NSF Engineering Research Center
for Computer Integrated Surgical
Systems and Technology

LABORATORY FOR
Computational
Sensing + Robotics
THE JOHNS HOPKINS UNIVERSITY

A Microsurgical Assistant for Retinal Surgery

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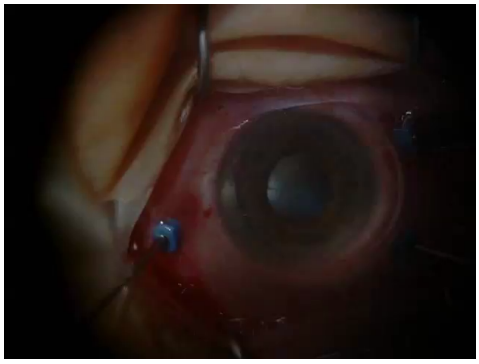
JOHNS HOPKINS
WHITING SCHOOL
of ENGINEERING

Goal: Human-machine partnership to fundamentally improve interventional medicine

Slide credit: Marcin Balicki

Vitreoretinal Microsurgery



Alcon Vitreosurgery Instrument

- **Retinal disease is the leading cause of new blindness in the Western World**
- **Most frequent indications for retinal surgery include**
  - Retinal detachment
  - Vitreous hemorrhage
  - Macular puckers
  - Macular holes
  - Diabetic retinopathy
- **Success rates depend critically on difficult technical steps:**
  - Removing scar tissue from the retina (e.g., in retinal detachment or macular puckers)
  - Peeling the internal limiting membrane (e.g., macular holes)
  - Cannulation of tiny vessels (e.g, retinal vein occlusion)

Limitations of Current Technology

- **Human sensor-motor limitations**
  - Hand tremor
  - Force perception
  - Tool-tissue relationships
- **Visualization**
- **Information fusion**
- **Ergonomics**

Microsurgical Assistant for Retinal Surgery

Goals

- Develop technology addressing fundamental limitations in retinal microsurgery
- Integrate into comprehensive system
- Validate performance
- Transfer to clinical use

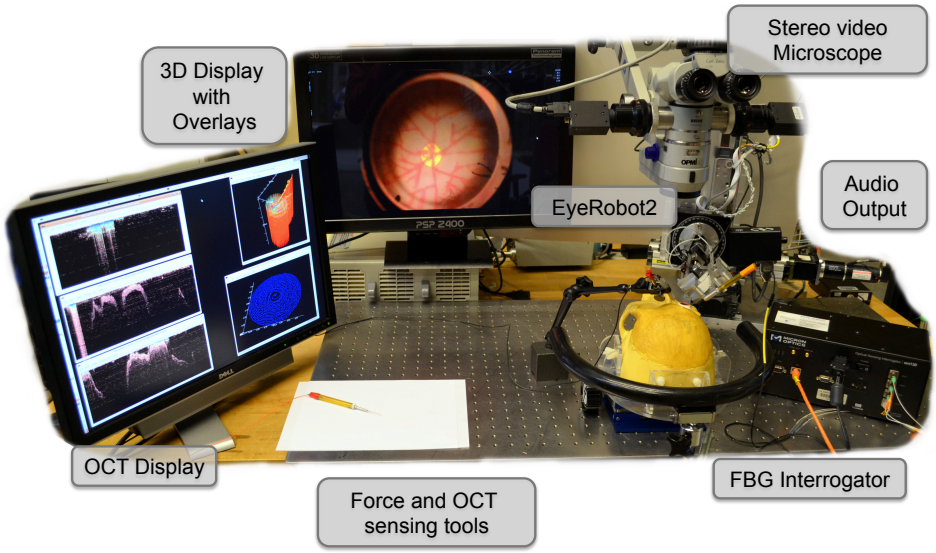
Team

- **WSE:** R. Taylor, G. Hager, J. Kang, P. Kazanzides, A. Deguet, B. Vagvolgyi, I. Iordachita, R. Richa, X. Liu, M. Balicki, X. He, B. Hu, B. Gonec, K. Olds
- **SoM:** J. Handa, P. Gehlbach, S. Sunshine, N. Cutler
- **CMU:** C. Riviere, B. Becker, R. MacLachlan

Current Funding

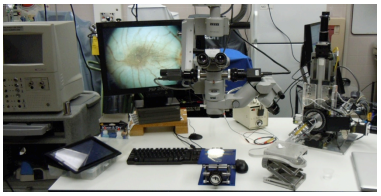
- NIH BRP5 R01 EB007969 (Taylor)
- NIH R01 EB000526 (Riviere)
- NIH R01 EY021540 (Kang)

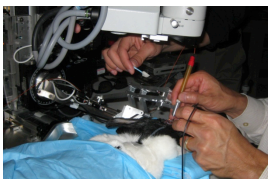
Microsurgery Assistant Workstation

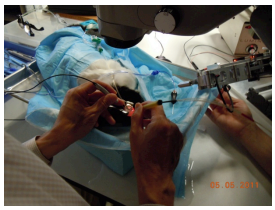


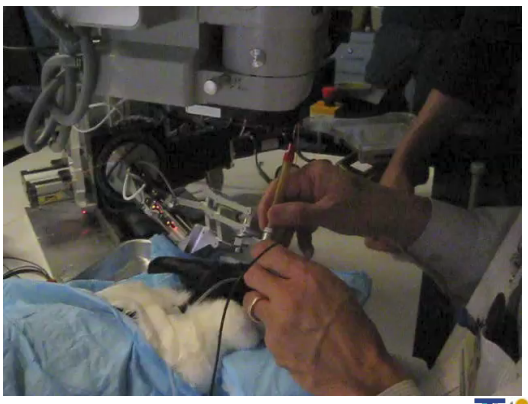
In-Vivo Experiments

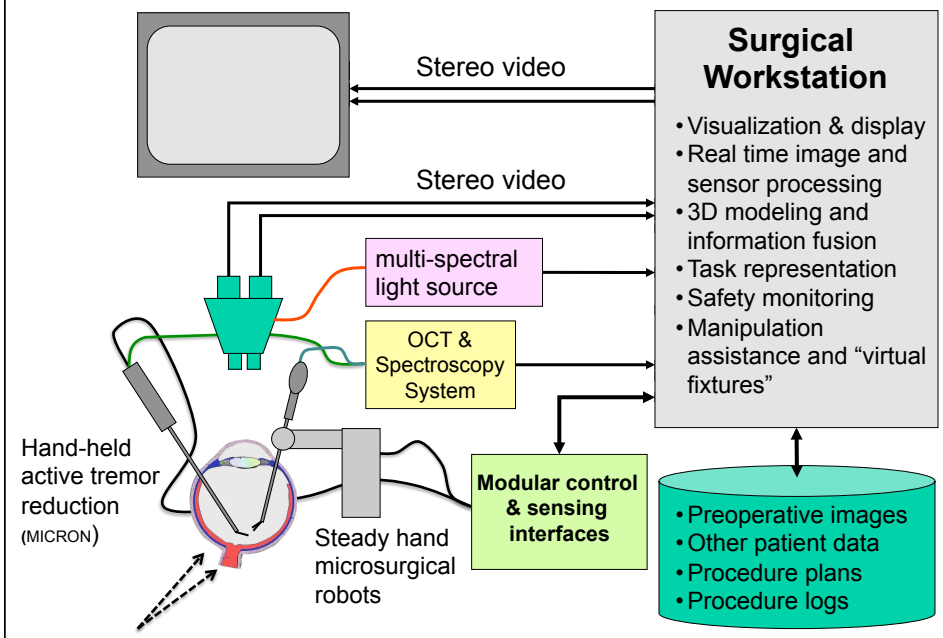
- Overall System Performance
- System Ergonomics
- Collect Data
  - Robot / Force / OCT
  - Video / Audio



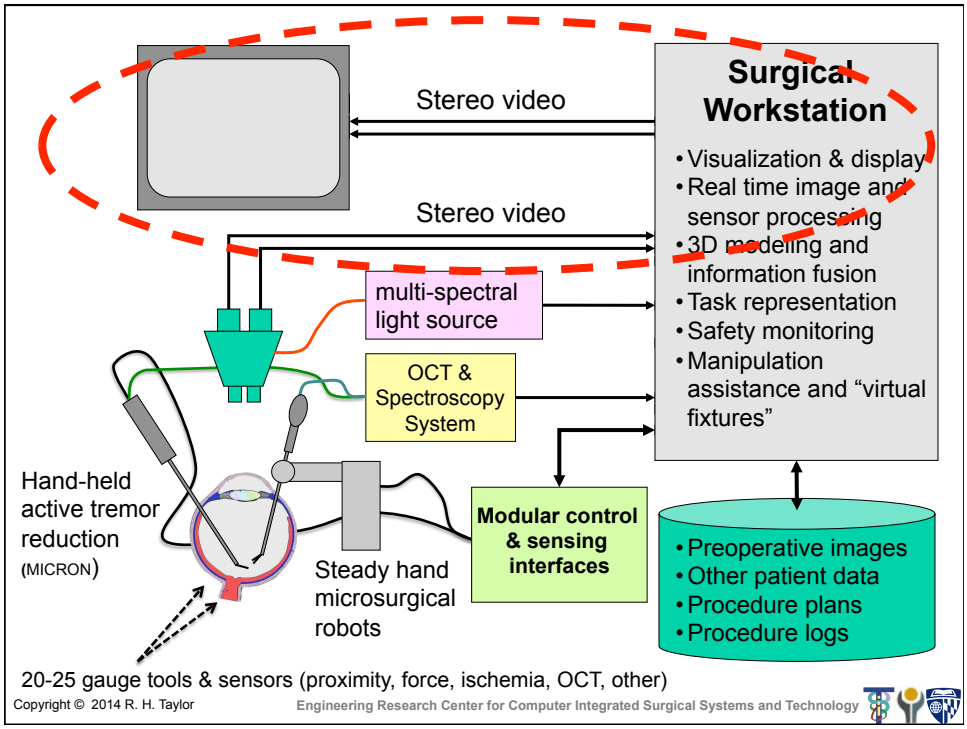




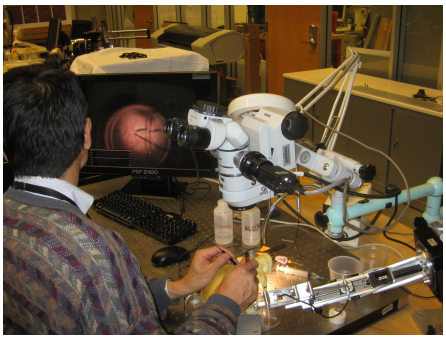




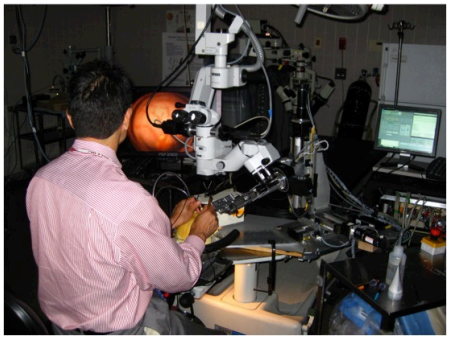
20-25 gauge tools & sensors (proximity, force, ischemia, OCT, other)



Video Microscopes



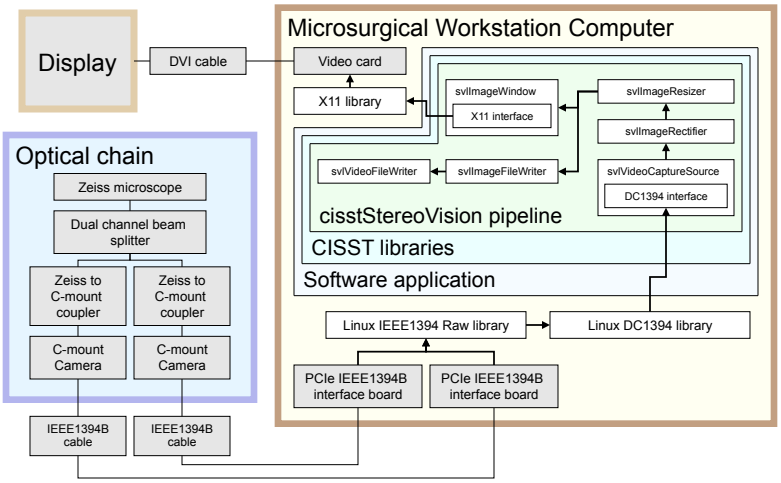
Hackerman Engineering Lab



Wilmer OR1

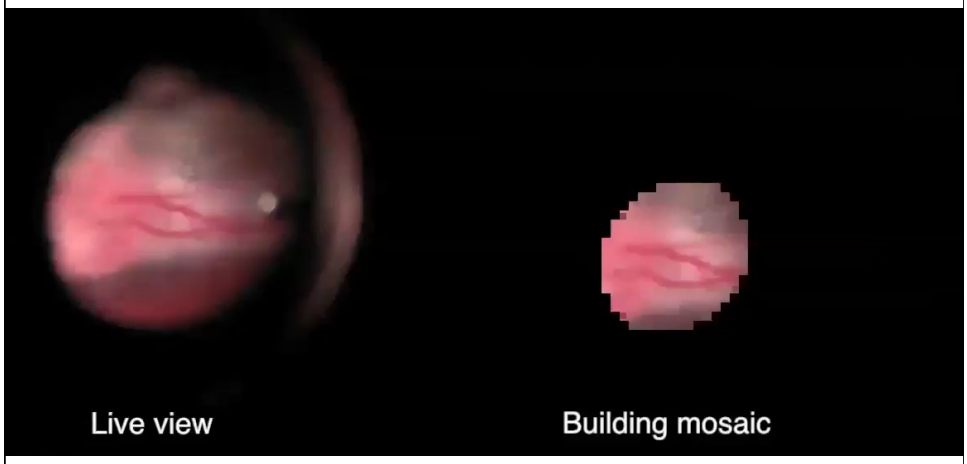
- Fire wire HD cameras attached to Zeiss operating microscopes
- Stereo video display with polarized glasses
- Permits easy overlay of information
- Architecture does not depend on technology choice

CISST Microsurgical Video Infrastructure



Example Video Microscopy Application (HW+SW)

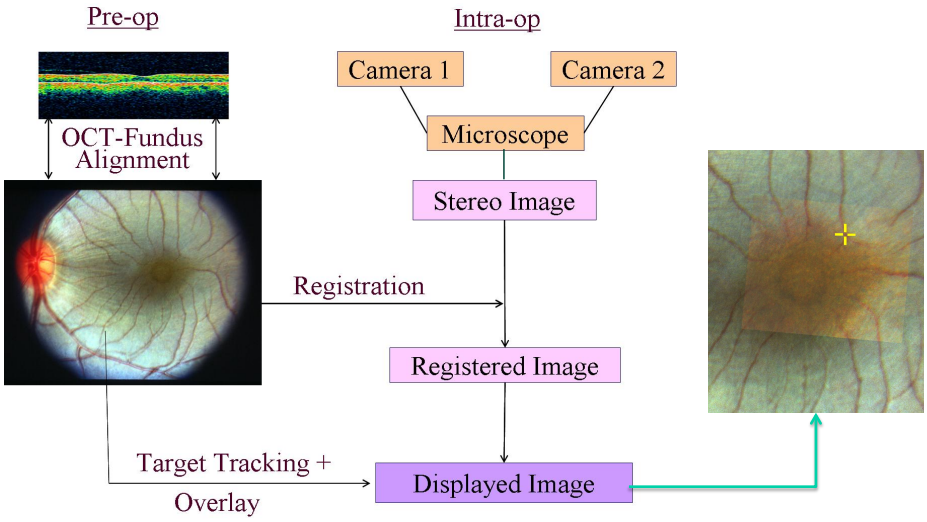
Retina Mosaicking, Annotation, and Registration



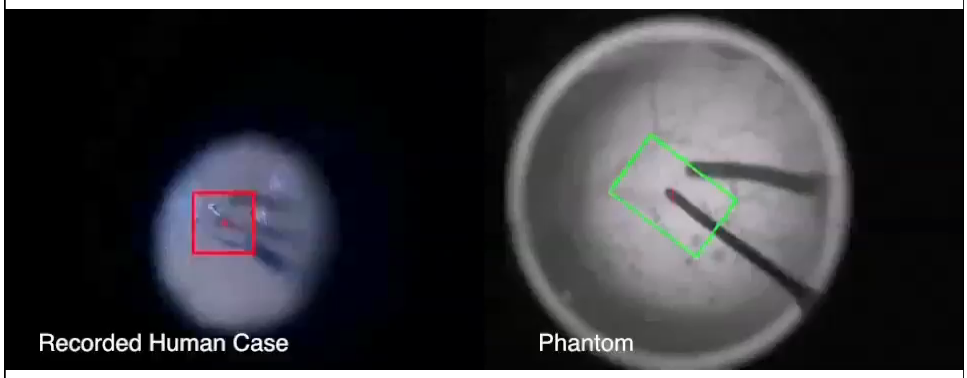
R. Richa, B. Vagvolgyi, R. Taylor, G. Hager, *MICCAI 2012*,

Example: Fusion of preoperative fundus image and OCT-based targeting to microscope images

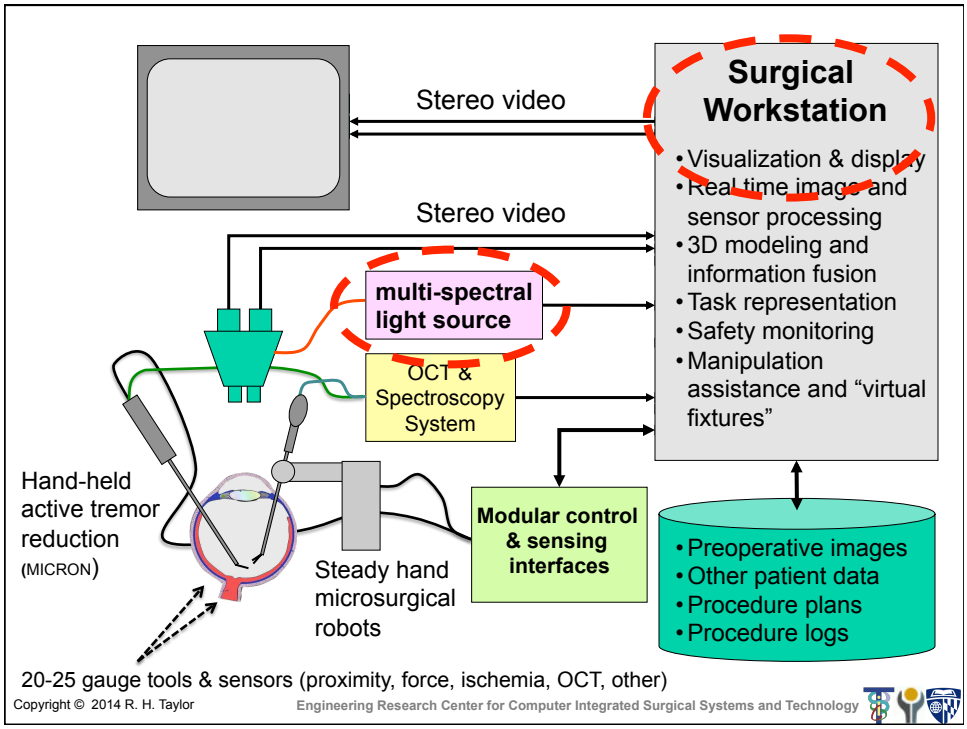
Ioana Fleming, Sandrine Voros, Balazs Vagvolgyi, Zach Pezzementi, Dr. Jim Handa, Russ Taylor, Greg Hager



Tool and Retina Tracking



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



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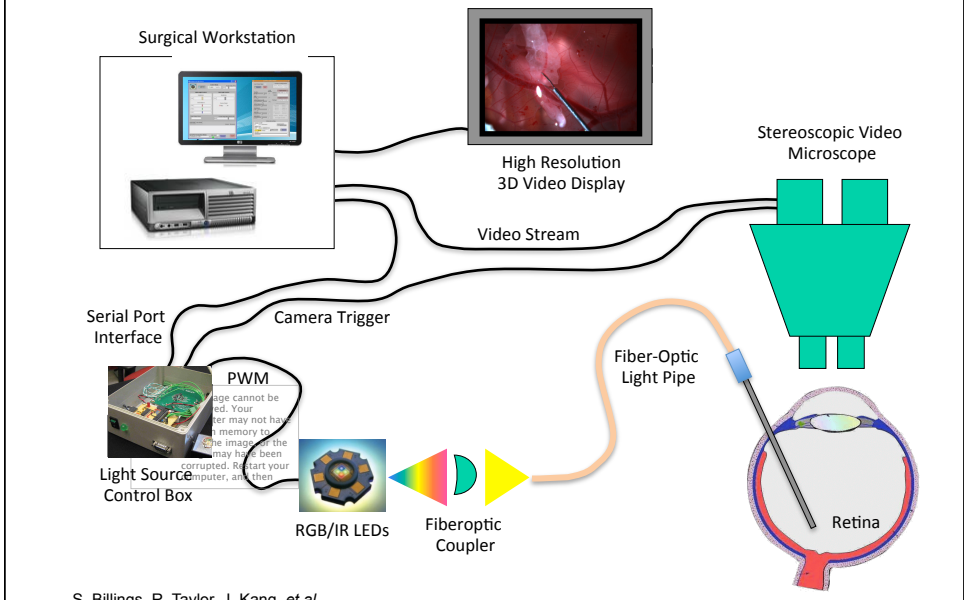
Active Programmable Multispectral Illumination



S. Billings, R. Taylor, J. Kang, *et al.*

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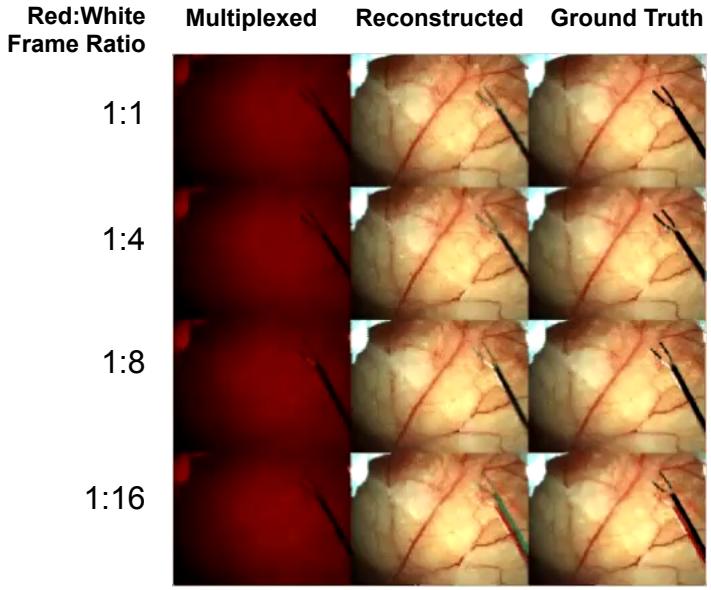
Synthetic full color from multiplexed illumination



R. Snitzman, S. Billings, R. Taylor ,G. Hager *et al.*

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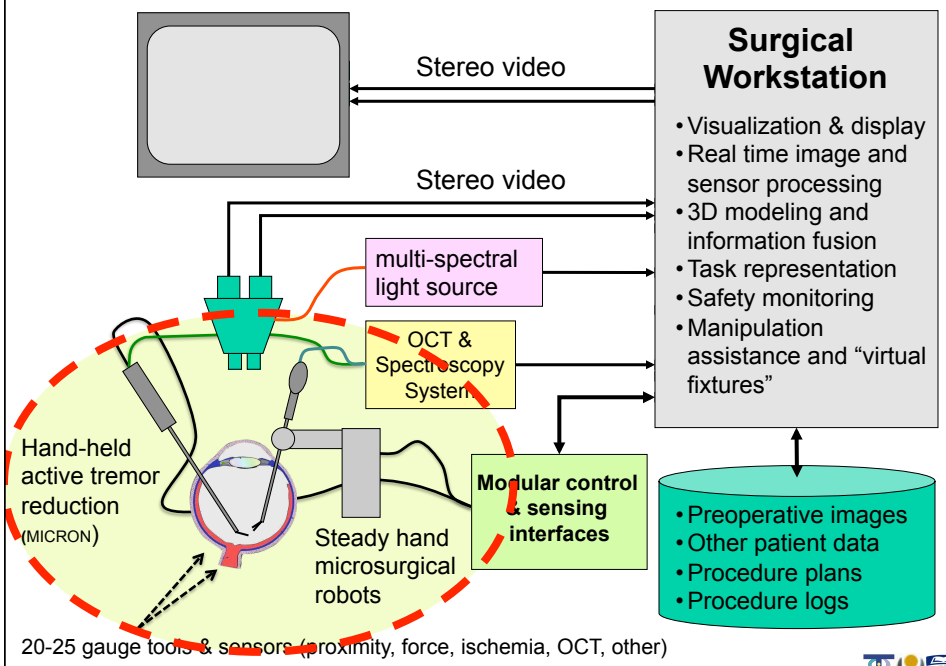

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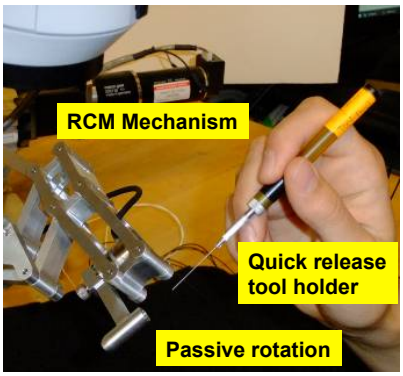
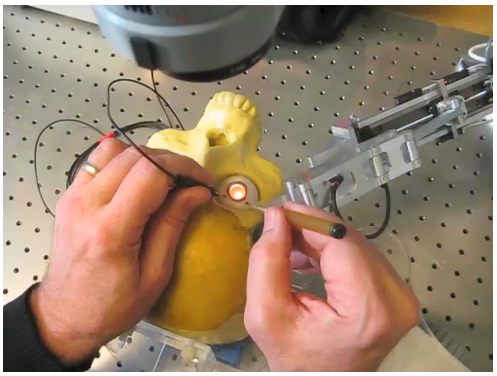
JHU Steady Hand "Eye Robot"

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





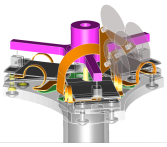
- Highly precise robot
- Hands-on cooperative control or teleoperation
- Several generations in lab

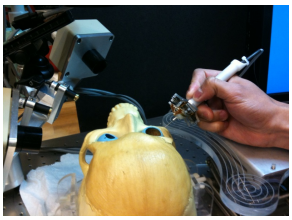
- Precise, stable platform for developing "smart" surgical instruments and sensors
- Virtual fixtures and advanced control

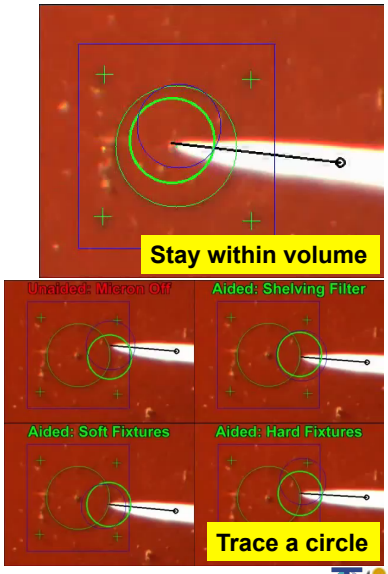
MICRON active tremor cancellation device

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



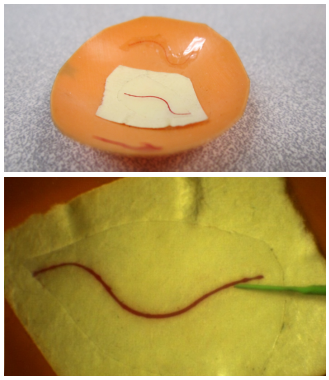


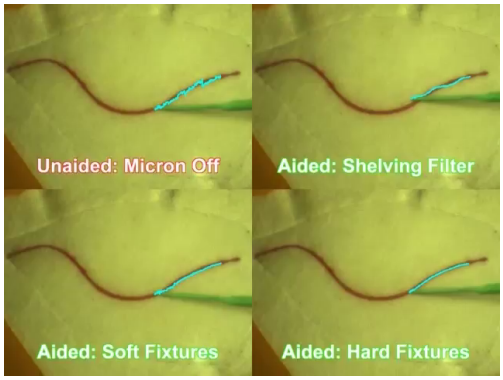


MICRON active tremor cancellation device

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

Vision-guided vessel following





5.0 mm

Surgeon Results

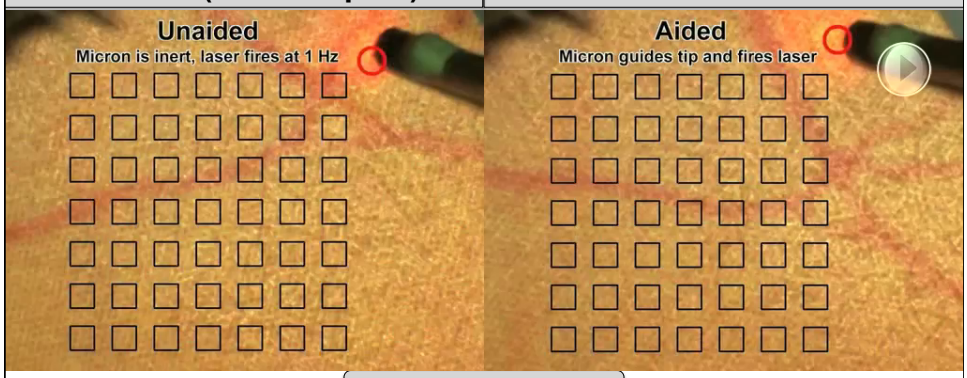
B. Becker, Vision-Based Control of a Handheld Micromanipulator for Robot-Assisted Retinal Surgery, Ph.D. thesis in Robotics, Carnegie Mellon University, 2012.

MICRON active tremor cancellation device

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

Laser Photocoagulation on Porcine Retina

Unaided (2.0 Hz repeat)	Aided



Surgeon Results

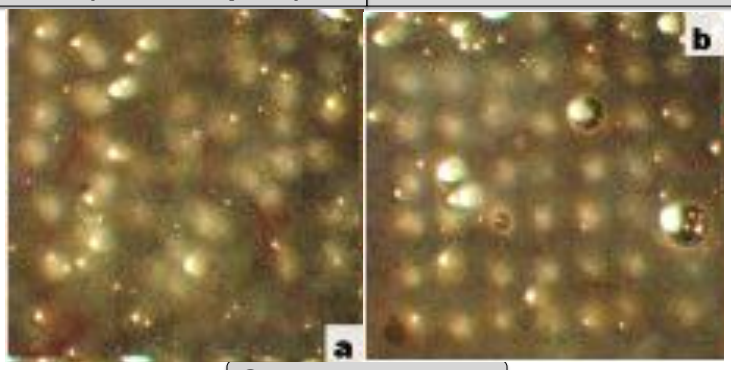
B. Becker, Vision-Based Control of a Handheld Micromanipulator for Robot-Assisted Retinal Surgery, Ph.D. thesis in Robotics, Carnegie Mellon University, 2012.

MICRON active tremor cancellation device

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

Laser Photocoagulation on Porcine Retina: Results

Unaided (2.0 Hz repeat)	Aided



Surgeon Results

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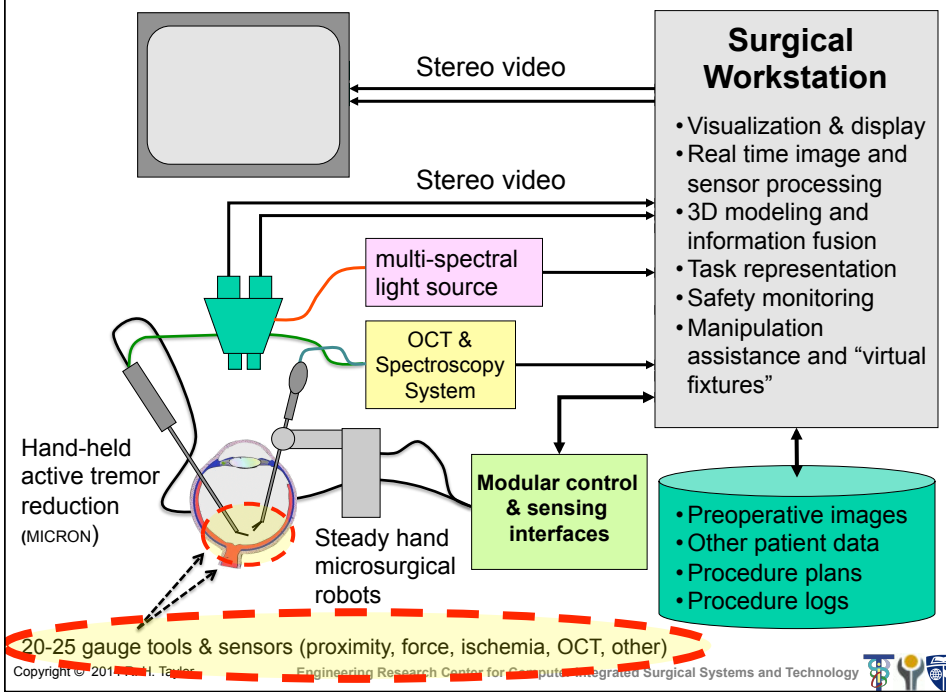
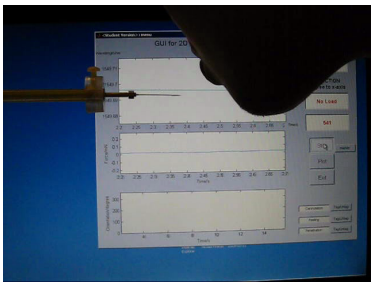
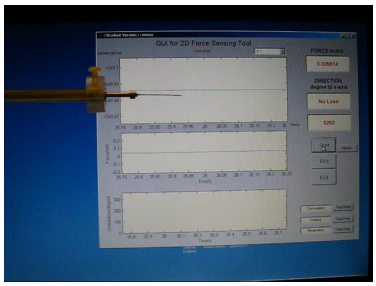
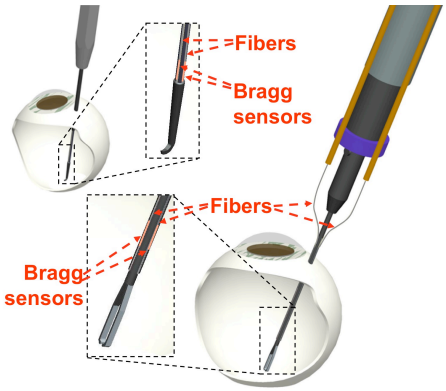


Force Sensing Surgical Instruments





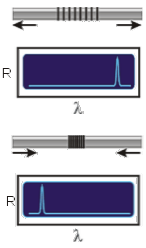
- Incorporate fiber optic force sensors into 0.5 mm diameter surgical tools
- 0.25 mN force sensitivity

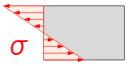


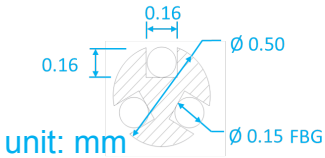
Iordachita, Sun, Balicki, …, Kang, Handa, Gehlbach, Taylor

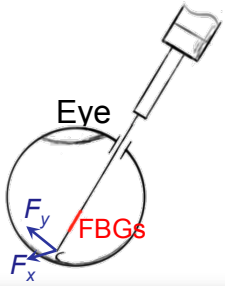
2-DOF Force Sensing Tools

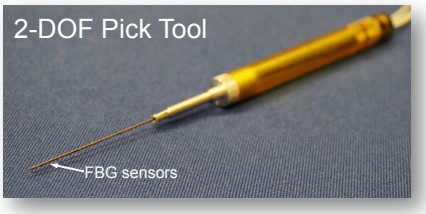
Fiber Bragg Grating (FBG sensors)



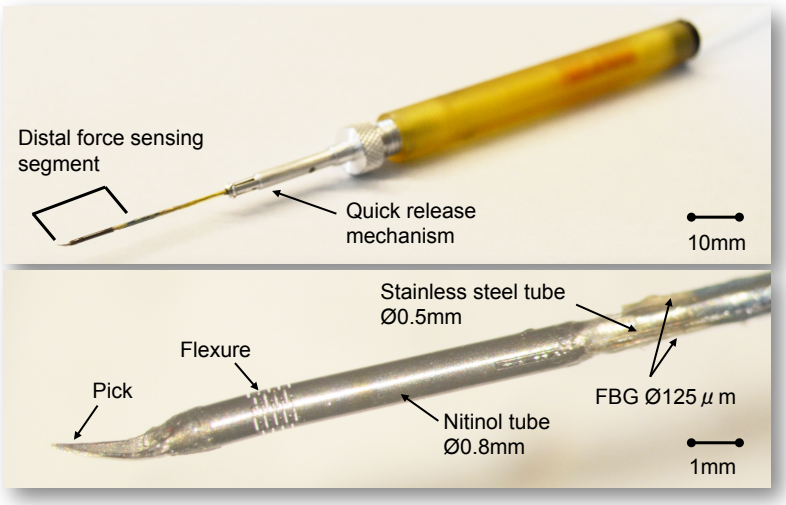






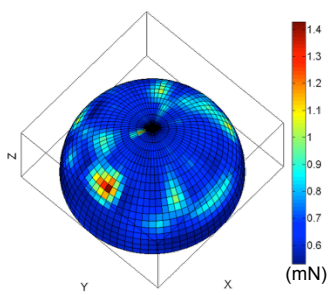


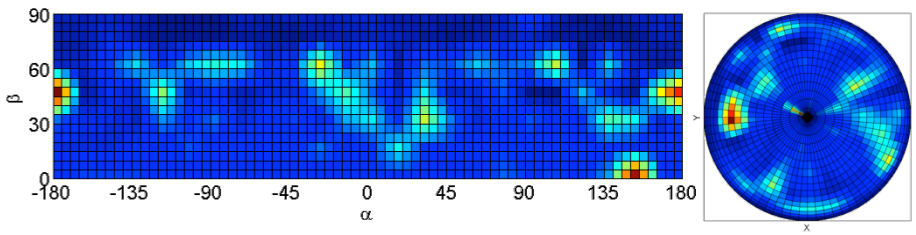
3-DOF Force Sensing Pick Tool



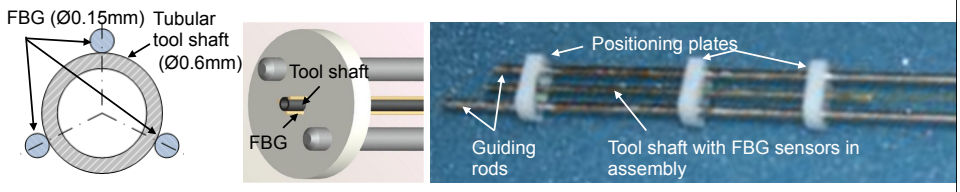
3 DOF Tool Calibration: F_z RMS Error

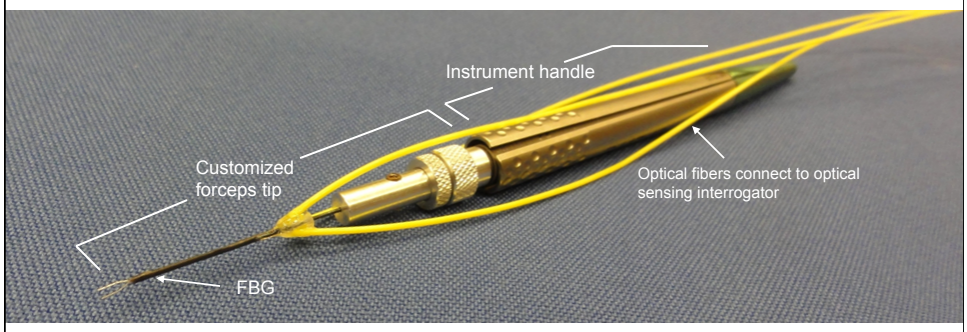
- Overall RMS error with 2nd order Bernstein polynomial: 0.67 mN
- Estimation performance in each force direction (total 168 poses)
  - 84.5% (142 poses) < 0.75 mN
  - 96.4% (162 poses) < 1 mN





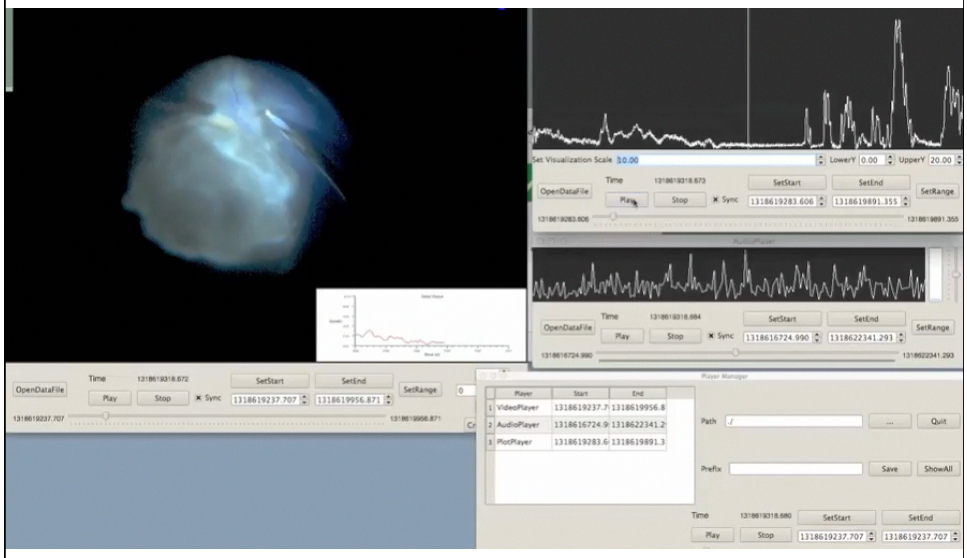
Forceps Tool





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

In-vivo force experiment

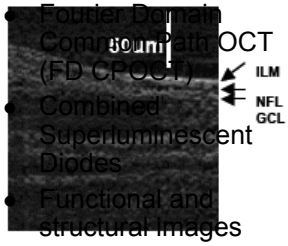


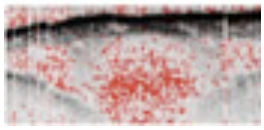
Xingchi He, Marcin Balicki, Jin U. Kang, Peter Gehlbach, James Handa, Russell Taylor, Iulian Iordachita
"Force sensing micro-forceps with integrated fiber Bragg grating for vitreoretinal surgery", SPIE 2012

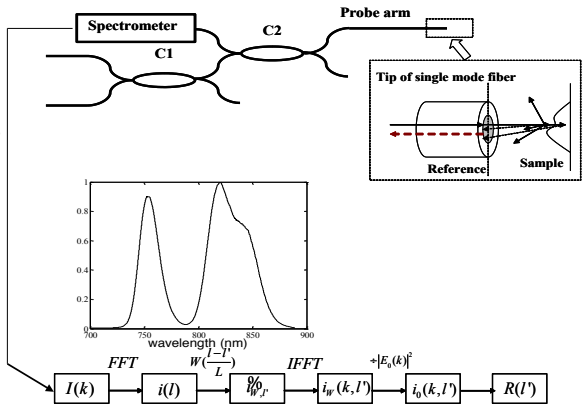
Imaging (OCT) Built Into 0.5mm Surgical Tool

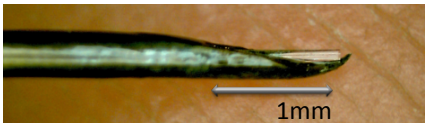
M. Balicki, J. Han, X. Liu, I. Iordachita, P. Gehlbach, J. Handa, R. Taylor, J. Kang.

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

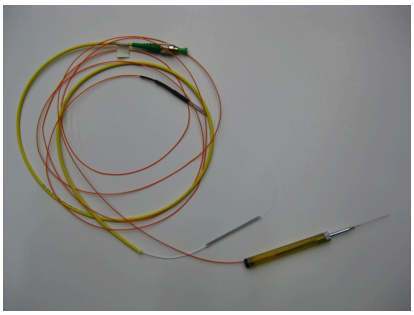


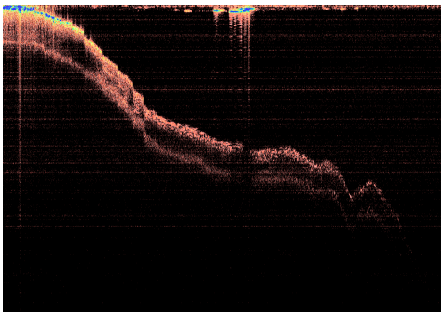


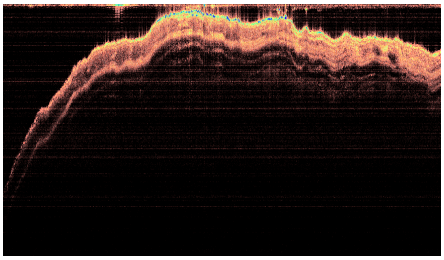




Freehand B-mode scans of rabbit retina







Imaging (OCT) Built Into 0.5mm Surgical Tool

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

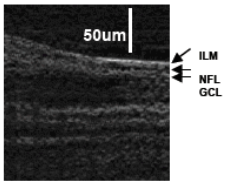


Fig.1. OCT image of a porcine retina

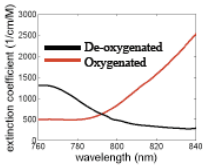
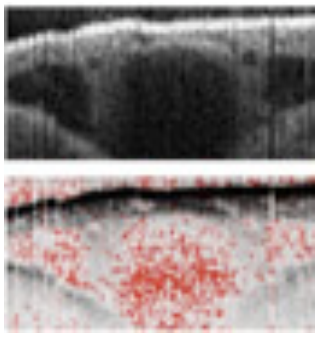


Fig.2. Measured extinction coefficients as a functi of oxygenated and de-oxygenated blood.



Functional OCT based on spectrum

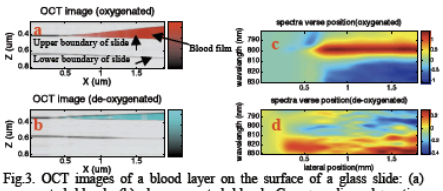
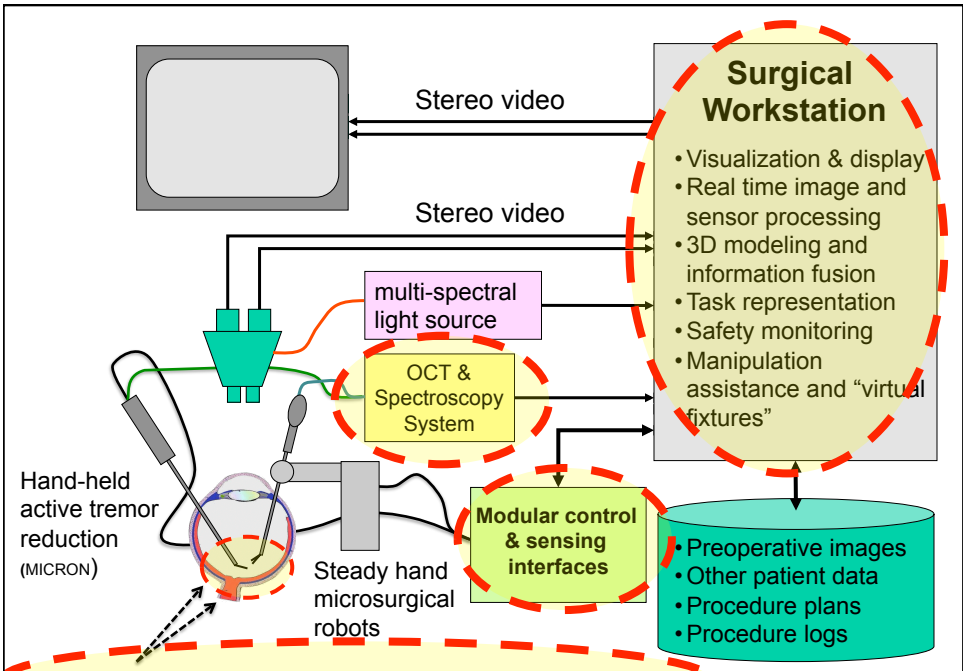
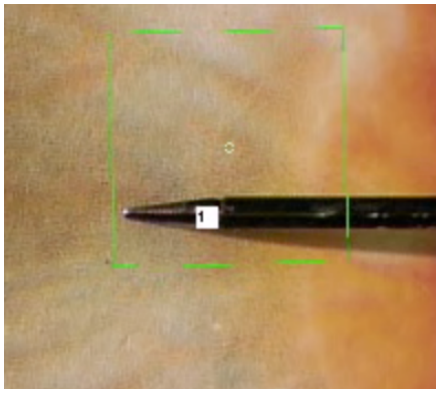
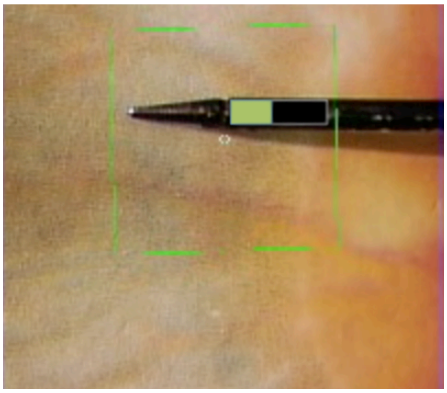


Fig.3. OCT images of a blood layer on the surface of a glass slide: (a) oxygenated blood; (b) de-oxygenated blood. Corresponding absorption spectra verses position for (c) oxygenated layer; (d) de-oxygenated layer



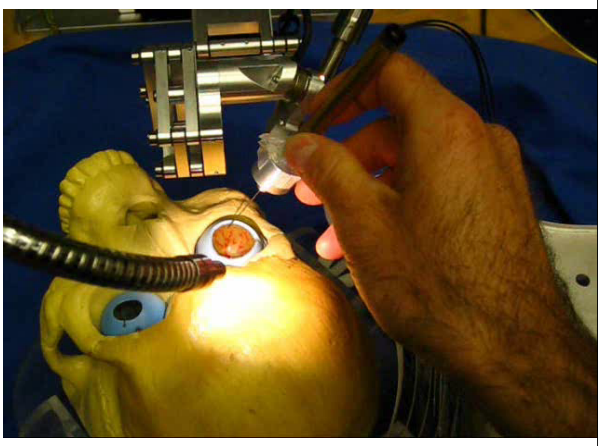
Video overlay of tool tip forces



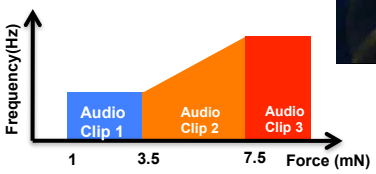


Use of Audio and Voice

- Voice commands and annotation
- Auditory sensory substitution

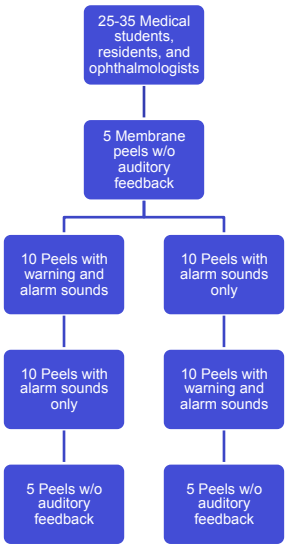


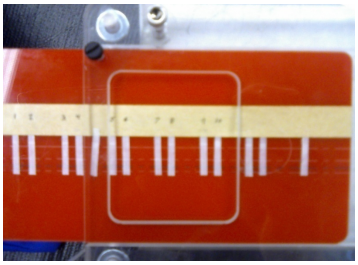
Example Audio Response to Force Input



M. Balicki, *et al.*

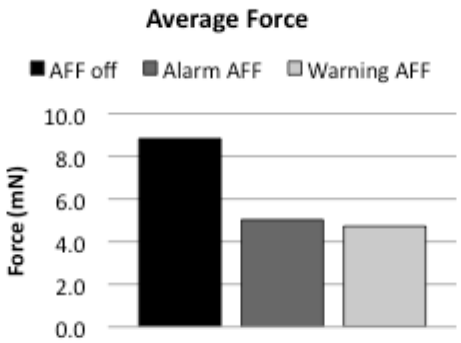
Freehand Audio Substitution Trial

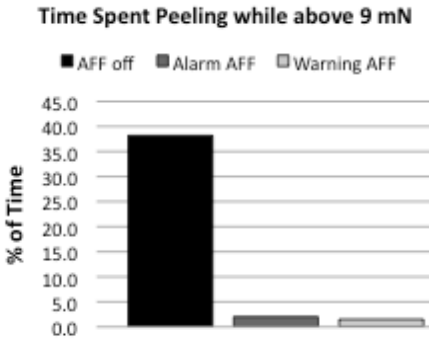




N. Cutler, M. Balicki, M. Finkelstein, J. Wang, P. Gehlbach, J. McGready, I. Iordachita, R. Taylor, and J. Handa, "Auditory Force Feedback Substitution Improves Surgical Precision During Simulated Ophthalmic Surgery", Investigative Ophthalmology & Visual Science, vol. 54- 2, pp. 1316-24, 2013; PMC3597188.

Freehand Audio Substitution Trial

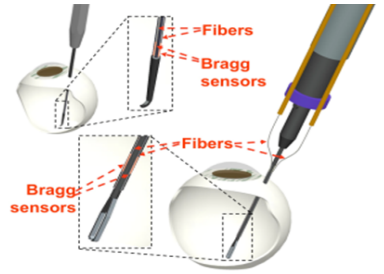


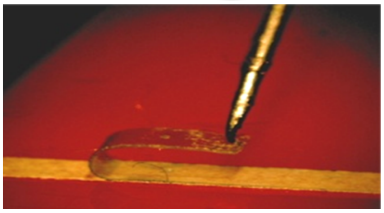


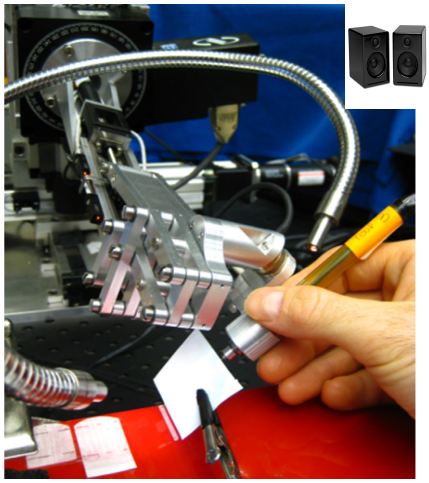
N. Cutler, M. Balicki, M. Finkelstein, J. Wang, P. Gehlbach, J. McGready, I. Iordachita, R. Taylor, and J. Handa, "Auditory Force Feedback Substitution Improves Surgical Precision During Simulated Ophthalmic Surgery", Investigative Ophthalmology & Visual Science, vol. 54- 2, pp. 1316-24, 2013; PMC3597188.

Micro-force Sensing in Robot Assisted Membrane Peeling

Goal: Lower applied forces in simulated retinal membrane peeling.

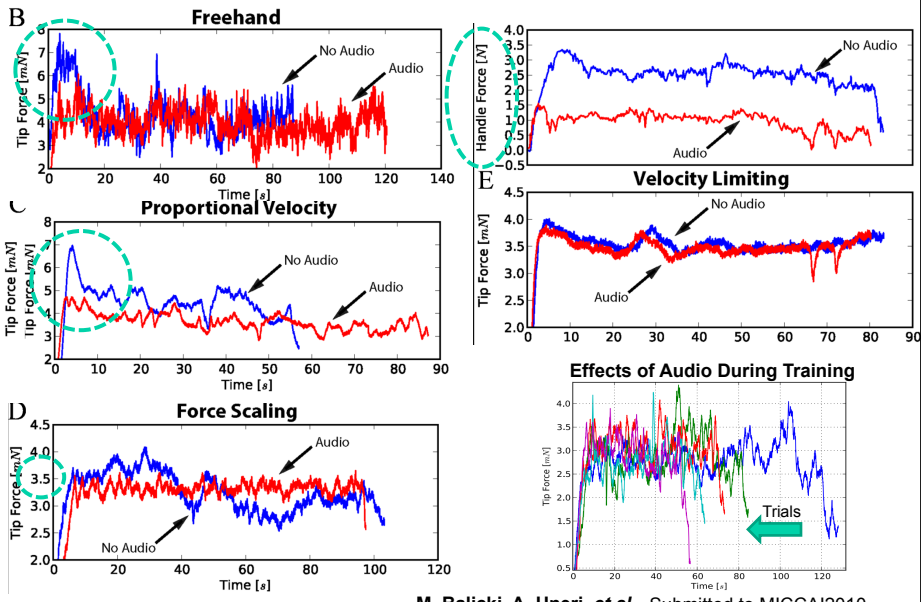






How: Use end-point micro-force sensing with cooperatively controlled robot

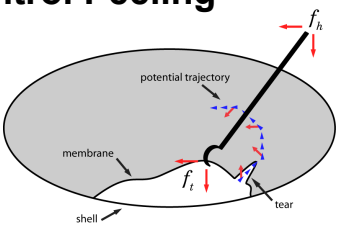
Results



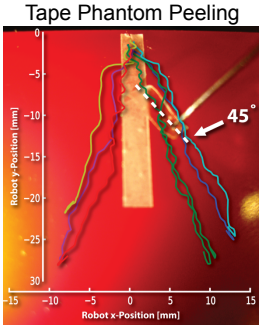
M. Balicki, A. Uneri, *et al.* Submitted to MICCAI2010

Enhanced Cooperative Control Peeling Algorithm

The algorithm biases operator-robot interaction towards the direction of least tissue resistance while limiting forces.

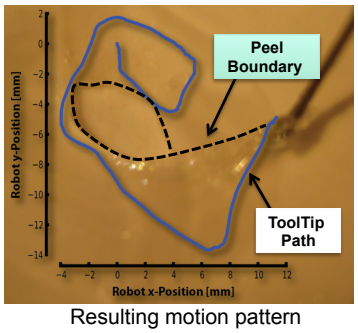


Tape Phantom Peeling



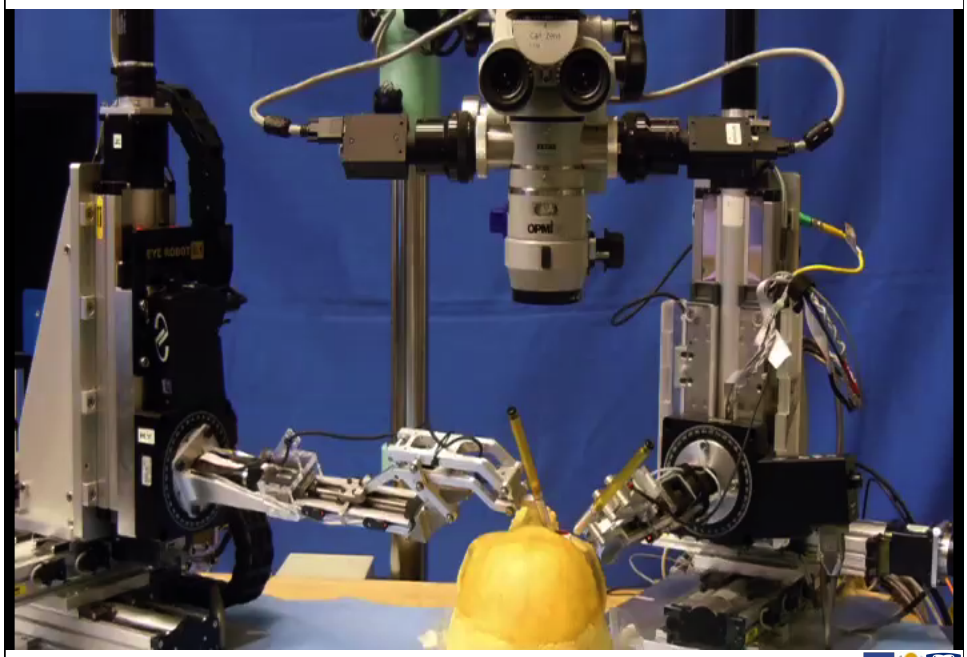
Peeling angles converge to 45 °

Inner Egg Shell Membrane Peeling

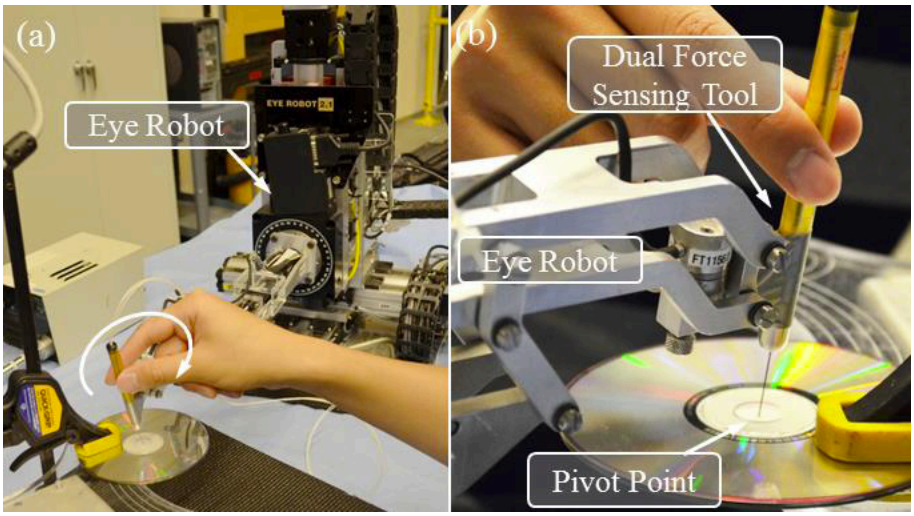


Resulting motion pattern resembles commonly used capsulorhexis technique

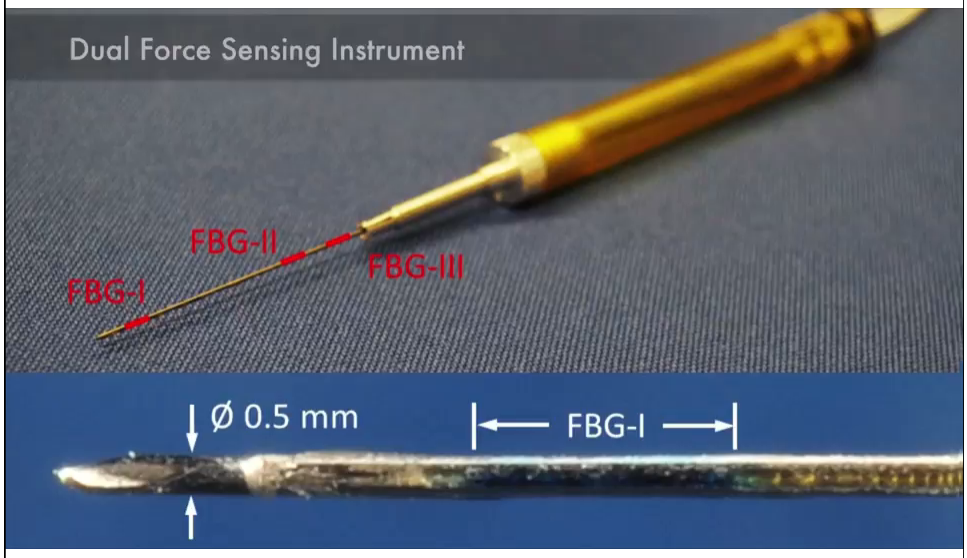
A. Uneri, M. Balicki *et al.*
Submitted to BioRob2010



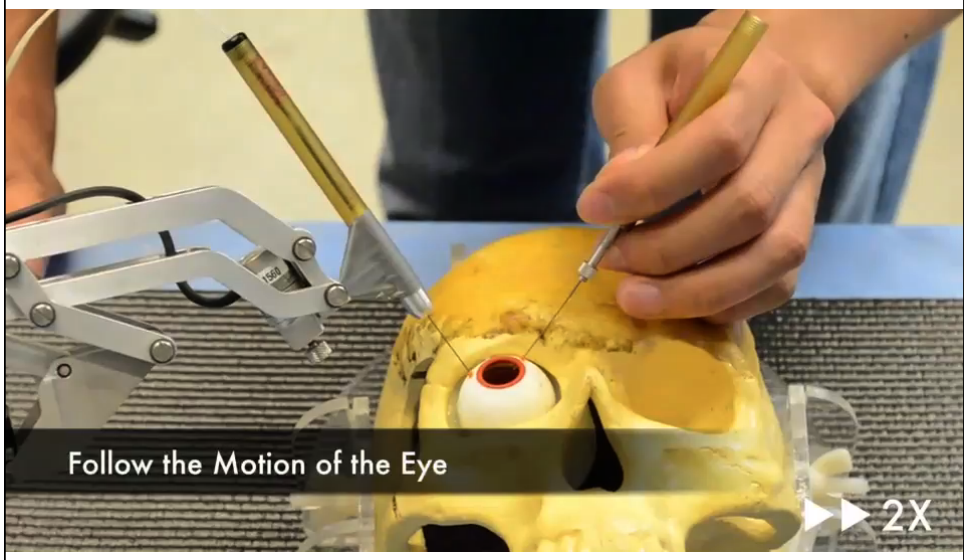
Dual Force Sensor



Dual Force Sensor



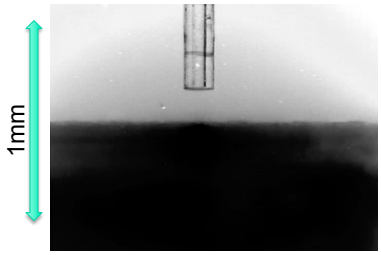
Dual Force Sensor

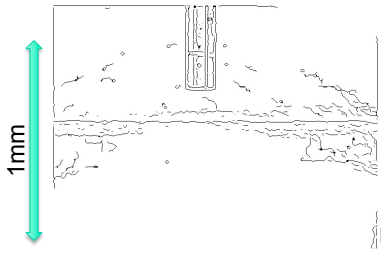


X. He, Marcin Balicki, P. Gehlbach, J. Handa, R. Taylor, and I. Iordachita
"Variable Admittance Robot Control with A New Dual Force Sensing Instrument for Retinal Microsurgery", *ICRA* 2014.

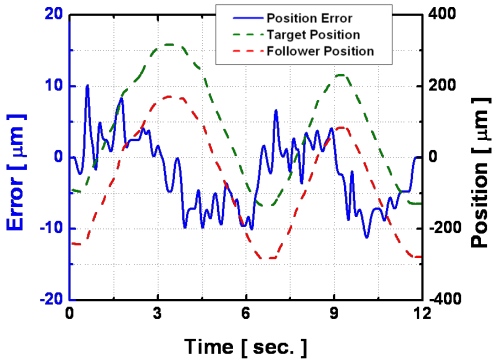
Autonomous Surface Following

M. Balicki, J.-H. Han, I. Iordachita, P. Gehlbach, J. Handa, R. H. Taylor, and J. Kang, *MICCAI 2001*



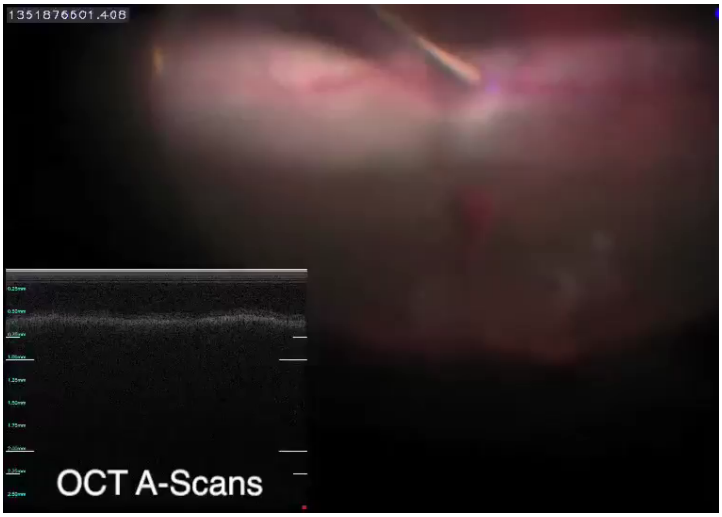


Noise Rem. /Thresholded/Canny



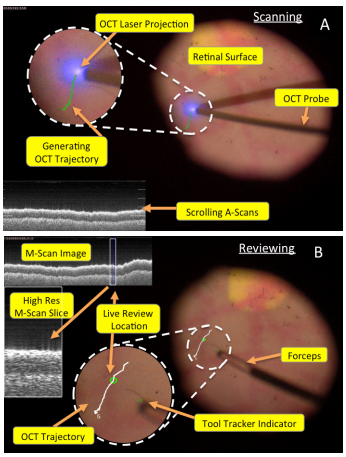
* 500 µm/s Velocity Limit

OCT of Rabbit Retina with Micron-held Probe



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

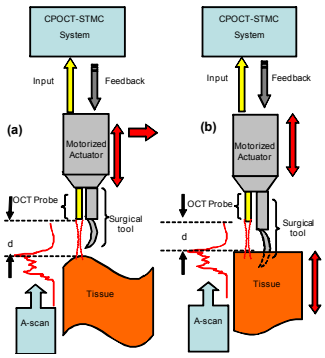
M-Scan



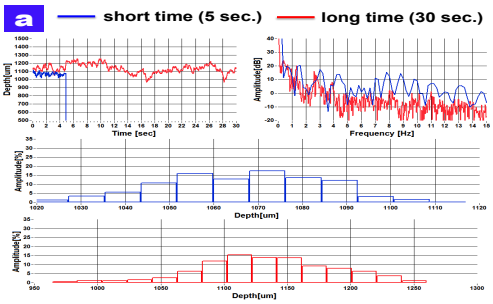
M. Balicki, R. Richa, B. Vagvolgyi, J. Handa, P. Gehlbach, J. Kang, P. Kazanzides, and R. Taylor, "Interactive OCT Annotation and Visualization System for Vitreoretinal Surgery", Medical Image Computing and Computer-Assisted Interventions (MICCAI), Nice, October, 2012

OCT-Guided Motion Control and Compensation with a One Degree-of-Freedom Hand-Held Robot

J. Kang, P. Gehlbach, C. Song, *et al.*



Hand Tremor

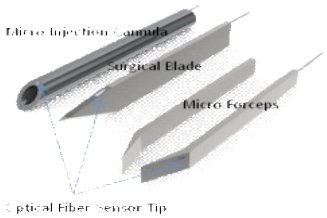


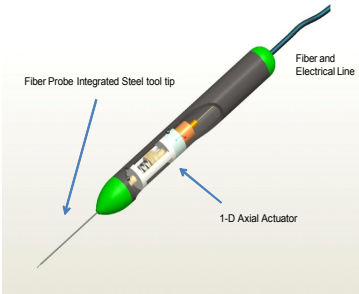
Two basic functions
of the CPOCT-STMC system:
(a) Topological and motion compensation (Safety Barrier),
(b) Targeting and surgical intervention

NIH R01 EY021540

Smart Tool Evolution

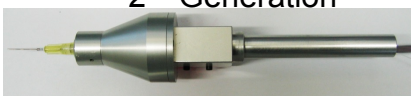
J. Kang, P. Gehlbach, C. Song, *et al.*



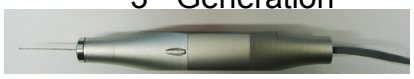


1st Generation

2nd Generation

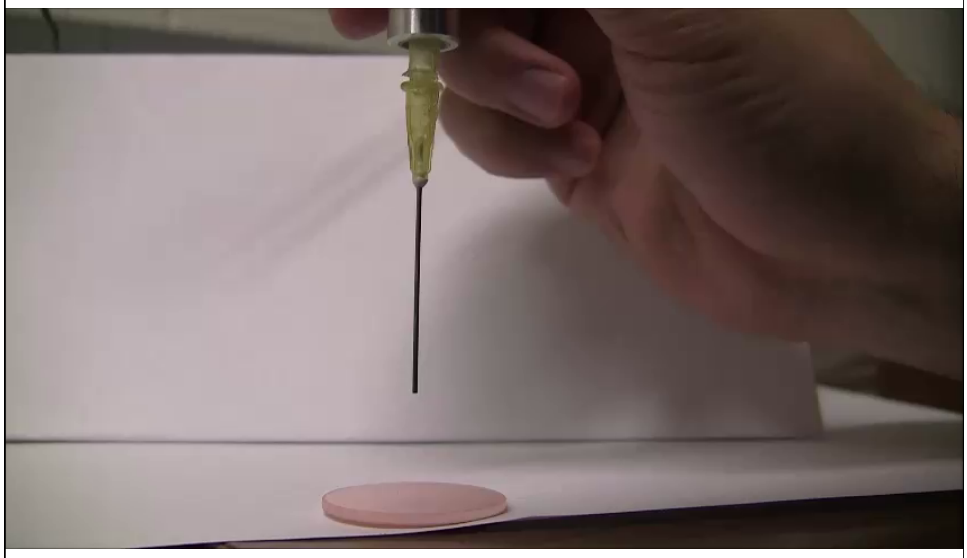


3rd Generation



Safety Barrier

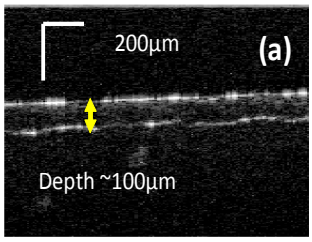
J. Kang, P. Gehlbach, C. Song, *et al.*

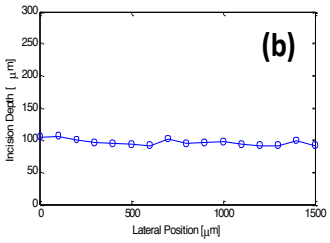


Sensor Guided Incision

J. Kang, P. Gehlbach, C. Song, *et al.*

On





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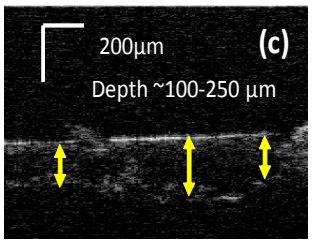
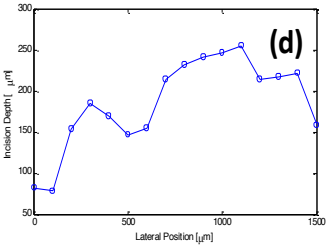
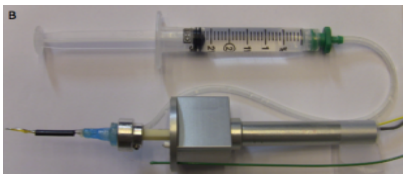
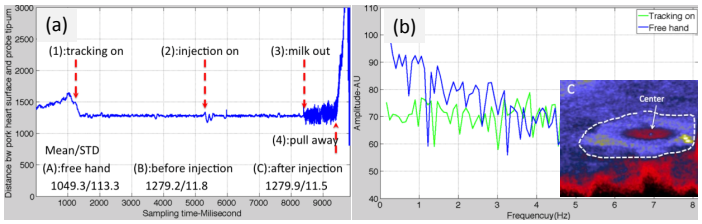




SMART Micro-Injector

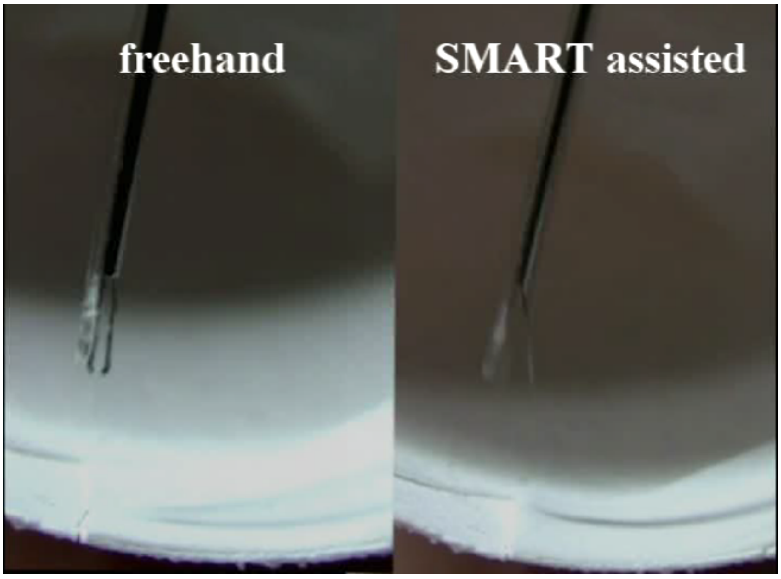
J. Kang, P. Gehlbach, C. Song, *et al.*





Smart Micro-Forceps

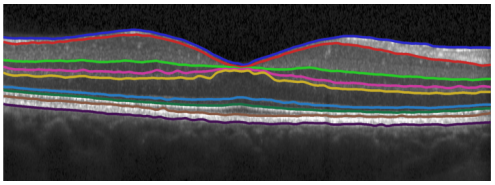
J. Kang, P. Gehlbach, C. Song, *et al.*



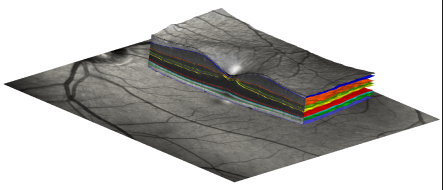
Other JHU Work: Automatic layer segmentation of macular OCT data

A. Lang, A. Carass, …, J. Prince (NIH R21EY022150)

Segmentation of 9 layers

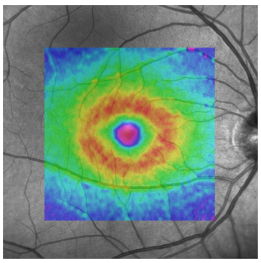


Fully 3D

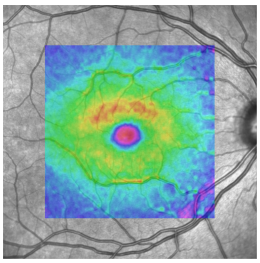


GCL+IPL thickness analysis for multiple sclerosis

Healthy control

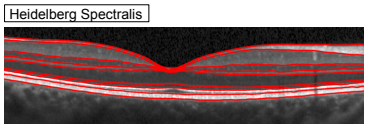


MS Subject

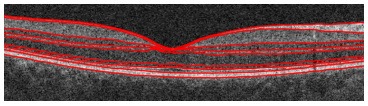


Consistent segmentation between scanners

Heidelberg Spectralis



Zeiss Cirrus



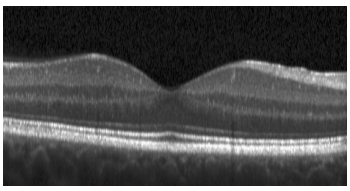
Difference in macular thickness < **4.5** across scanners

A. Lang, A. Carass, M. Hauser, E.S. Sotirchos, P.A. Calabresi, H.S.Ying, and J.L. Prince, ``Retinal layer segmentation of macular OCT images using boundary classification", Biomedical Optics Express,4(7):1133-1152, 2013

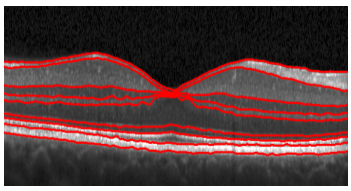
Other JHU Work: Automatic layer segmentation of macular OCT data

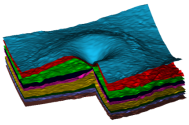
A. Lang, A. Carass, …, J. Prince (NIH R21EY022150)

Input volume



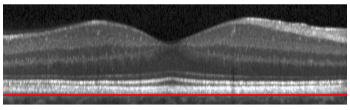
Output segmentation

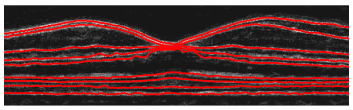


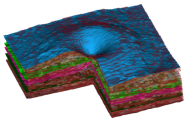


Flatten to RPE ⇩

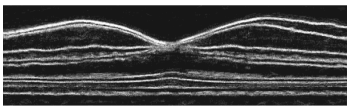
⇧ Unflatten







Apply random forest classifier ⇘ Boundary probabilities ⇗ Optimal surface fitting (Garvin et al. TMI 2009)



A. Lang, A. Carass, M. Hauser, E.S. Sotirchos, P.A. Calabresi, H.S.Ying, and J.L. Prince, ``Retinal layer segmentation of macular OCT images using boundary classification", Biomedical Optics Express,4(7):1133-1152, 2013

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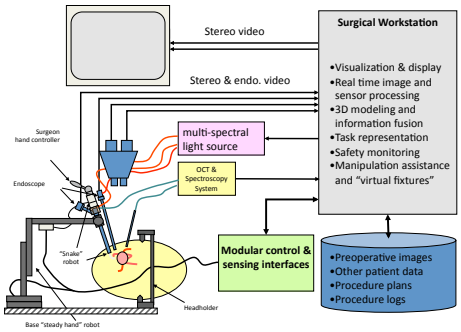
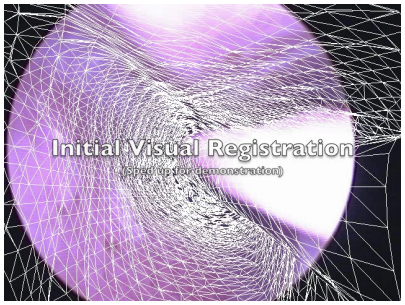
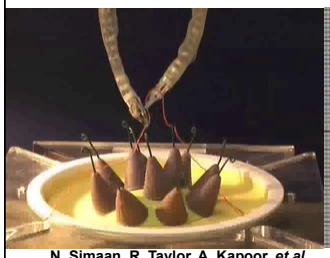
Other possible targets: ENT & Neurosurgery





D. Mirota, H. Wang, R. Taylor, M. Ishii, G. Hager



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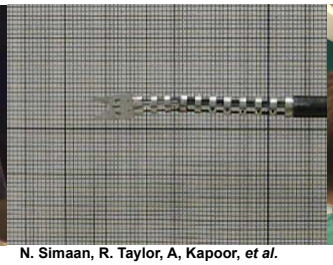
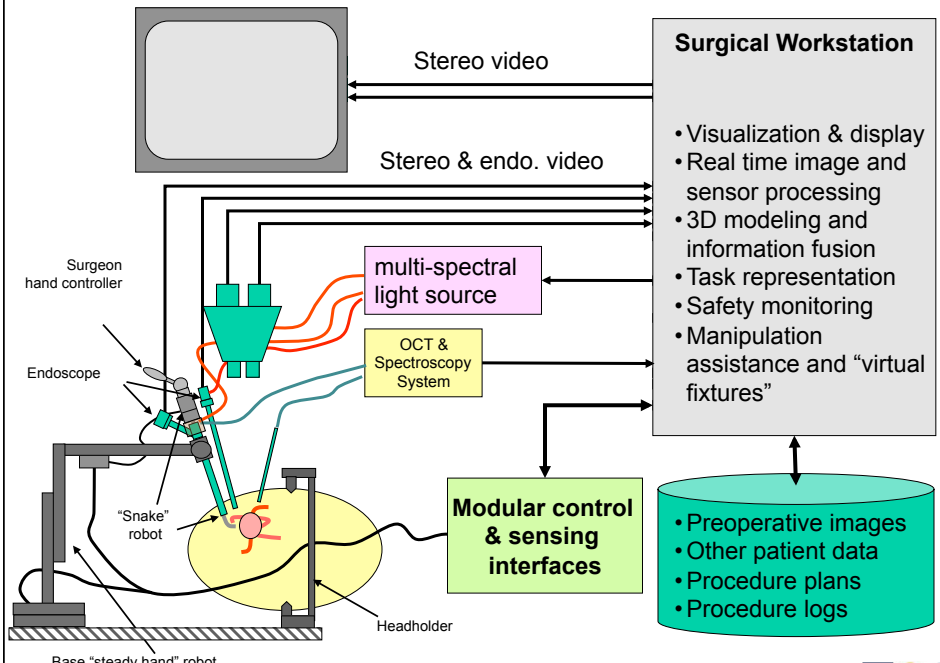
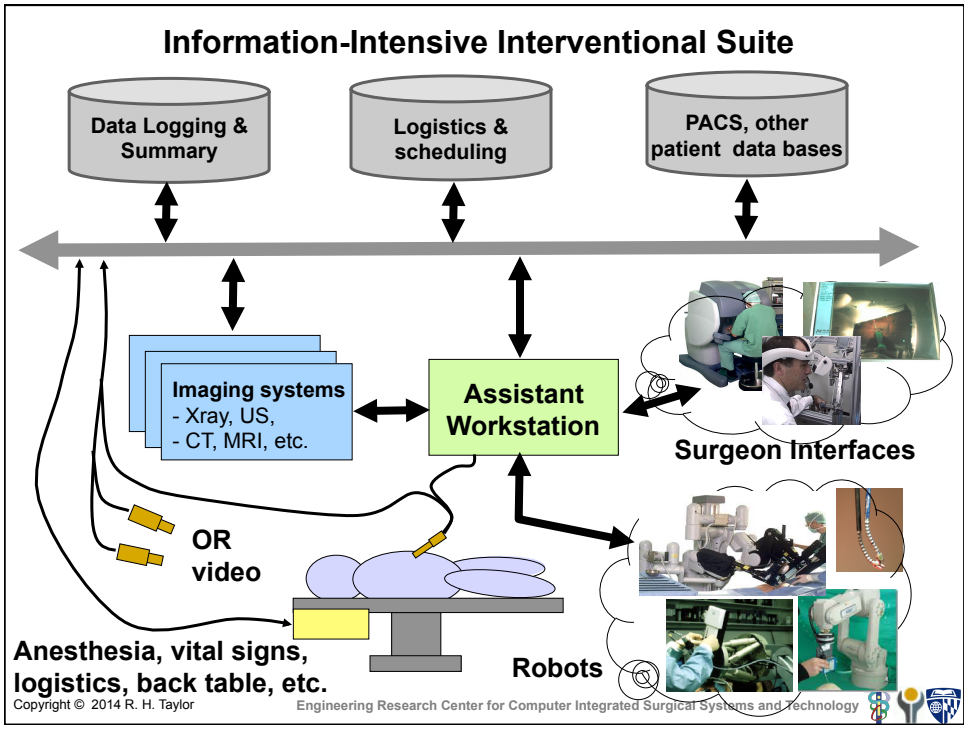


N. Simaan, R. Taylor, A, Kapoor, *et al.*

P. Kazanzides, C. Baird, *et al.*




Information-Intensive Interventional Suite
Data Logging & Summary
Logistics & scheduling
PACS, other patient data bases
Imaging systems
- Xray, US,
- CT, MRI, etc.
Assistant Workstation
Surgeon Interfaces
OR video
Anesthesia, vital signs, logistics, back table, etc.
Robots
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