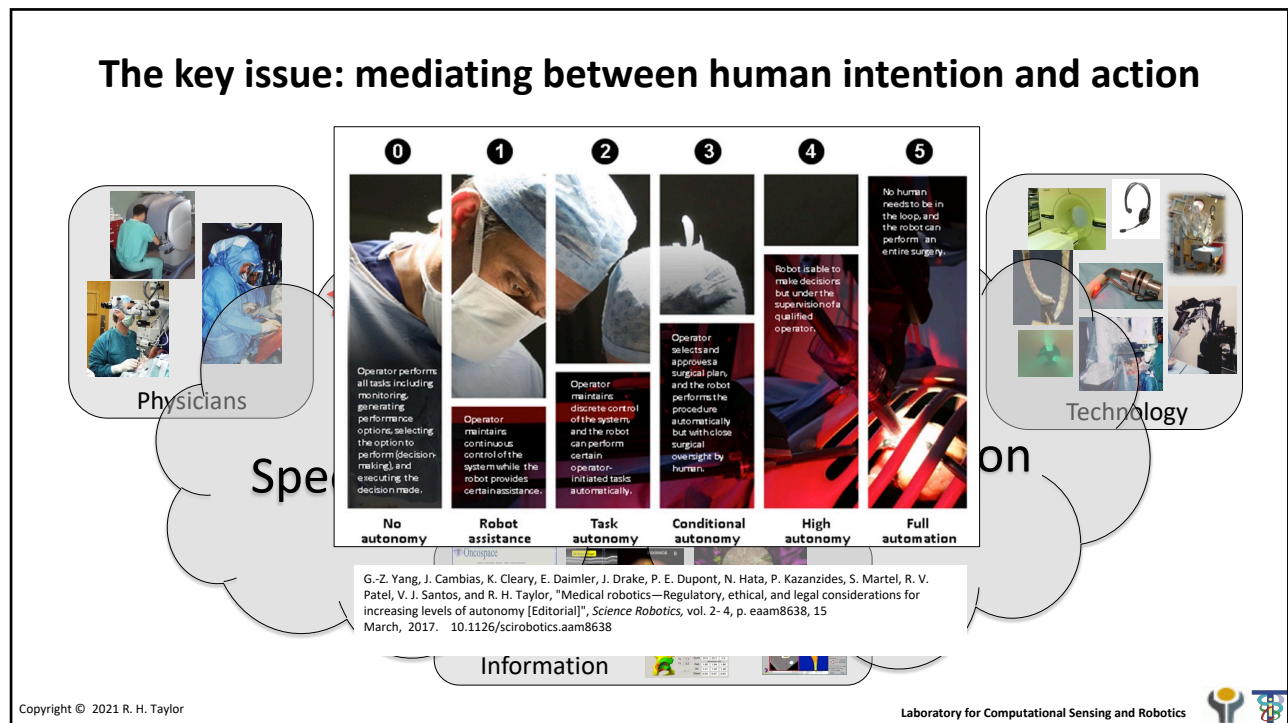
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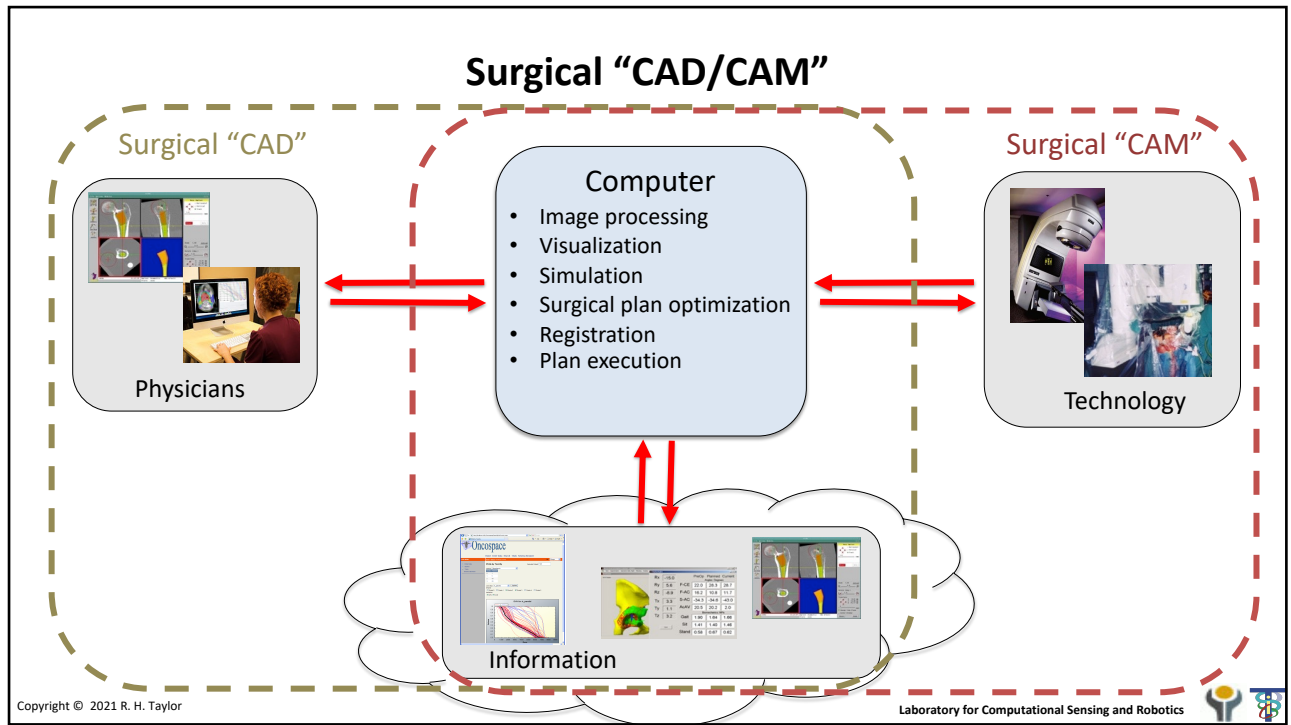
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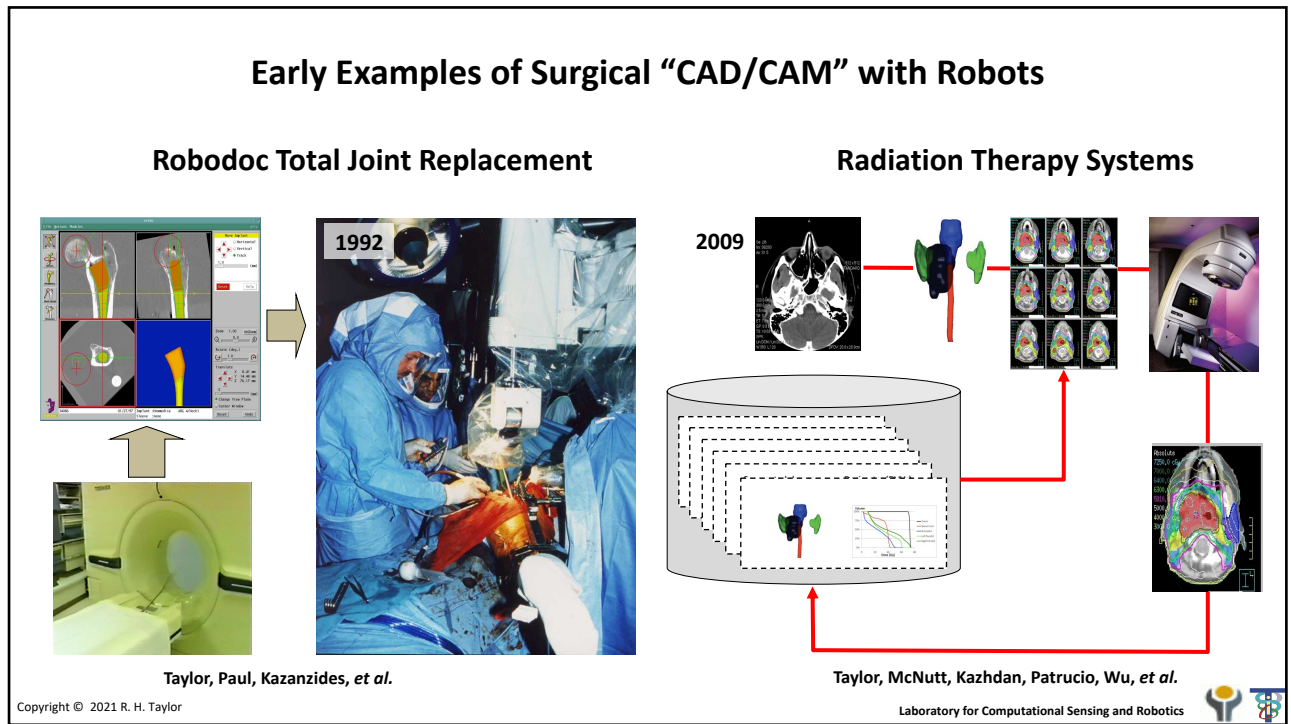
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Robotic Joint Replacement Surgery

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

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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3D-2D Registration of Osteotomy Fragments

$$\arg \min_{\theta_1, \dots, \theta_N \in SE(3)} \sum_{m=1}^M S \left(I_m, \sum_{n=1}^N \mathcal{P}_m (I_{CT}; \theta_n) \right)$$

Fixed Images with Moving Image Edges

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R. Grupp, R. Murphy, M. Armand, R. Taylor

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Ultrasound-assisted Registration

(1) Generate surface model from CT

(2) Digitize proximal bone using tracked pointer

(3) Collect tracked US images of distal bone

(4) Register points/contours to surface model

S. Billings, H. J. Kang, A. Cheng, E. Boctor, P. Kazanzides, and R. Taylor, "Minimally invasive registration for computer-assisted orthopedic surgery: combining tracked ultrasound and bone surface points via the P-IMLOP algorithm", Int. J. Computer Assisted Radiology and Surgery, p. (epub ahead of print), 2015. <http://dx.doi.org/10.1007/s11548-015-1188-z> DOI 10.1007/s11548-015-1188-z

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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...

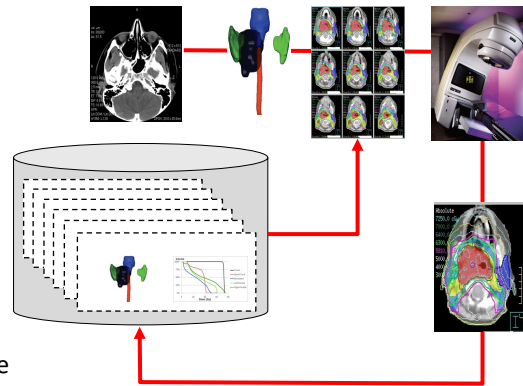
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Example: External Beam Radiation Therapy Systems

- “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.)



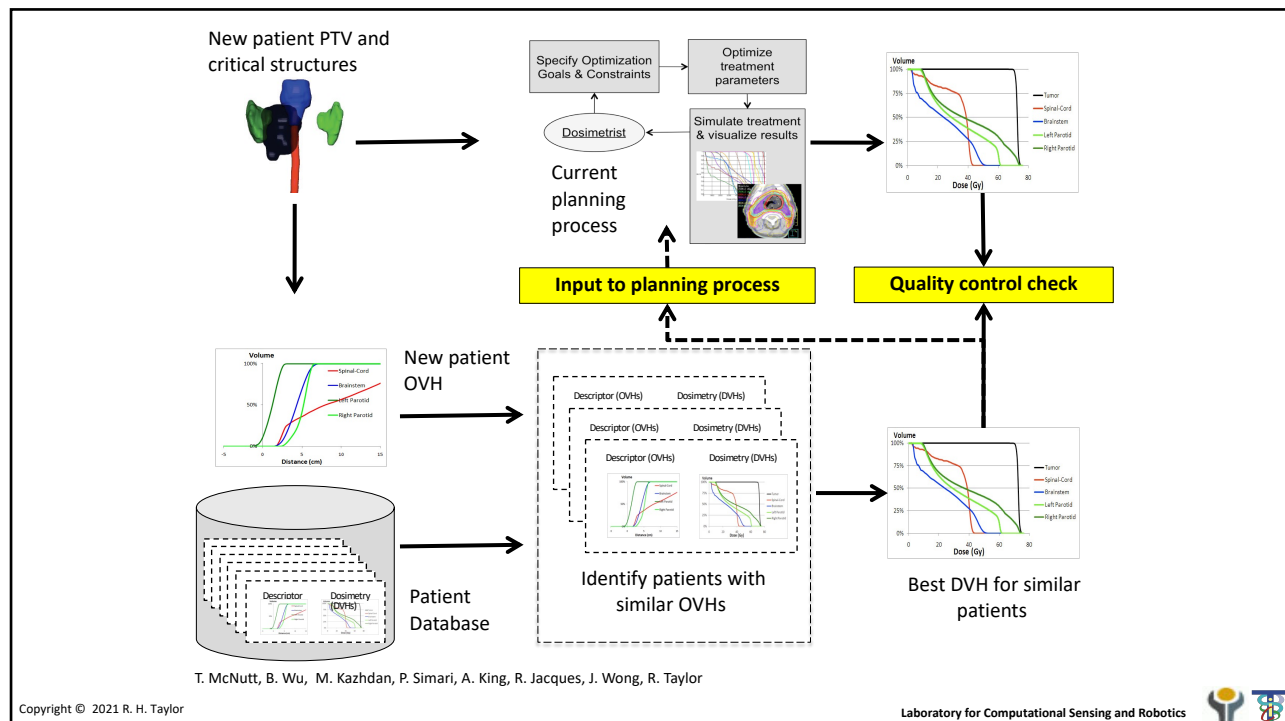
JHU Faculty: Todd McNutt, Russell Taylor, Mischa Kazhdan, Ilya Shpitser, Sauleh Siddiqui

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

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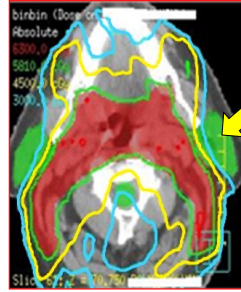
Sample automated radiation planning result

T. McNutt, A. Patriciu, B. Wu, R.. Taylor *et al.*

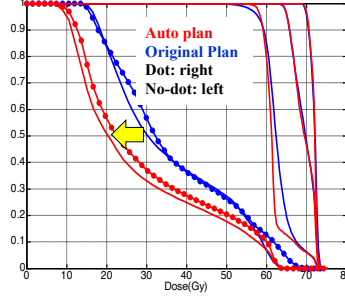
Original plan



Automated plan



30% reduction in dose to parotids



	brain (Gy) (max)	Brainstem (Gy) (max)	Cord4mm (Gy) (max)	L inner ear (Gy)(mean)
original	61.25	54.58	41.75	57.18
re-plan	56.33	46.48	37.89	43.72
	R inner ear (Gy) (mean)	mandible (Gy) (max)	larynx for edema (V50)	esophagus (Gy)(max)
original	40.57	66.58	61%	63.74
re-plan	38.38	63.78	59%	61

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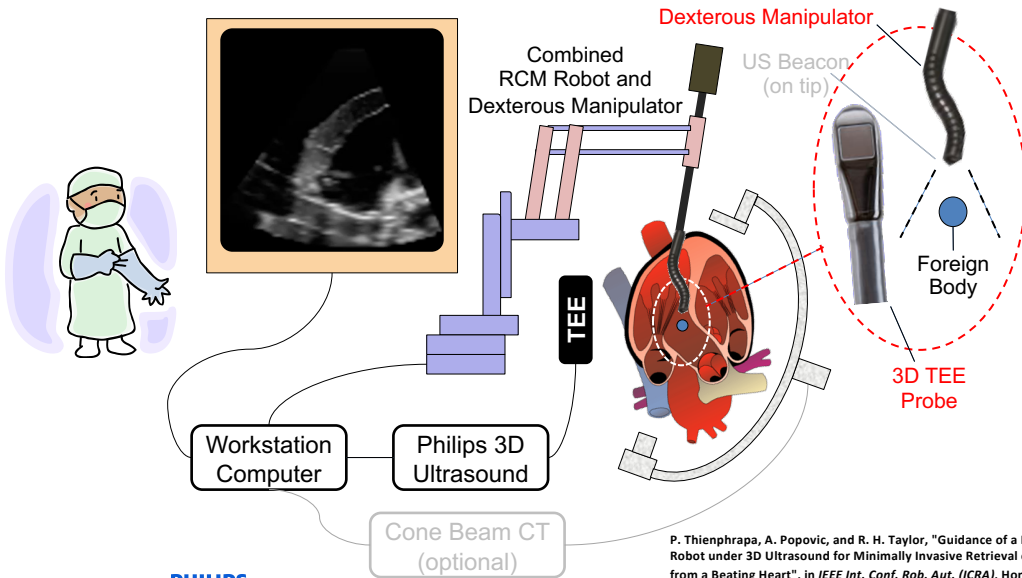
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Beating Heart MIS with 3D US Guidance

Paul Thienphrapa, Aleksandra Popovic, Russell Taylor



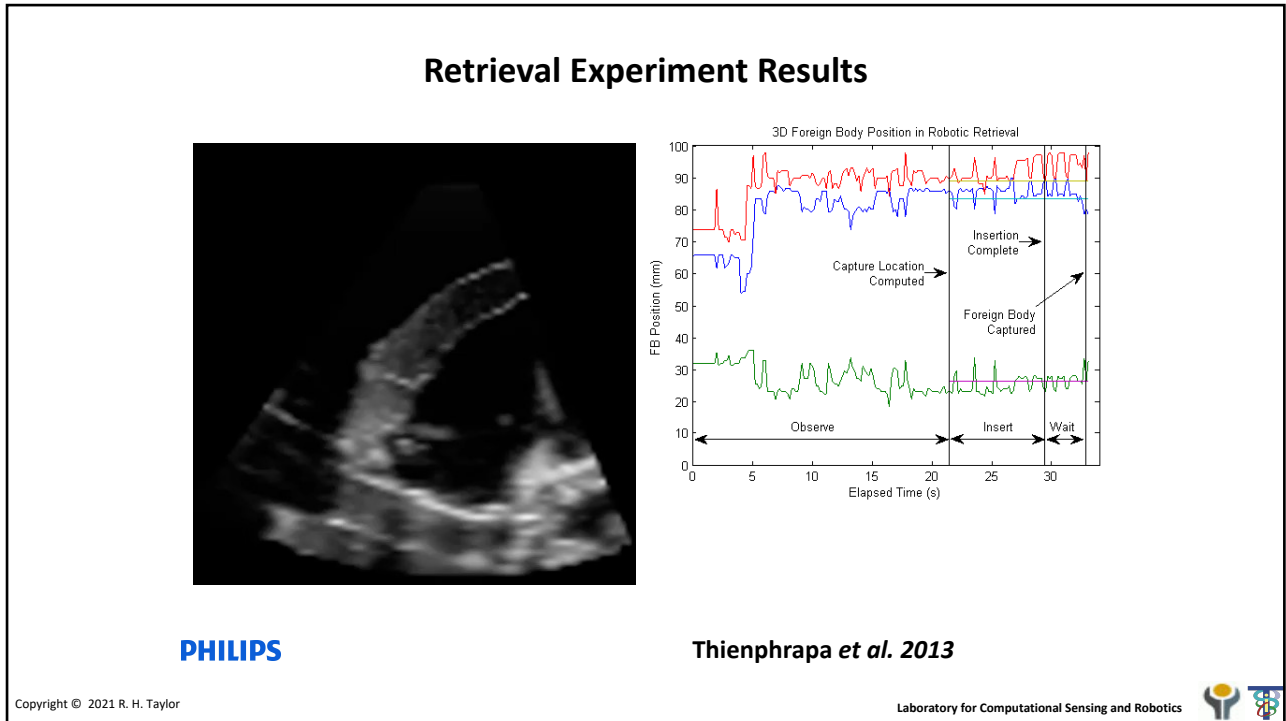
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P. Thienphrapa, A. Popovic, and R. H. Taylor, "Guidance of a High Dexterity Robot under 3D Ultrasound for Minimally Invasive Retrieval of Foreign Bodies from a Beating Heart", in *IEEE Int. Conf. Rob. Aut. (ICRA)*, Hong Kong, May 31-Jun 6, 2014. pp.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

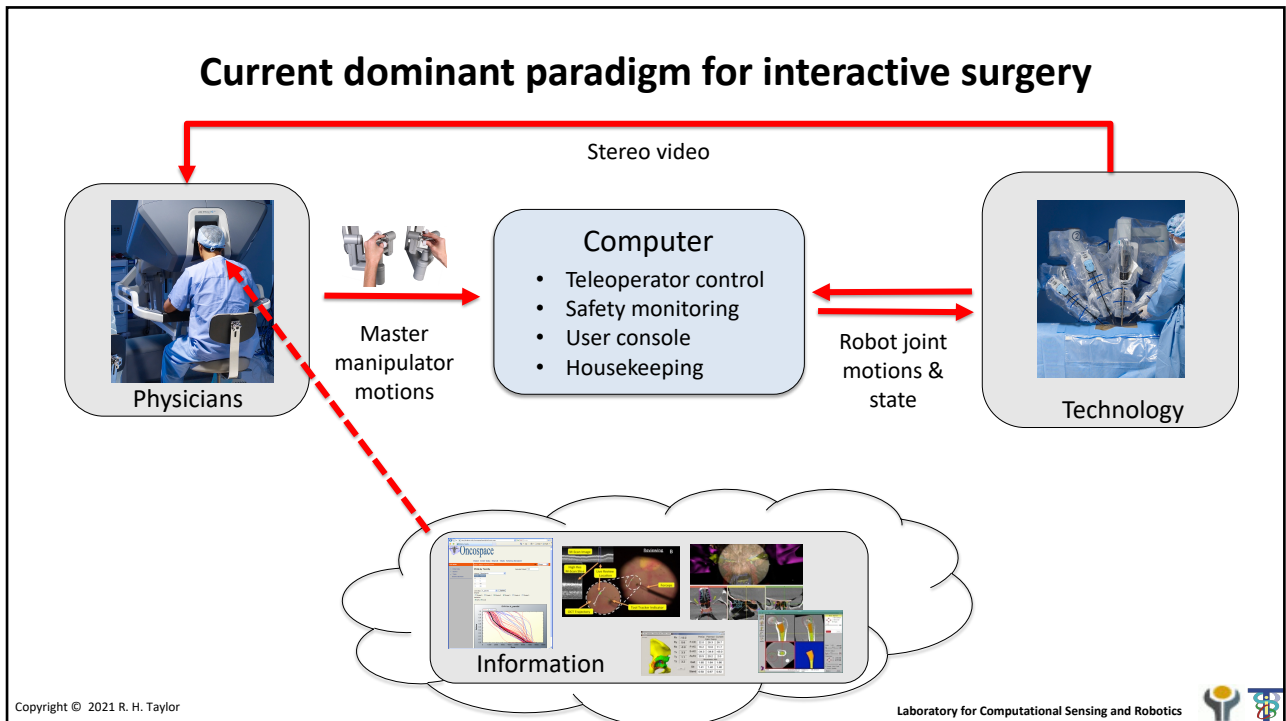
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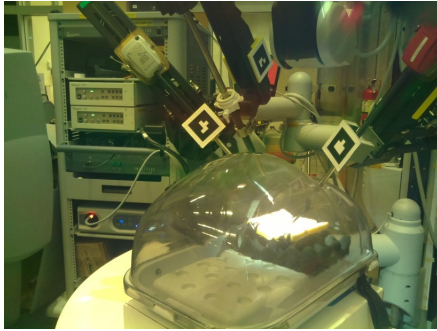
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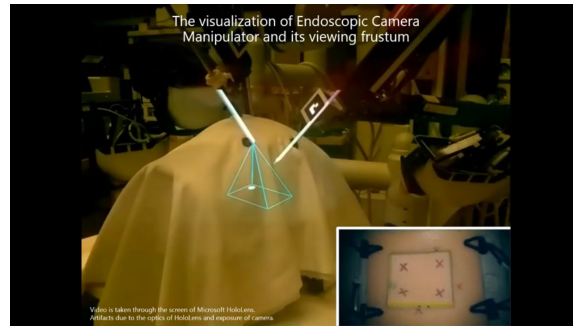
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Augmented Reality: da Vinci Patient-Side Assistant

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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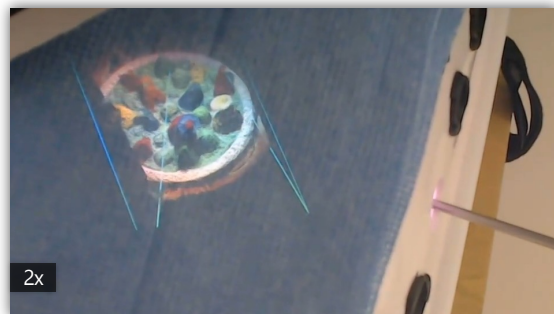
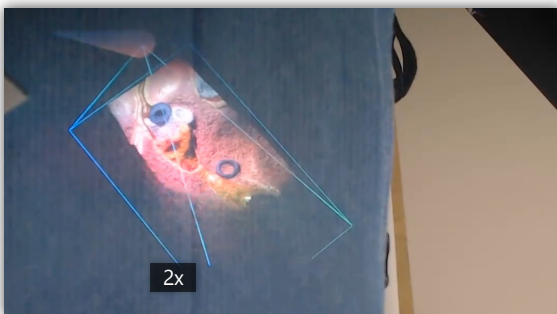
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Augmented Reality: Laparoscopic Guidance

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



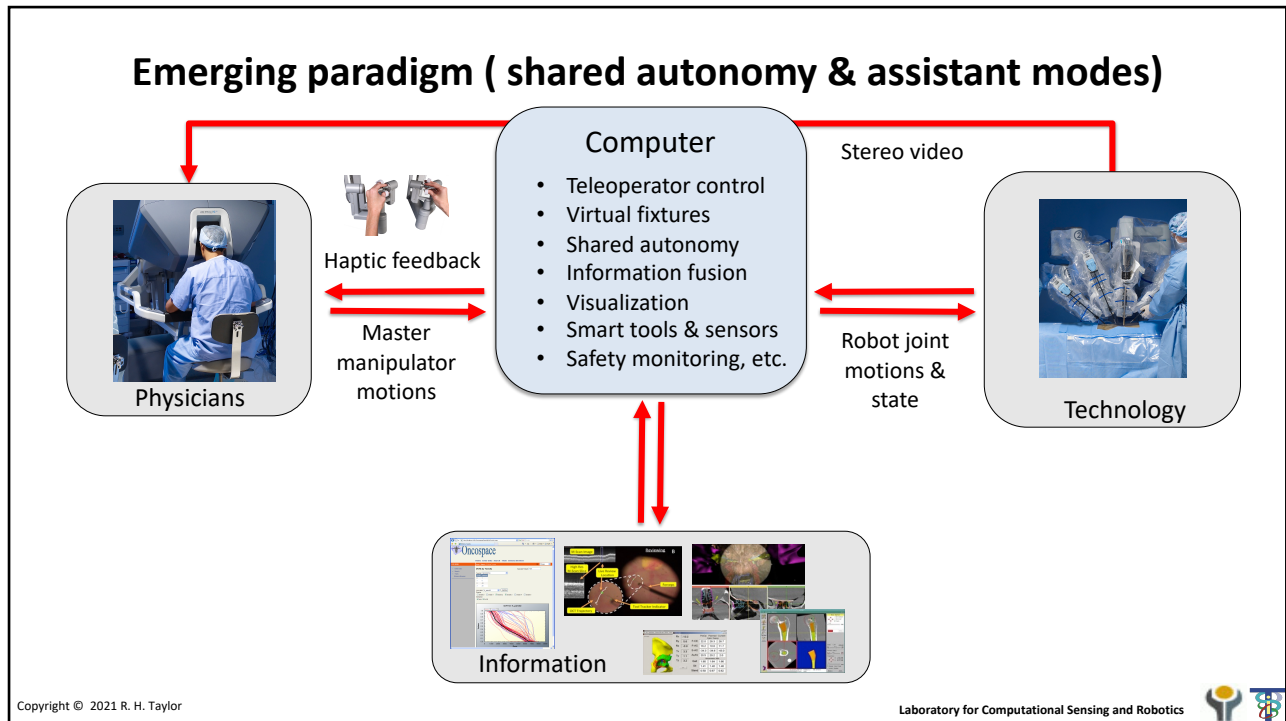
L. Qian, X. Zhang, A. Deguet, P. Kazanzides. "ARAMIS: Augmented Reality Assistance for Minimally Invasive Surgery Using a Head-Mounted Display." *MICCAI* 2019.

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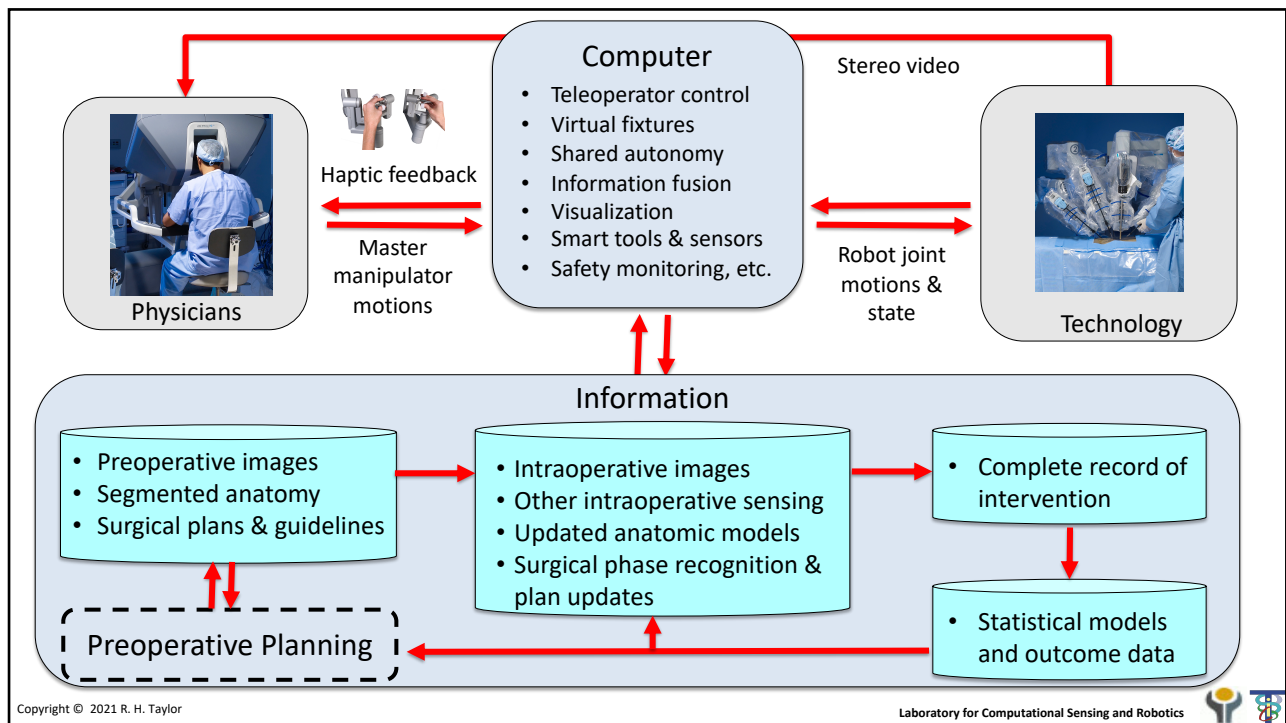
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Intelligent Medical Robotic Systems and Equipment Lab

Smart Autonomous Surgery

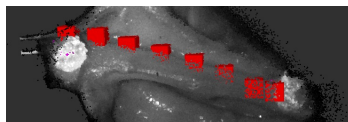
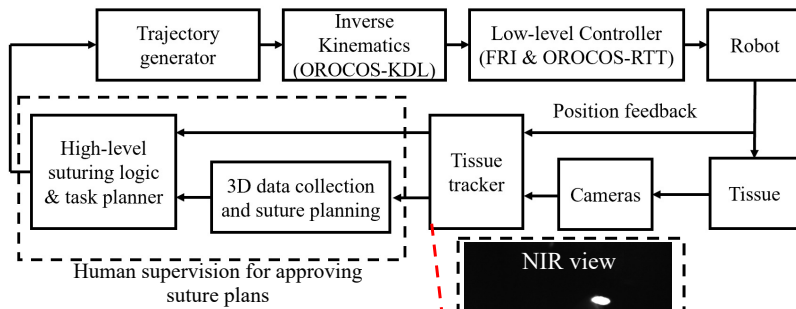


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Intelligent Medical Robotic Systems and Equipment Lab

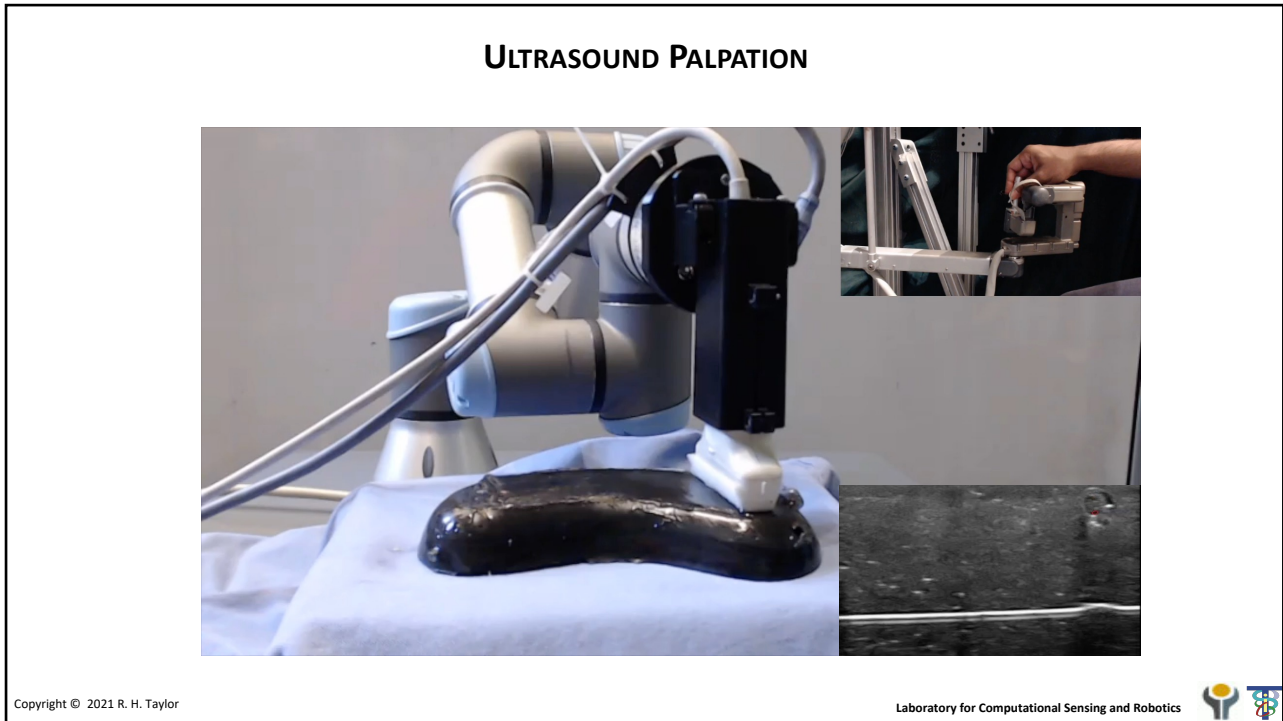


Suture planning is done at the end of breathing cycle to reduce 3D model inaccuracy caused by tissue's motion. Robot is controlled under a remote center of motion (RCM) and motions are synced with breathing and the planned sutures.

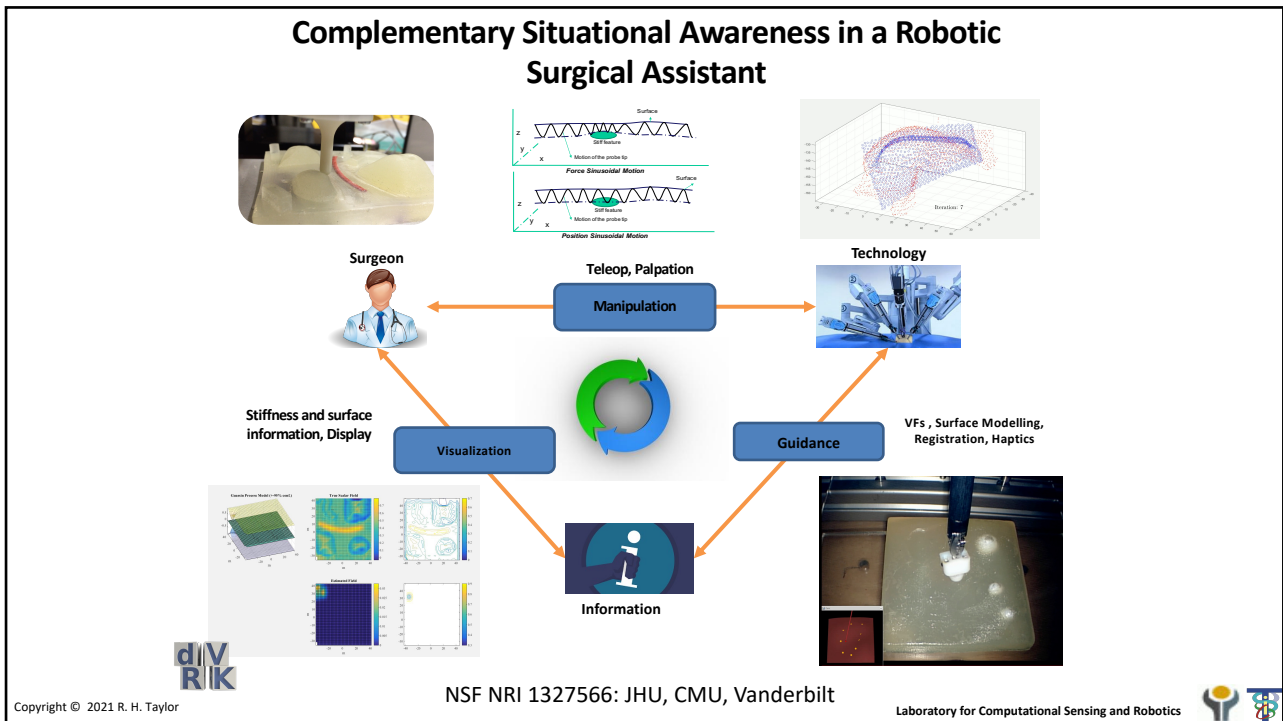
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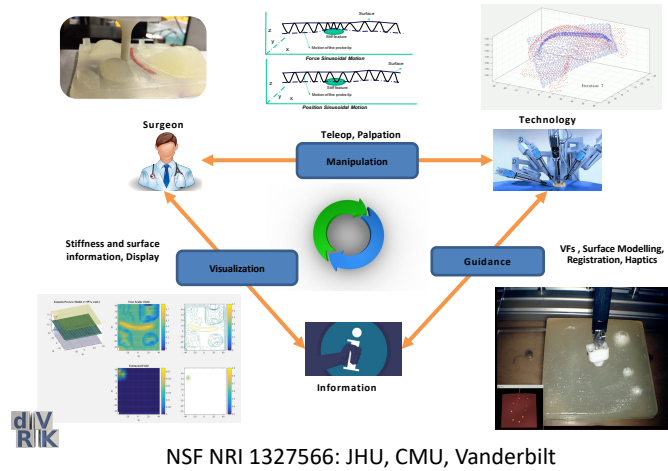


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Complementary Situational Awareness in a Robotic Surgical Assistant



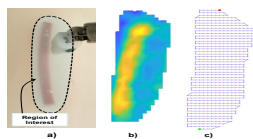
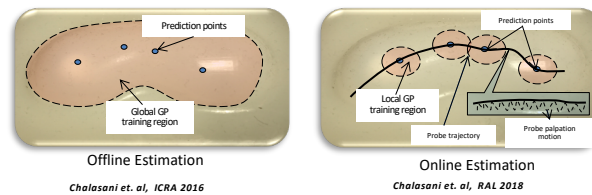
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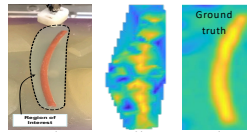
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CONTINUOUS STIFFNESS AND GEOMETRY UPDATE

Preetham Chalasani, Russell Taylor



Results from automated Sinusoidal palpation



Teleoperated palpation w. superimposed motion



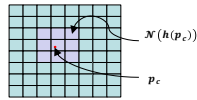
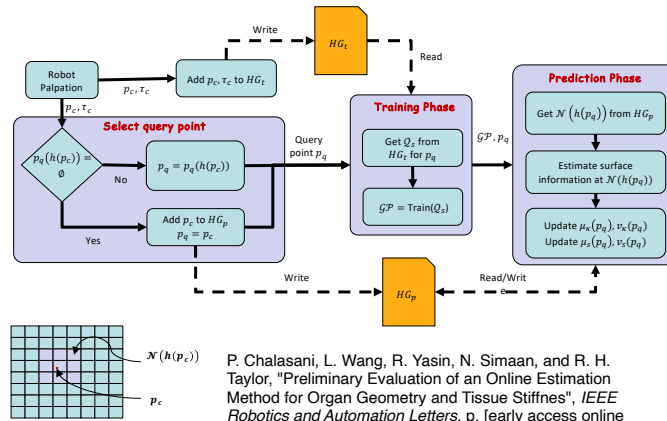
Automated Sinusoidal Palpation

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Online Geometry and Stiffness Update



P. Chalasani, L. Wang, R. Yasin, N. Simaan, and R. H. Taylor, "Preliminary Evaluation of an Online Estimation Method for Organ Geometry and Tissue Stiffness", *IEEE Robotics and Automation Letters*, p. [early access online version], 2018. 10.1109/LRA.2018.2801481

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Semi-Autonomous Palpation Example

Constrained Semi-Autonomous Telemanipulated Palpation with Assistive Virtual Fixtures

Preetham Chalasani, Long Wang, Rashid Yasin, Peter Kazanzides, Nabil Simaan and Russell H. Taylor



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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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Anatomy-Based Virtual Fixtures: An Additional Complication

Virtual fixture is often used for increased efficiency and operation safety. However, it is challenging to automatically generate virtual fixture for complex anatomies. Existing researches usually approximate the anatomical shape when using parametric forms such as ellipsoid [4][5][6], or using sparse level-set functions [7]. The process is labor intensive, and the virtual fixture cannot accurately reflect the anatomical shape.

Virtual fixture approximates the anatomy as an ellipsoid

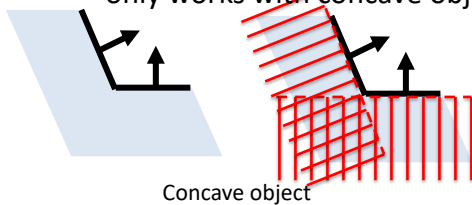
[4] R. Prada and S. Payandeh, "A study on design and analysis of virtual fixtures for cutting in training environments," in First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics Conference. IEEE, 2005, pp. 375–380.
 [5] S. Park, R. D. Howe, and D. F. Torchiana, "Virtual fixtures for robotic cardiac surgery," in International Conference on Medical Image Computing and Computer-Assisted Intervention. Springer, 2001, pp. 1419–1420.
 [6] M. M. Marinho, B. V. Adorno, K. Harada, and M. Mitsuishi, "Dynamic active constraints for surgical robots using vector-field inequalities," *IEEE Transactions on Robotics*, vol. 35, no. 5, pp. 1166–1185, 2019.
 [7] J. Ren, R. V. Patel, K. A. Mclsaac, G. Guiraudon, and T. M. Peters, "Dynamic 3-d virtual fixtures for minimally invasive beating heart procedures," *IEEE transactions on medical imaging*, vol. 27, no. 8, pp. 1061–1070, 2008.

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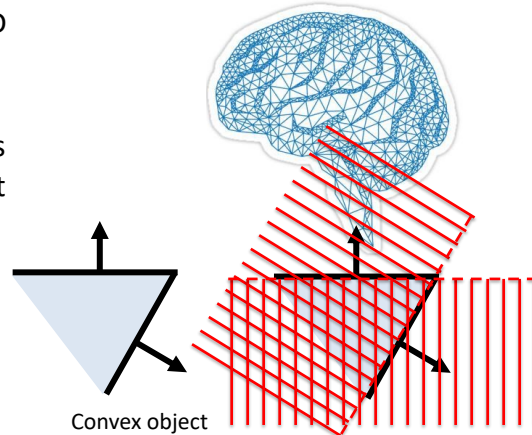
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Challenges

- Mesh is an intuitive representation of 3D objects, which is widely used in medical imaging.
- Prior work [8] proposes to treat triangles in mesh as plane constraints. However, it only works with concave objects.



Concave object



Convex object

[8] M. Li, M. Ishii, and R. H. Taylor, "Spatial motion constraints using virtual fixtures generated by anatomy," IEEE Transactions on Robotics, vol. 23, no. 1, pp. 4–19, 2007.
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Virtual Fixture Formulation

- In this work, an anatomical mesh-based virtual fixture is proposed
 - Generates virtual fixture for complex anatomy automatically
 - Implements an efficient and dynamic formulation

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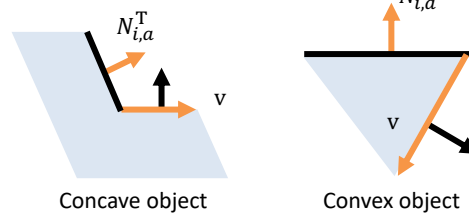


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Virtual Fixture Formulation

- Mesh-based constraint formulation algorithm is based on closest point (CP) and local geometry
 - Store mesh as principle-direction tree (PD-Tree) [9] and define a motion sphere
 - Determine the closest point on triangles
 - Determine the local geometry

$$\text{geometry} = \begin{cases} \text{concave if } N_{i,a}^T v > 0 \\ \text{convex if } N_{i,a}^T v < 0 \end{cases}$$



[9] Williams, R. Taylor, and L. Wolff, "Augmented kd techniques for accelerated registration and distance measurement of surfaces," Computer Aided Surgery: Computer-Integrated Surgery of the Head and Spine, pp. 1–21, 1997.

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Virtual Fixture Formulation

- Mesh-based constraint formulation algorithm is based on closest point (CP) and local geometry

Algorithm 1: Polygon Mesh Constraint

Input: PD-Tree, Current Position x

Result: List of Active Plane Constraints \mathcal{L}

Find intersected triangles \mathcal{T} , corresponding closest points CP and face normals \mathcal{N} ;

for triangle $\mathcal{T}_i \in \mathcal{T}$ **do**

if CP_i *in-triangle* & $N_i^T(x - CP_i) \geq 0$ **then**

 add $\{N_i, CP_i\}$ to \mathcal{L} ;

else if CP_i *on-edge* **then**

 Find adjacent triangle(s) $\mathcal{T}_{i,a}$;

if $CP_i == CP_{i,a}$ & *locally convex* **then**

 add $\{x - CP_i, CP_i\}$ to \mathcal{L} ;

else if $N_{i,a}^T(x - CP_i) \geq 0$ & *locally concave*

then

 add $\{N_i, CP_i\}$ to \mathcal{L} ;

end

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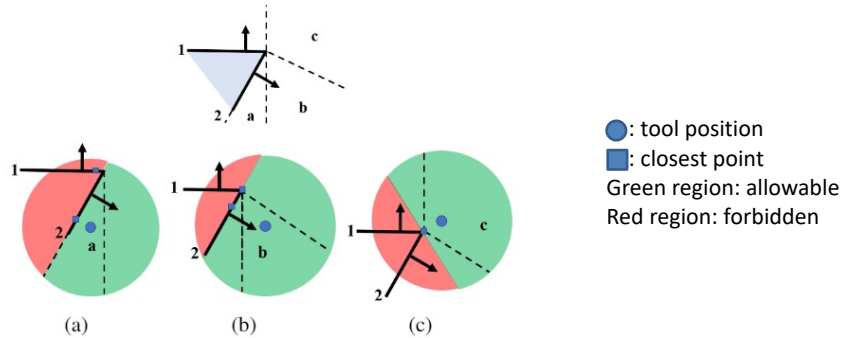
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Virtual Fixture Formulation

- Mesh-based constraint formulation algorithm is based on closest point (CP) and local geometry



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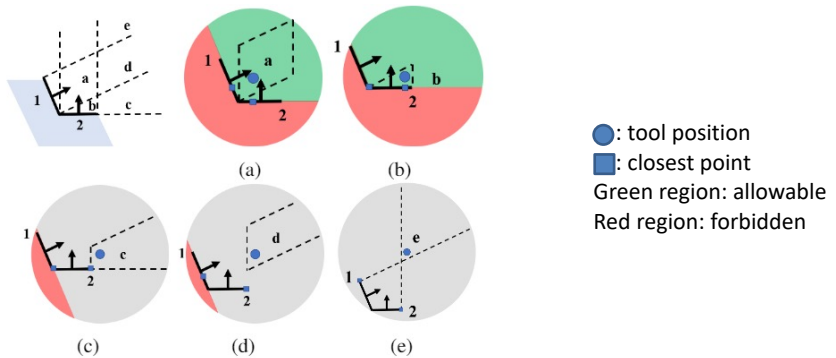
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Virtual Fixture Formulation

- Mesh-based constraint formulation algorithm is based on closest point (CP) and local geometry



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Virtual Fixtures for Craniostyosis

Skull Cutting Experiment

Skull phantoms are cut along a straight path using dVRK and a piezoelectric cutter.

Z. Li, A. Gordon, T. Looi, J. Drake, C. Forrest, and R. H. Taylor, "Anatomical Mesh-Based Virtual Fixtures for Surgical Robots", in International Conference on Intelligent Robots and Systems (IROS), Las Vegas, Oct. 25-29, 2020.

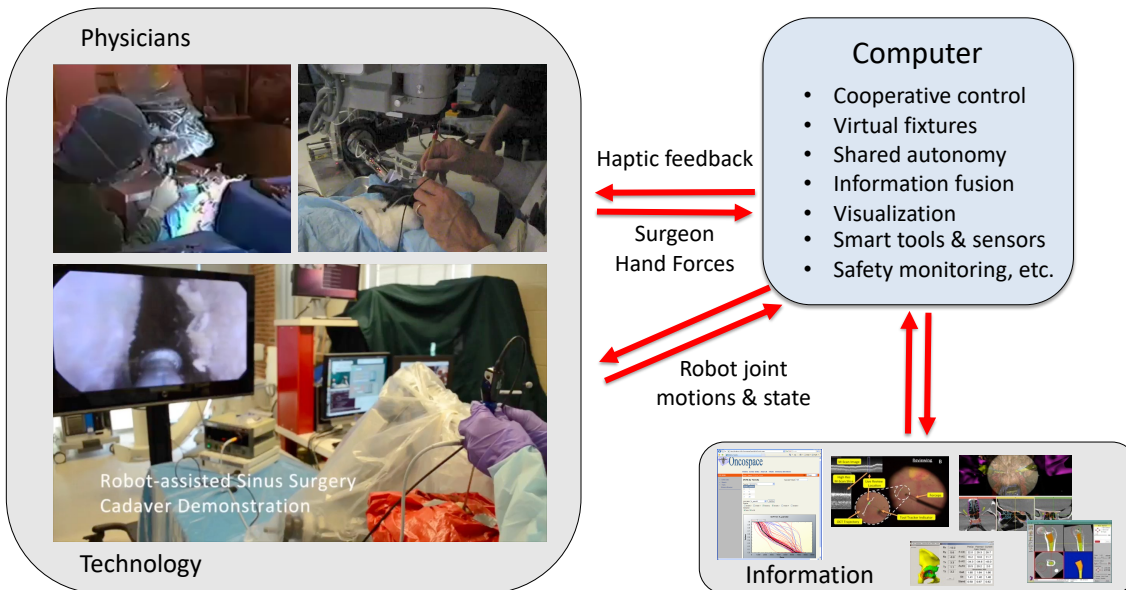
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Emerging paradigm (shared autonomy & assistant modes)



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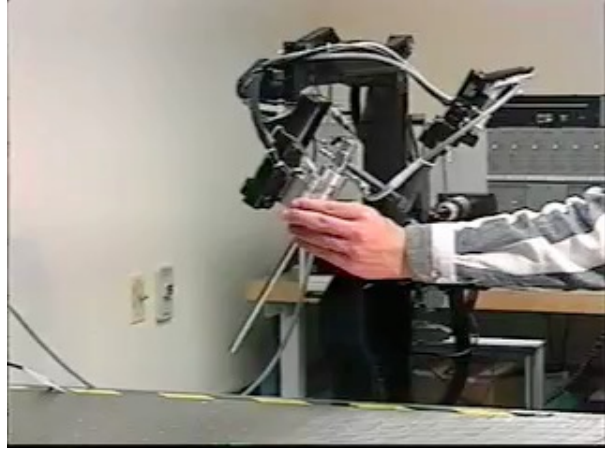


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Steady Hand Manipulation



Robodoc Canine Surgery, 1990



LARS Robot in IBM Lab, ca. 1993

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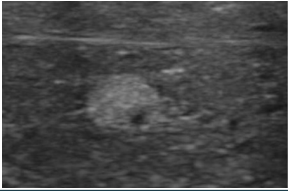
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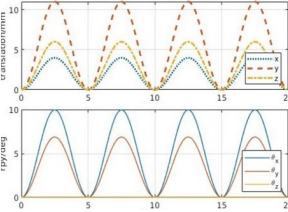
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Image-based automated tracking of lesion to stabilize view in biopsy

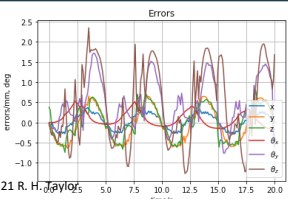
Target view



Target motion

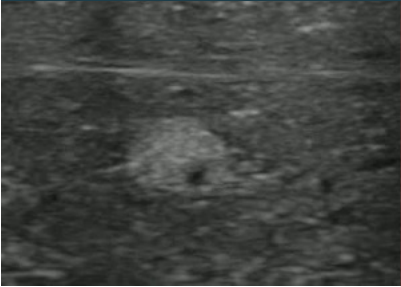


Errors over time

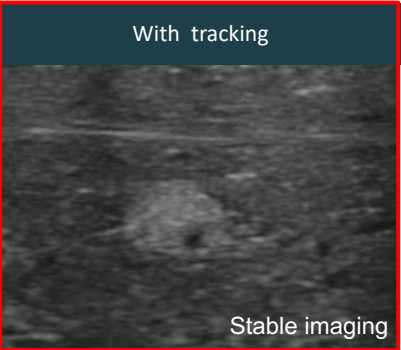


- **Target motion:**
 - 4, 11 and 6 mm along axial, lateral and elevational axes
 - 10 and 6 degree about x and y axes (w/o in-plane rotation)
- **Error:**
 - Translations: less than 0.7 mm
 - Rotations: less than 2 degree
- No fine tuning. Same linear probe used for CNN training.

No tracking



With tracking




Stable imaging

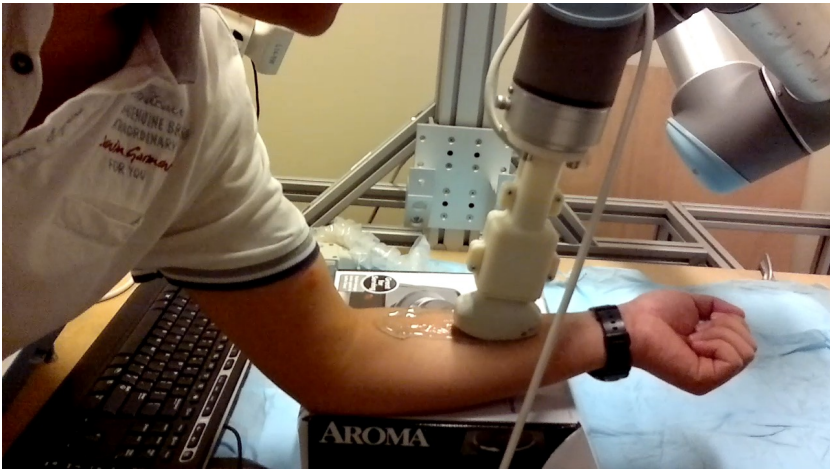
T. Xie, M. Shahbazi, Y. Wu, R. H. Taylor, and E. M. Bector, "Stabilized ultrasound imaging of a moving object using 2D B-mode images and convolutional neural network", in *Proc.SPIE*, 2020 <https://doi.org/10.1117/12.2550198> 10.1117/12.2550198. Laboratory for Computational Sensing and Robotics

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

Emad Bector, *et al.*





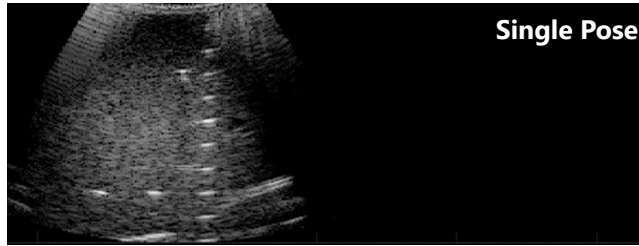
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Synthetic-Tracked Aperture Ultrasound (STrAtUS) Imaging Using Robotic Guidance & Virtual Fixtures

Emad Bector, *et al.*



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Cadaver Study: Sinus Surgery with Virtual Fixtures



Robot-assisted Sinus Surgery
Cadaver Demonstration

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

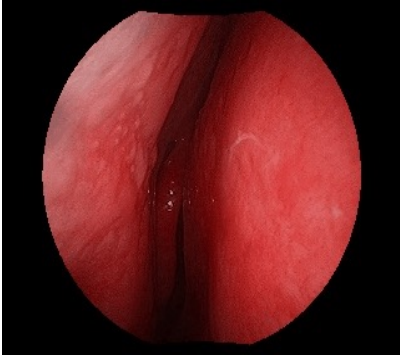
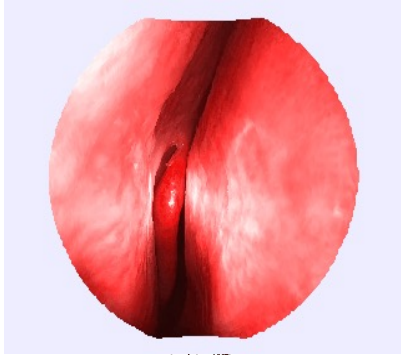
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3D airway reconstruction during nasal endoscopic procedures without external tracking devices

Monoscopic Endoscope Video

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.

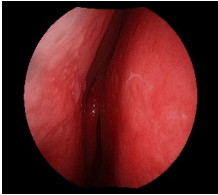
Dense Point Cloud Reconstruction

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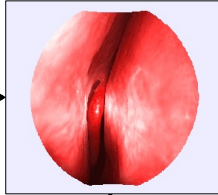
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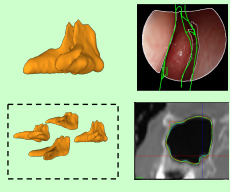
A "smart" sinus endoscopy assistant



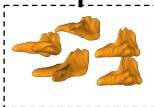
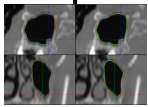
Recovery of 3D anatomy from endoscopic video



Navigation
Quantitative endoscopy
Assistance Modes
Learning & Training



Registration

- Dense point cloud recovery from untracked monocular endoscope video
- Registration to preoperative CT or statistical model
- Intraoperative navigation and surgical assistance

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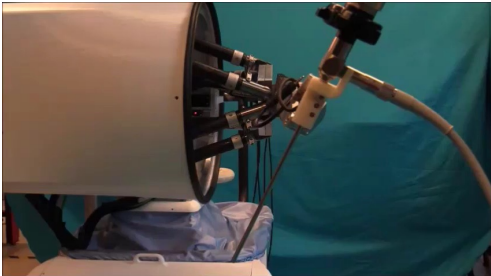
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The Galen Platform



Technology:

- Custom 5-DOF architecture
- “Steady Hand” cooperative control
- Hand tremor cancellation
- Virtual fixtures



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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Ease of Use:

- Same footprint as a person
- Accommodates standard instruments
- Minimal change to existing surgical workflow

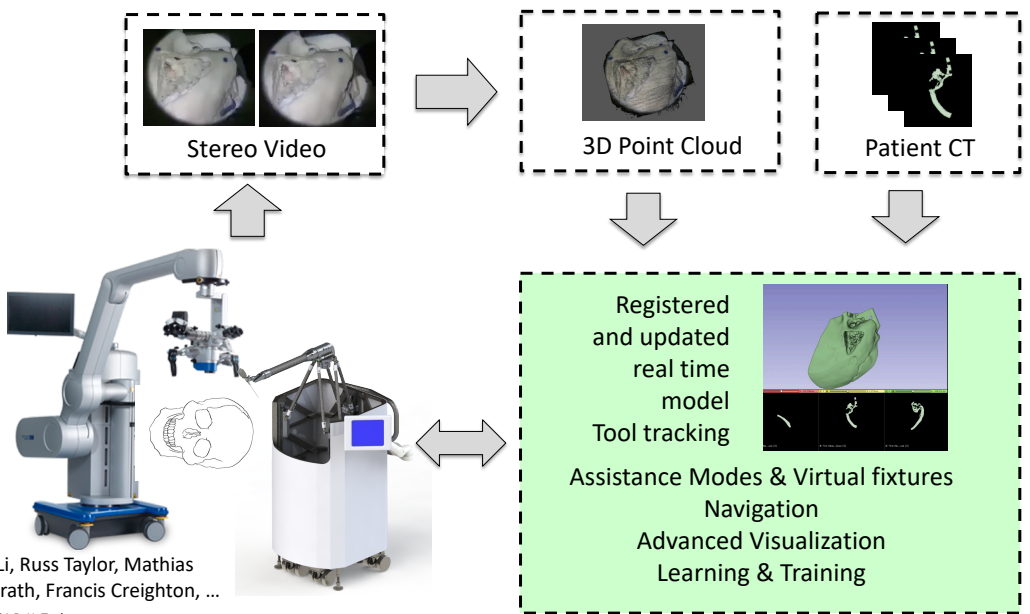
Broad Applications:

- ENT, spine, brain, trauma,

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A “smart” skull base surgical assistant




Stereo Video → 3D Point Cloud → Patient CT

Registered and updated real time model
Tool tracking

Assistance Modes & Virtual fixtures
Navigation
Advanced Visualization
Learning & Training

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

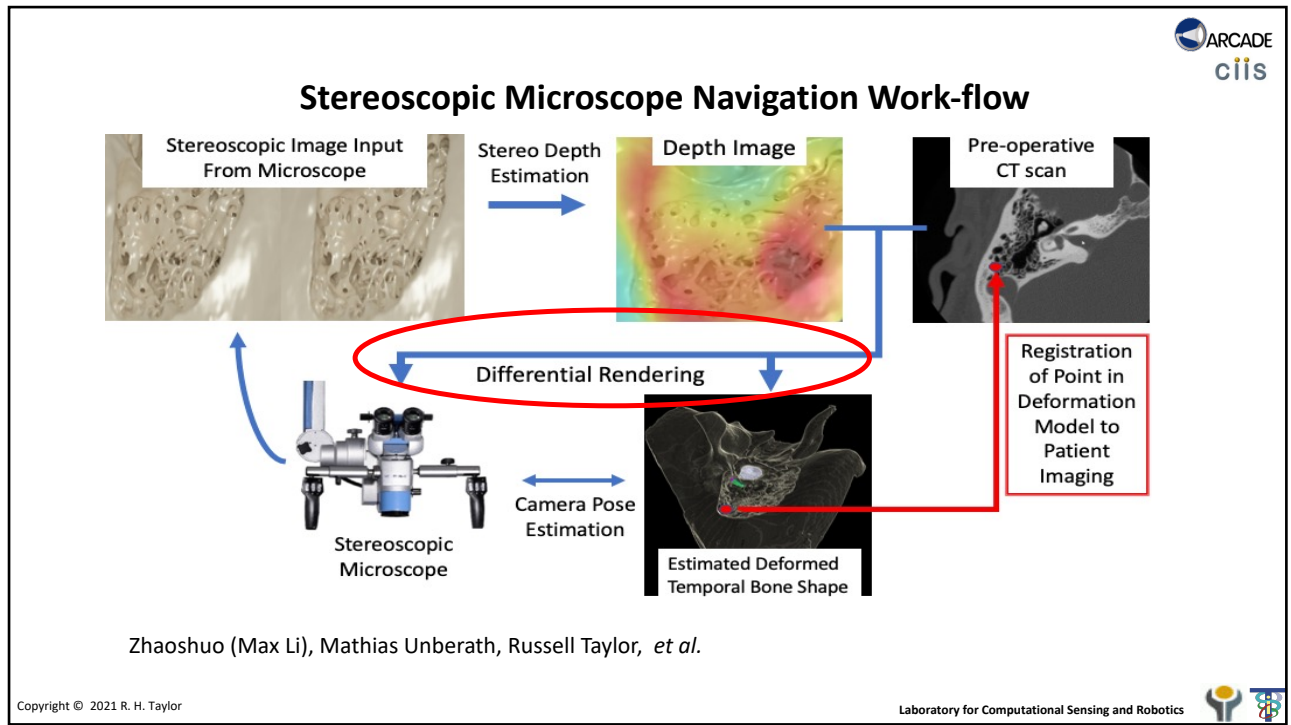
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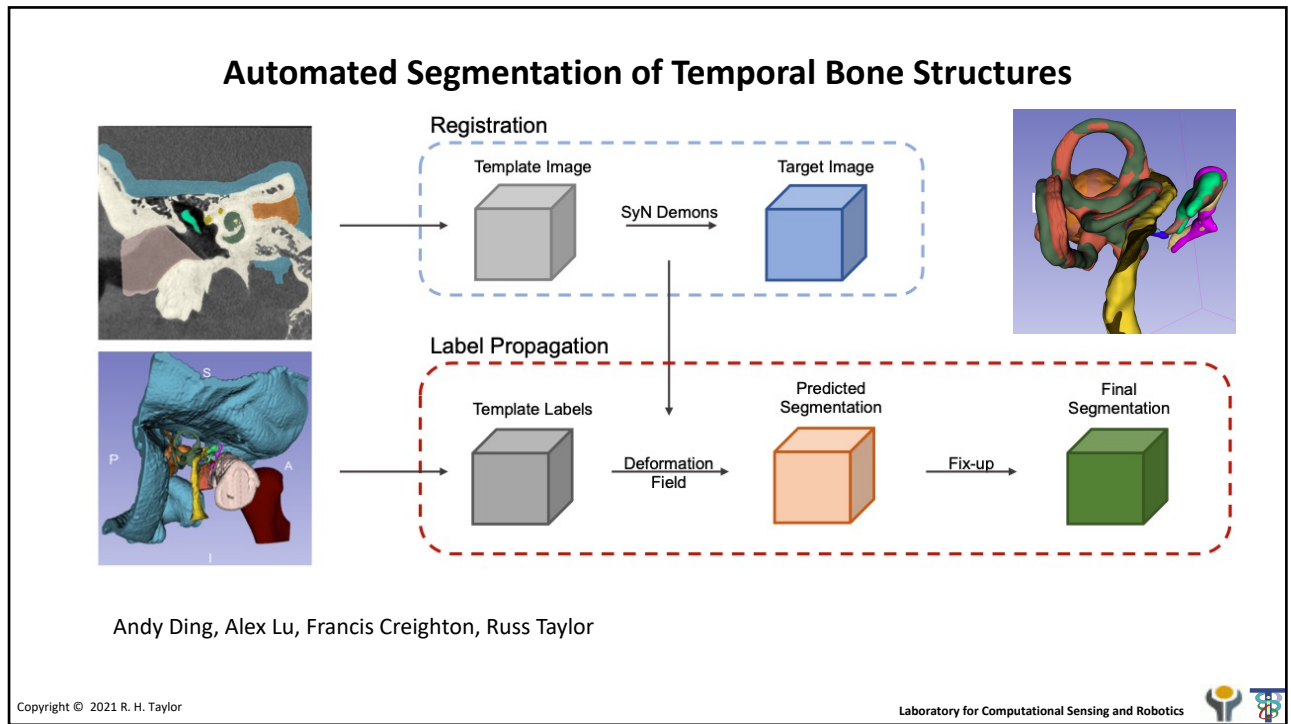
Zhaoshuo Li

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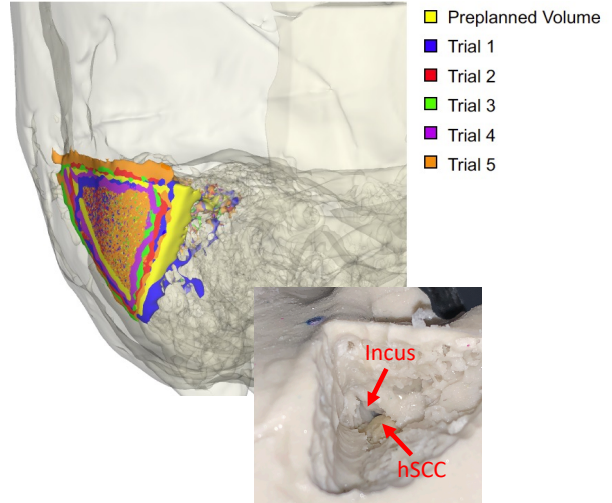
63



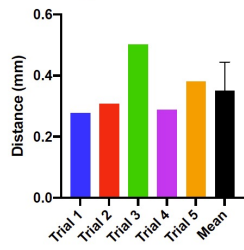
64

Results

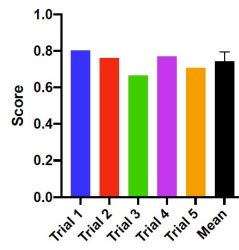
- Mean time to completion: 221 +/- 35 seconds (3.6 min)
- Average Hausdorff Distance ~0.3mm



A Average Hausdorff Distances



B Dice Coefficients



Andy Ding, Alex Lu, Francis Creighton, Russ Taylor

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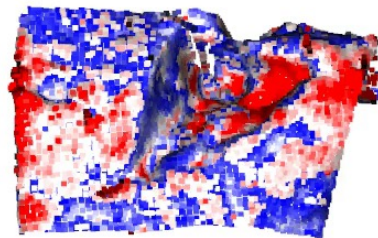


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Registration Result



	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.*

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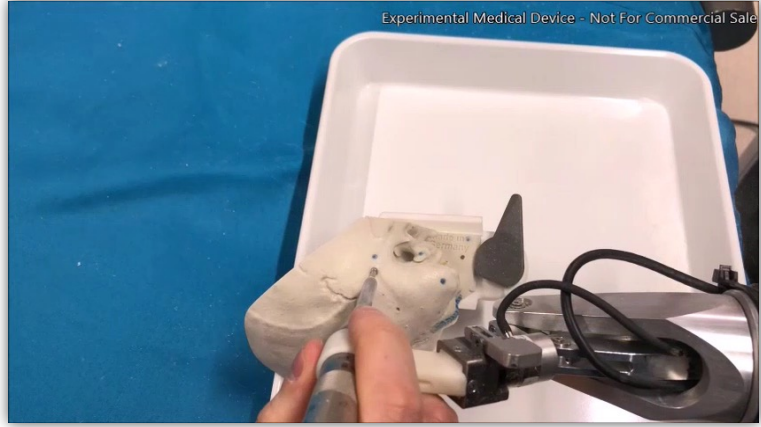
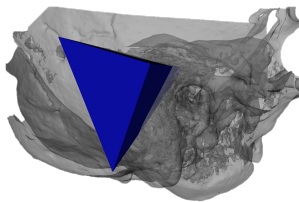


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Virtual Fixtures for Mastoidectomy



- 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.

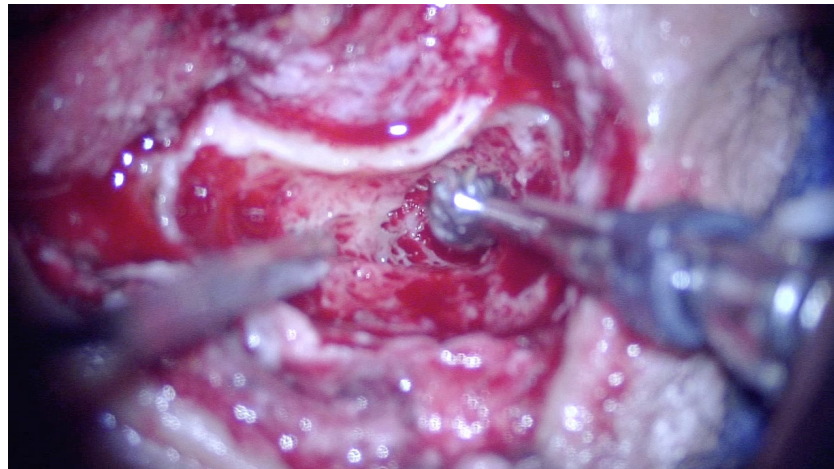
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Next Steps: Incorporate Instrument Tracking



Sue-Min Cho, Zhaoshuo (Max Li), Mathias Unberath, Russell Taylor, *et al.*

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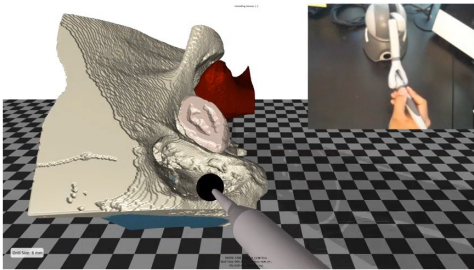
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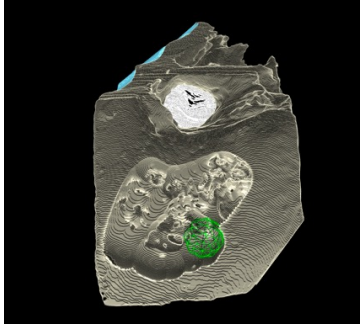


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Virtual Reality for Synergistic Surgical Training and Data Generation

Demo of virtual drilling simulator





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

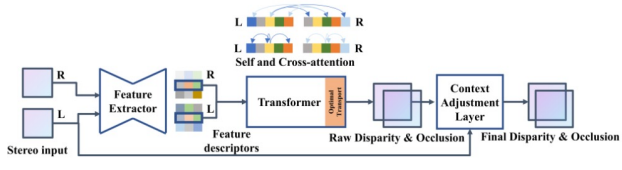
Adnan Munawar, Francis Creighton, Mathias Unberath, Zhaoshuo (Max Li), Russell Taylor, *et al.*

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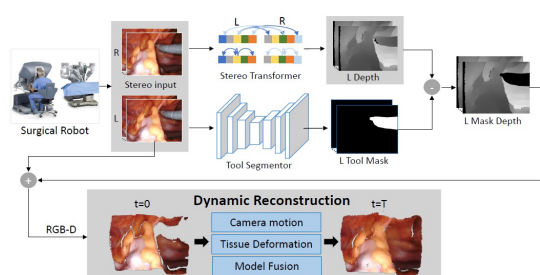
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Surgical Scene Depth Estimation and Reconstruction

Surgical vision: depth estimation and 3D reconstruction from robotic stereo videos



[Li et al. ICCV 2021]



[Long et al. MICCAI 2021]

Revisiting Stereo Depth Estimation From a Sequence-to-Sequence Perspective with Transformers

Zhaoshuo Li, Xingtong Liu, Nathan Drenkow, Andy Ding, Francis X. Creighton, Russell H. Taylor, and Mathias Unberath
Johns Hopkins University

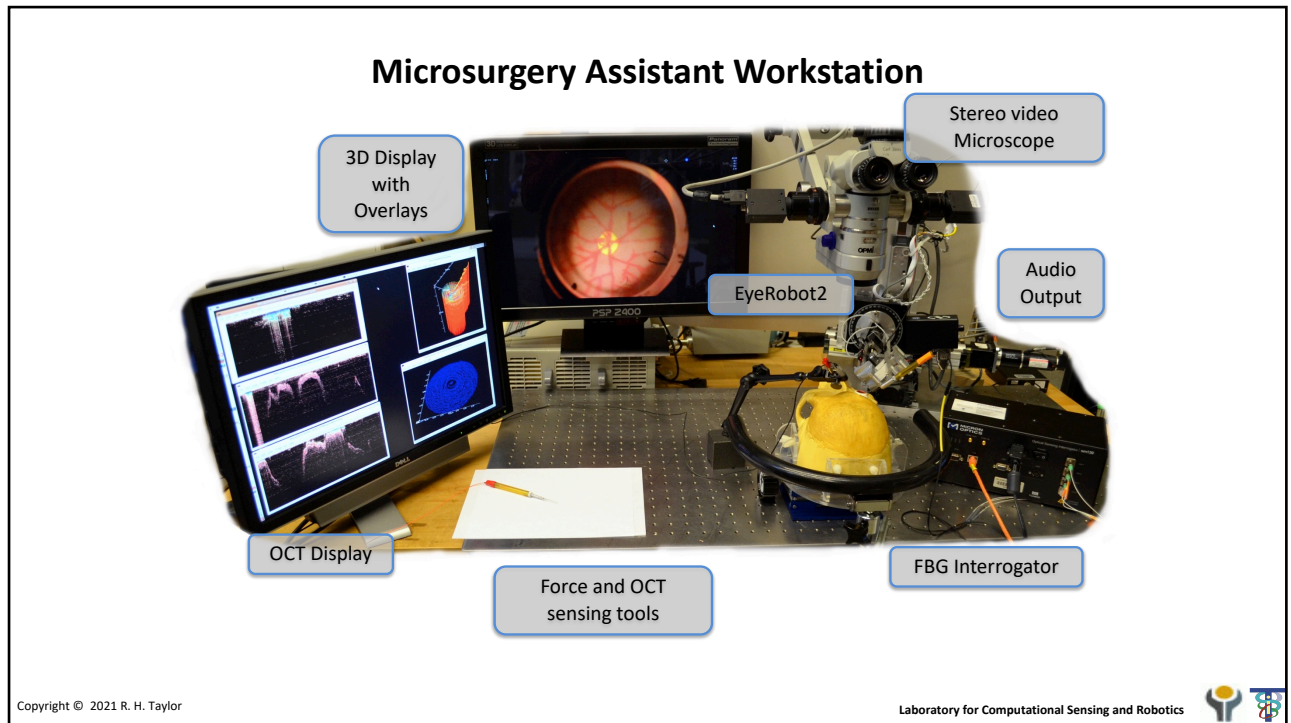
E-DSSR: Efficient Dynamic Surgical Scene Reconstruction with Transformer-based Stereoscopic Depth Perception

Yonghao Long¹, Zhaoshuo Li², Chi Hang Yee³,
Chi Fai Ng³, Russell H. Taylor², Mathias Unberath², and Qi Dou^{1,4}

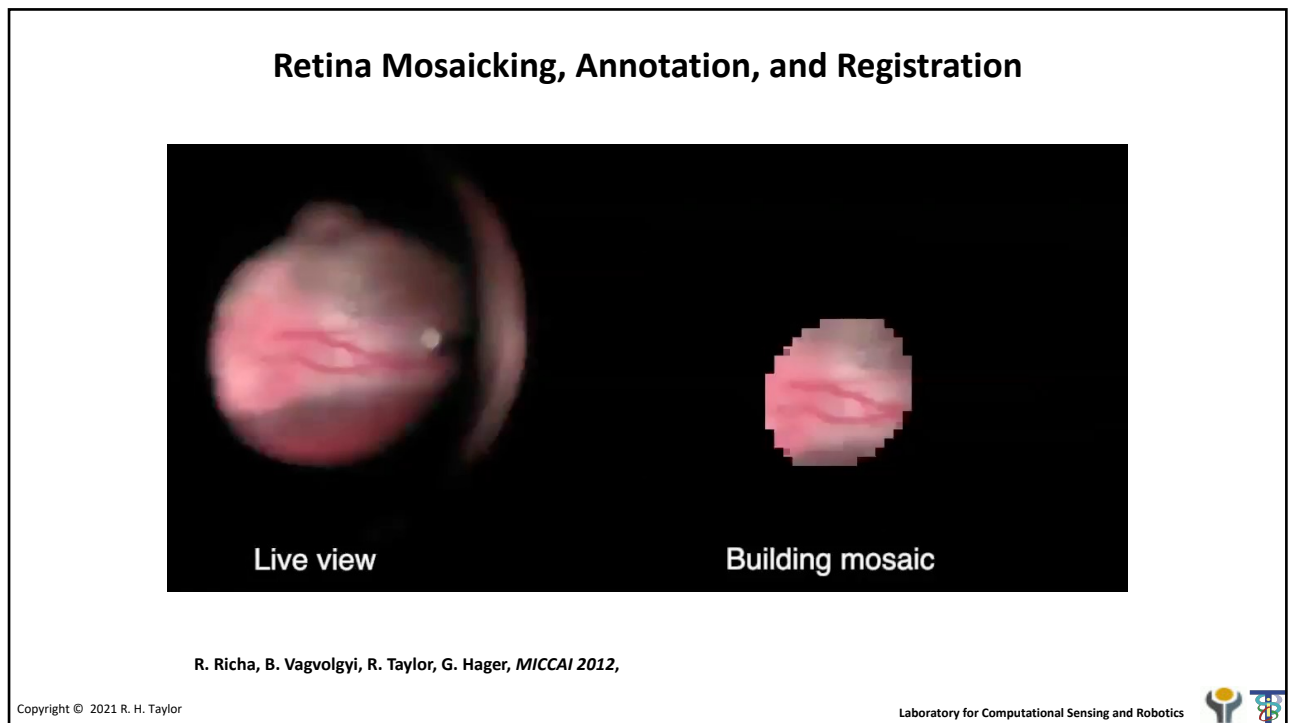
¹ Dept. of Computer Science and Engineering, The Chinese University of Hong Kong
² Department of Computer Science, Johns Hopkins University
³ SH Ho Urology Centre, Dept. of Surgery, The Chinese University of Hong Kong
⁴ T Stone Robotics Institute, The Chinese University of Hong Kong

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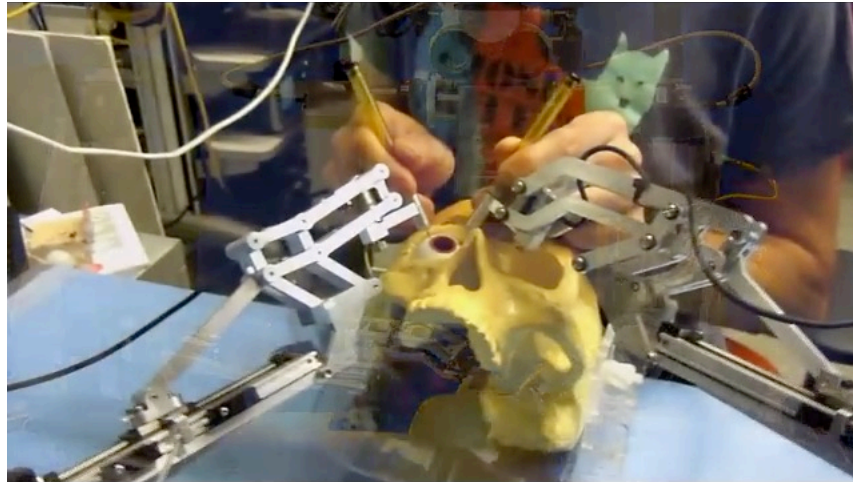
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Bilateral Robot-Assisted Retinal Surgery

Iulian Iordachita, *et al.*



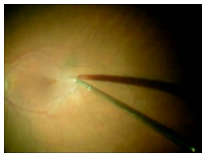
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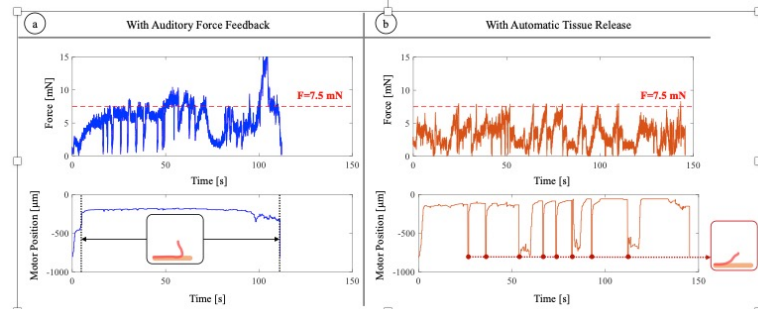
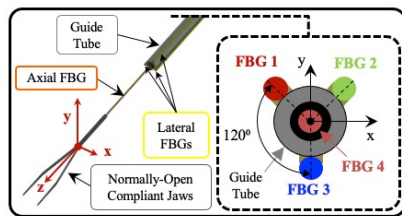
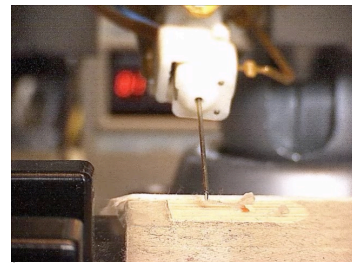
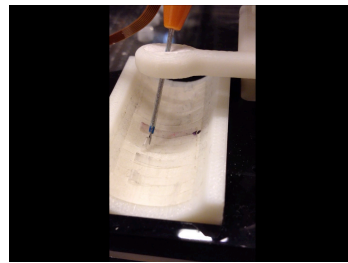
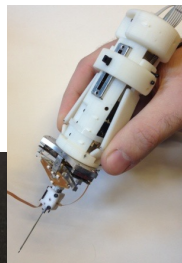
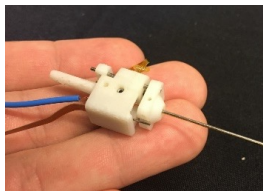


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Example: Force-limited Retinal Membrane Peeling



https://www.youtube.com/watch?v=jCpZ255_VVI&feature=emb_logo



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

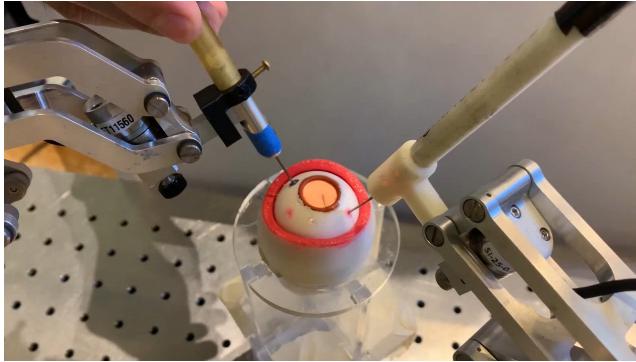
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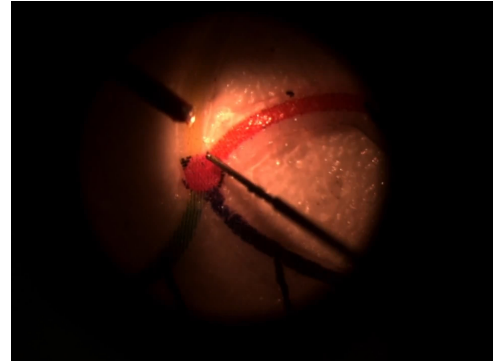
75

Automatic Light Pipe Actuating System in Bilateral Surgery

Automatic light pipe actuation



Microscope view



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

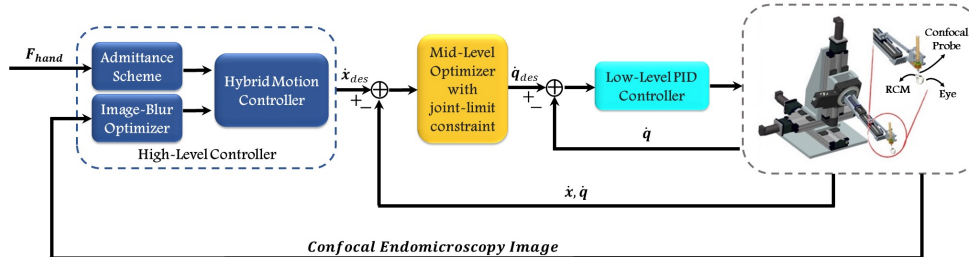
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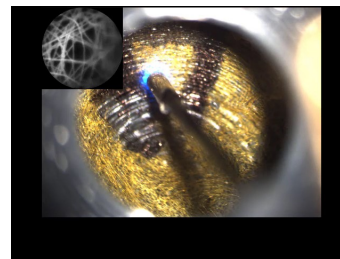
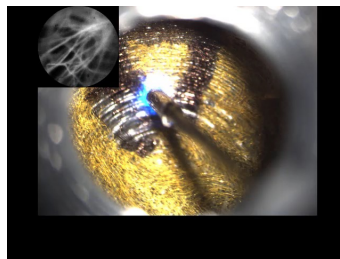


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Robot-assisted confocal endoscopic imaging for retinal surgery



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", *IROS 2019*.

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Intelligent Medical Robotic Systems and Equipment Lab

Smart Autonomous Surgery

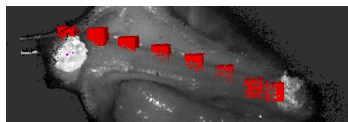
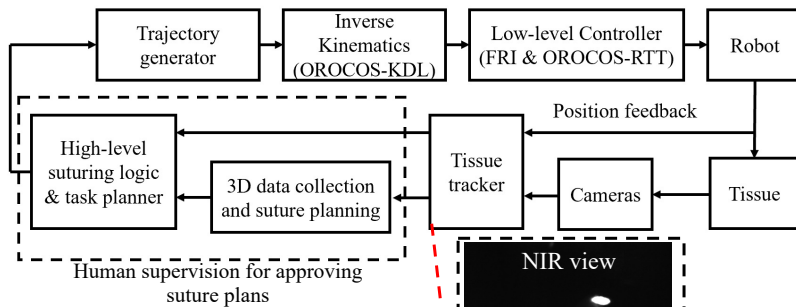


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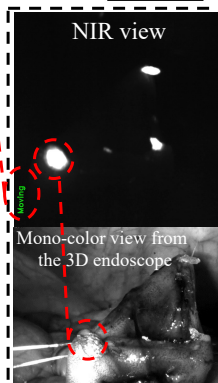
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Intelligent Medical Robotic Systems and Equipment Lab

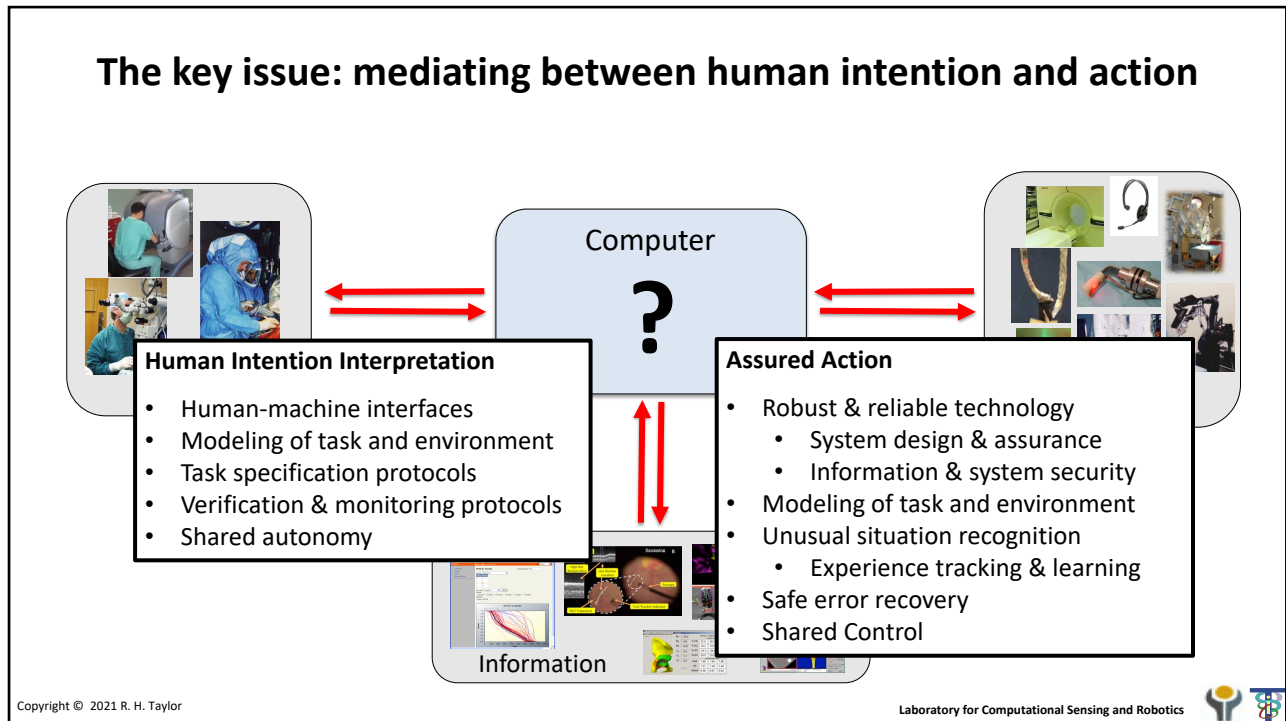


Suture planning is done at the end of breathing cycle to reduce 3D model inaccuracy caused by tissue's motion. Robot is controlled under a remote center of motion (RCM) and motions are synced with breathing and the planned sutures.

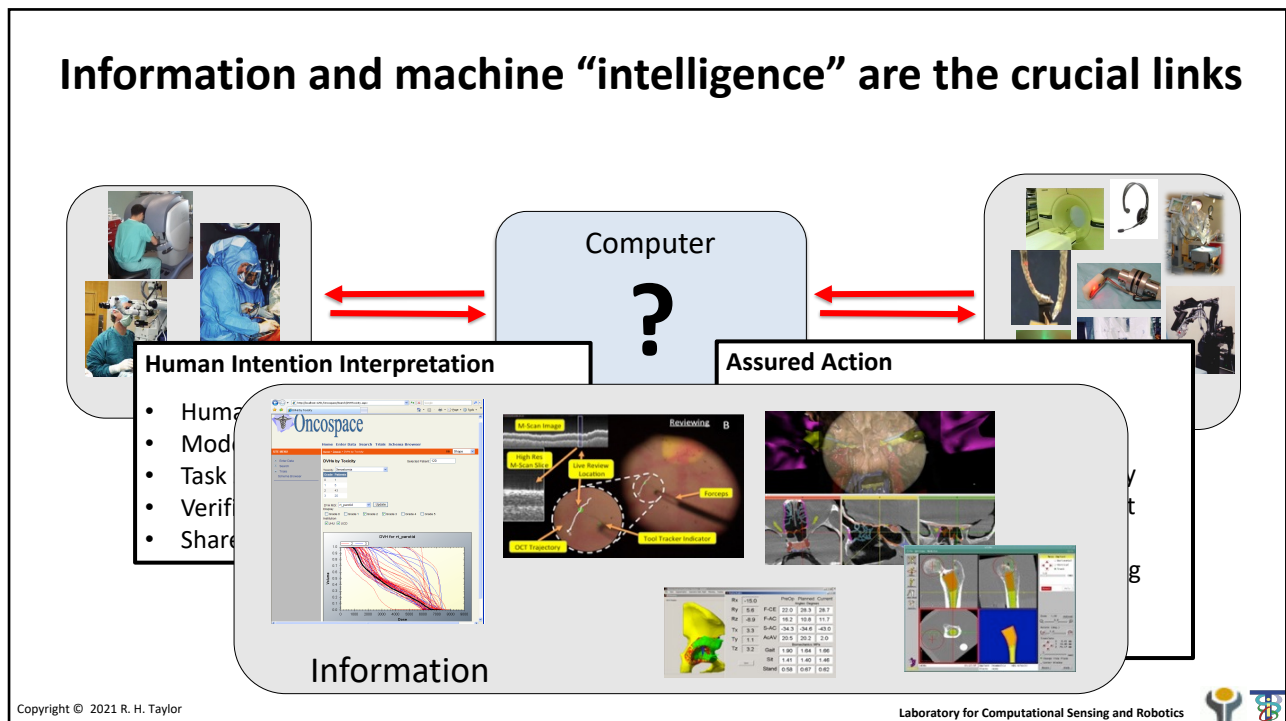
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