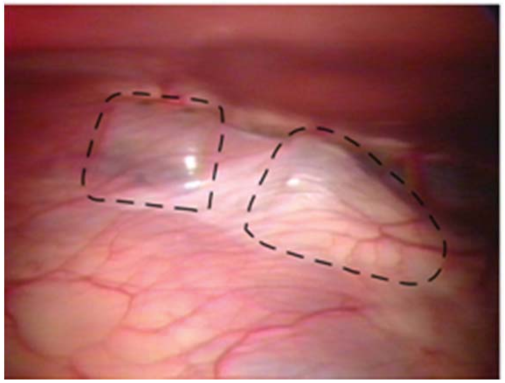
Compensation of Physiological Motion for Enhanced Surgical Accuracy



Cameron Riviere, Ph.D.
Director, Surgical Mechatronics Laboratory
The Robotics Institute
Carnegie Mellon University

Carnegie Mellon
THE ROBOTICS INSTITUTE

Assistive interfaces for surgery

Goal:

- Improve surgical performance
  - accuracy
  - access
- as unobtrusively as possible
  - ease of use
  - minimal disruption of existing clinical practice

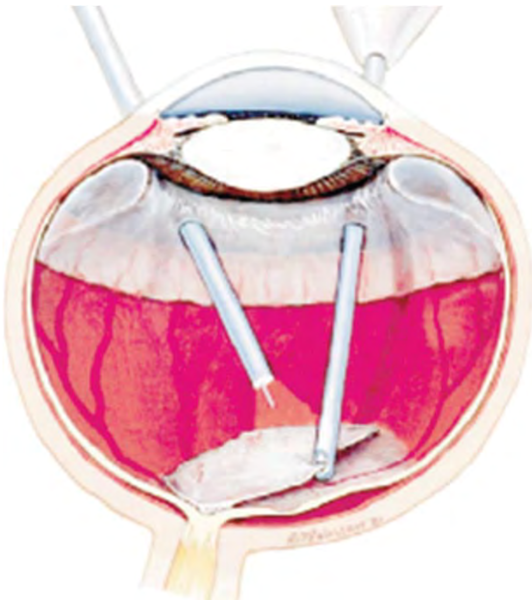
Compensating biological motion for accuracy enhancement

- Surgeon
  - Physiological hand tremor
- Patient
  - Heartbeat
  - Respiration

Physiological Hand Tremor

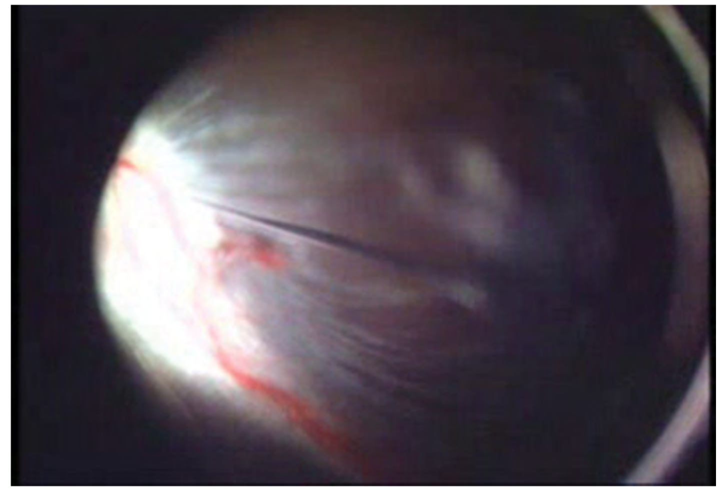
Vitreoretinal Microsurgery: difficult

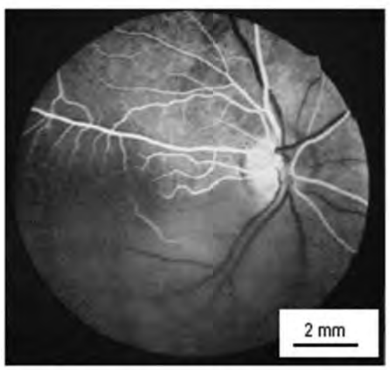
- Removal of membranes ≤ 20 μm thick from retina



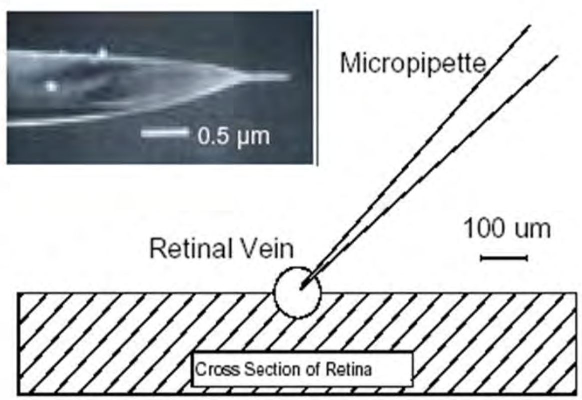
Vitreoretinal microsurgery: beyond difficult

- Injection of anticoagulant using intraocular cannulation to treat retinal vein occlusion (∅ < 100 µm)
- Presently no effective treatment





Retina with occluded retinal vein



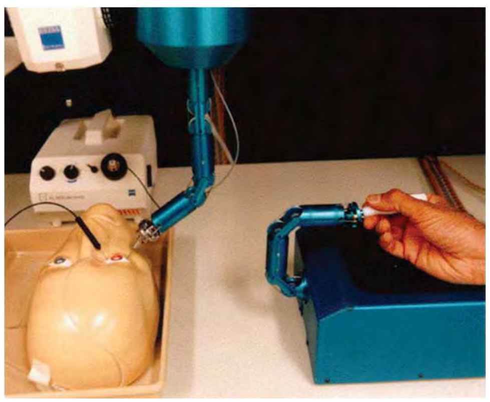
Tremor Suppression

- Teleoperation
- Shared control
- Active compensation

Tremor Suppression

- Teleoperation
- Shared control
- Active compensation

RAMS (JPL)



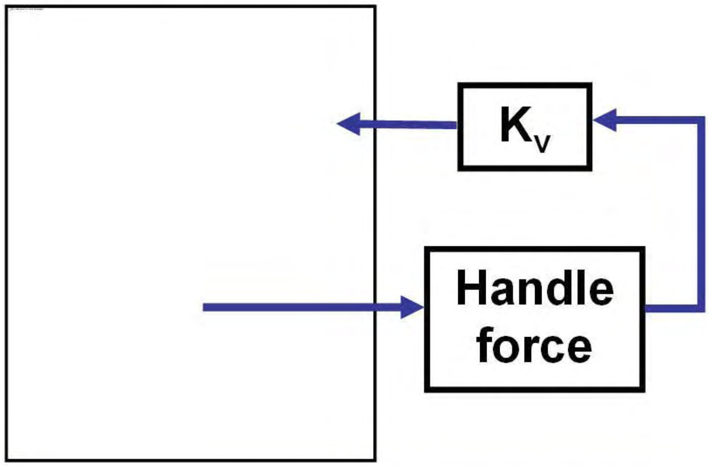
Tremor Suppression

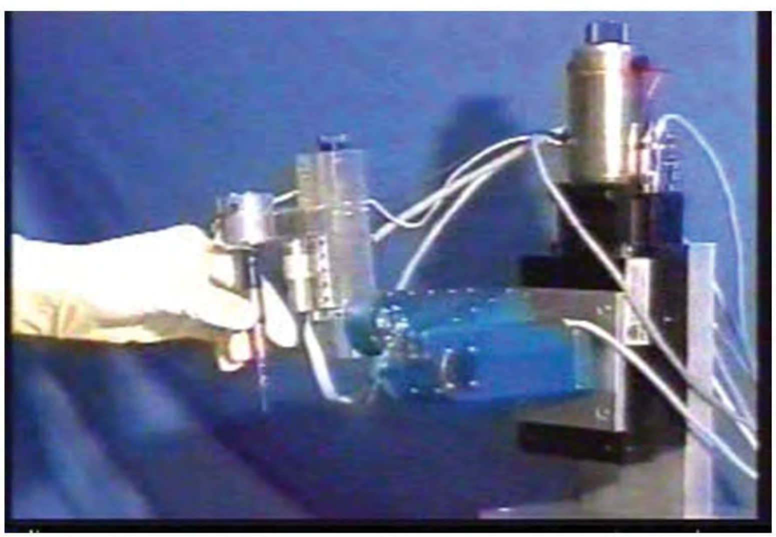
- Teleoperation
- Shared control
- Active compensation

Steady-hand robot

Iordachita, Kapoor, Kazanzides, Taylor (Johns Hopkins)

Shared control



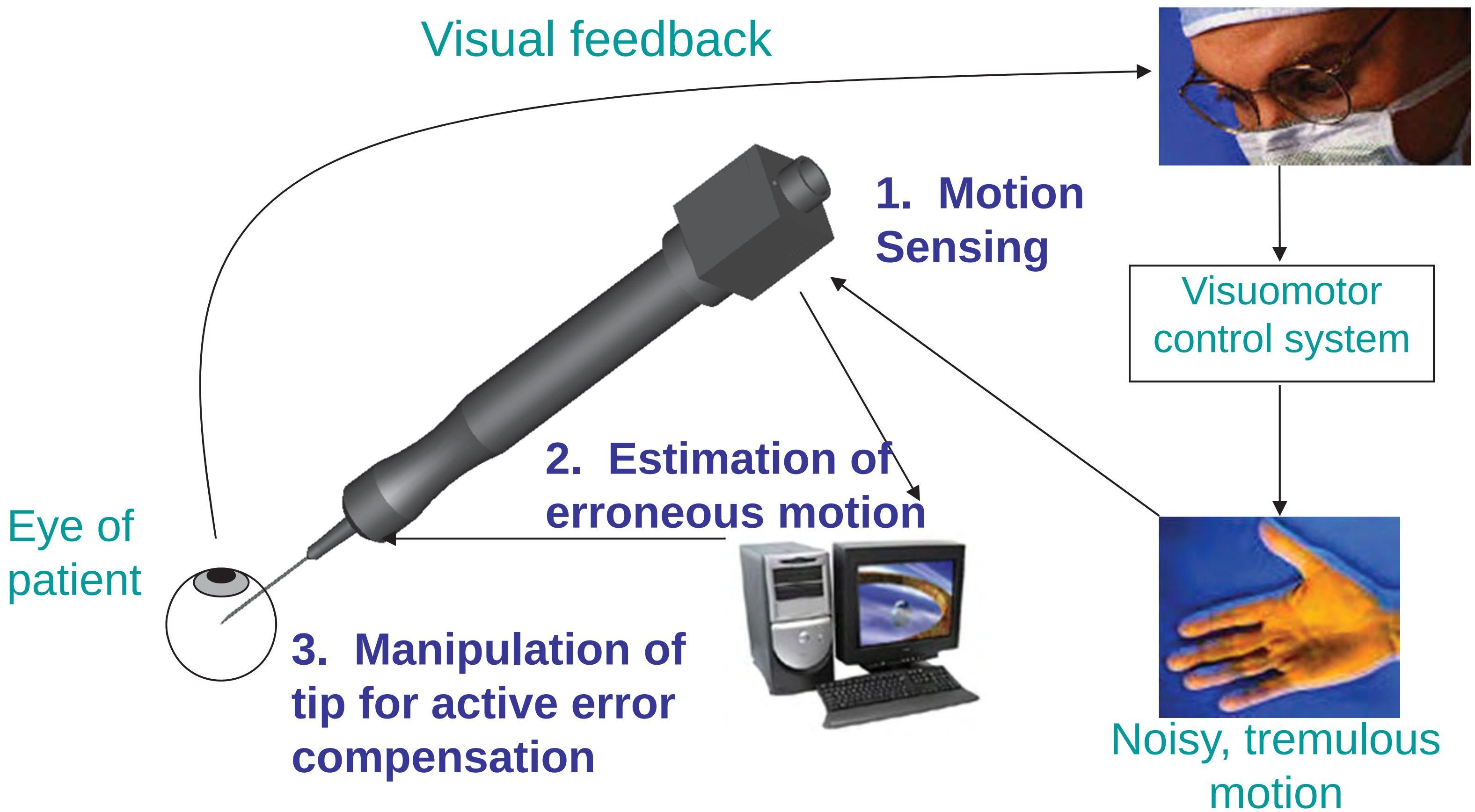


Tremor Suppression

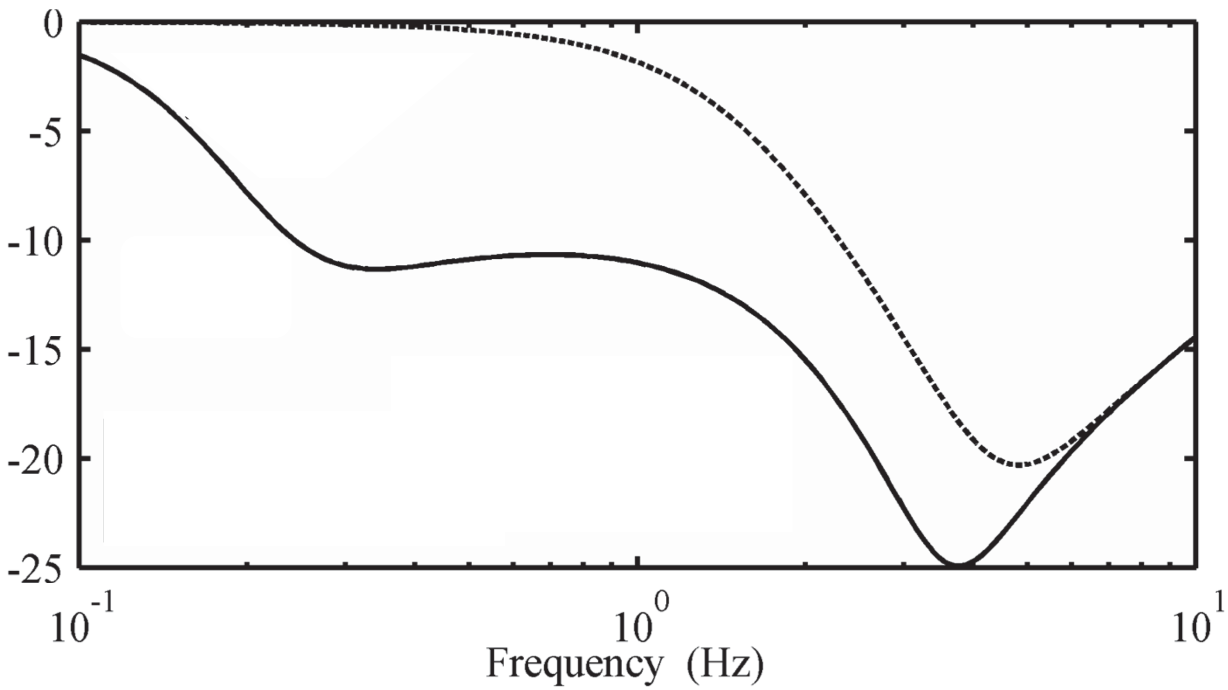
- Teleoperation
- Shared control
- Active compensation

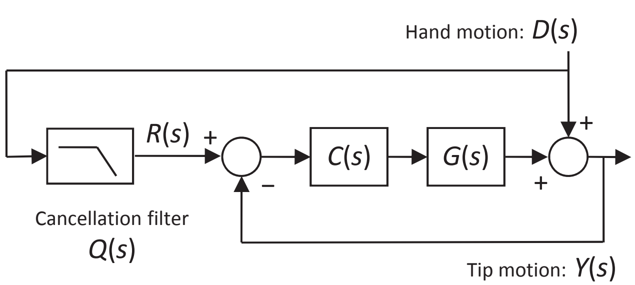
Micron

Active handheld micromanipulator



Cancellation filter



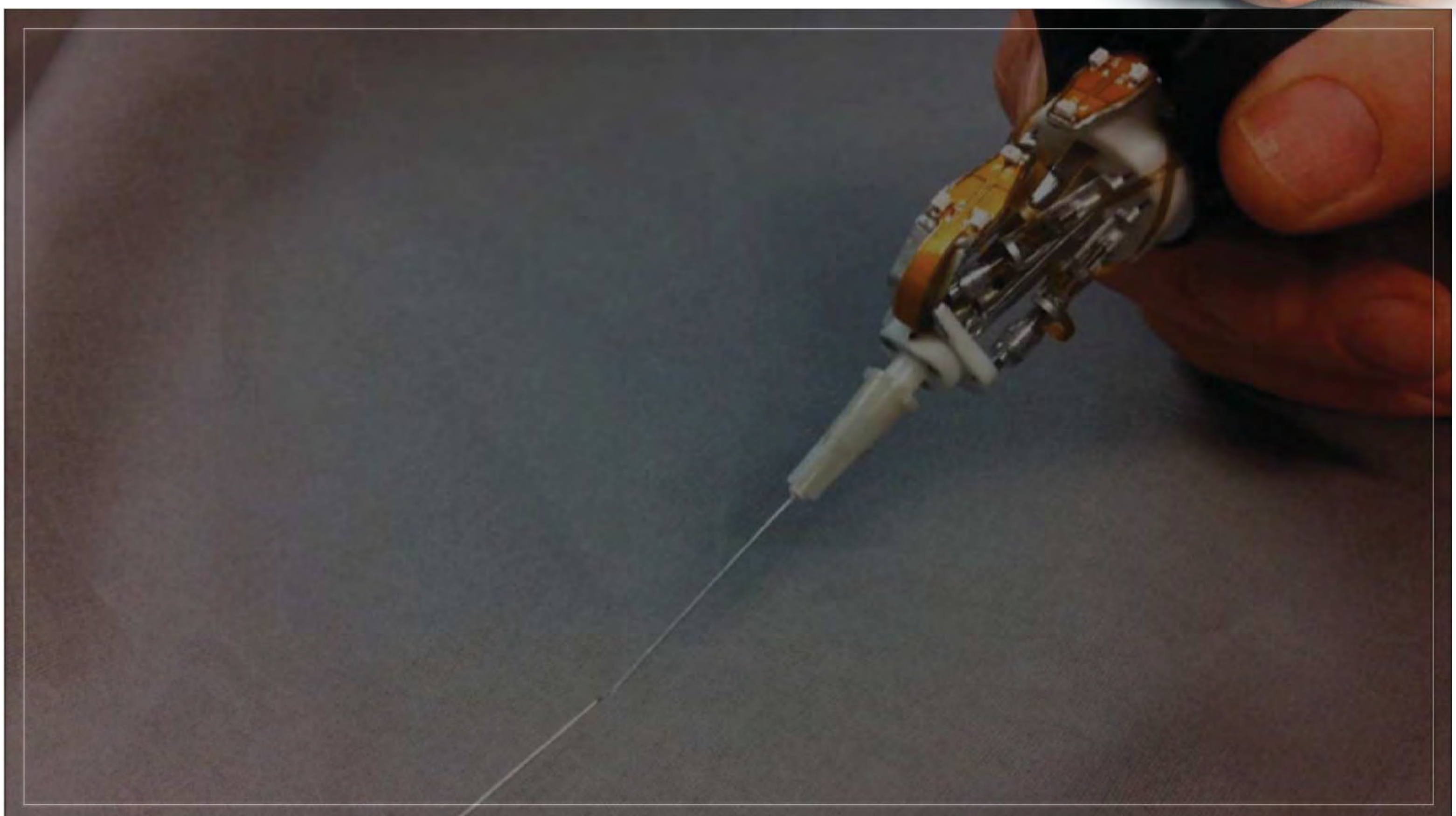


2 prototypes

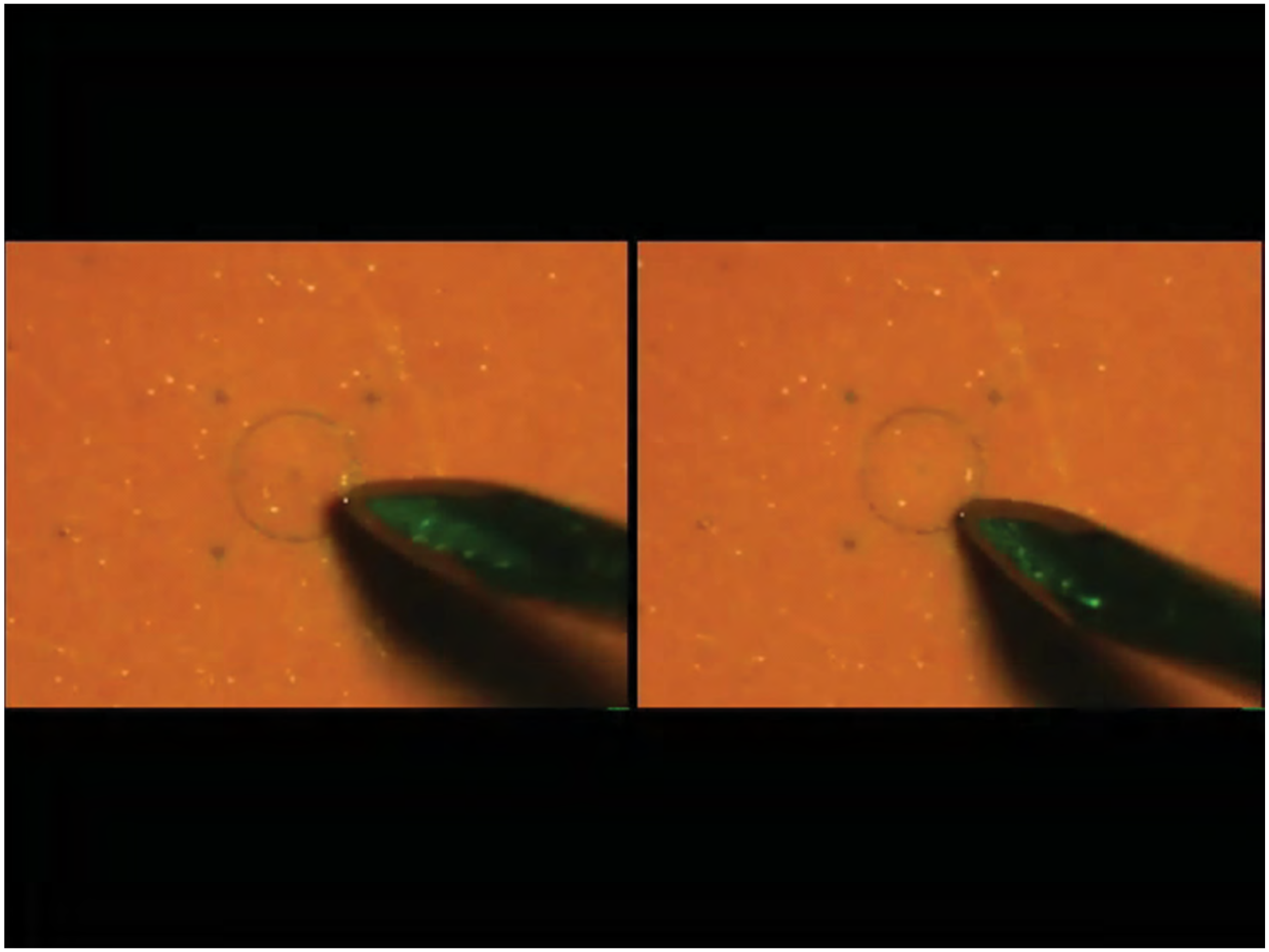
- 6DOF optical tracking
- 3DOF actuation
- Piezoelectric benders
- ROM = 0.4 mm

- 6DOF optical tracking
- 6DOF actuation
- Ultrasonic linear motors
- ROM = 4 mm

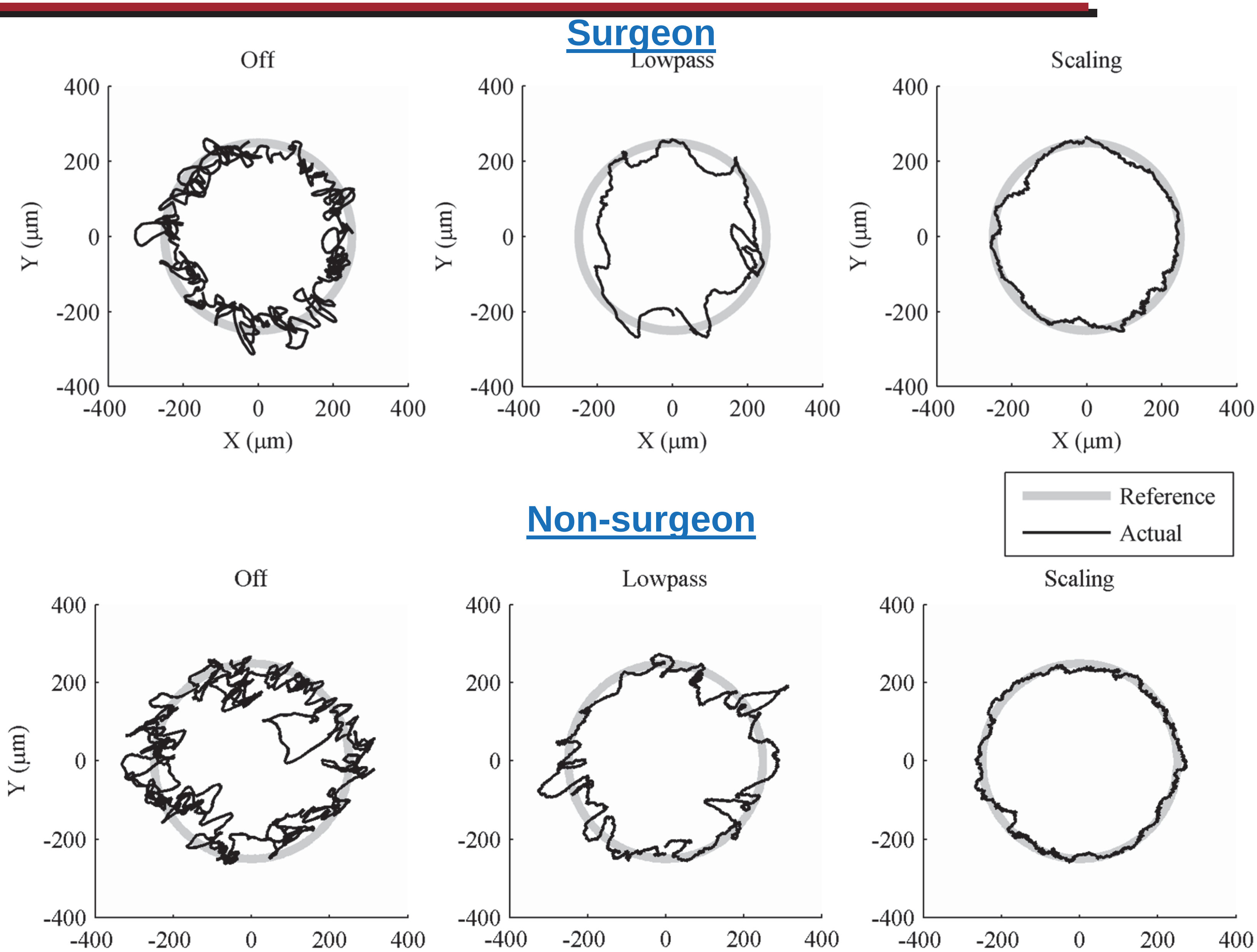
Handheld Performance



Circle-Tracing Performance



Tracing results

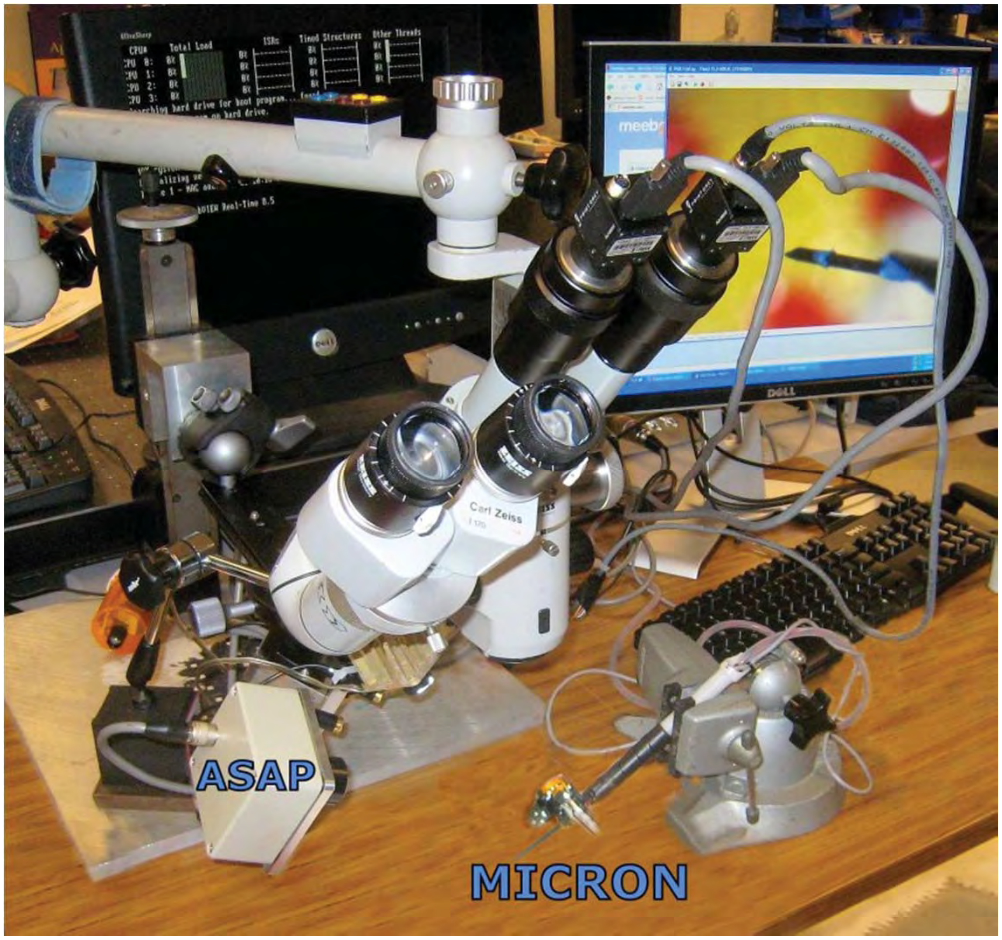


Comparison of approaches

COMPARISON OF MICROSURGERY MANIPULATION AIDS

	Unaided	Master/slave	Cooperative	Micron
Motion scaling:	No	Yes	No	Yes
Workspace intrusion:	No	Slave arm & master	Arm	Active tool, sensor sightlines
Force feedback:	1:1	Research area	Yes (superimposed on damping)	1:1
Set and forget hold:	No	Yes	Yes	No
Features:	Current practice	Could combine all of the above features, telemedicine	Inexpensive position-output actuators and simple control	Hand-held operation improves user acceptance and safety, mechanical simplicity
Challenges/costs:	Tremor limits accuracy & repeatability	Unproven force feedback performance / greatest mechanical and control complexity (high cost)	Dexterity fundamentally limited by force → rate user interface and low control bandwidth	Manipulator size and range, high bandwidth control / measurement subsystem cost

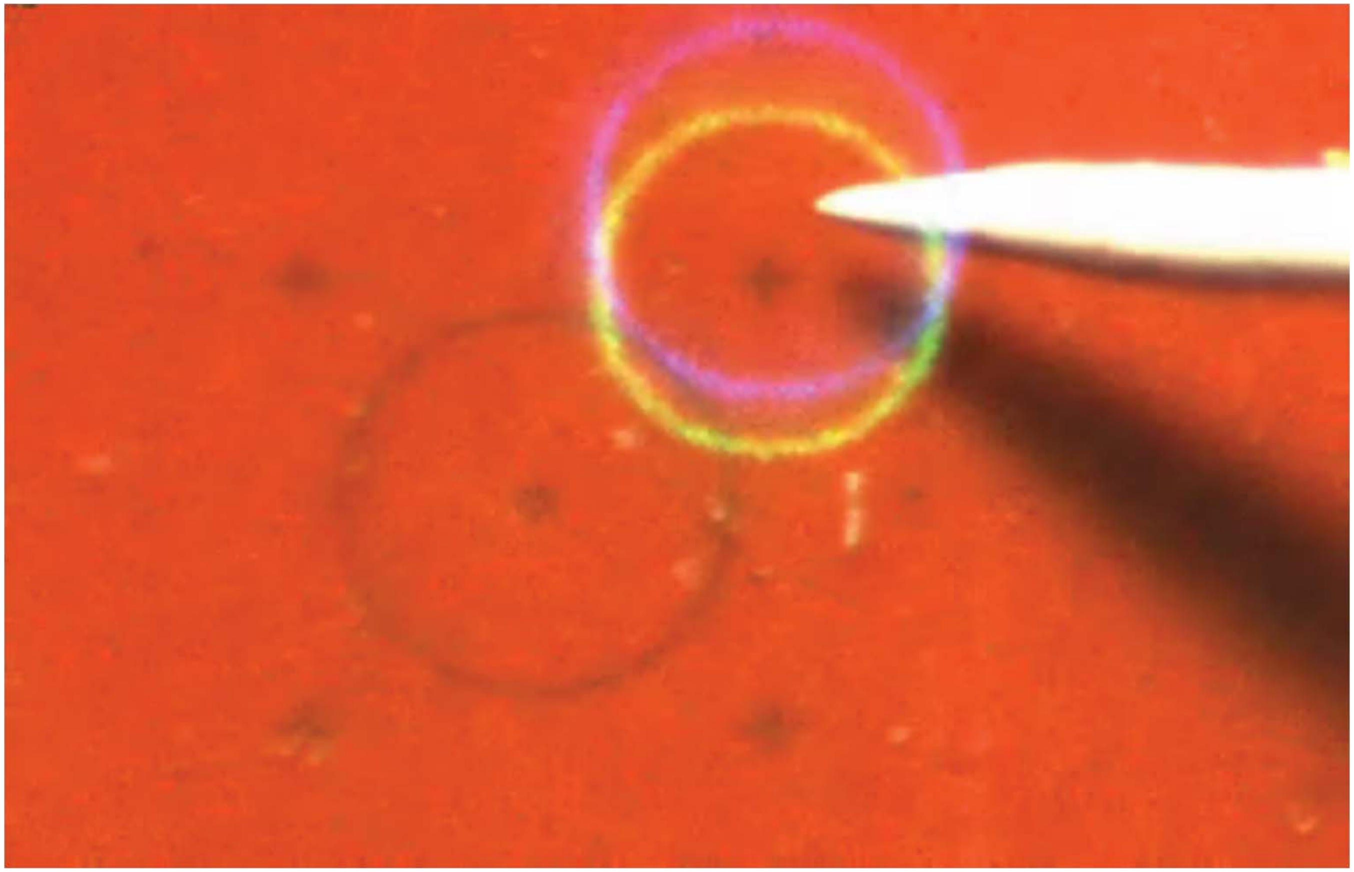
Stereo Visual Tracking



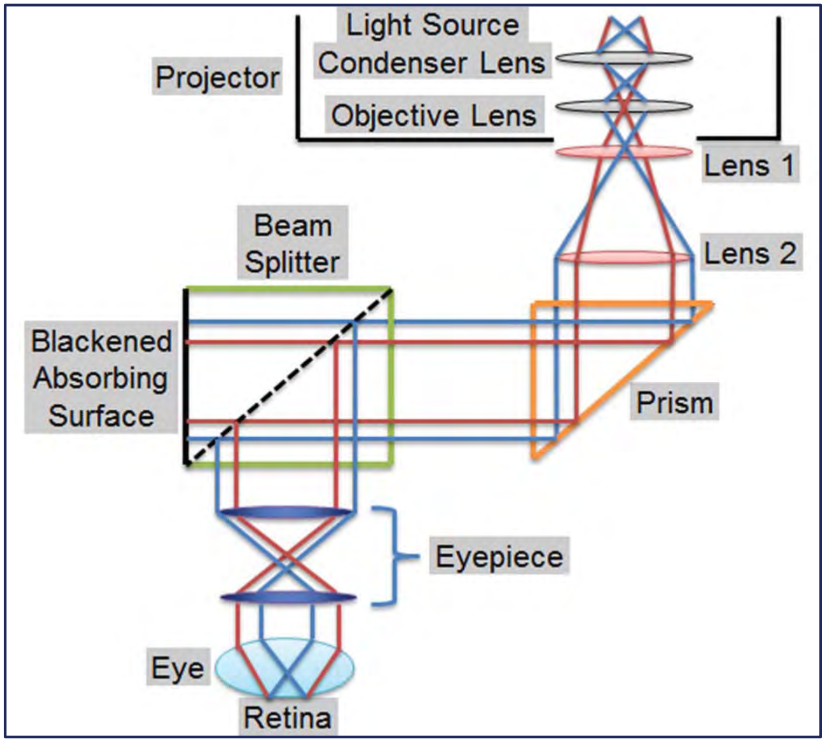
Control Modes

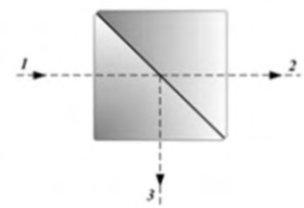
- Active compensation of tremor
- Motion scaling
- Semiautomated scanning
- Visual servoing
- Avoidance zones
- Position-based virtual fixtures

Image Guidance

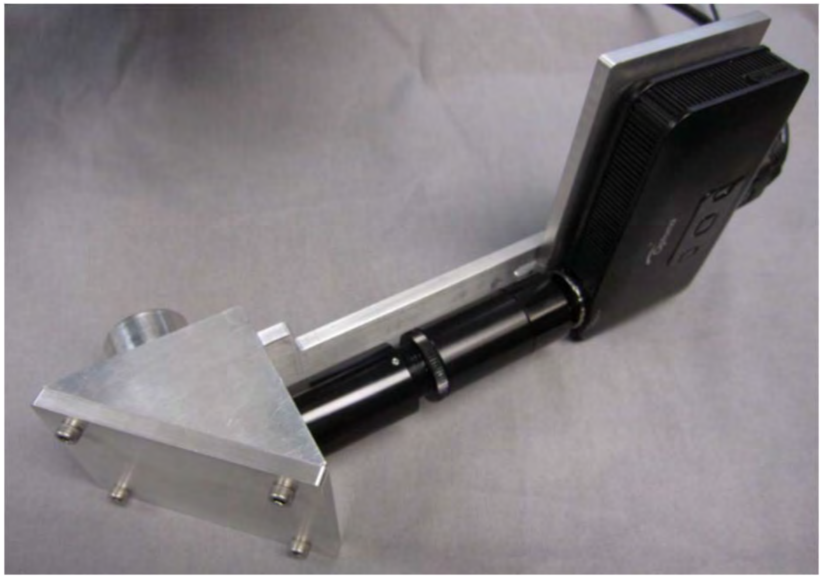


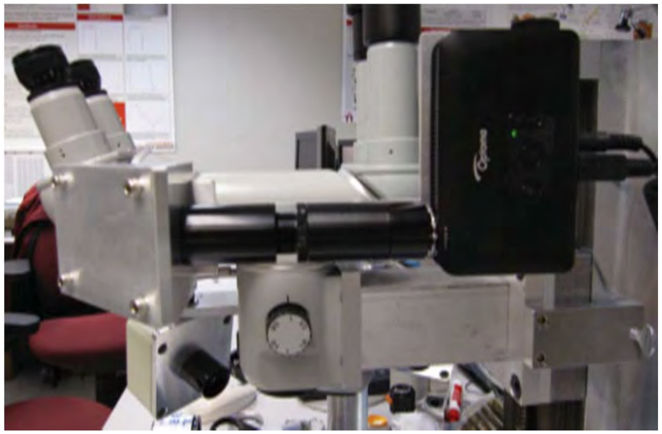
Augmented-Reality Display: Design

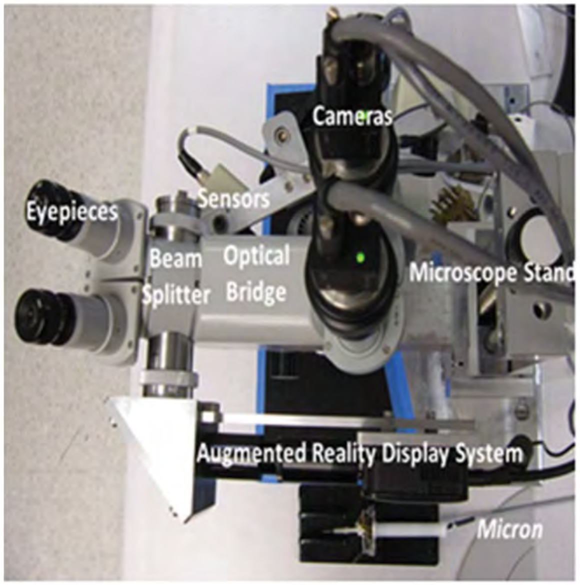




Assembled System



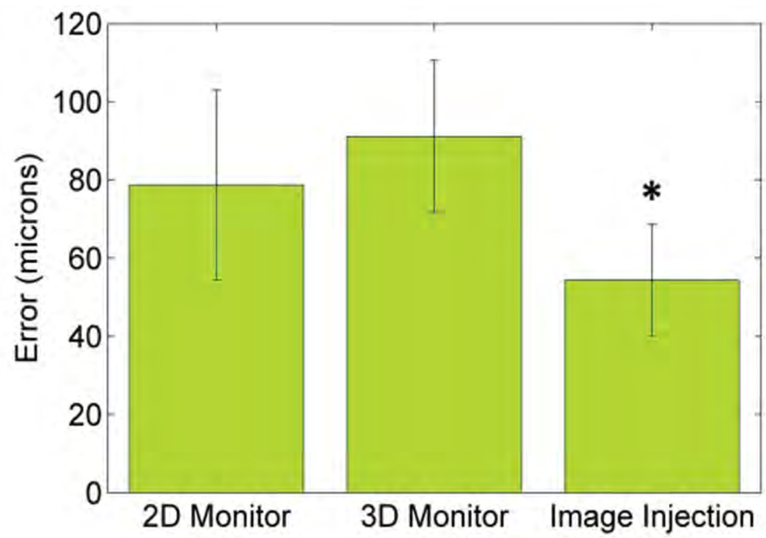




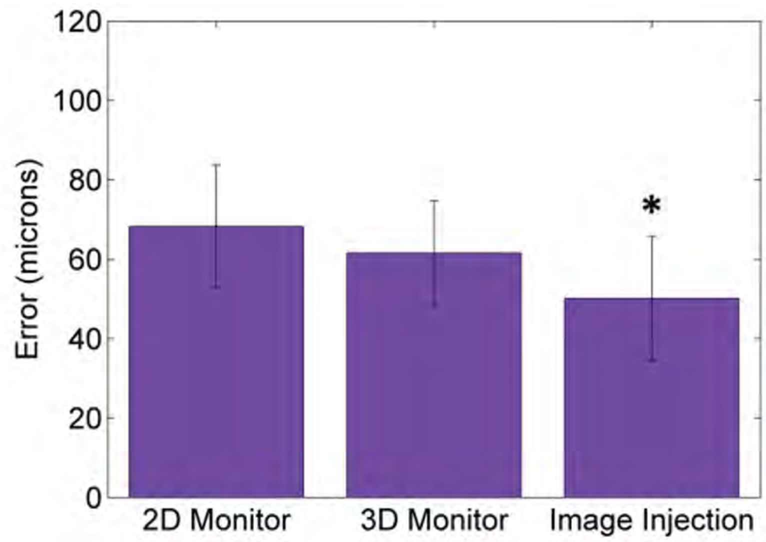
Comparison with 2D and 3D Monitors

Circle tracing

Surgeon

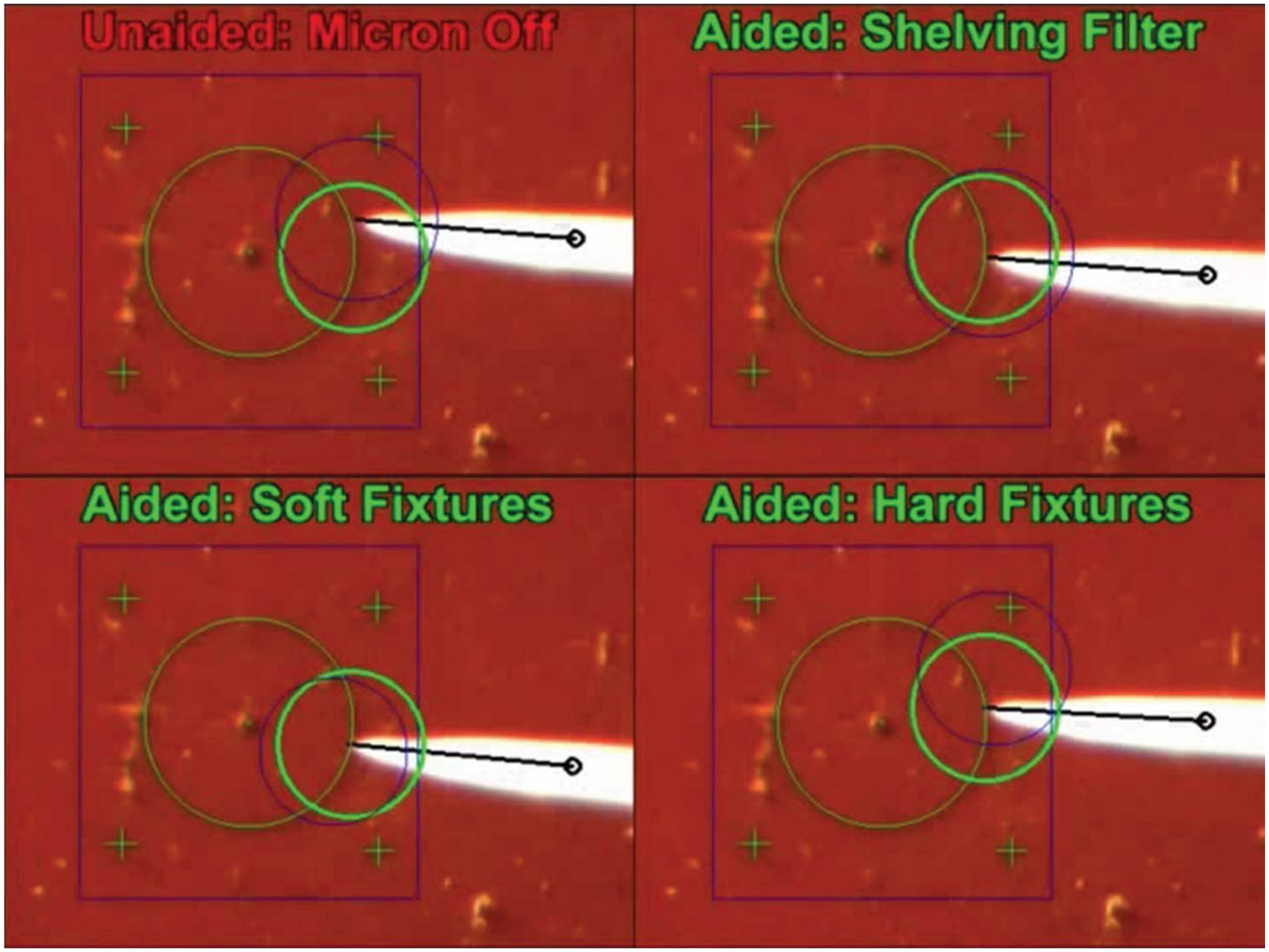


Novices



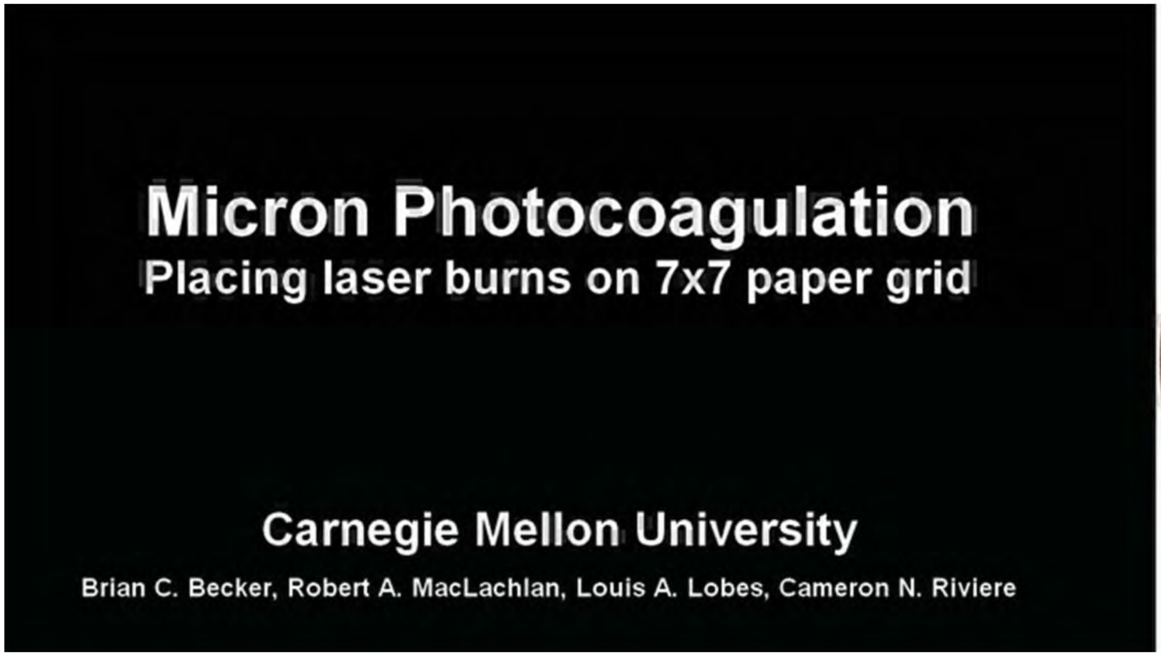
Circle Tracing

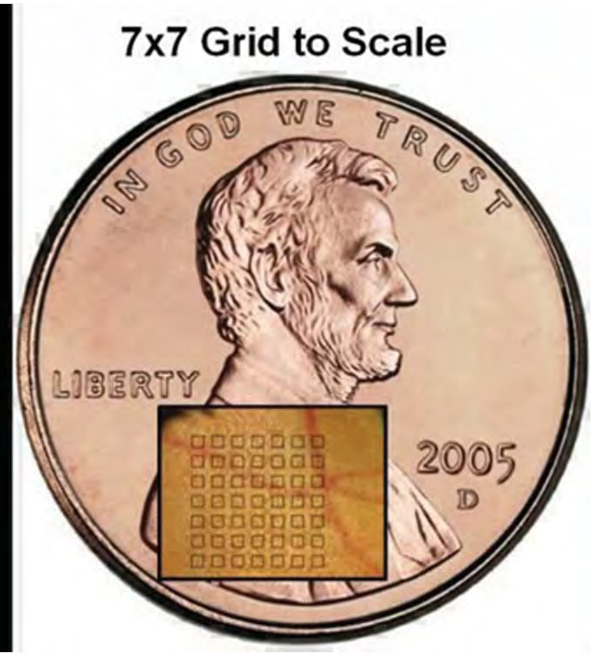
4 different control modes



Semiautomated scanning

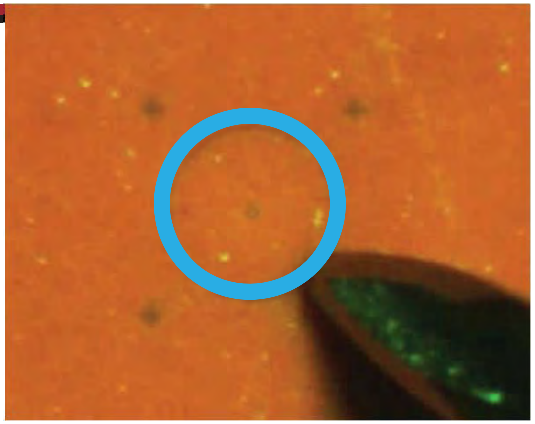
for patterned laser photocoagulation



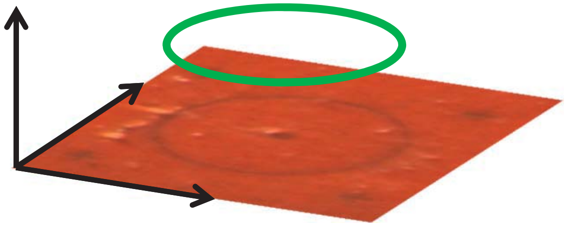


Research Hypotheses

1. *Tip constraints increase accuracy and safety*

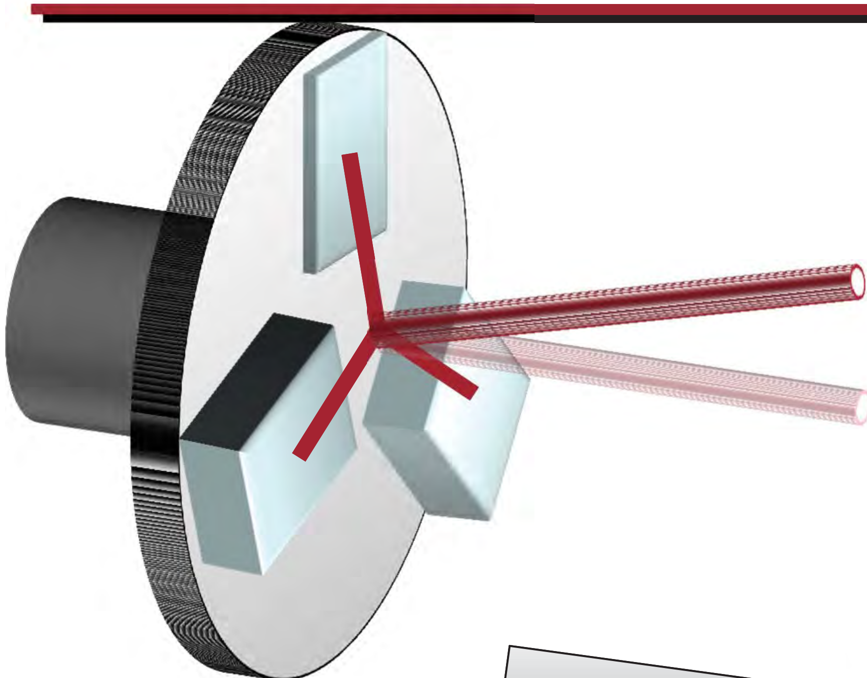


2. *Visual feedback provides context for tip constraints*



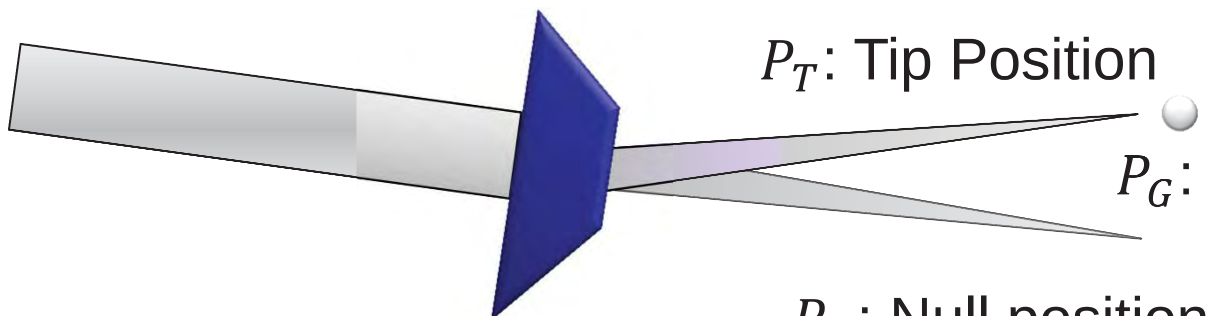
3. *Task-specific tip constraints aid surgical procedures*

Position-Based Virtual Fixtures



Tip Position

Null position



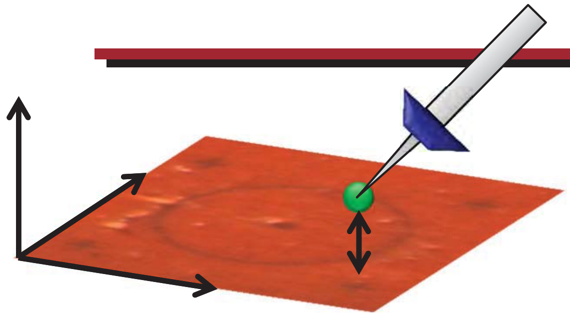
P_T: Tip Position

P_G: Goal

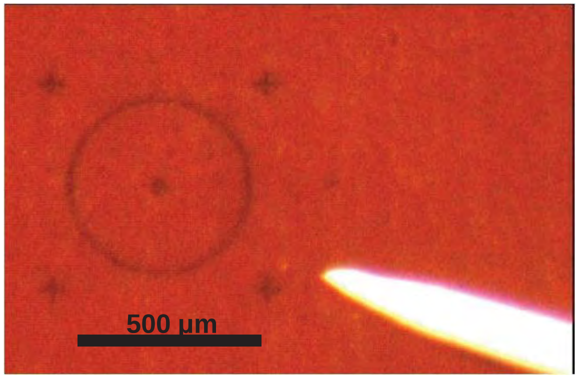
P_N: Null position

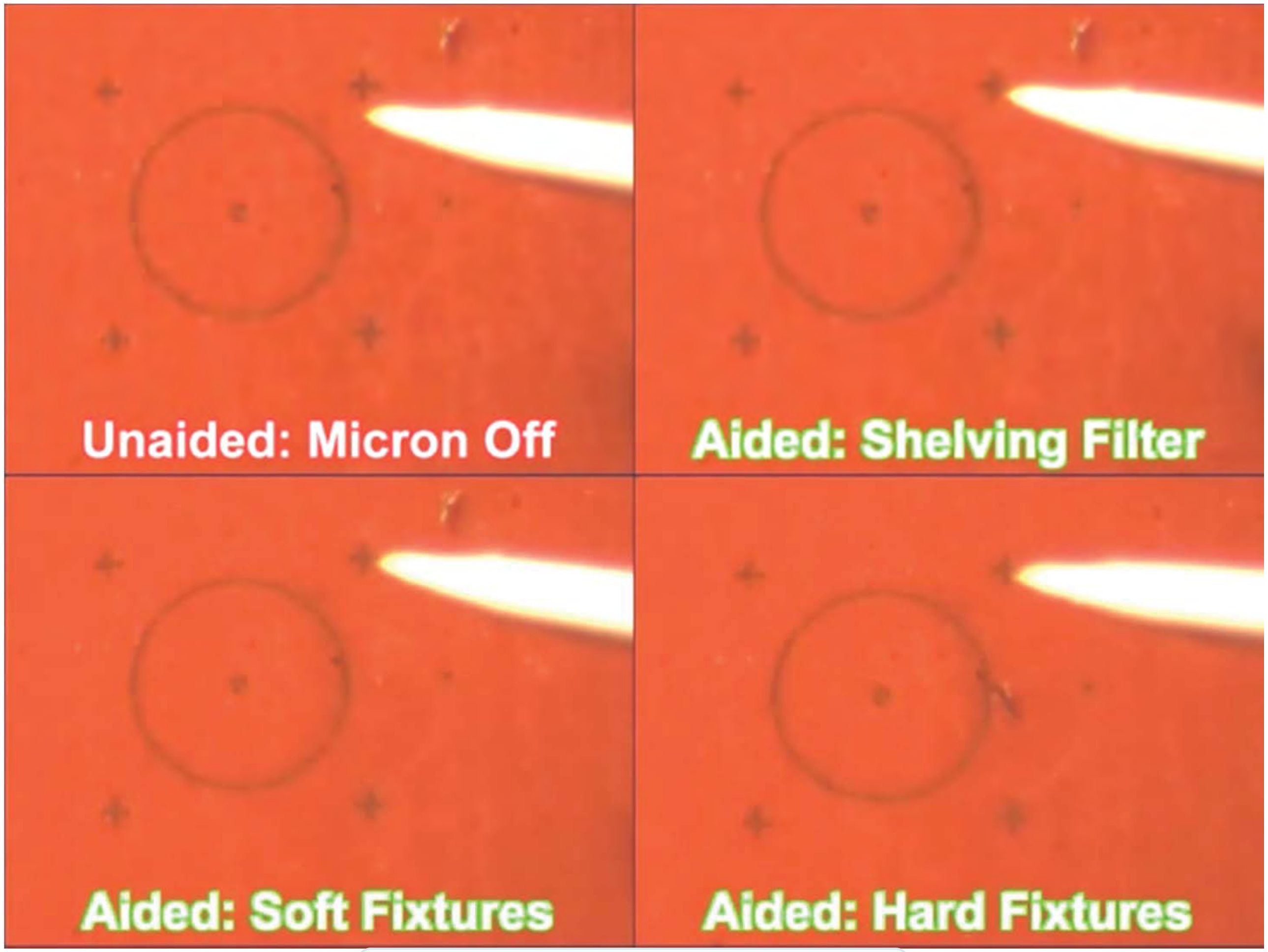
Key assumption: surgeon attempts to place null position on target

Point Virtual Fixture



Hold Still





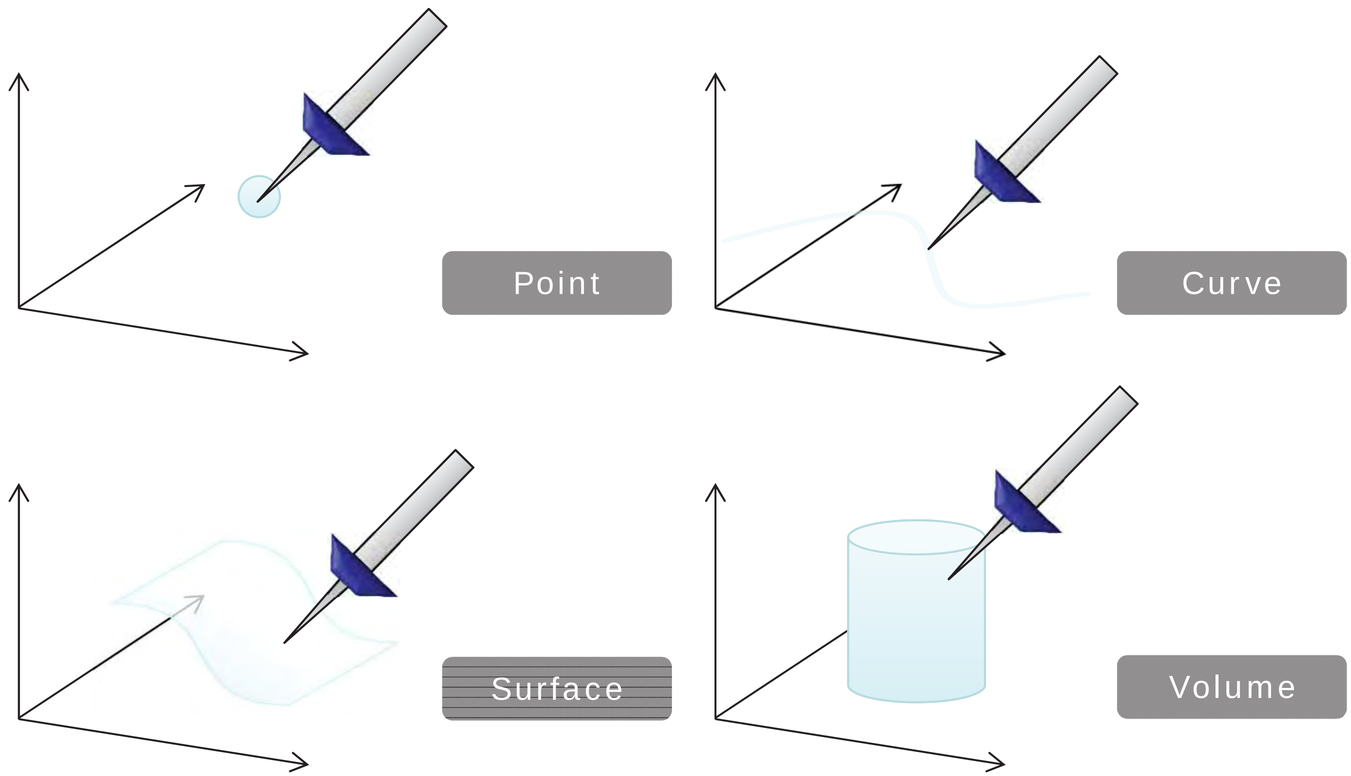
500 µm

Surgeon Results

Carnegie Mellon
THE ROBOTICS INSTITUTE

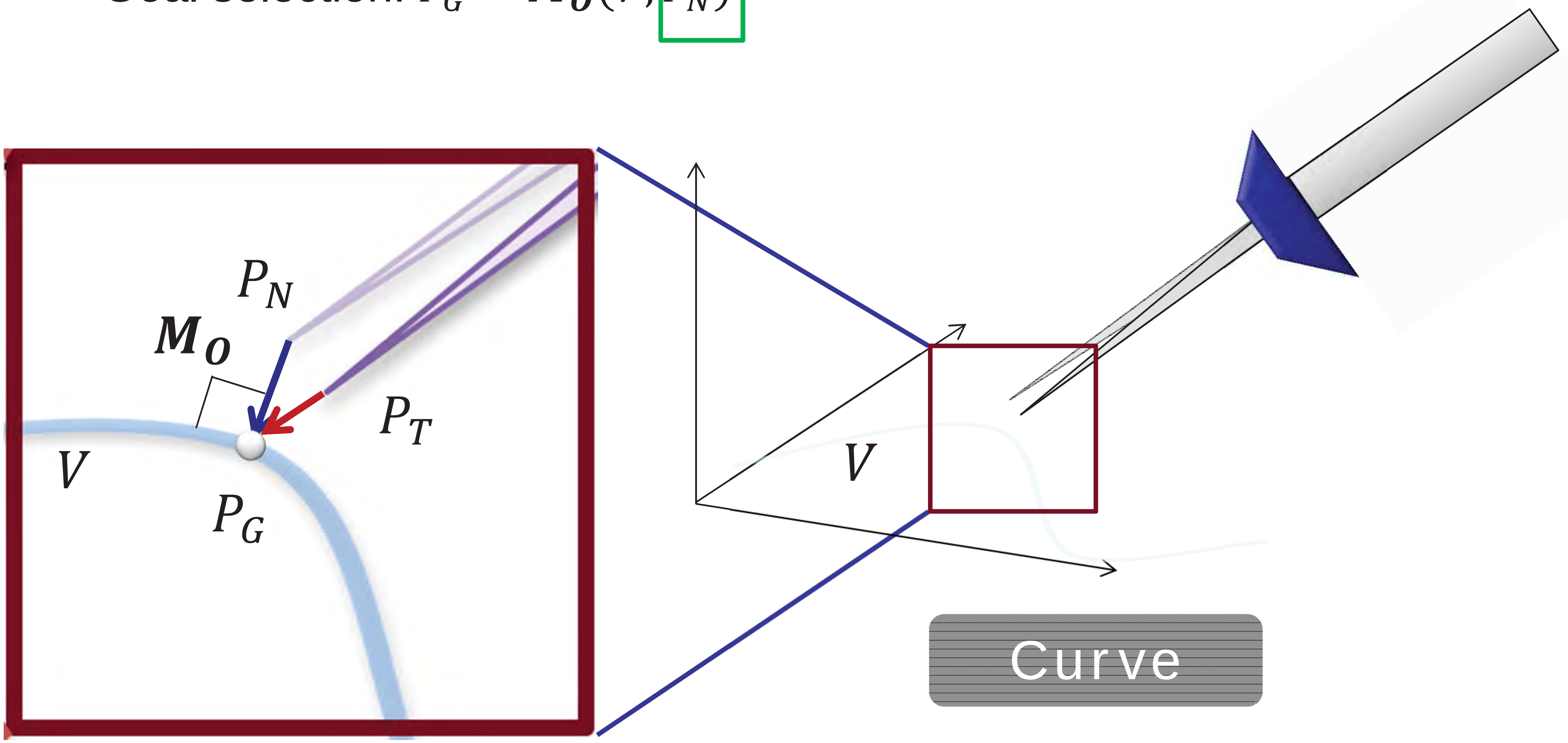
Higher-Order Virtual Fixtures

- Virtual fixture V
  - Higher DOF subspace
  - Tip to lie on subspace
- Implement as moving point virtual fixture



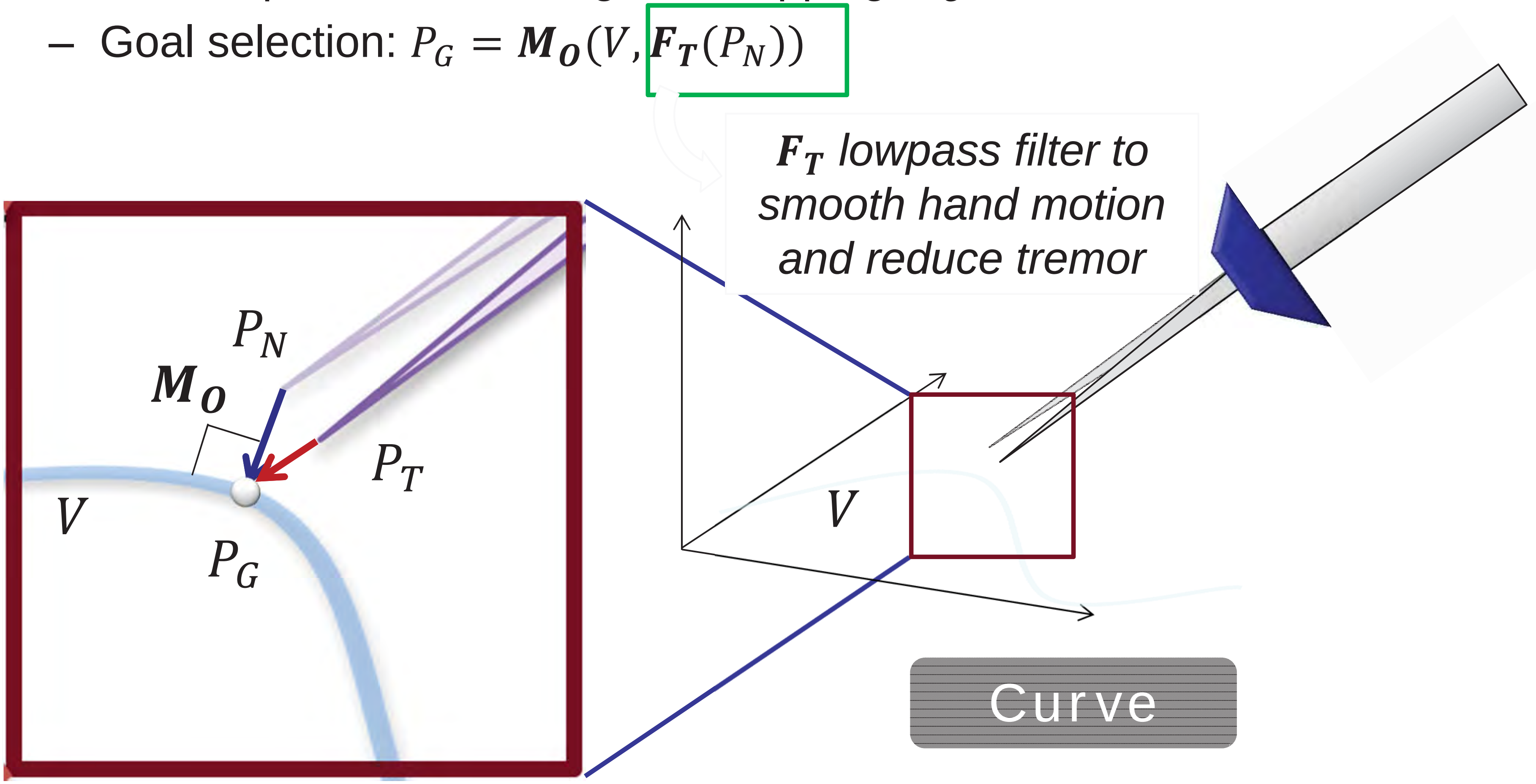
Higher-Order Virtual Fixtures

- Mapping to fixture
  - Closest point on V: orthogonal mapping $\boldsymbol{M_O}$
  - Goal selection: $P_G = \boldsymbol{M_O}(V, P_N)$



Higher-Order Virtual Fixtures

- Mapping to fixture
  - Closest point on V: orthogonal mapping $\boldsymbol{M_O}$
  - Goal selection: $P_G = \boldsymbol{M_O}(V, \boldsymbol{F_T}(P_N))$



Motion Scaling

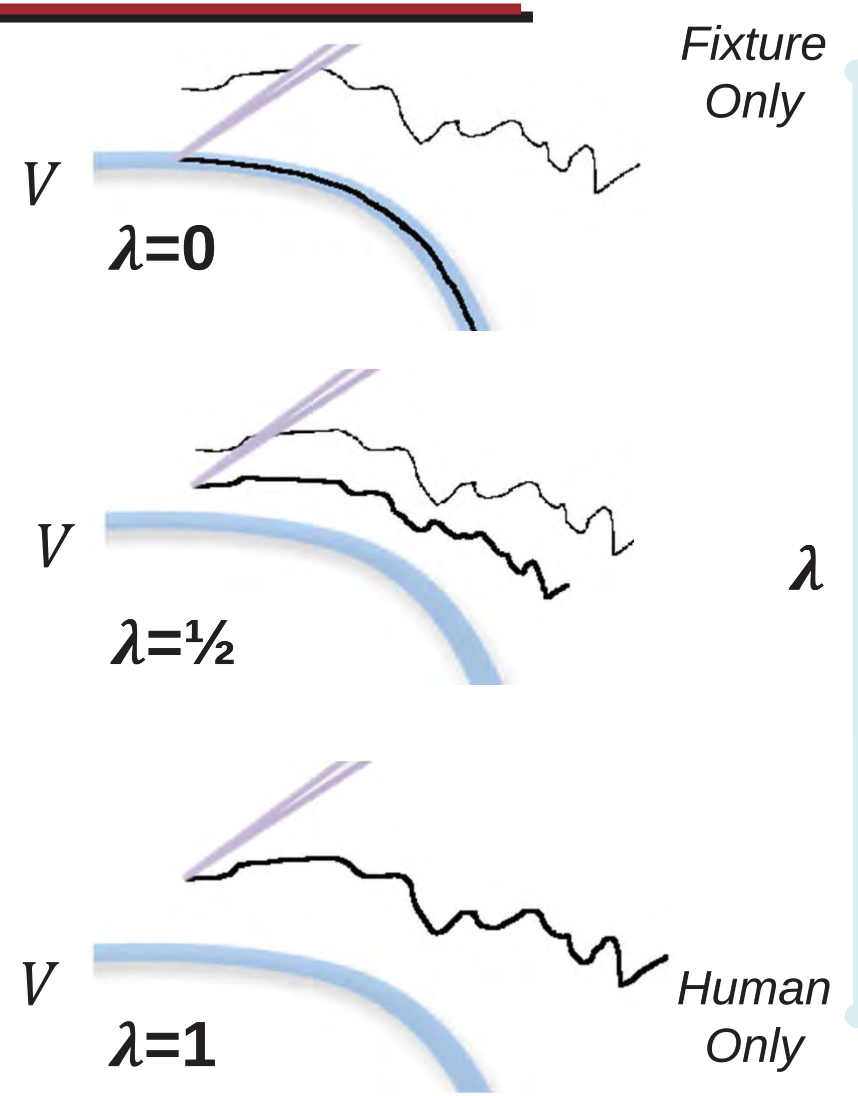
- Scale motion near fixture
  - λ: Scaling parameter
  - e: Error between human P_N and virtual fixture P_G

- Soft virtual fixture

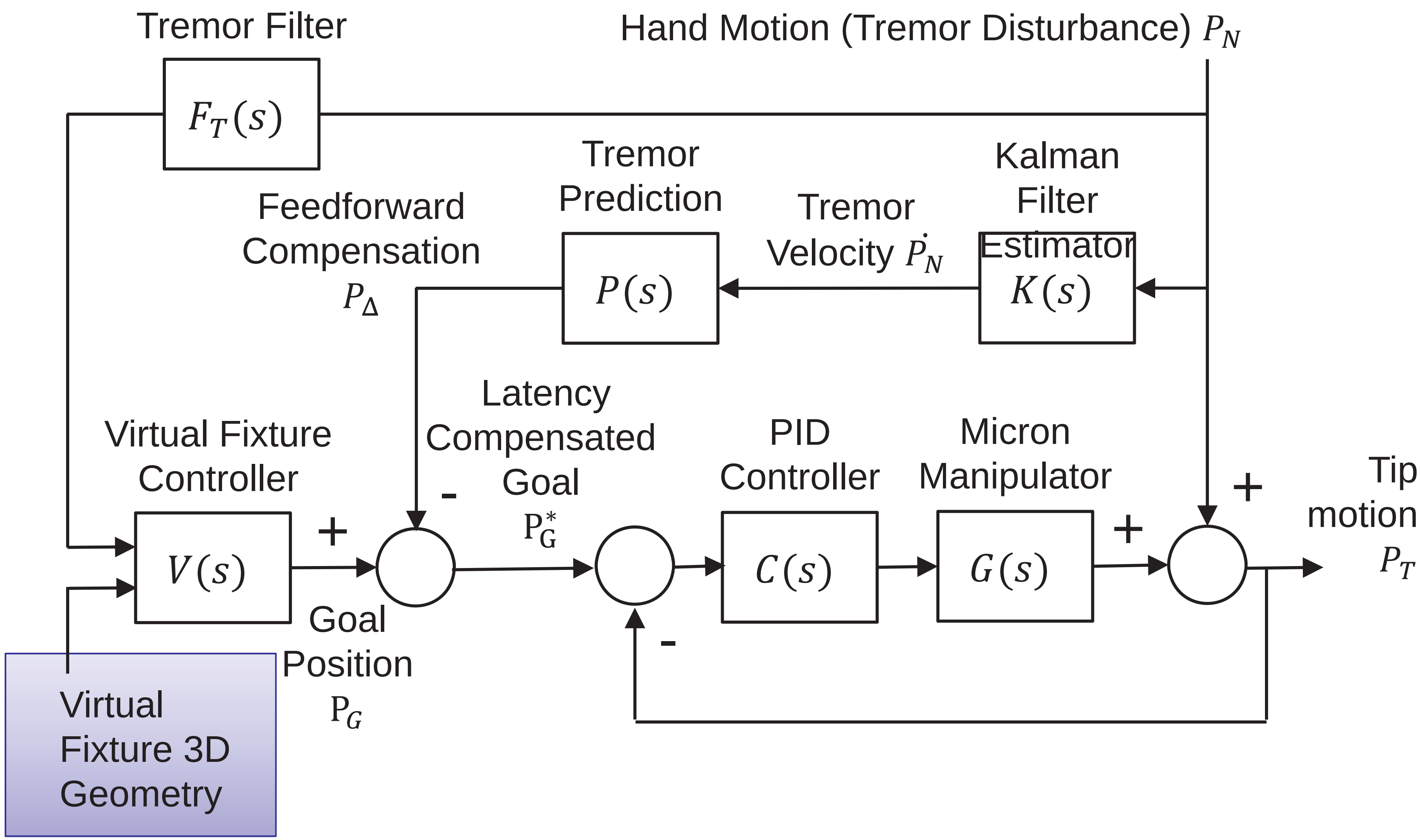
- Goal: $P_T = P_G + \lambda e$

Fixture goal point (for P_G)

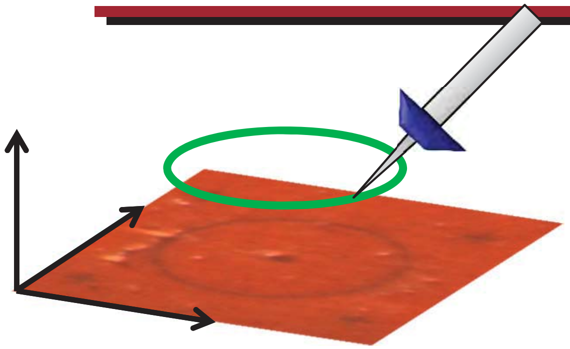
Use some of the human input (for λe)



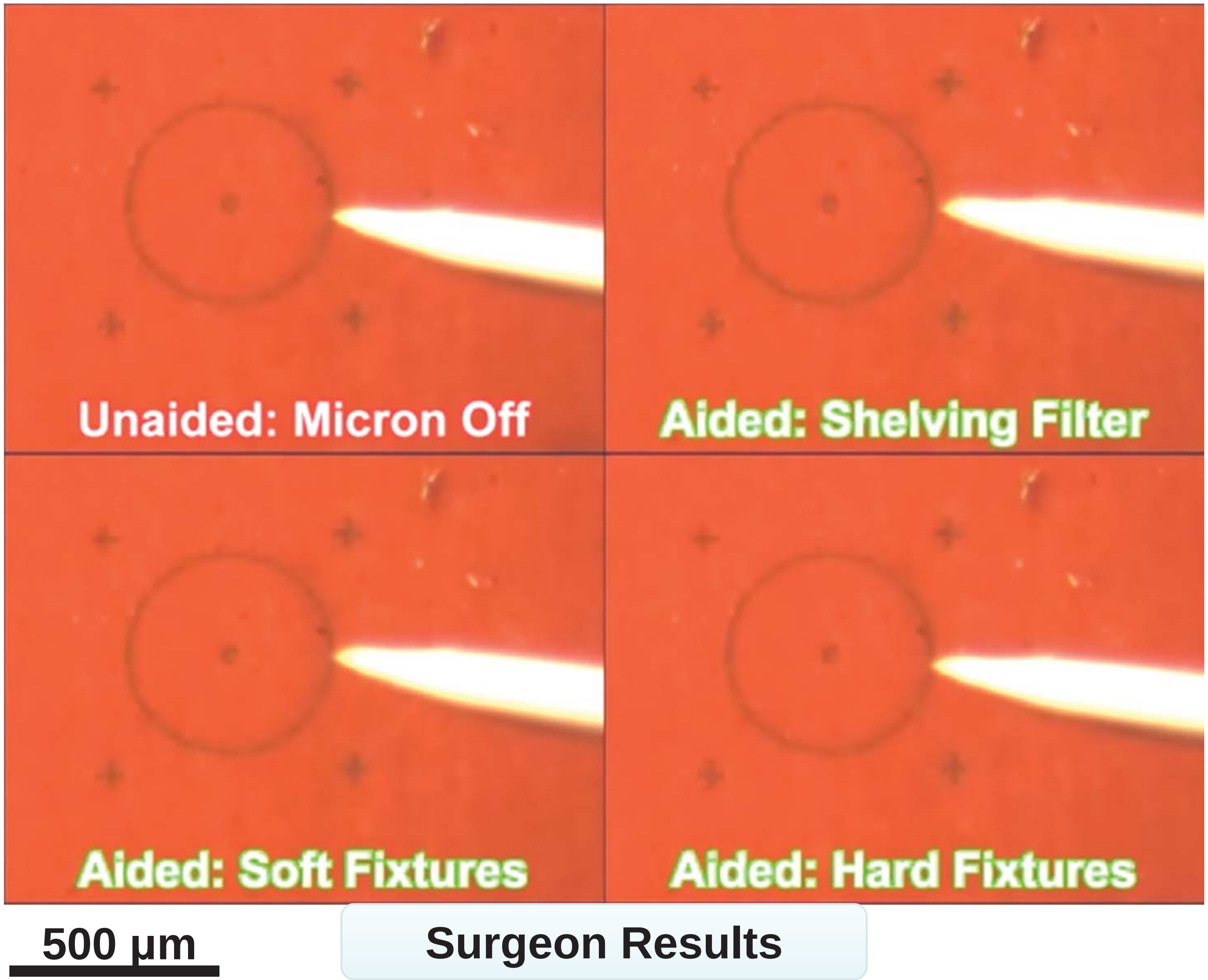
Virtual Fixture Generation



Circle Tracing

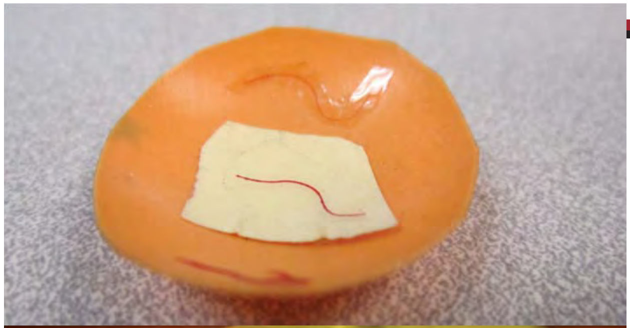


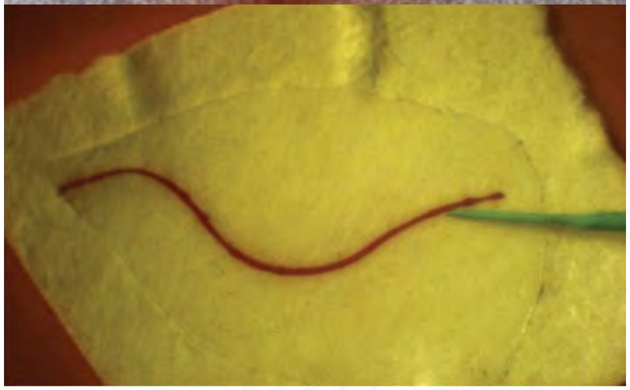
Circle Tracing

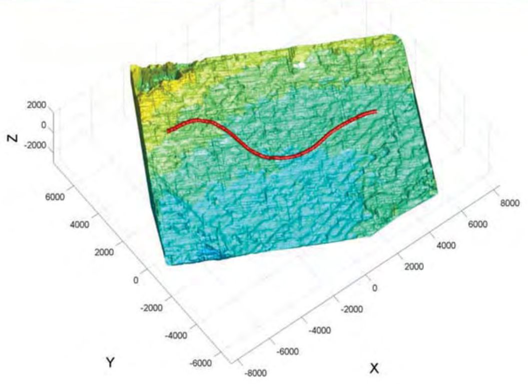


Surgeon Results

Vein Tracing



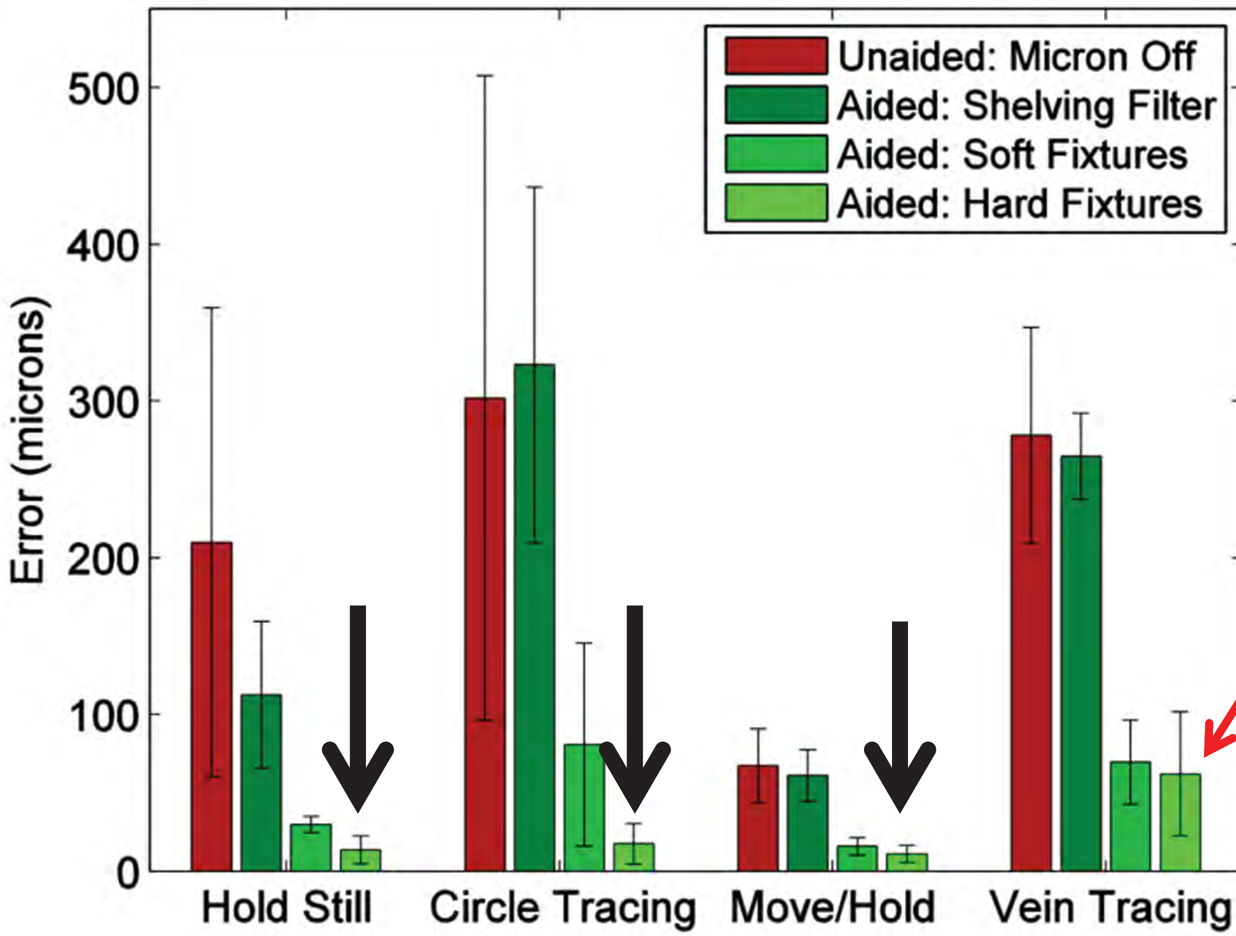




5.0 mm

Surgeon Results

Virtual Fixtures Results



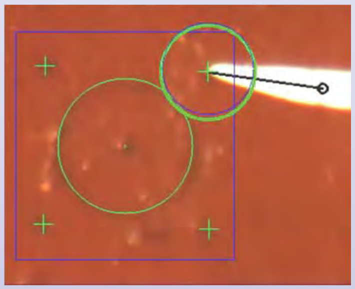
Surgeon Results

98% of error occurs while in saturation

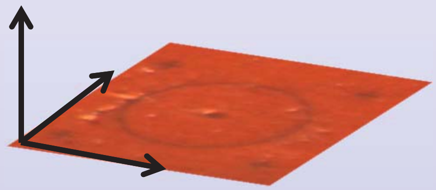
Virtual fixtures significantly reduce positioning error ($p < 0.05$)

30 Hz Real-Time Vision

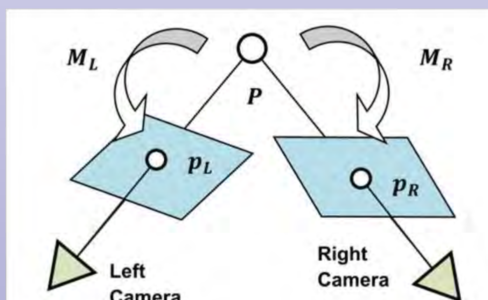
Multi-threaded CPU



Template/tip tracking



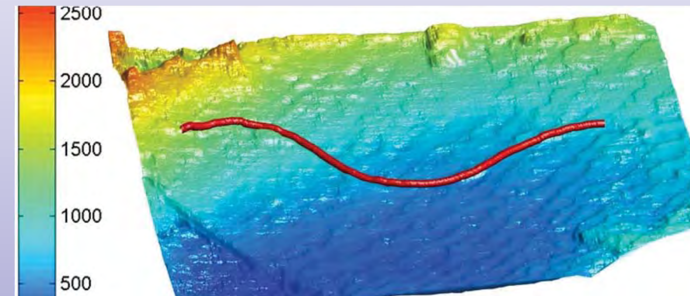
Surface reconstruction



Adaptive Camera Calibration

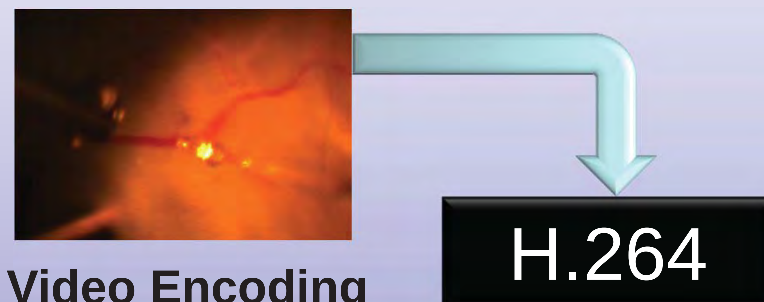
3D fitting

GPU-Accelerated



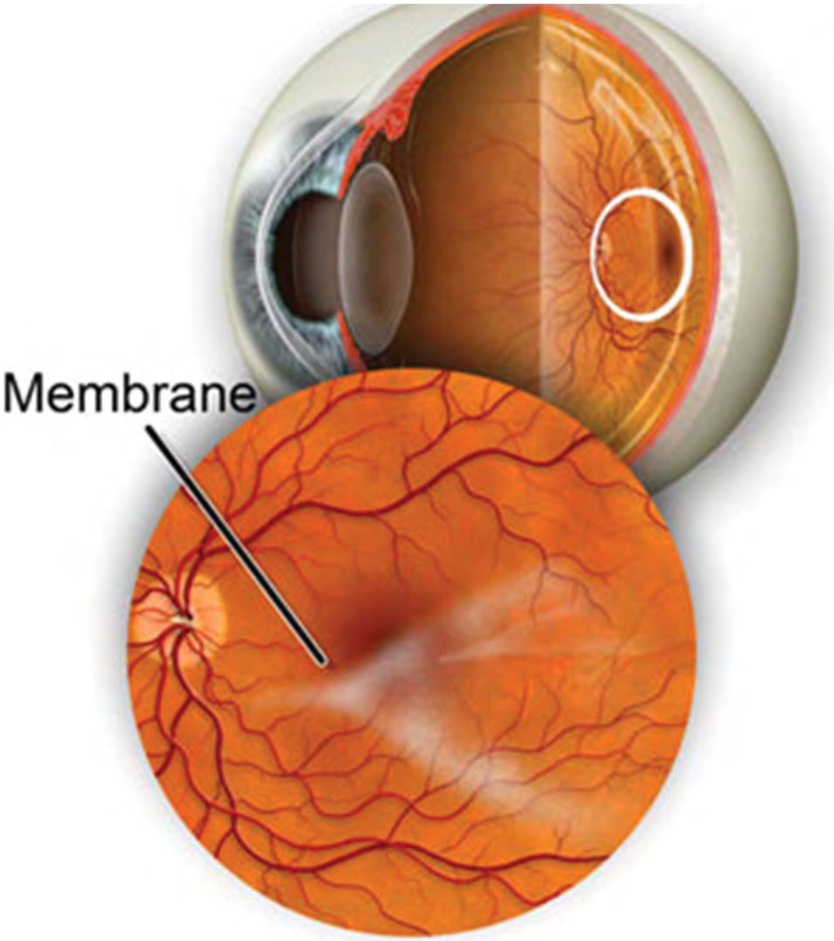
Dense Stereo Reconstruction

ASIC-Accelerated



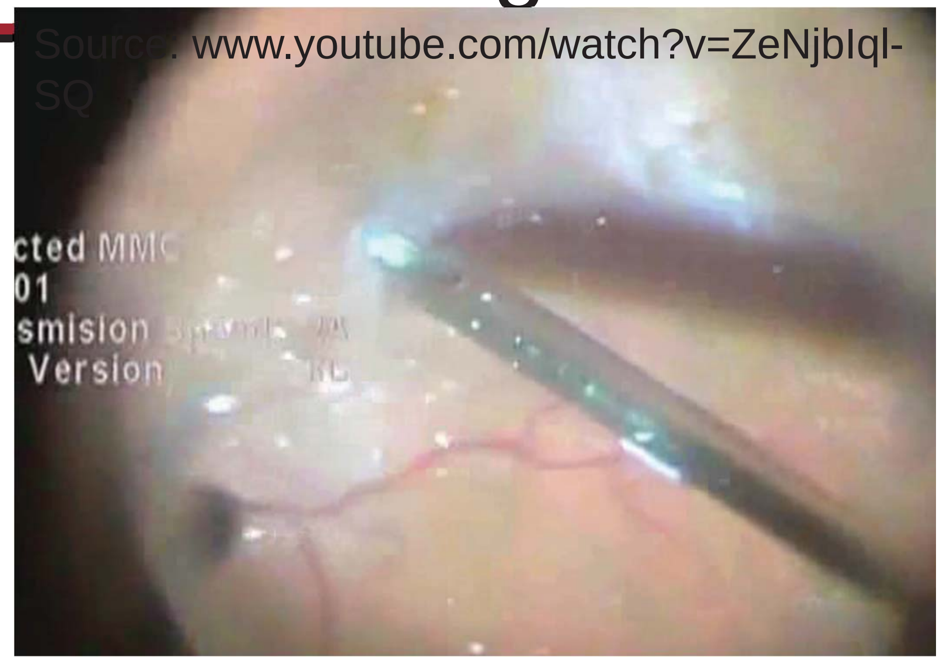
Video Encoding

Retinal Membrane Peeling



Procedure: *Remove membrane < 5 μm thick*

Source: www.youtube.com/watch?v=ZeNjbIql-SQ



Problem:

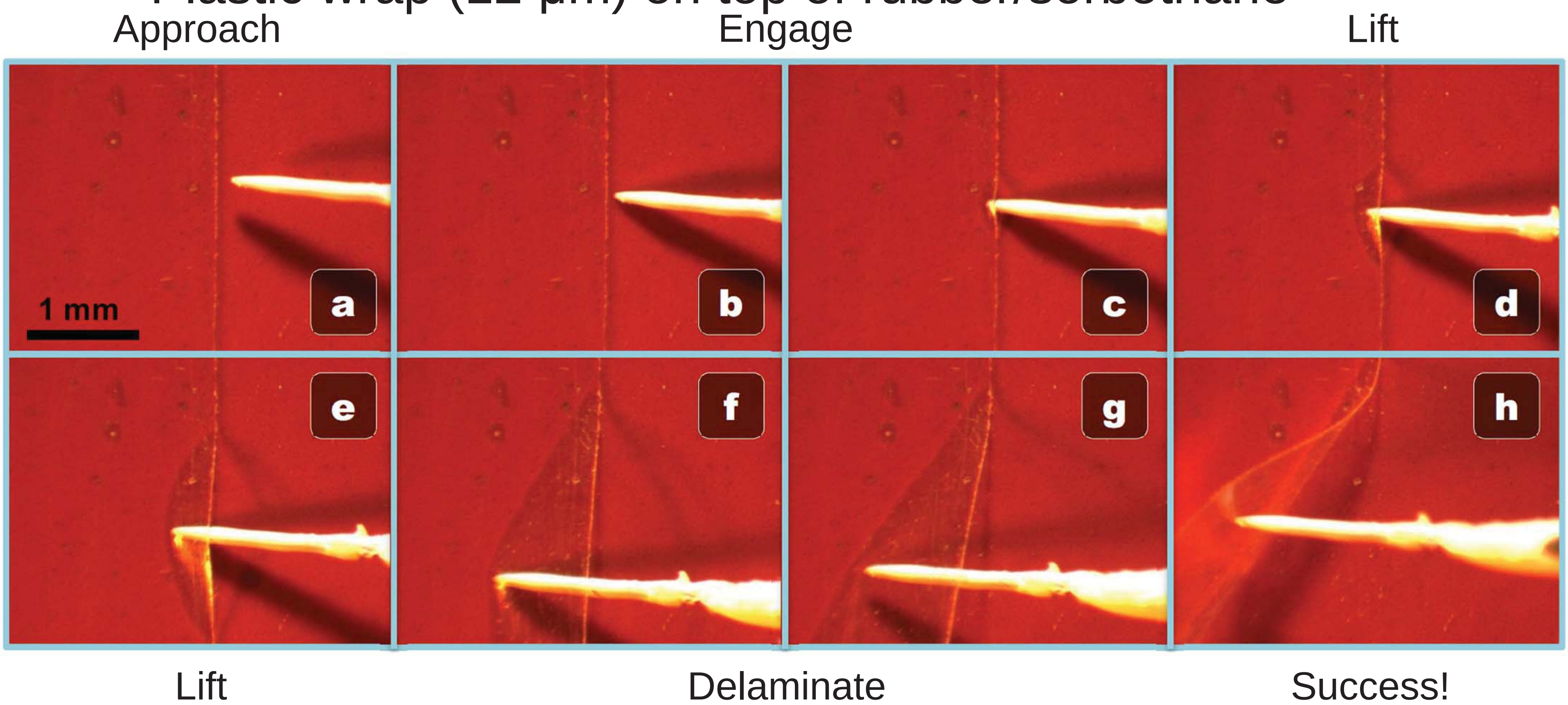
Retina tears at 5-8 mN

Goal:

Limits on force and speed

Peeling Procedure

- Plastic wrap (12 μm) on top of rubber/sorbothane

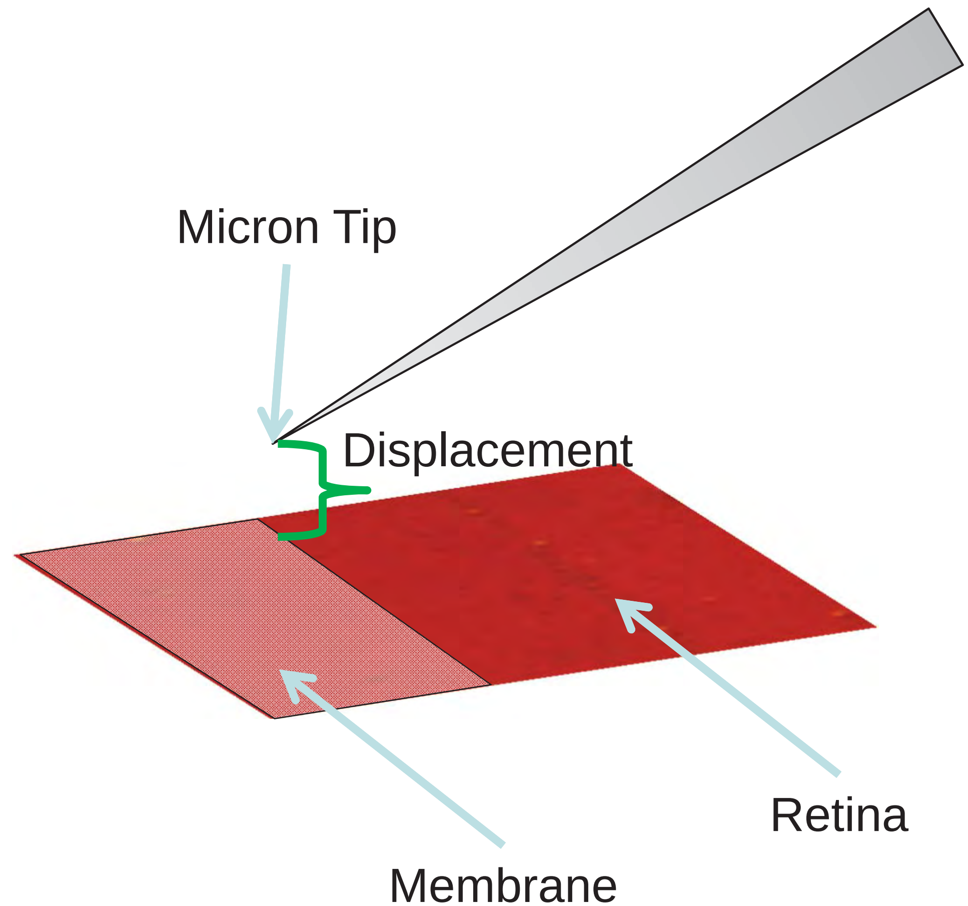


Carnegie Mellon
THE ROBOTICS INSTITUTE

Vision-Based Virtual Fixtures

- Goals
  - Increase precision
  - Limit force
  - Prevent retina tearing

- Vision-Based Behaviors
  - Motion-scaling
  - Hard-stop
  - Velocity Limiting

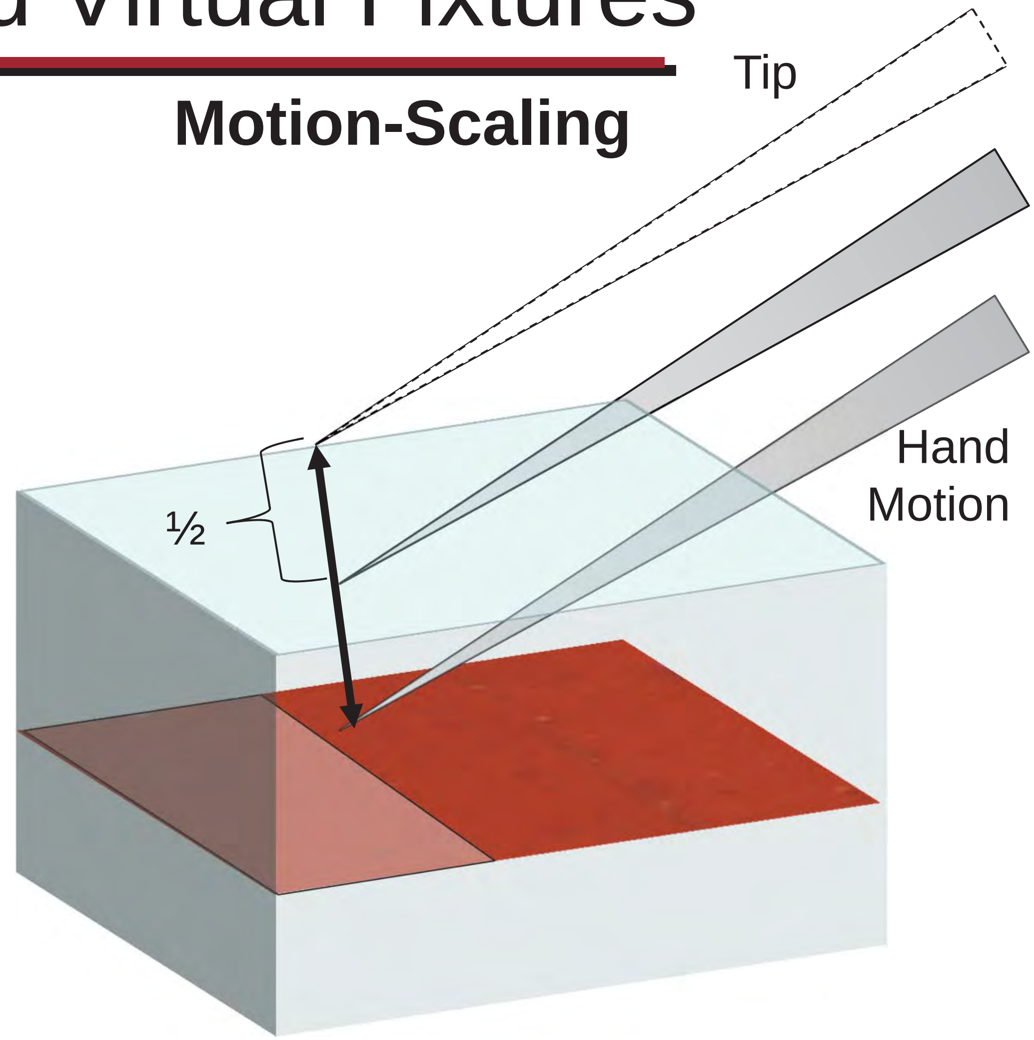


Carnegie Mellon
THE ROBOTICS INSTITUTE

Vision-Based Virtual Fixtures

- Goals
  - Increase precision
  - Limit force
  - Prevent retina tearing
- Behaviors
  - **Motion-scaling**
  - Hard-stop
  - Velocity Limiting

Motion-Scaling

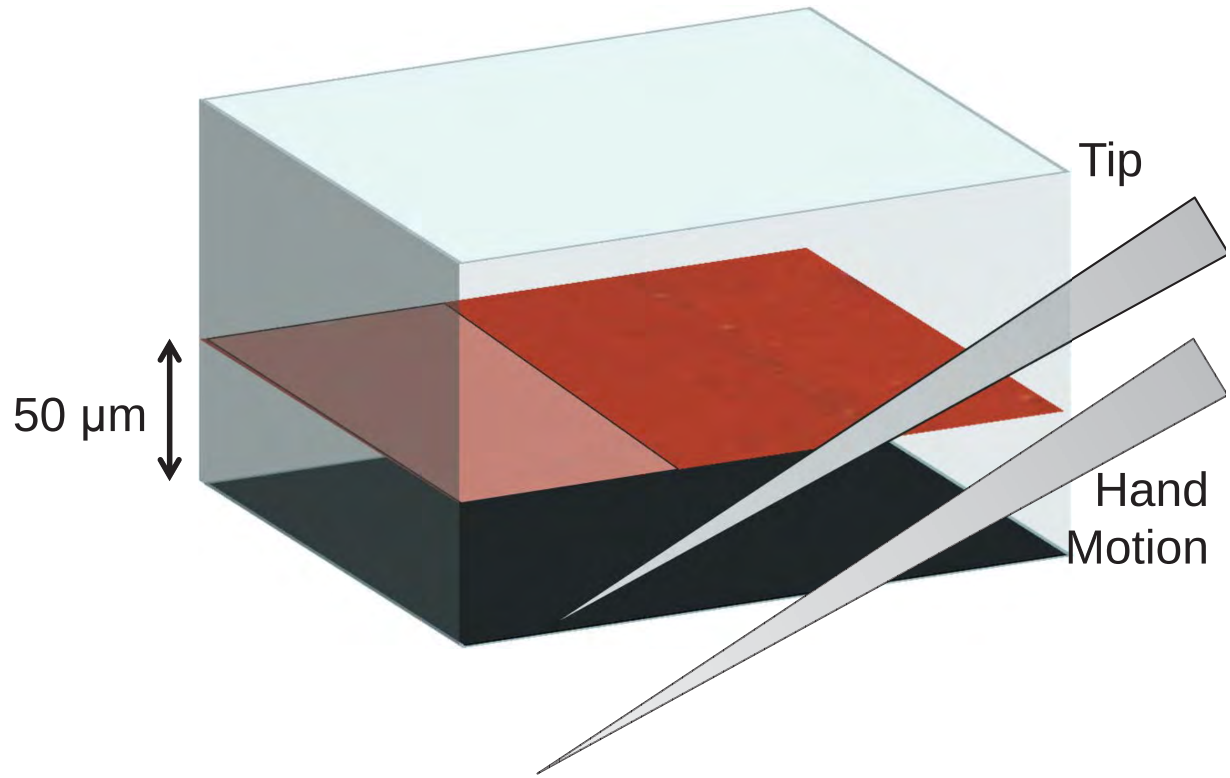


Vision-Based Virtual Fixtures

- Goals
  - Increase precision
  - Limit force
  - Prevent retina tearing

- Behaviors
  - Motion-scaling
  - **Hard-stop**
  - Velocity Limiting

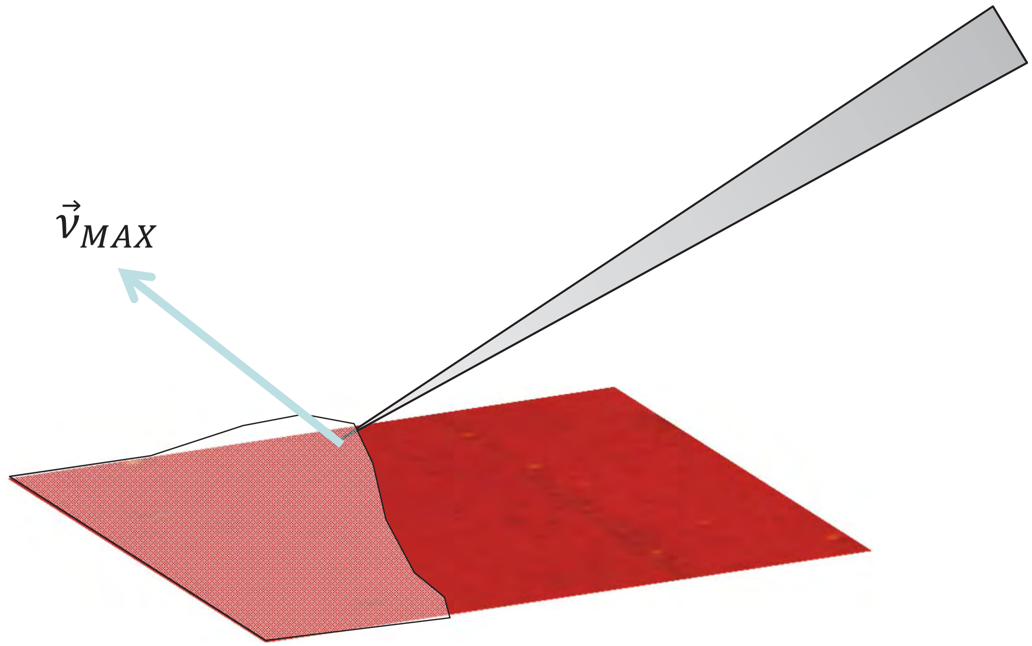
Hard Stop



Vision-Based Virtual Fixtures

- Goals
  - Increase precision
  - Limit force
  - Prevent retina tearing
- Behaviors
  - Motion-scaling
  - Hard-stop
  - **Velocity Limiting**

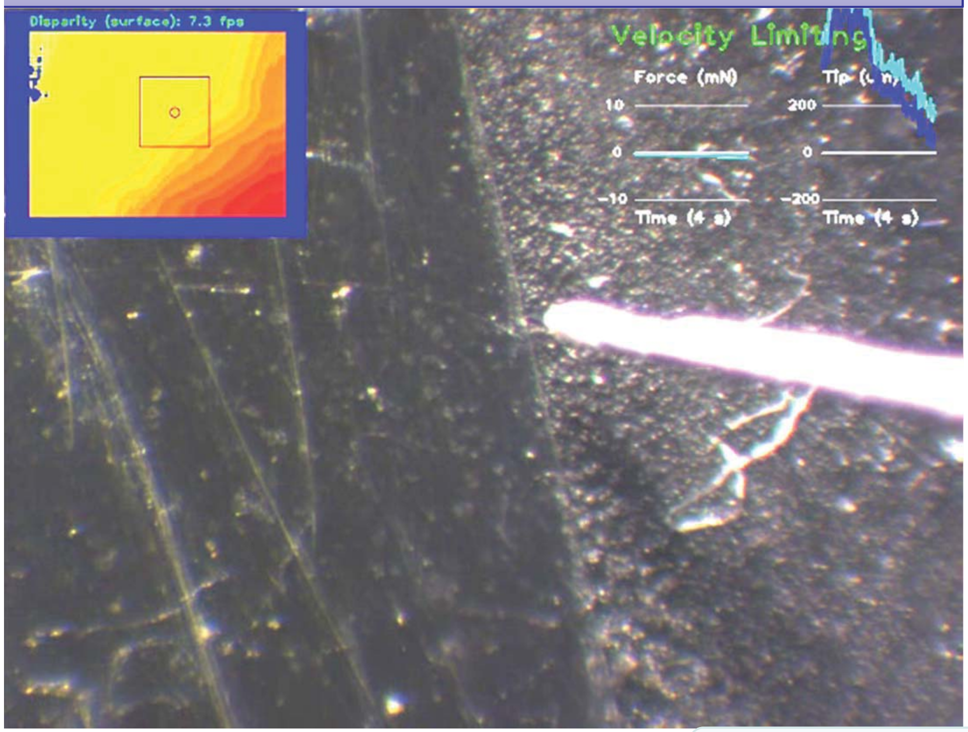
Velocity Limiting



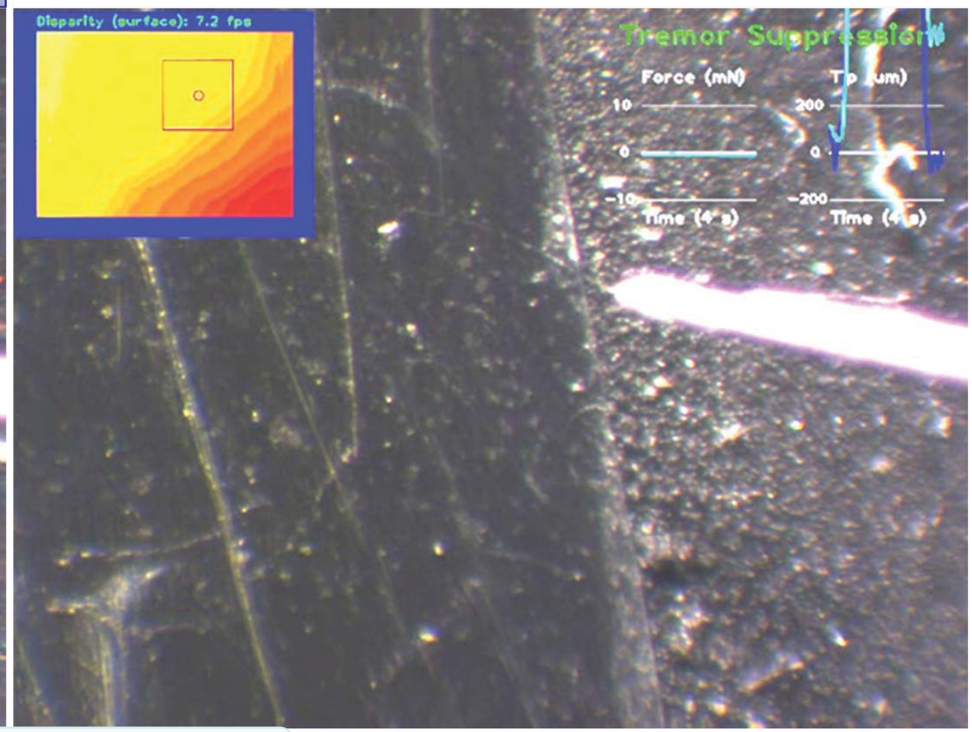
Results: Qualitative

Peeling Plastic Wrap from Sorbothane

Unaided



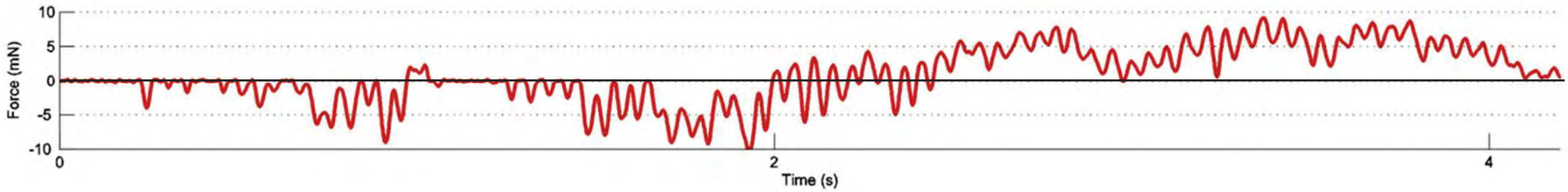
Unaided



Surgeon Results

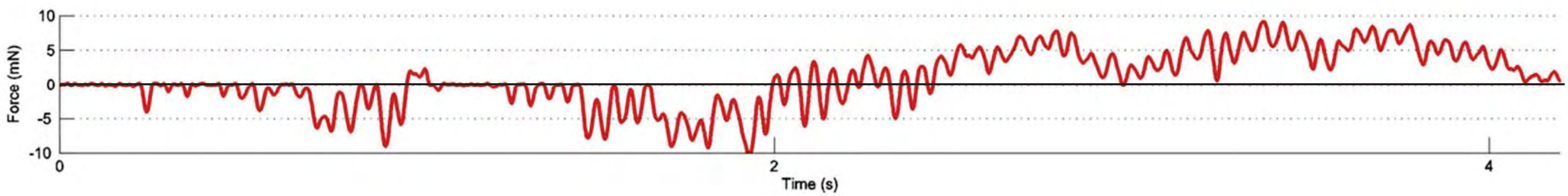
Carnegie Mellon
THE ROBOTICS INSTITUTE

Results: Forces



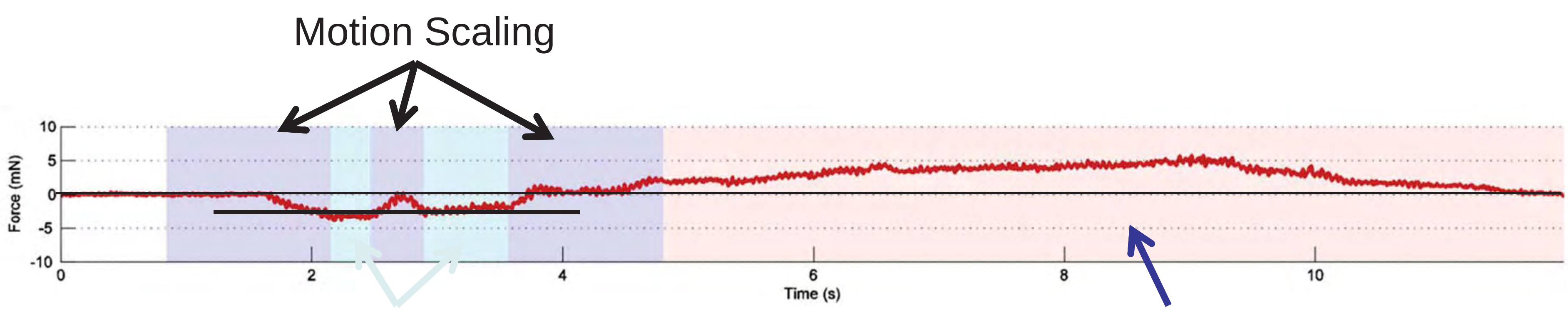
- Force magnitude > 8 mN
- Jerky force from tremor

Results: Forces



- Force magnitude > 8 mN
- Jerky force from tremor

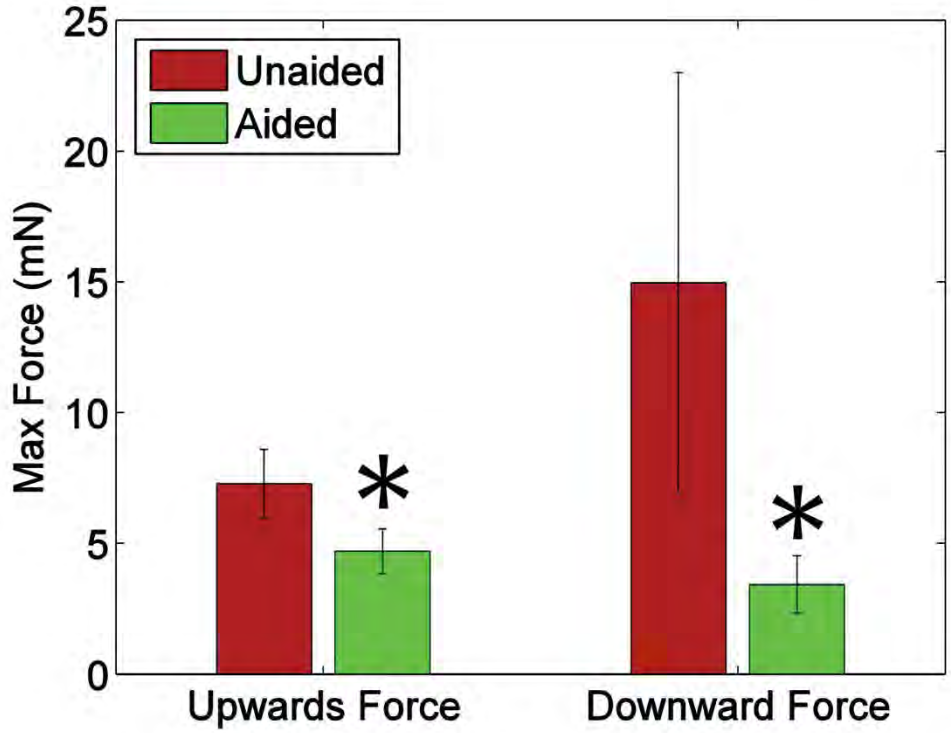
• Aided



- Hard stop limits force
- Velocity limiting smooths force

Results: Quantitative

Experienced retinal surgeon: 20 randomized trials

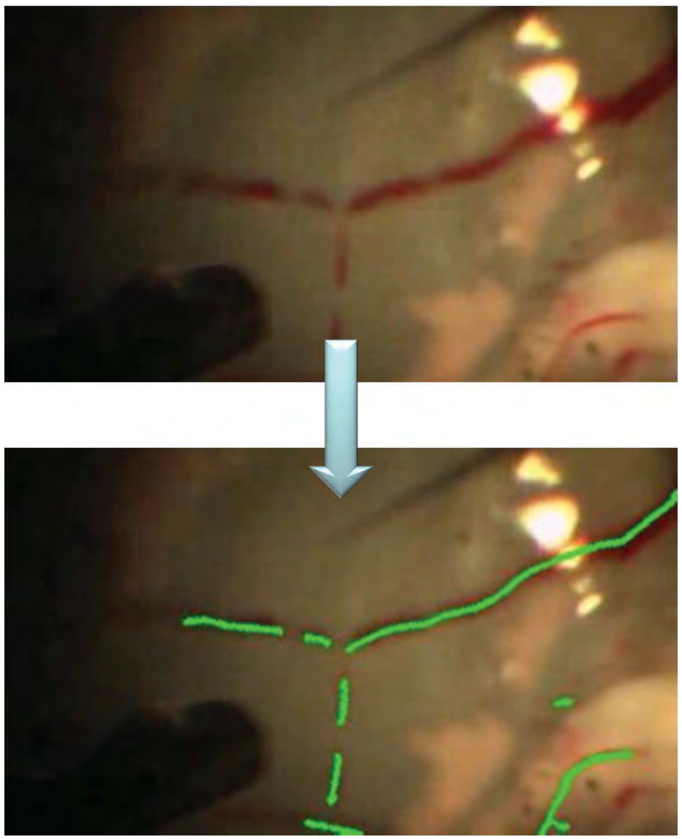


Surgeon Results

*Significantly reduces max force *($p < 0.05$)*

Retinal Vessel Detection

Goal: detecting and tracking vessels in challenging retinal environment for input to surgical robots

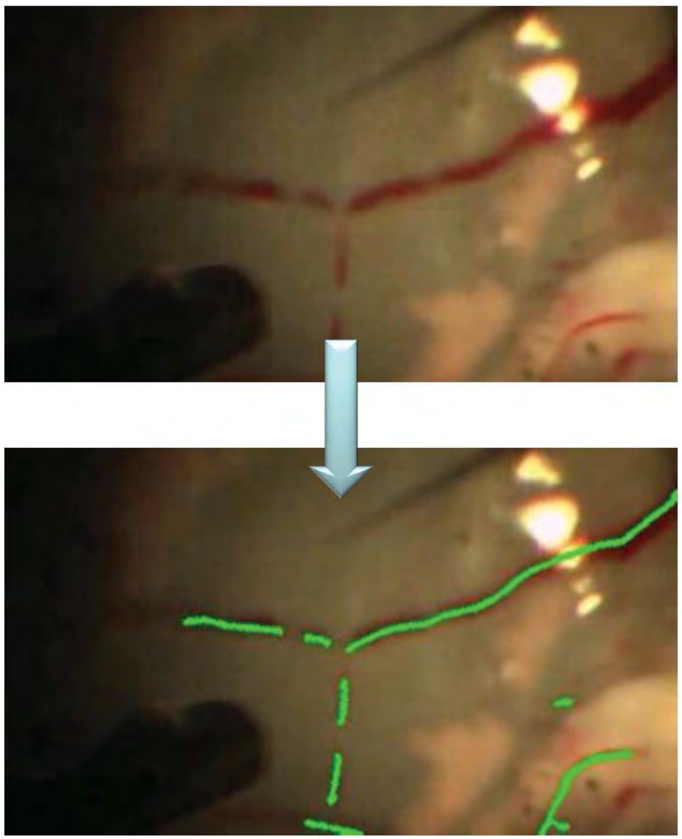


General Approaches

- **Vessel detection:** finds thin skeleton structures in images
- **Retinal registration:** finds transformations between images
    - **Sparse key-points:** SIFT/SURF
    - **Vasculature:** bifurcations
    - **Dense pixels:** cross-correlation
- **SLAM:** localizes and builds a map at the same time from observations

Retinal Vessel Detection

Goal: detecting and tracking vessels in challenging retinal environment for input to surgical robots



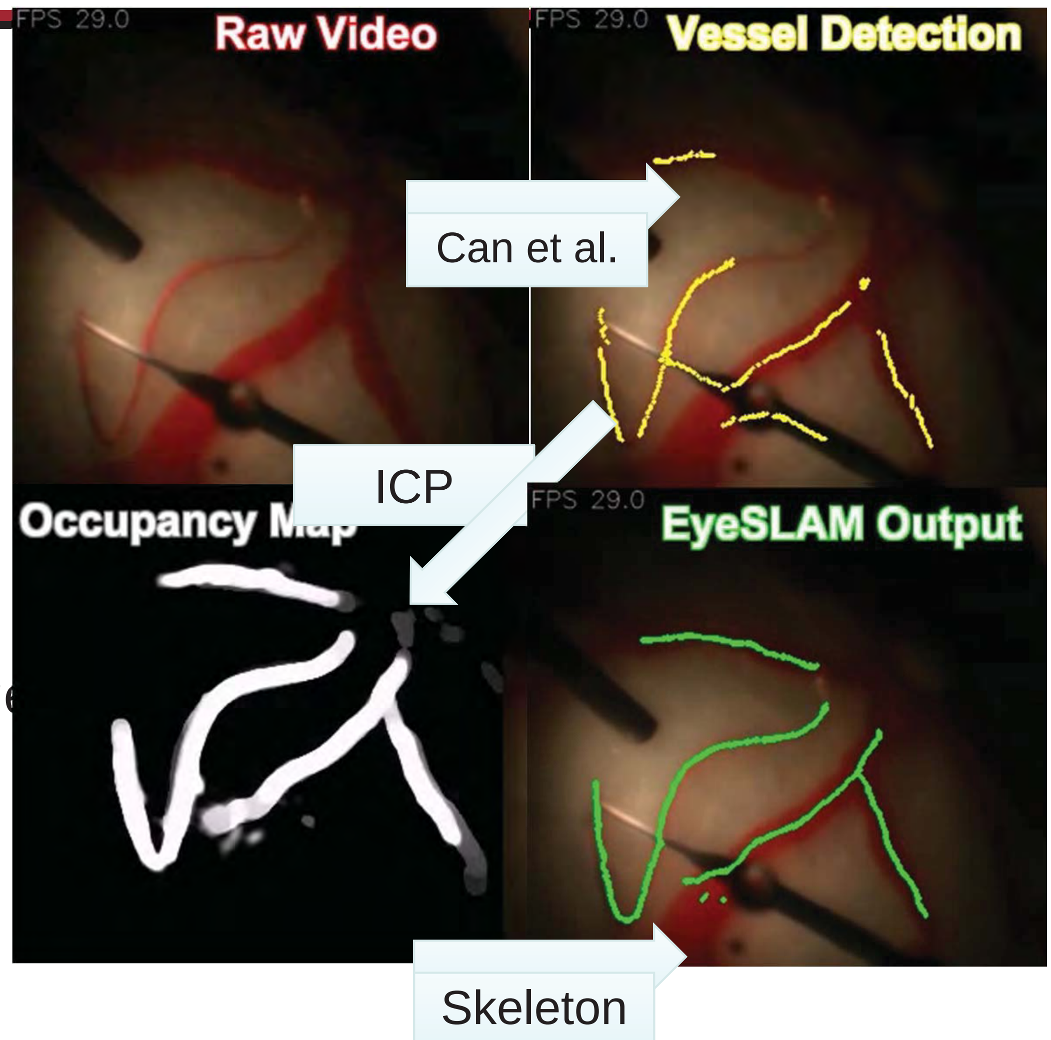
Algorithm	Year	Time
Chaudhuri et al.	1989	50 s
Can et al.	1999	0.03 s
Cha… al.		…min
Jian…		…s
Staa…		…min
Soa…		…in
Sofk…		…s
Men…		…min
Alo… al.		… s
Lupascu et al.	2010	2 min
Bankhead et al.	2012	0.2 s

Missing features:

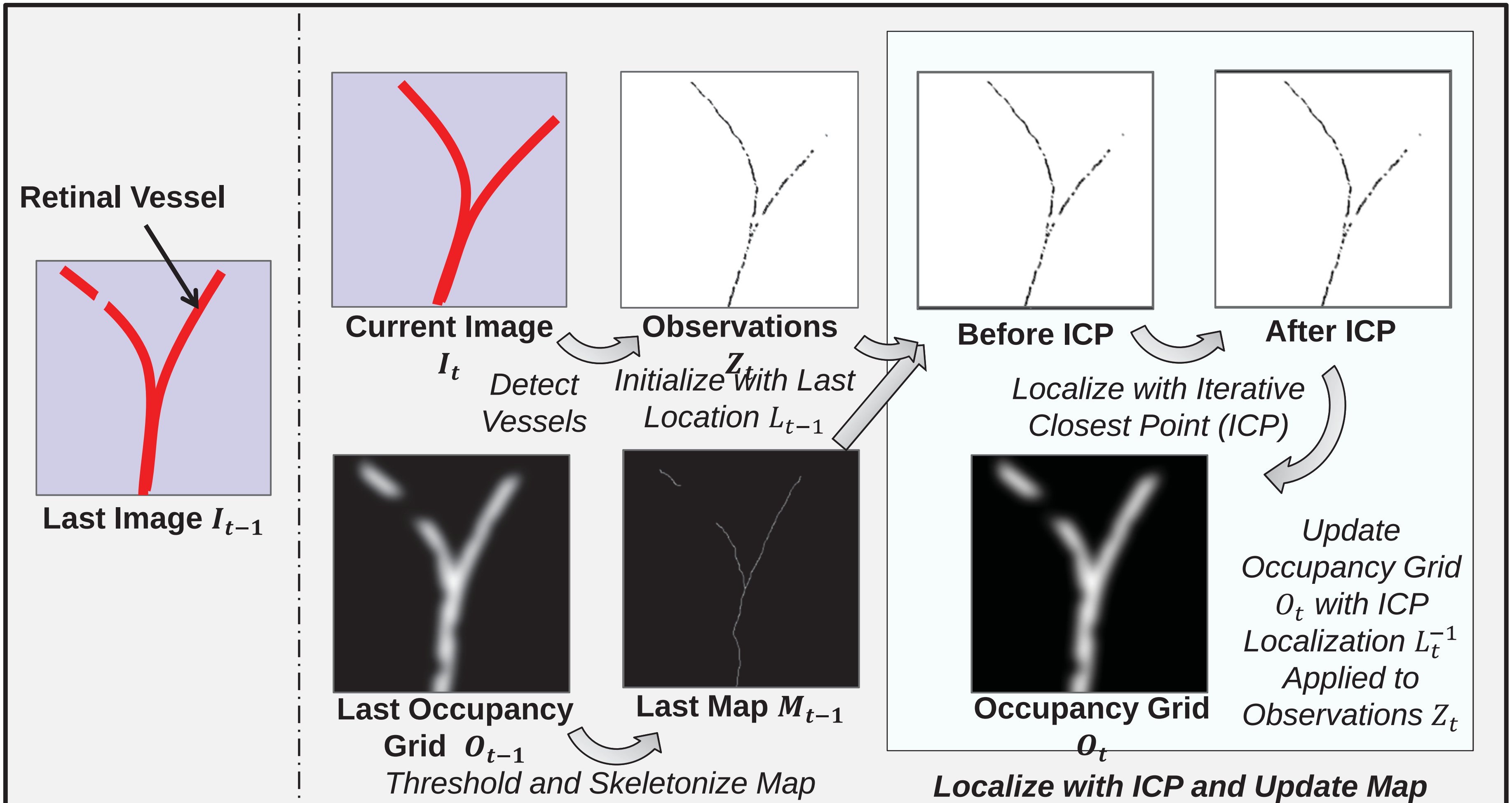
- Robustness to illumination changes
- Occlusions by lightpipe or instrument
- Localization of the retina movements

EyeSLAM Introduction

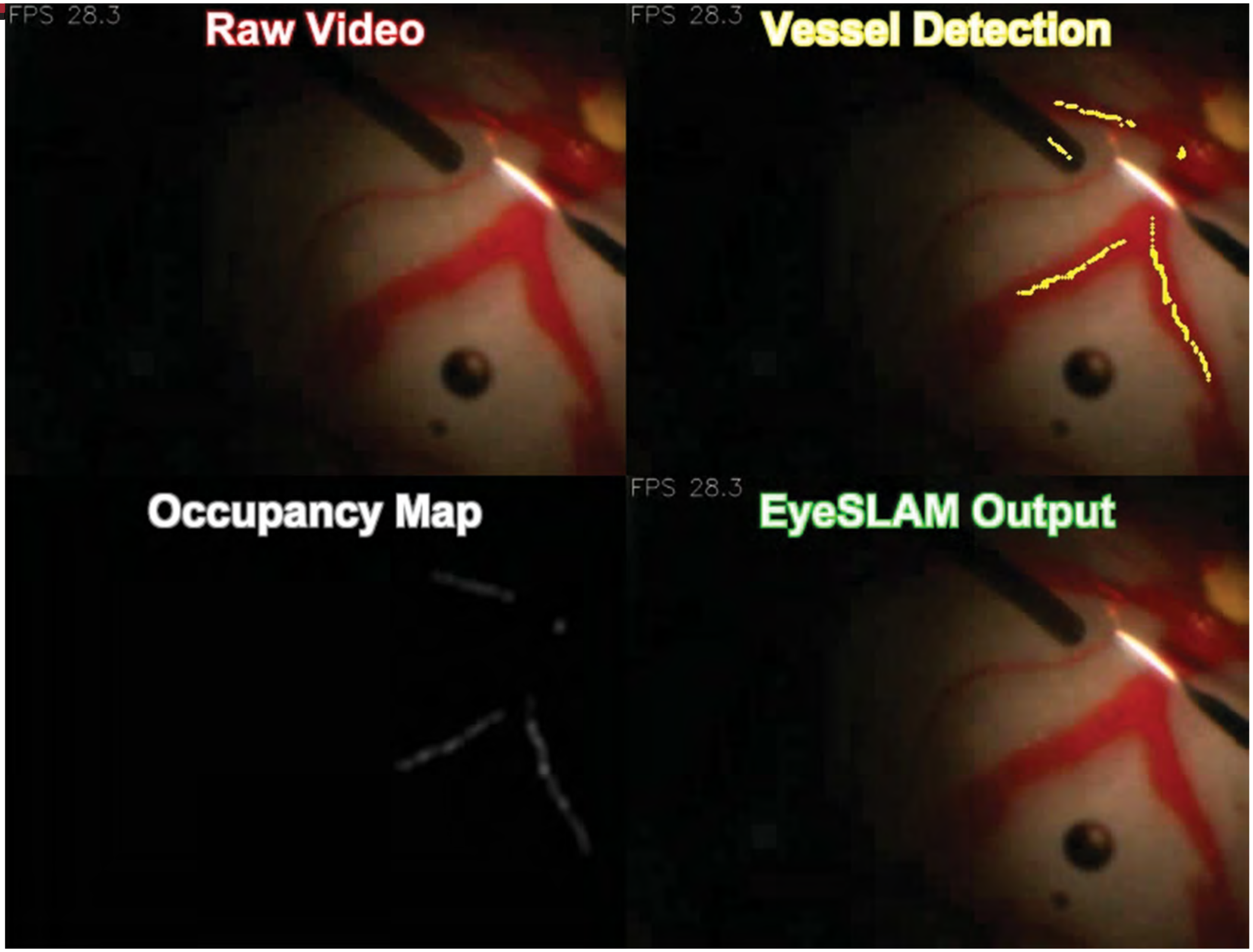
- Simultaneous Localization And Mapping (SLAM)
  - Features are vessels
  - Map is occupancy grid
  - Localization is ICP
- Pros
  - Fast: 30-40 Hz
  - Temporally consistent
  - Robust to illumination changes and occlusion



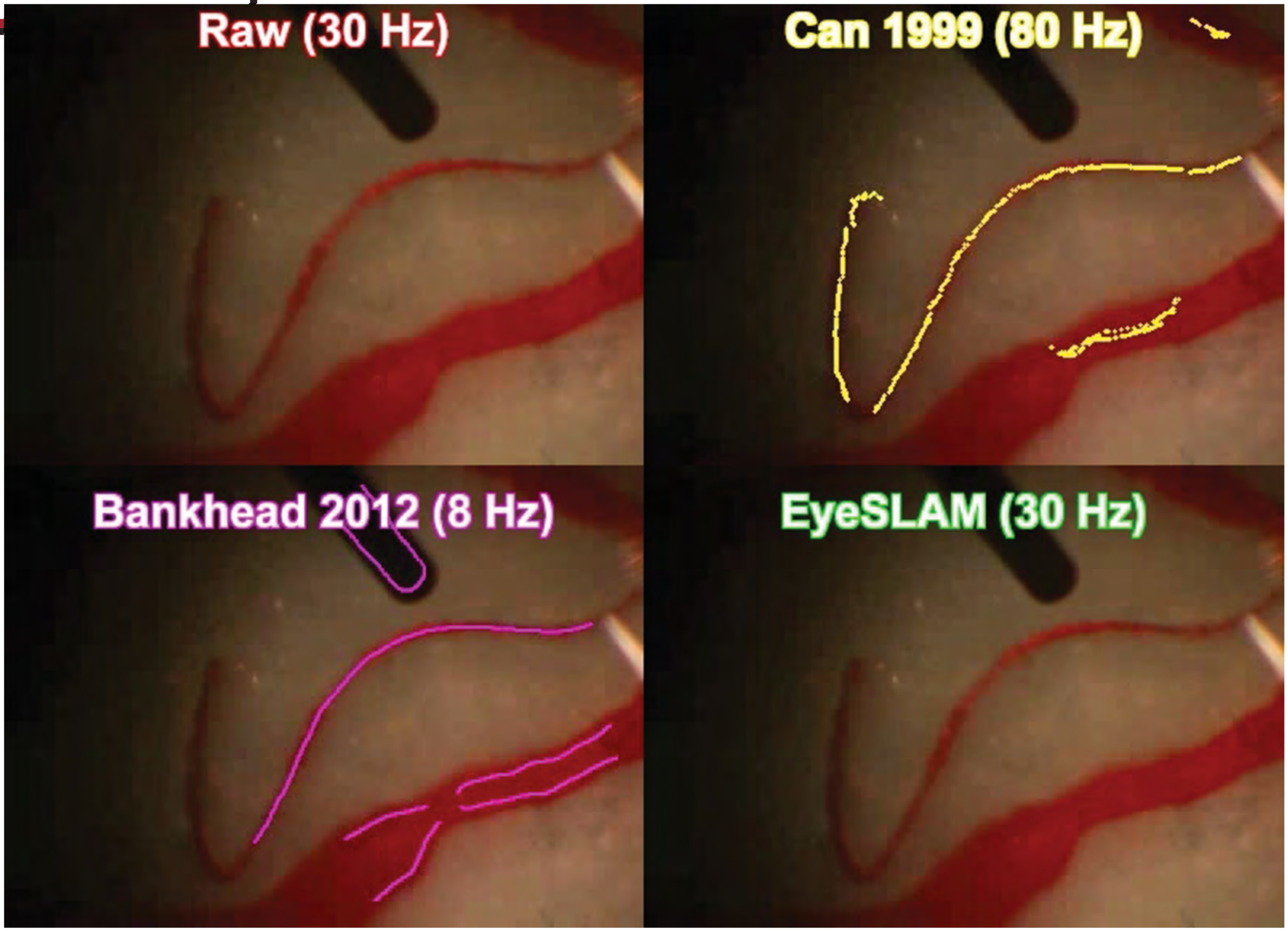
EyeSLAM Algorithm



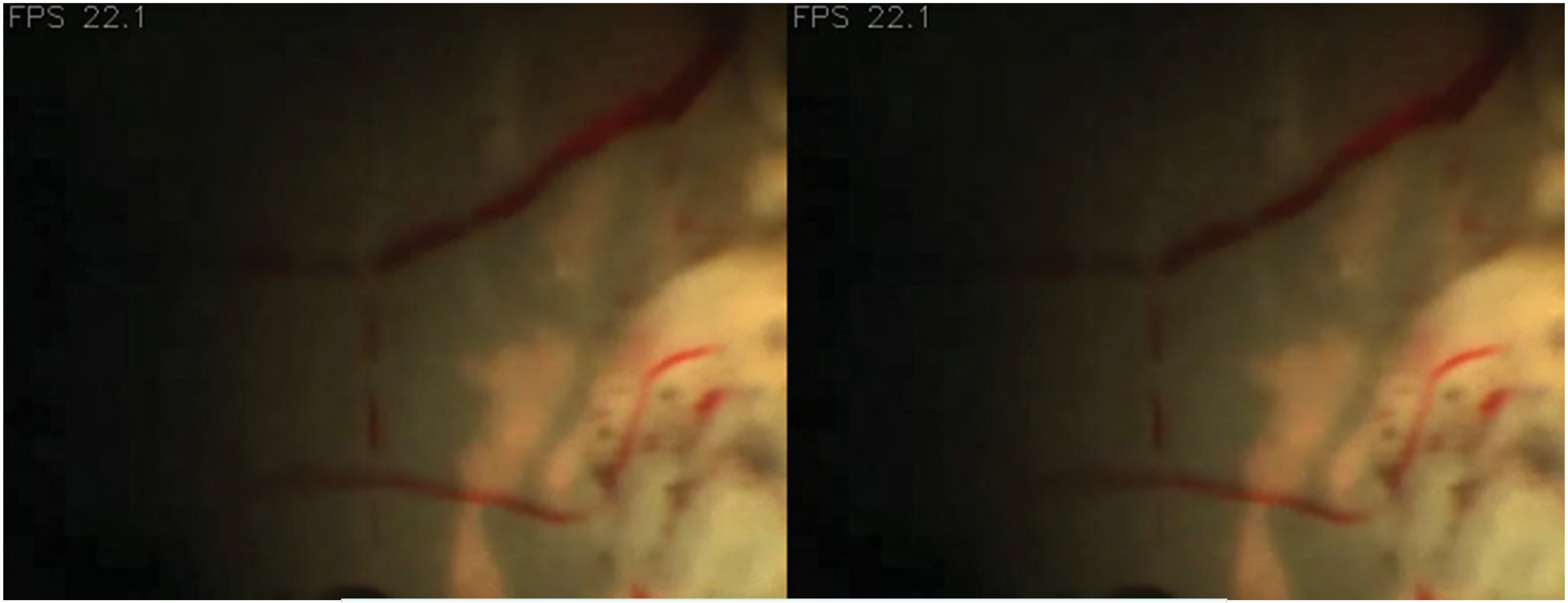
EyeSLAM Internals: Eyeball Phantom



Comparison to Vessel Detection

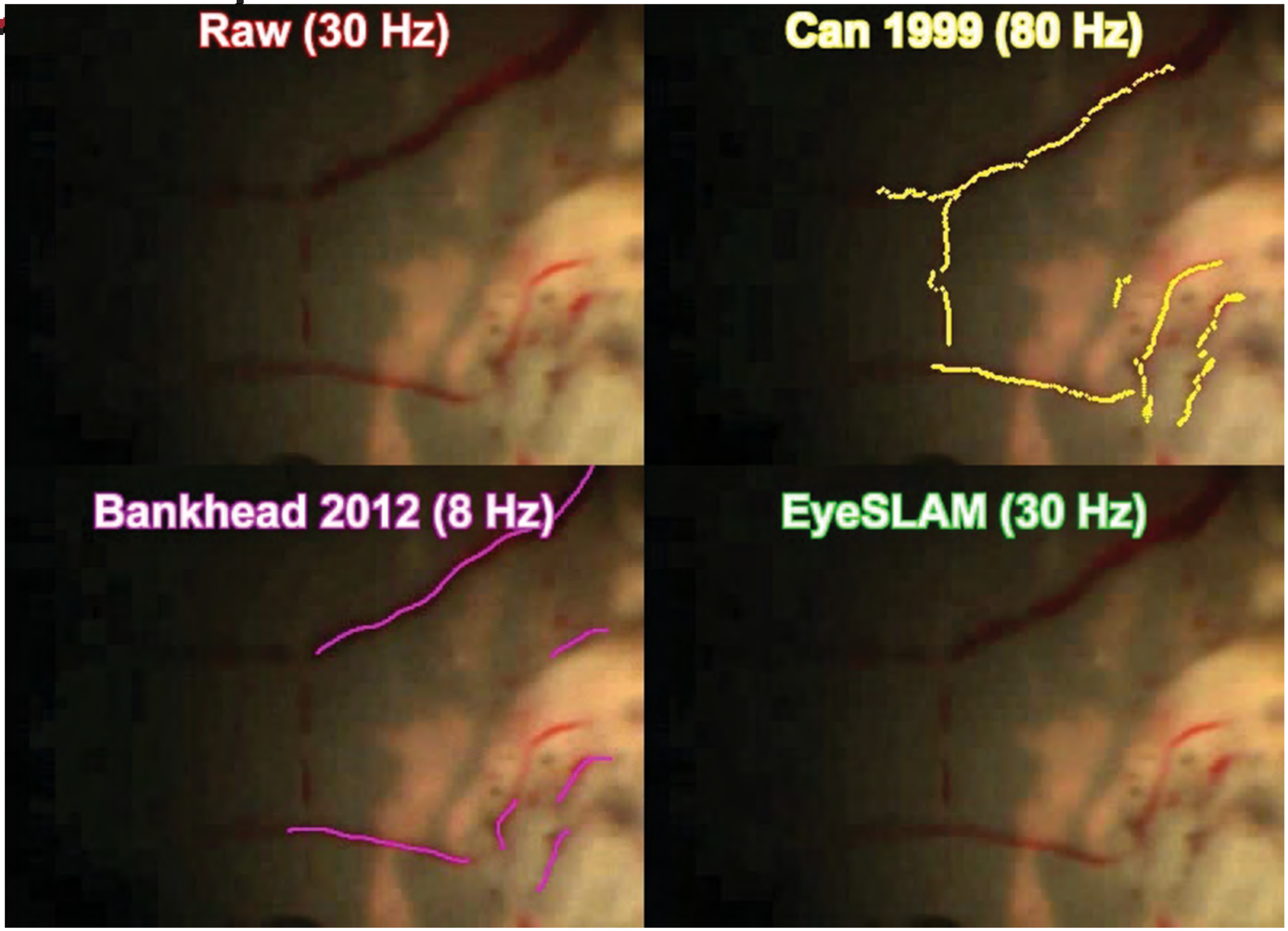


EyeSLAM Results in Porcine Retina



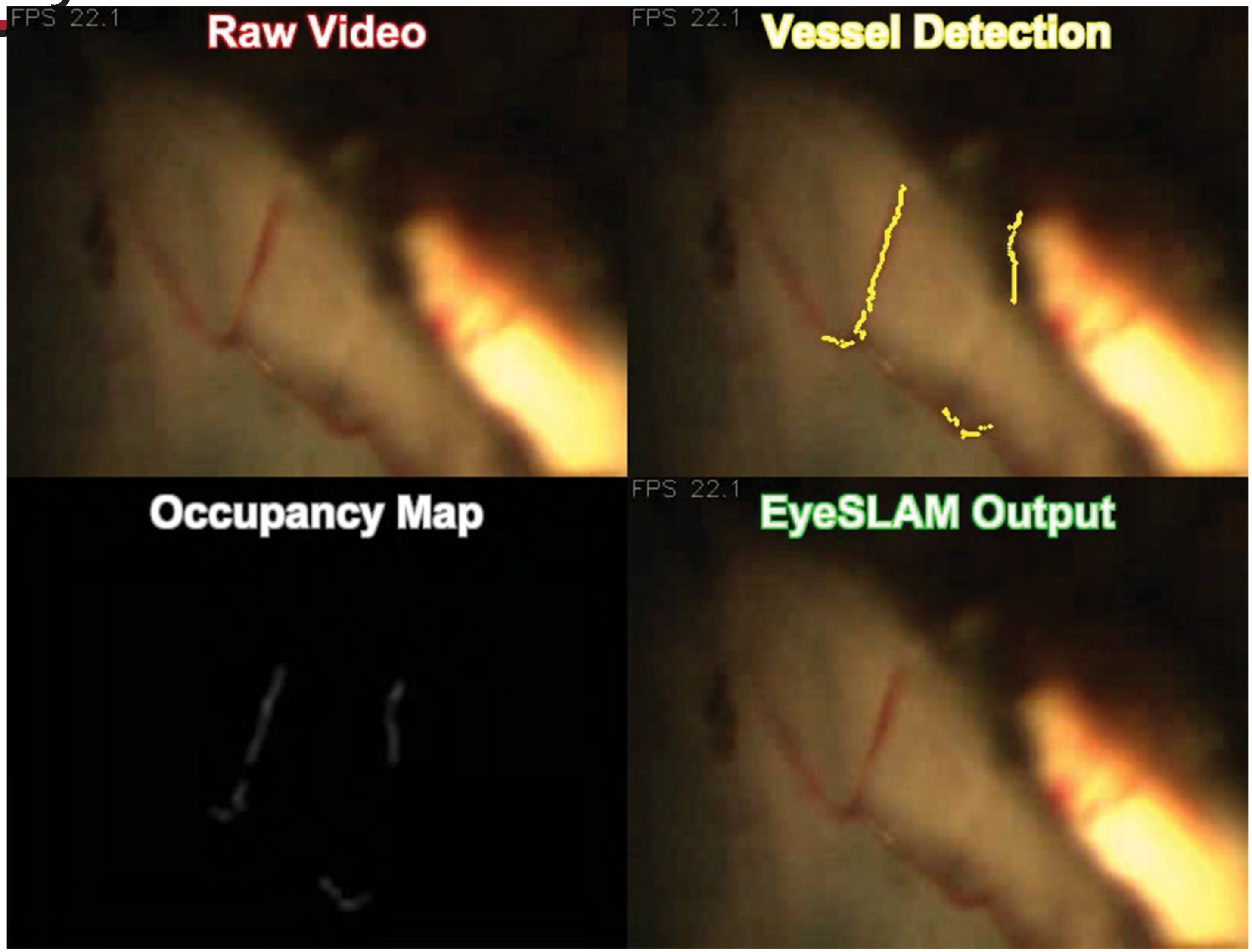
Surgeon Result: Attempted Cannulation in Porcine Retina

Comparison to Vessel Detection

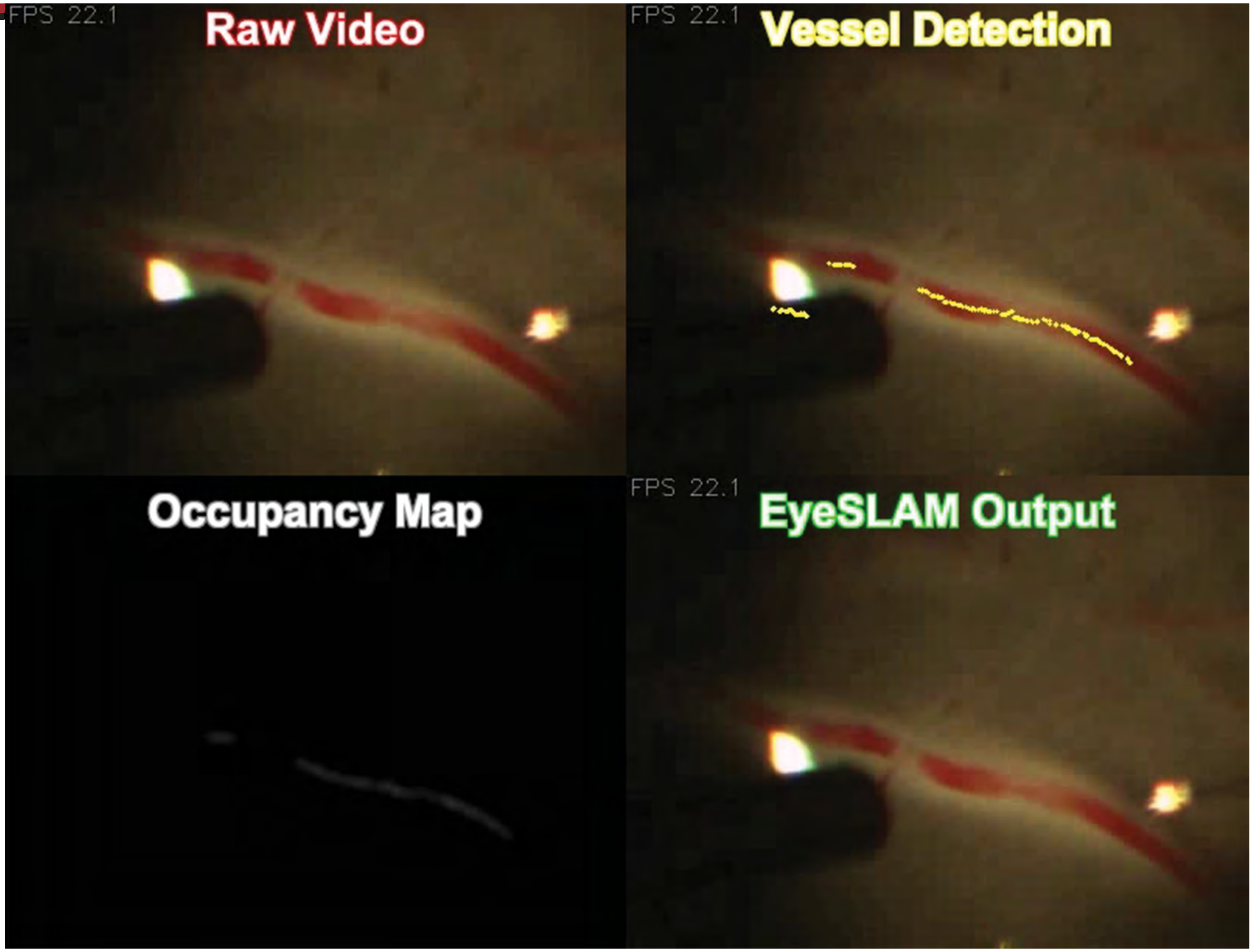


Carnegie Mellon
THE ROBOTICS INSTITUTE

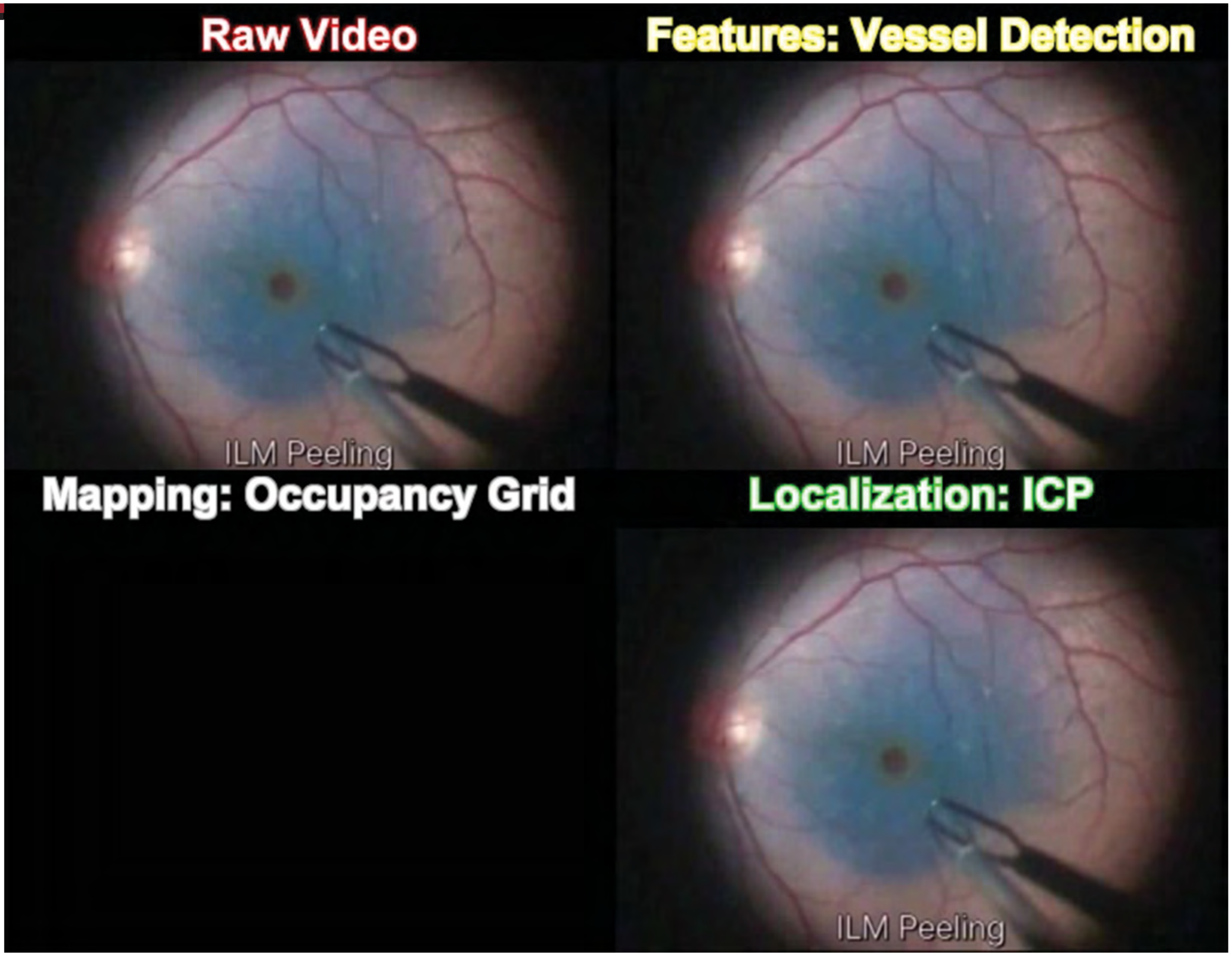
EyeSLAM Illumination Robustness



EyeSLAM with Occlusion



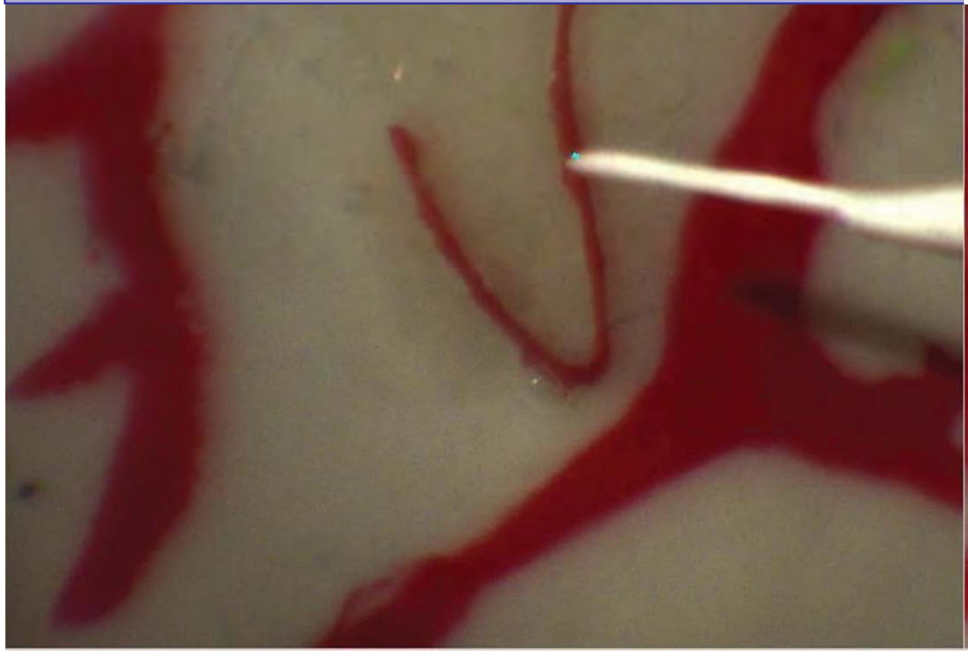
EyeSLAM on Retinal Procedure Video

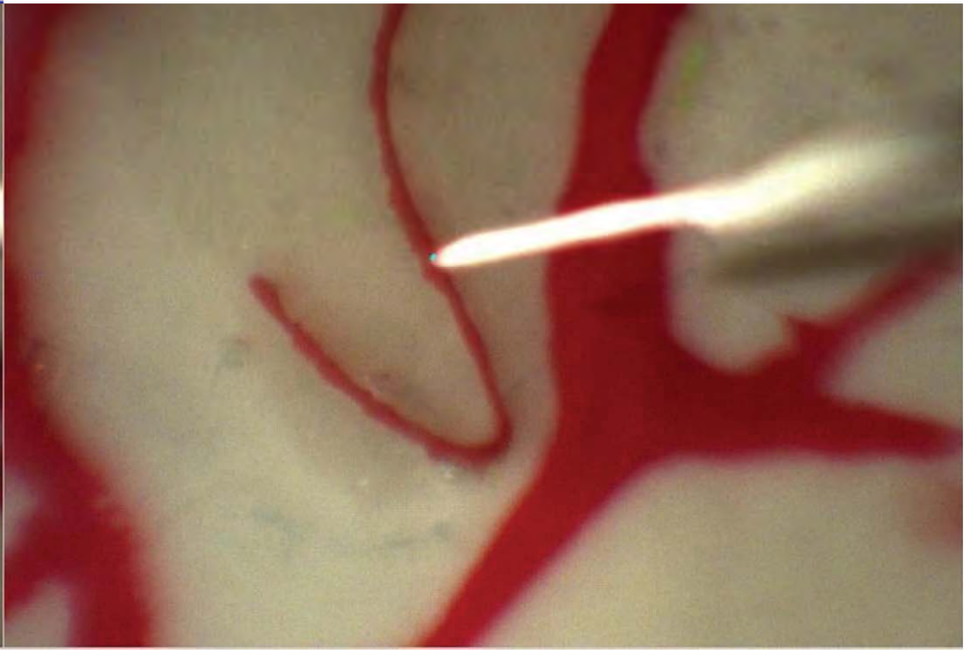


EyeSLAM with Micron Robot

- EyeSLAM tracks vein in eyeball phantom
- Micron enforces virtual fixture, keeping the instrument tip on the vein

Unaided – Micron Off	Aided – Hard Virtual Fixture





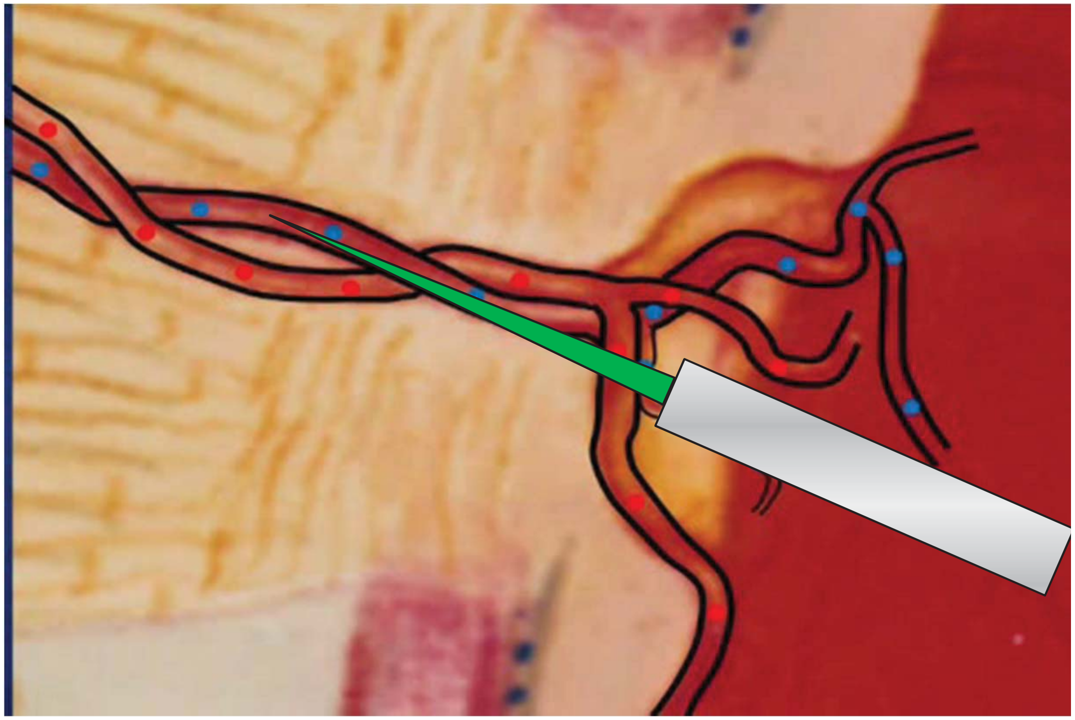
EyeSLAM Summary

- EyeSLAM is a real-time algorithm that:
  - Builds a map of the vasculature
  - Localizes the retinal movements
  - Handles occlusion and moving instruments
  - Robust to illumination changes
- Future work for EyeSLAM improvements
  - More sophisticated motion model (e.g. spherical)
  - Quantitative evaluation of accuracy
  - More robust vessel detection
  - Improve uncertainty to reduce jitter

Vessel Cannulation

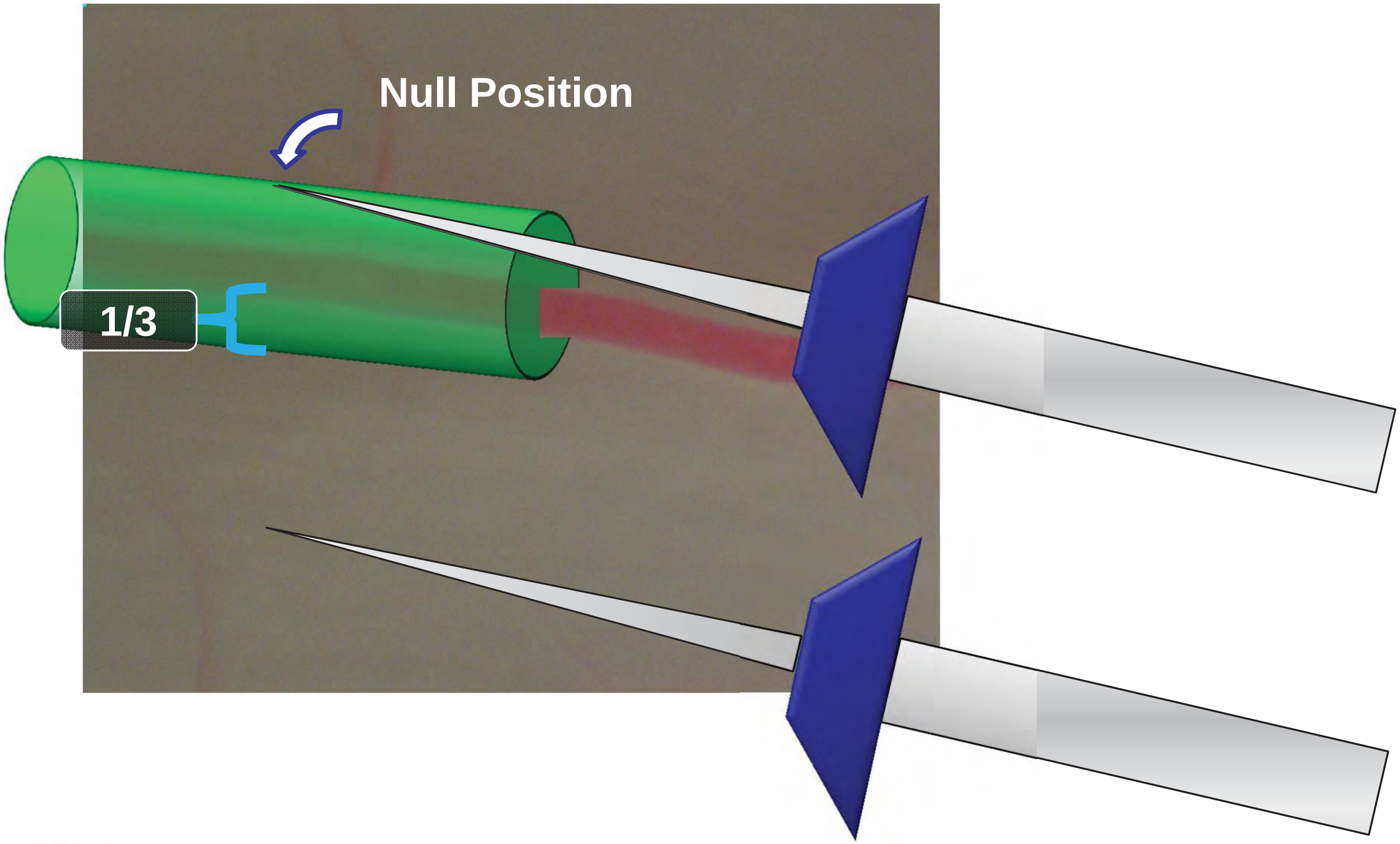
- Inject thrombolytic drugs (Weiss01, Bynoe05, Feltgen07)
- Very difficult (Joussen07)

- Behavior Aids
  - Steady approach
  - Motion scaling
  - Maintain position
  - Prevention zones



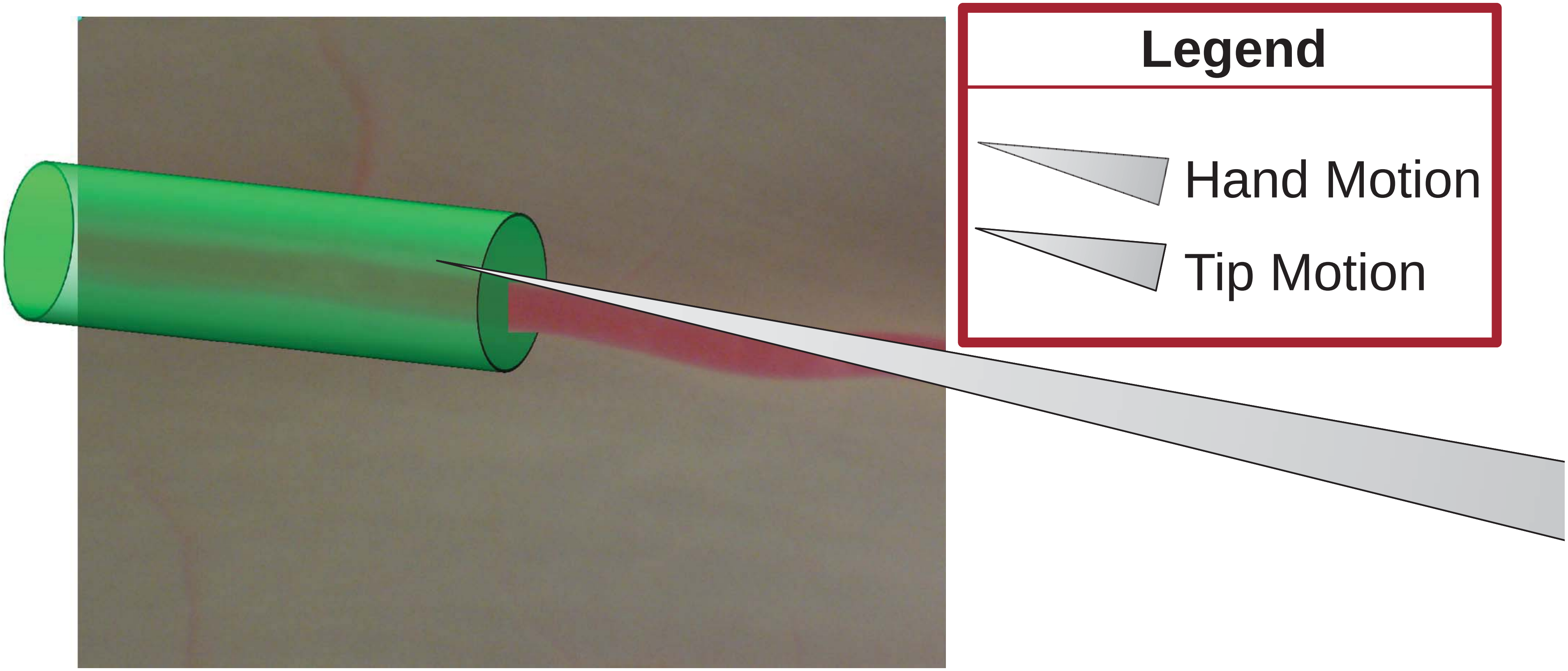
Retinal Vessel Occlusion (RVO)

Anisotropic Motion Scaling



...Plus Tremor Suppression

Combined with low pass filter to reduce tremor in axial direction



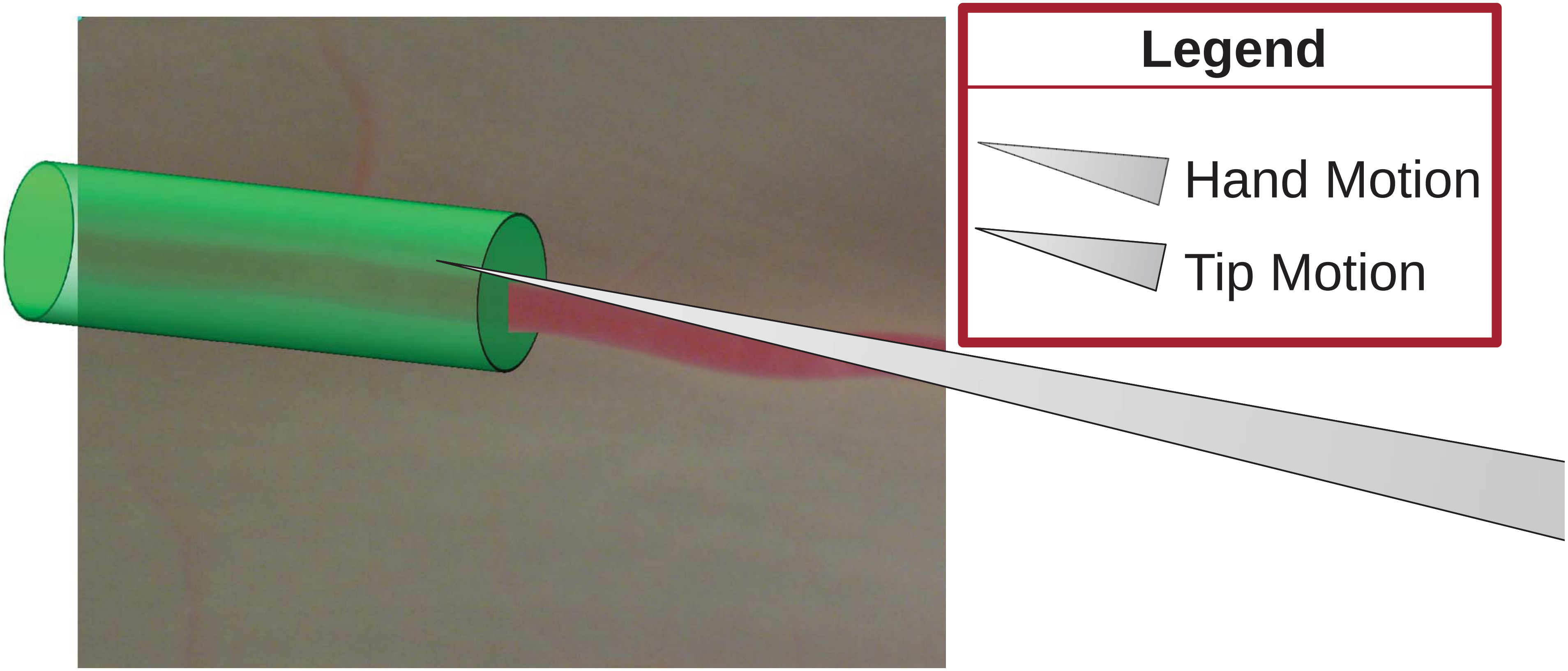
Legend

Hand Motion

Tip Motion

…Plus Tremor Suppression

Combined with low pass filter to reduce tremor in axial direction



Legend

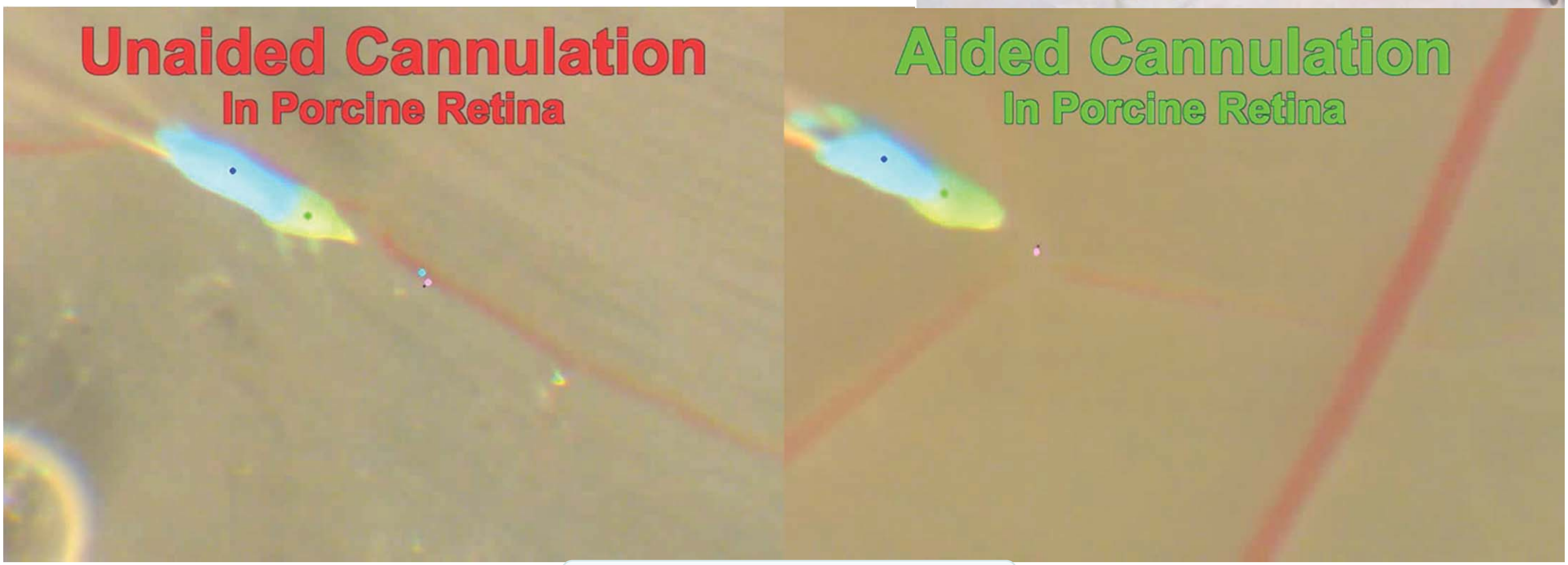
Hand Motion

Tip Motion

Carnegie Mellon
THE ROBOTICS INSTITUTE

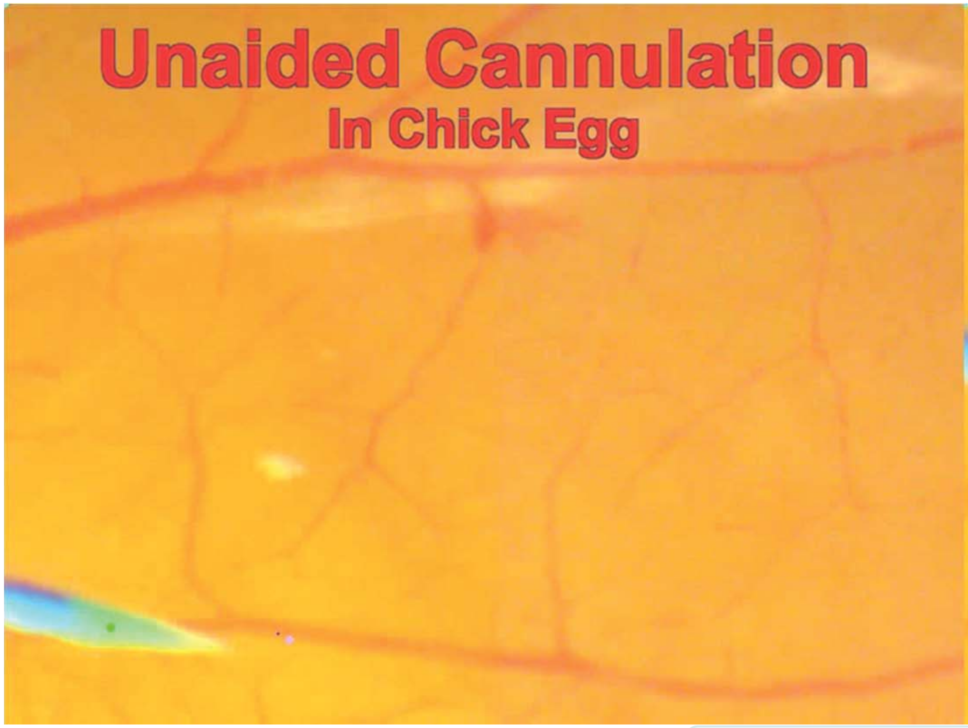
Results: Porcine Retina

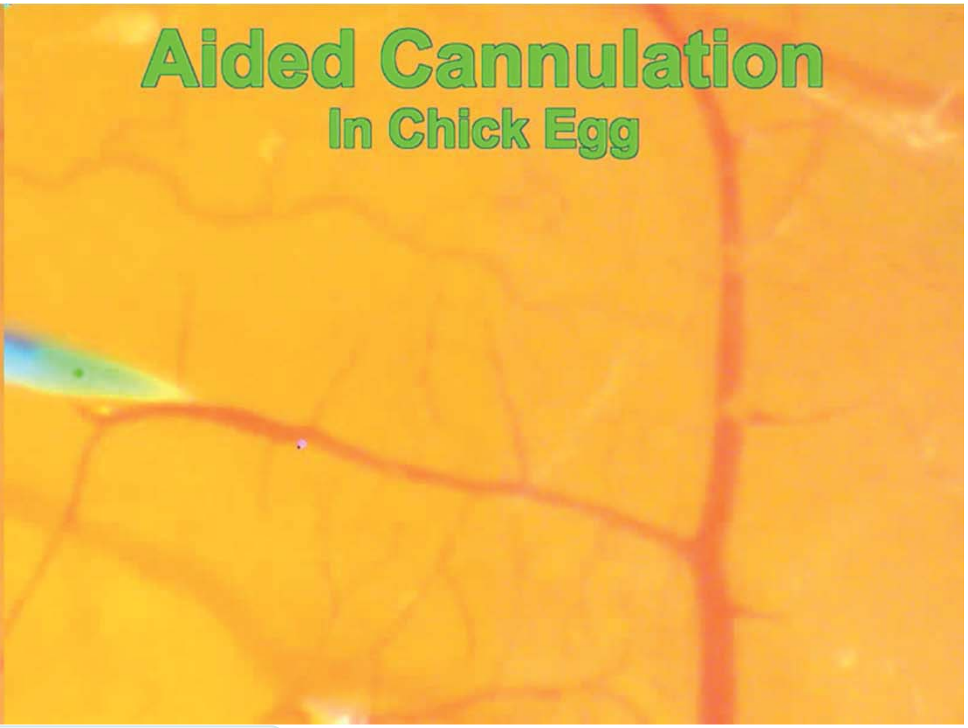
- Surgeon injecting air into vessel in "**open-sky**" setup



Surgeon Results

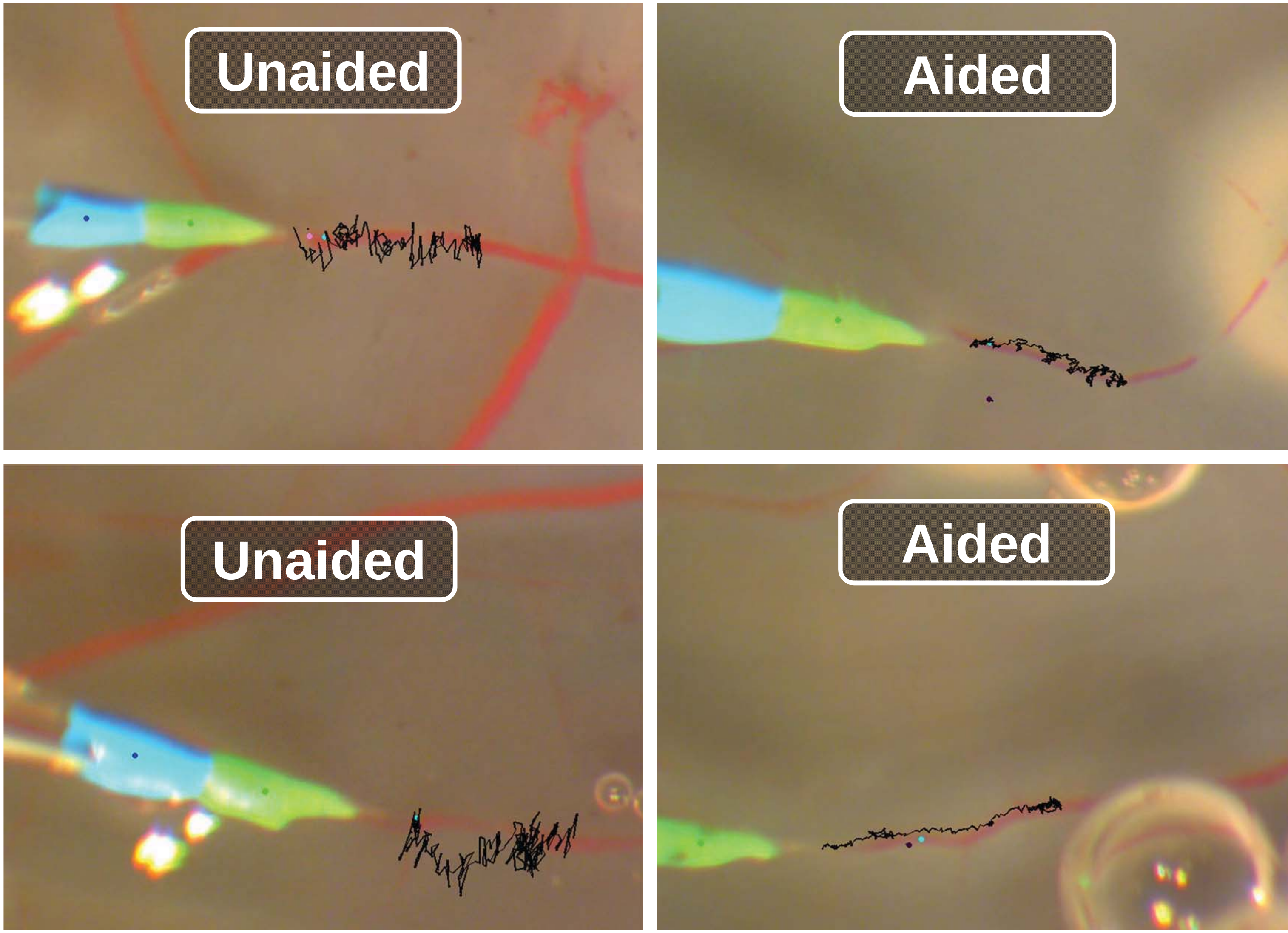
Results: Chick Eggs





Surgeon Results

Results: Tremor Traces

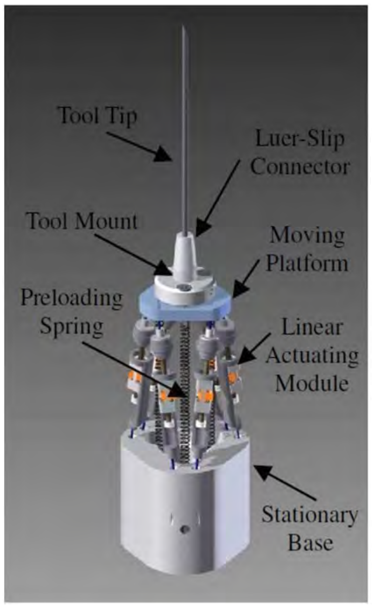


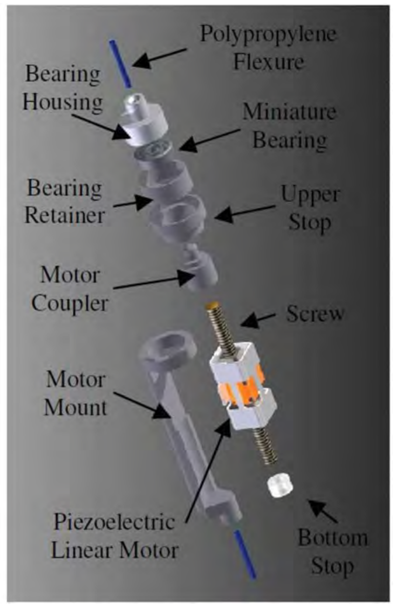
Surgeon Results

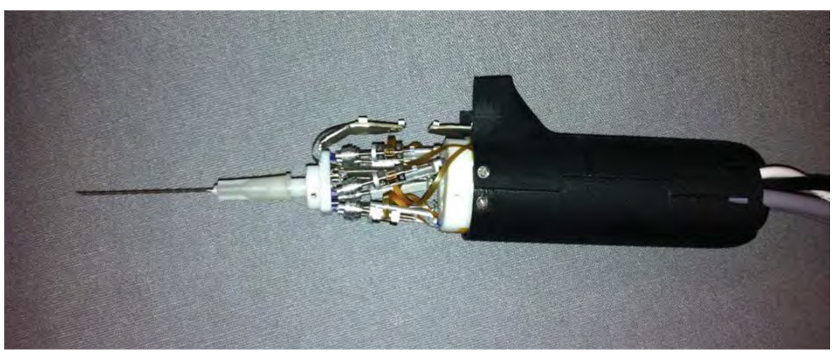
Reduce Side-to-side Positioning Error

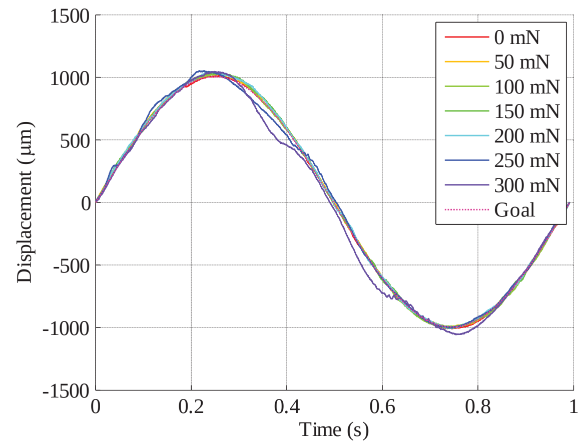
Reduce Collateral Damage

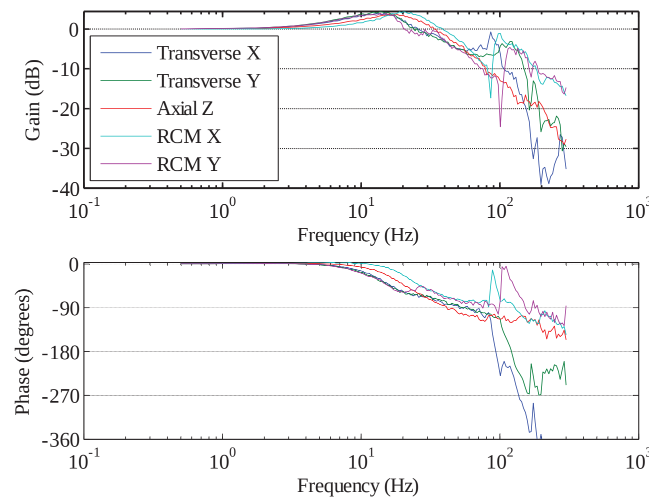
6DOF Micron











Carnegie Mellon
THE ROBOTICS INSTITUTE

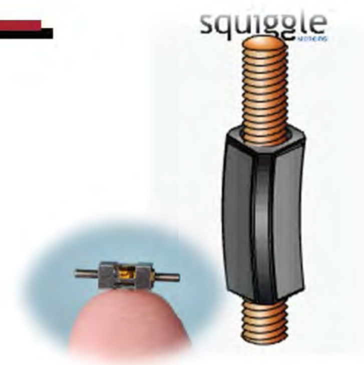
6DOF Micron

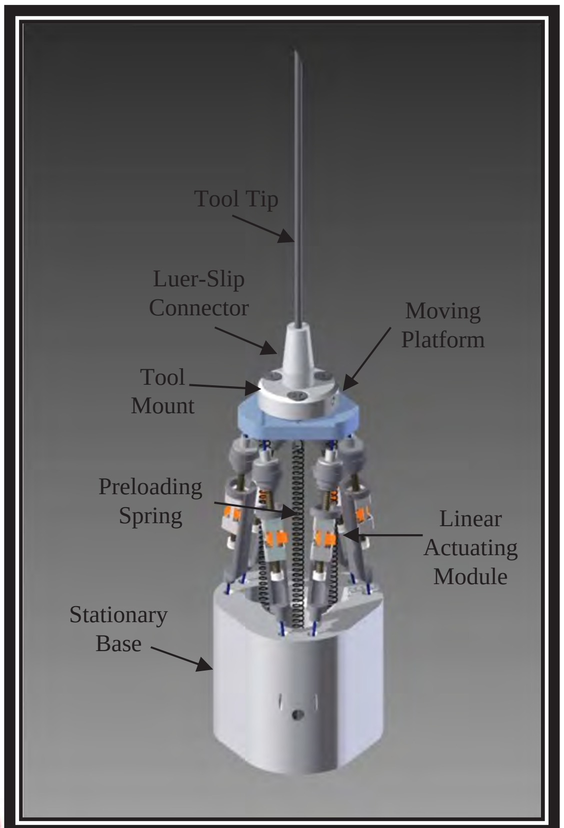
- Design Goal

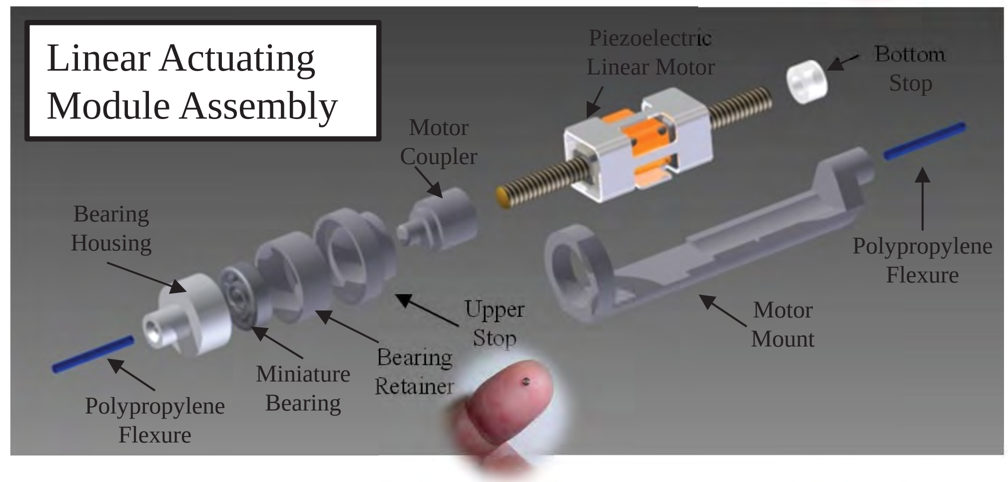
- Higher DOF (~6 DOF)
  - Translation in XYZ at End-Effector (3DOF)
  - Translation in XY at RCM (2 DOF)
  - Axial Rotation (1 DOF)
- Larger Workspace (~4 mm)
- Overall Diameter (~ 25 mm)
- External Load Capability
  - Side Load: Ideally 0.5 N (at least 0.2 N)
  - Normal Load: Ideally 3.0 N

Mechanical Design

- 6 DOF Parallel Micromanipulator



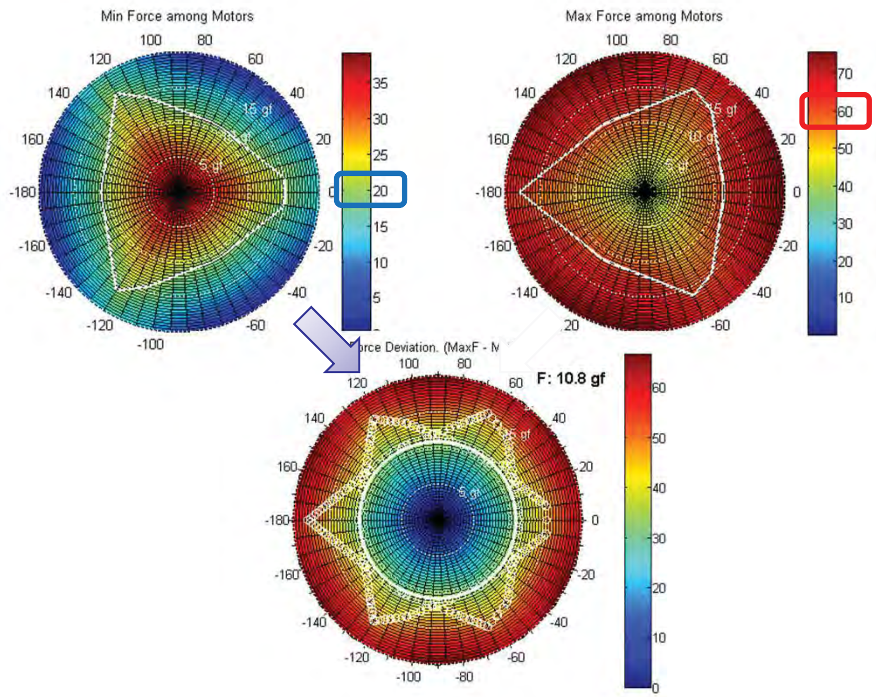




- Dimension:
  - Diameter: 23 mm, Height: 40 mm
- Actuator: SQUIGGLE® motor
  - Dimension: 2.8 mm x 2.8 mm x 6 mm
  - Stall Force: >80 gf at 4.5 V
  - Custom Screw of 14.5 mm
- Flexure Joint: #1-0 polypropylene suture, 1.5 mm length

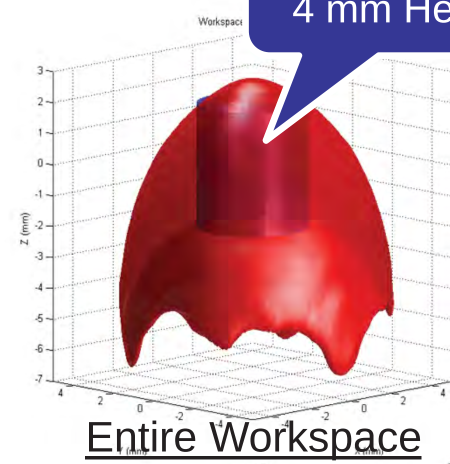
Workspace Analysis

- Sideload Capability

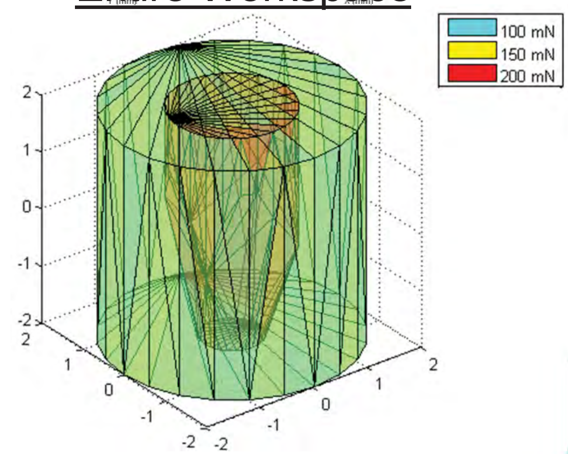


Sideload capability determined by available force range of the motor.

4 mm Diameter
4 mm Height

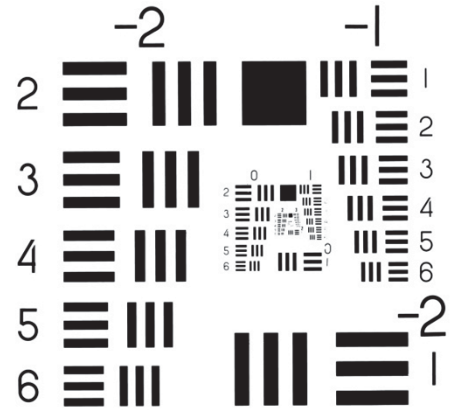


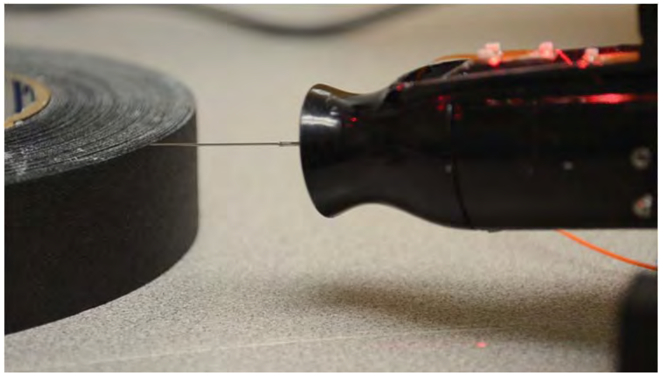
Entire Workspace

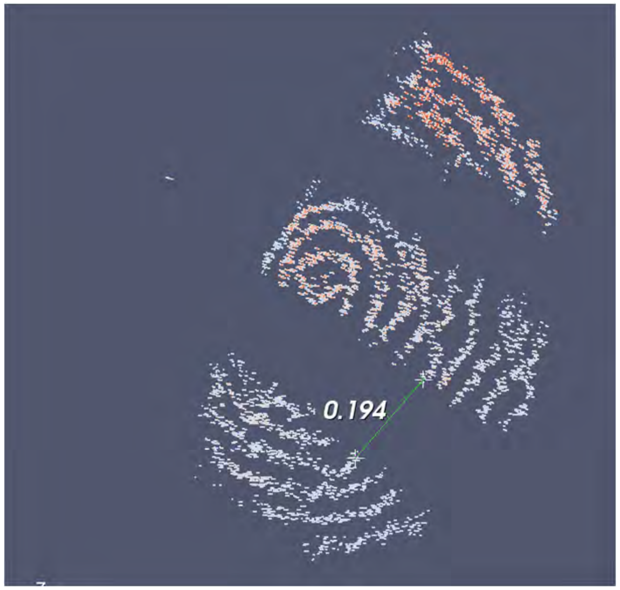


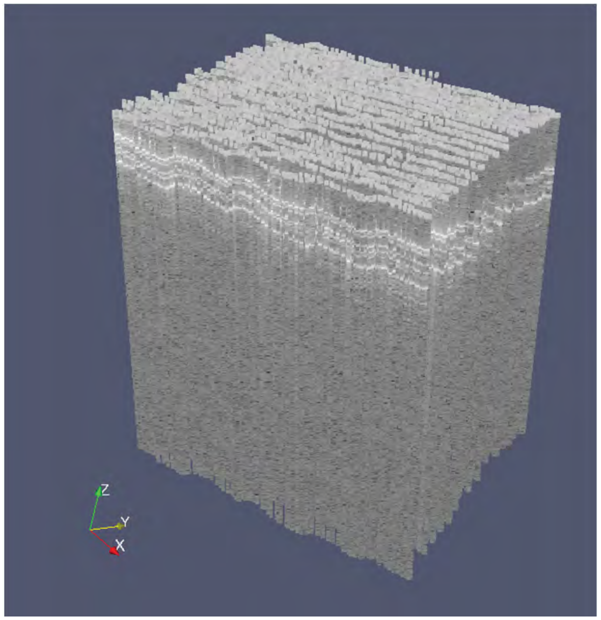
Sideload Capability

OCT Scanning







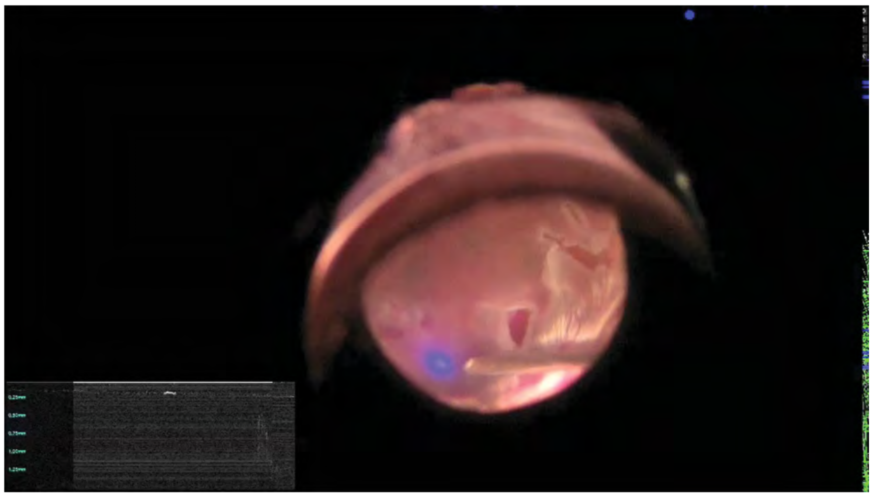


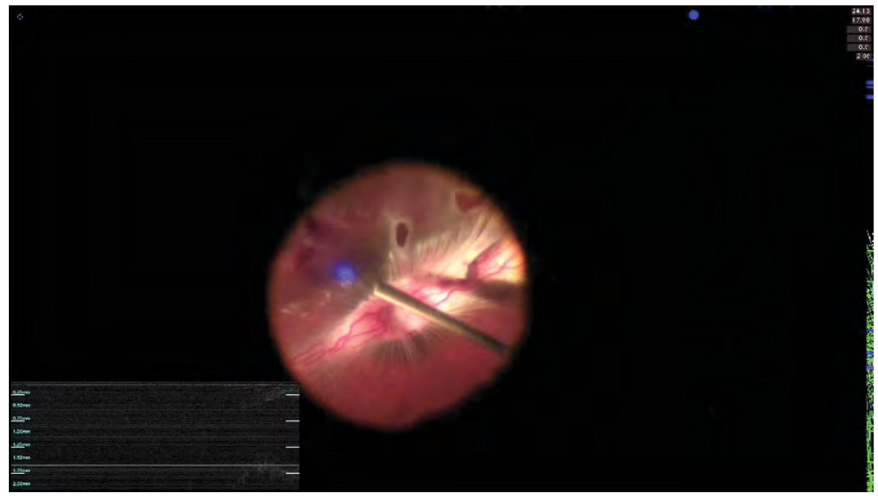
Yang et al., EMBC 2012.

OCT Scanning *in vivo*

B-scan

“M-scan”

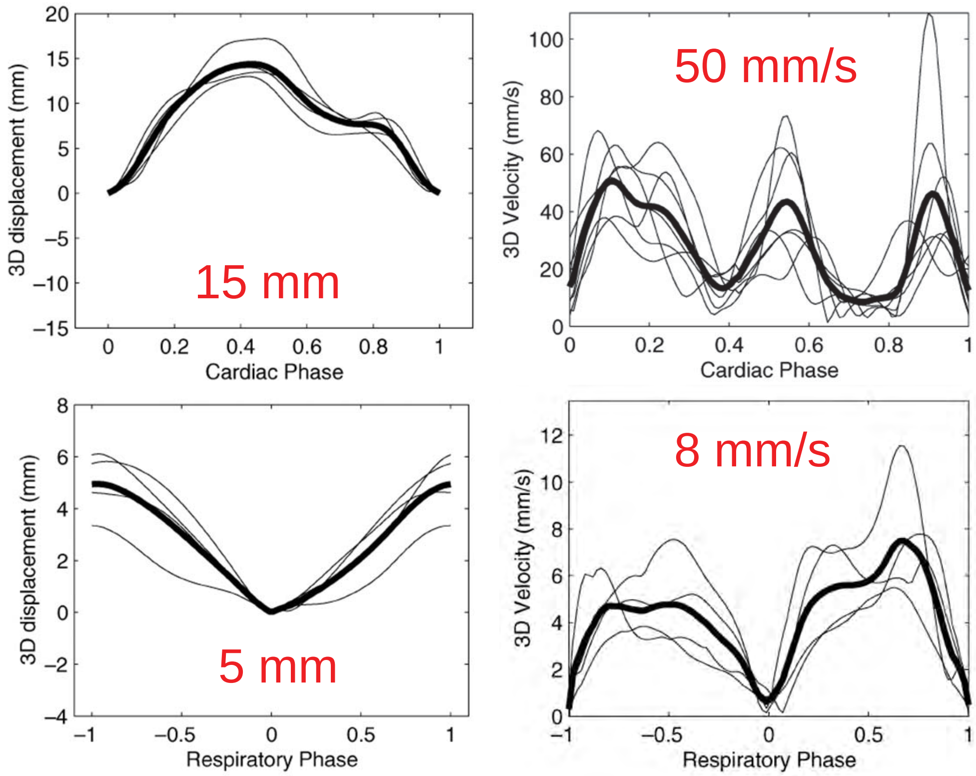




Carnegie Mellon
THE ROBOTICS INSTITUTE

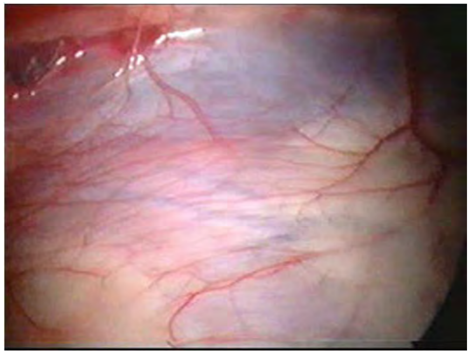
Heartbeat and Respiration

The heart moves a lot…



Figures from Shecter et al. (2006)

- organs surround heart
- pericardium forms virtual space
- large displacements
- high velocities



Heartbeat and Respiration Suppression

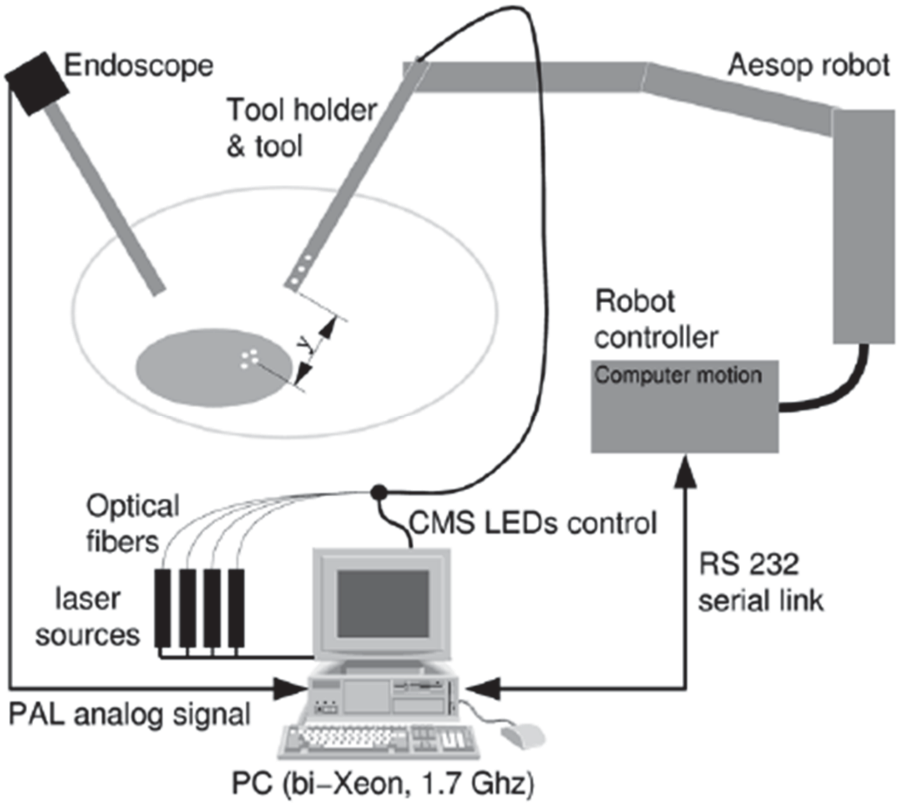
- Active compensation
- Passive compensation

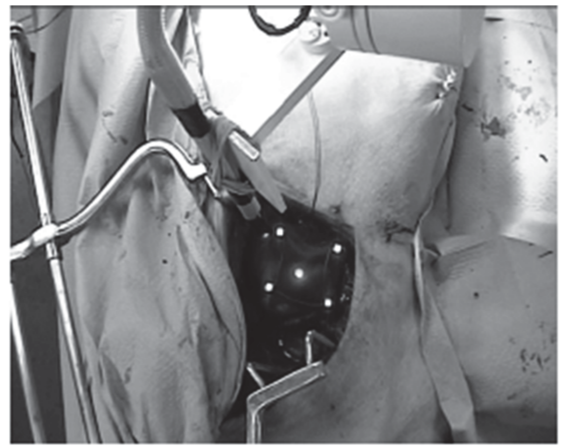
Heartbeat and Respiration Suppression

- Active compensation
- Passive compensation

Vision-based 3D active compensation

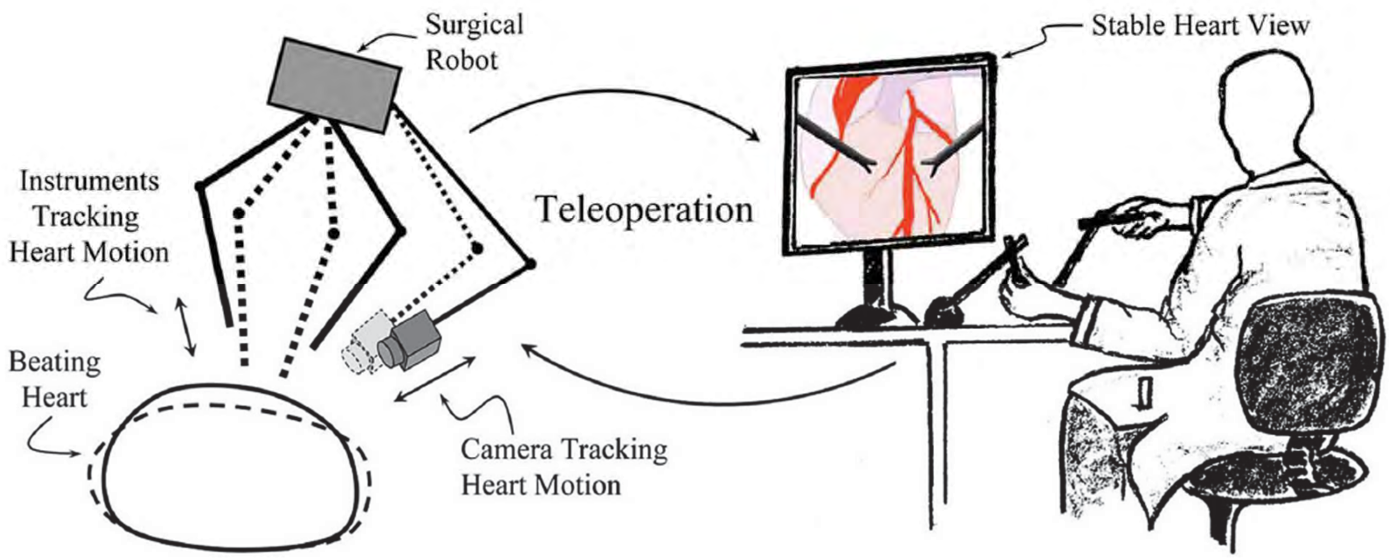
Ginhoux, Gangloff, de Mathelin, et al. (U. Strasbourg)

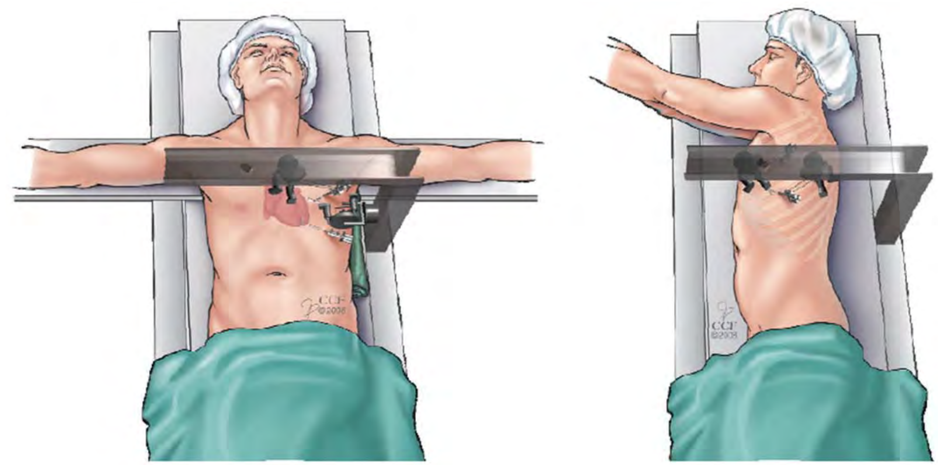




Telerobotic beating heart surgery

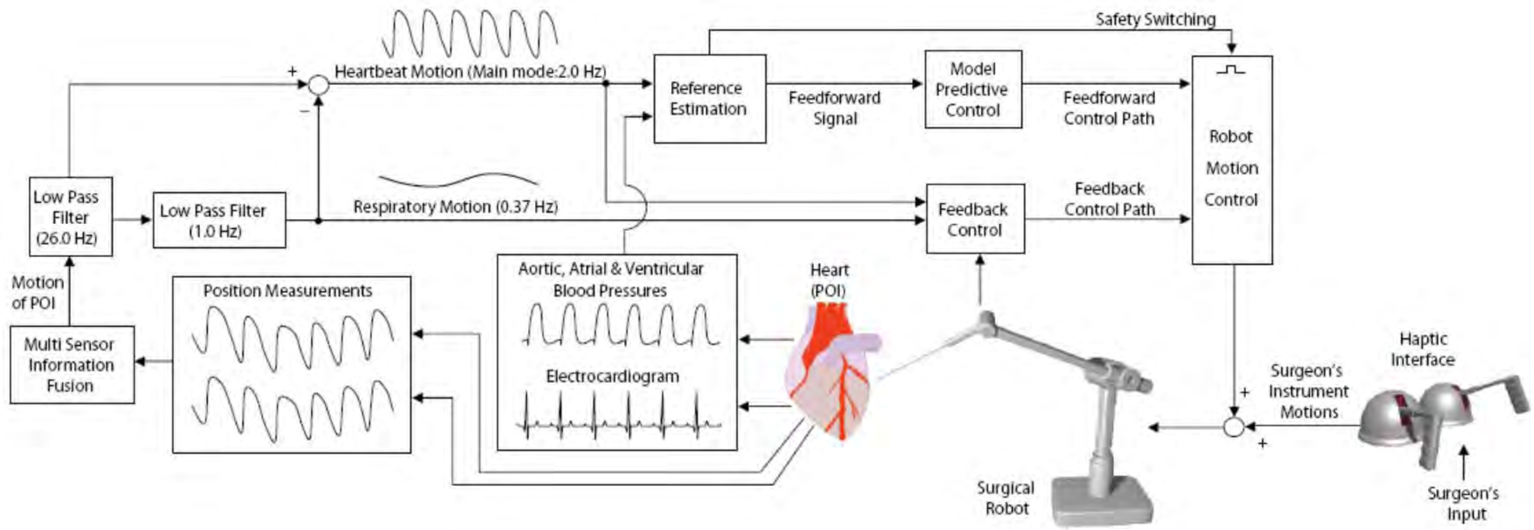
Çavuşoğlu et al. (Case Western Reserve U.)

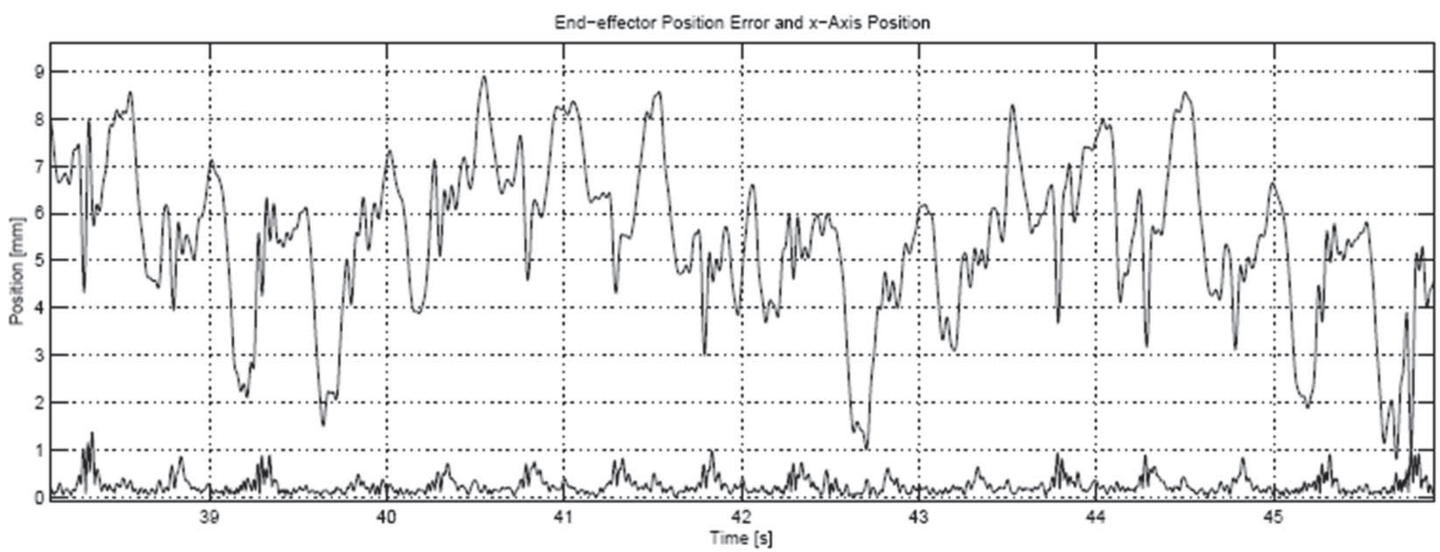




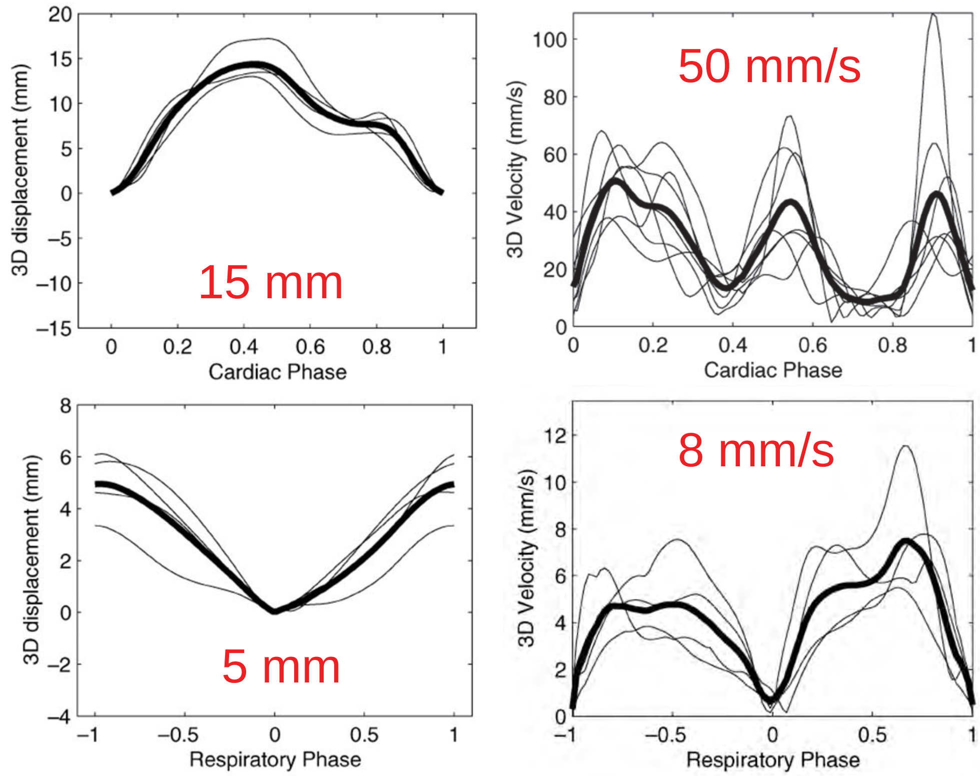
Telerobotic beating heart surgery

Çavuşoğlu et al. (Case Western Reserve U.)



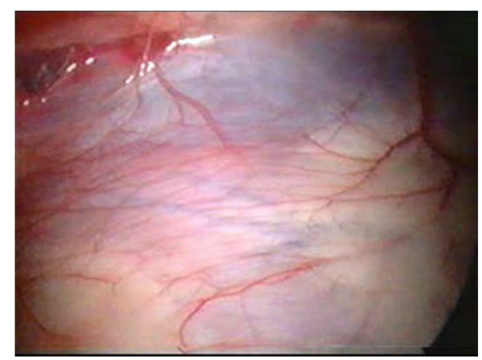


The heart moves a lot…

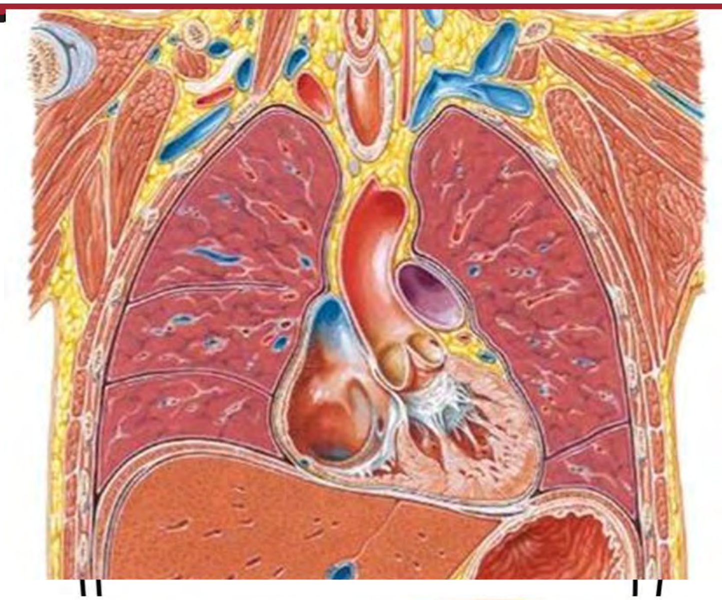


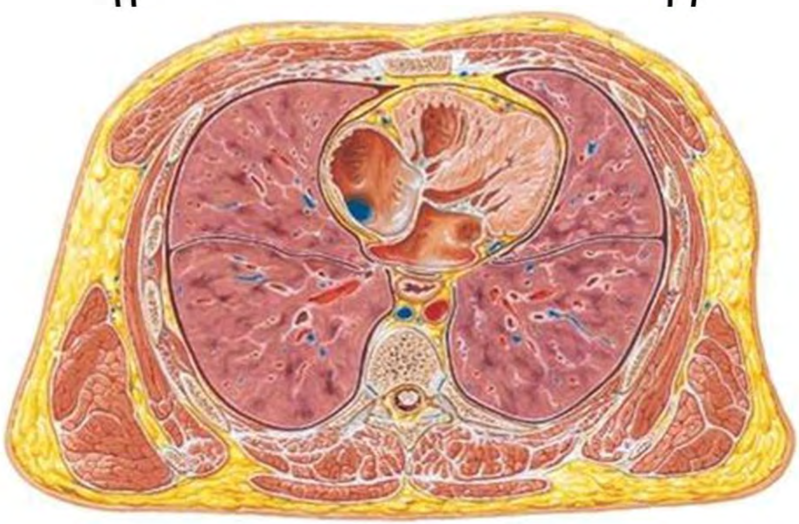
Figures from Shecter et al. (2006)

- organs surround heart
- pericardium forms virtual space
- large displacements
- high velocities



…and there is little room to move on the surface.





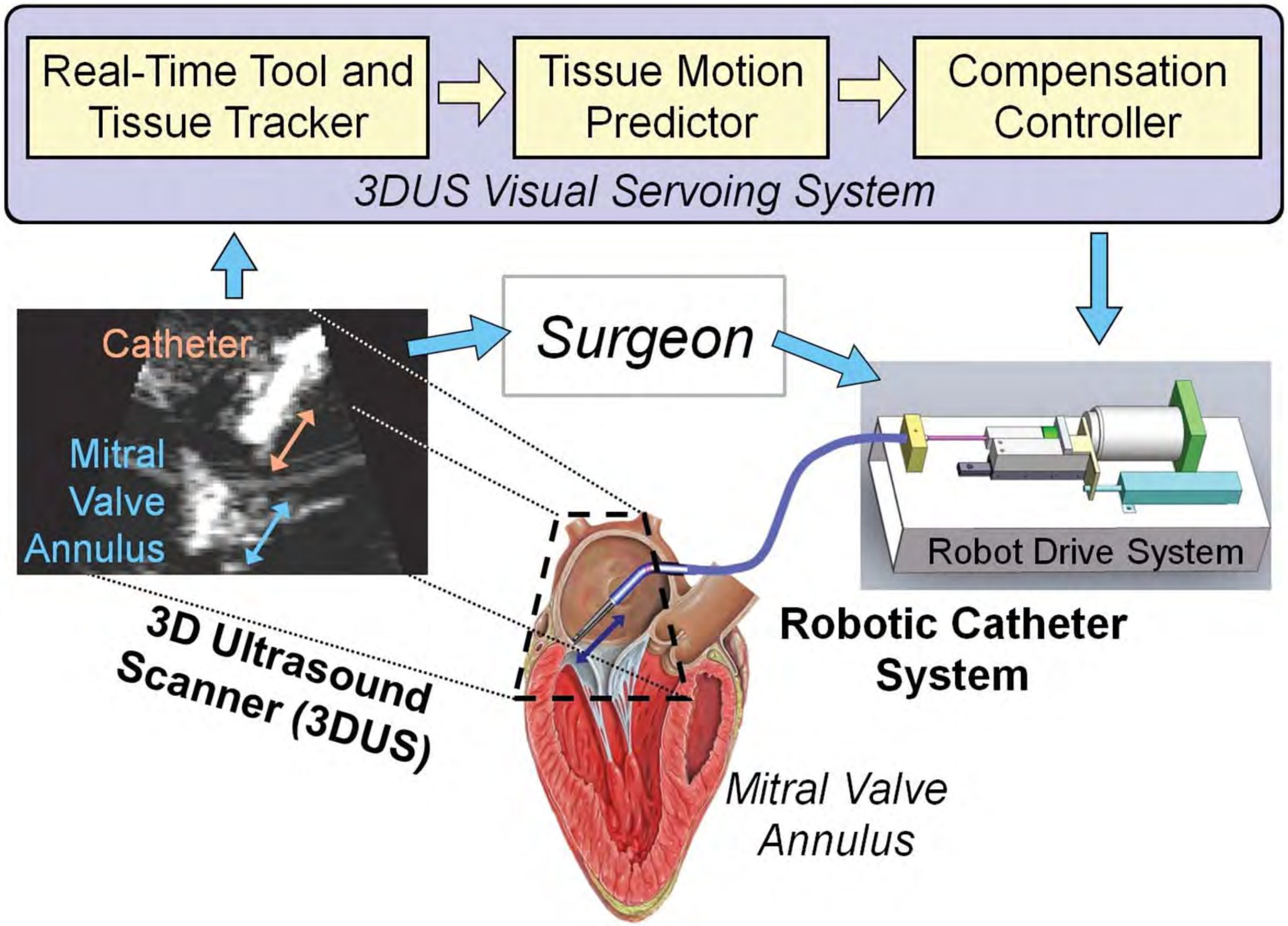
- organs surround heart
- pericardium forms virtual space

GyroLock cardiac stabilizer

Gagne, Piccin, Laroche,Gangloff, Diana (U. Strasbourg)

1DOF motion-compensated cardiac catheter

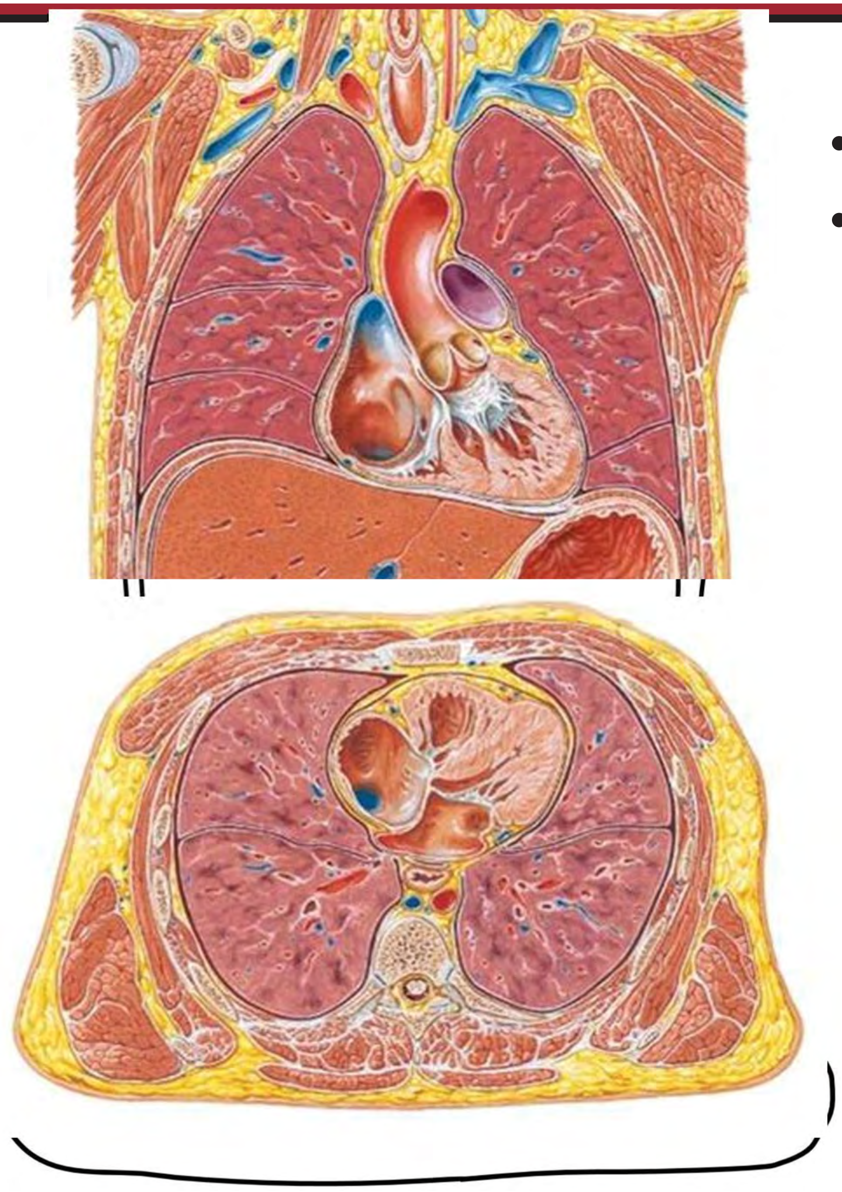
Kesner, Howe (Harvard)



Heartbeat and Respiration Suppression

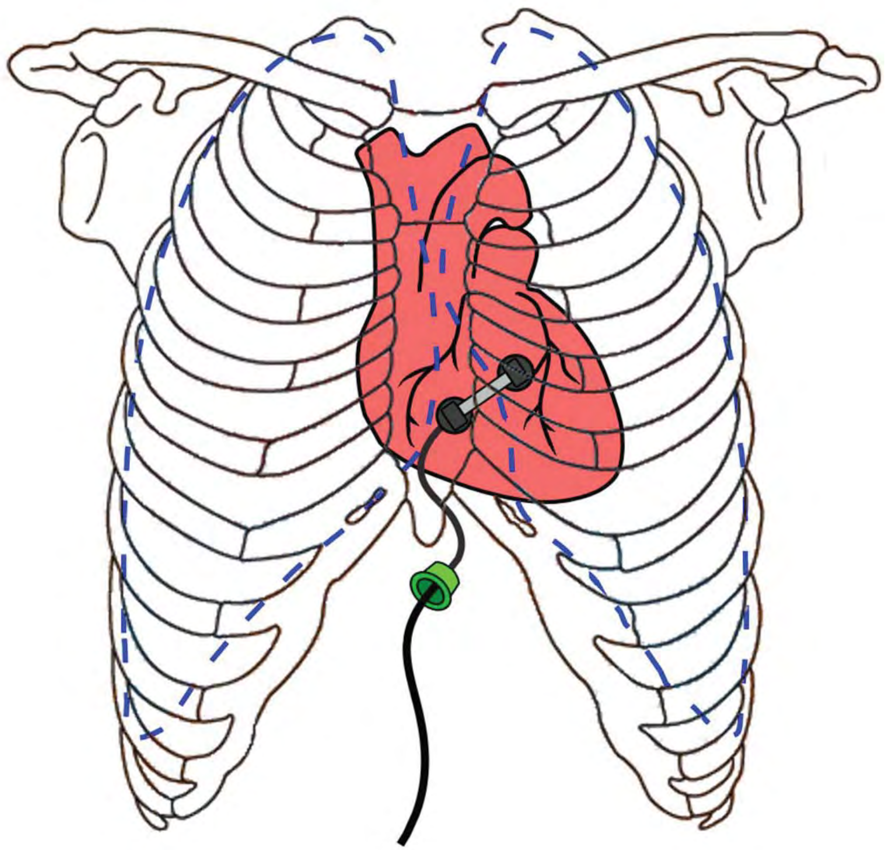
- Active compensation
- Passive compensation

…and there is little room to move on the surface.



- organs surround heart
- pericardium forms virtual space

Advantages of HeartLander paradigm



① flexibility
→ **no lung deflation**

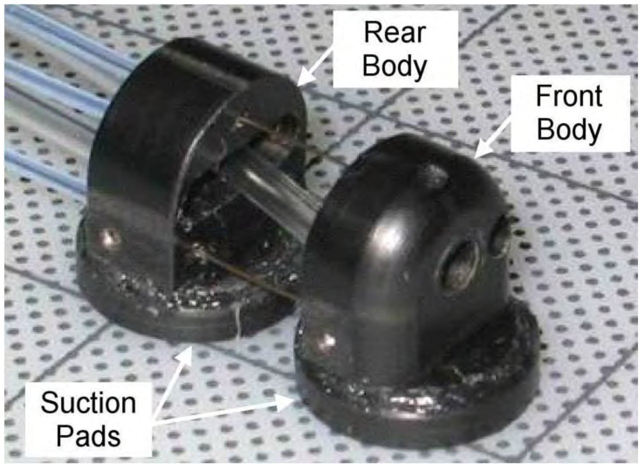
② epicardial prehension
→ **no stabilization**

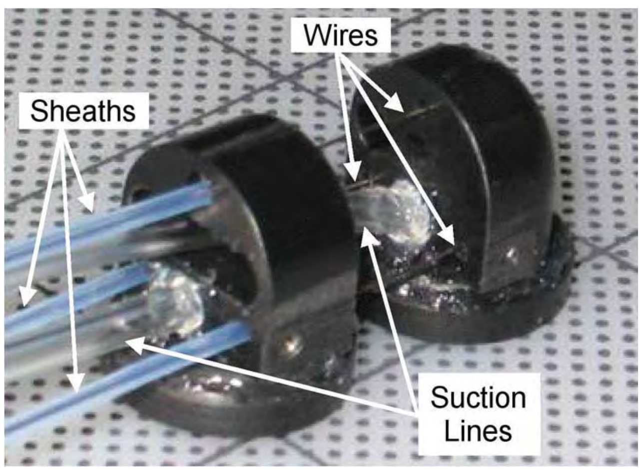
③ locomotion
→ **no access limitation**

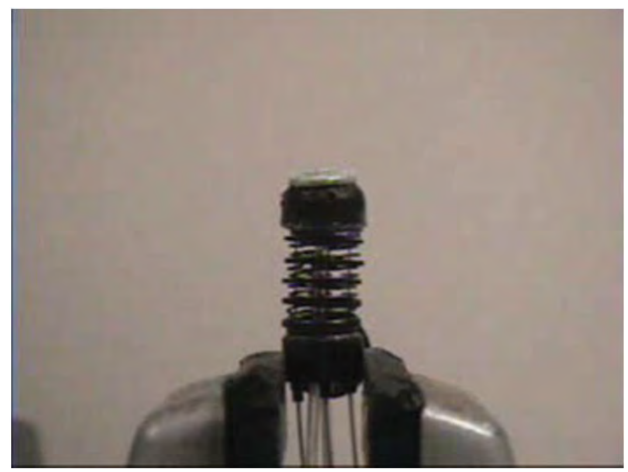
Potential interventions

- Surgical Applications
  - epicardial electrode placement (screw, suture)
  - intrapericardial drug delivery (needle)
  - cell transplantation (needle)
  - gene therapy for angiogenesis (needle)
  - epicardial atrial ablation (laser, electrode)
- Interventional Cardiology
- Electrophysiology

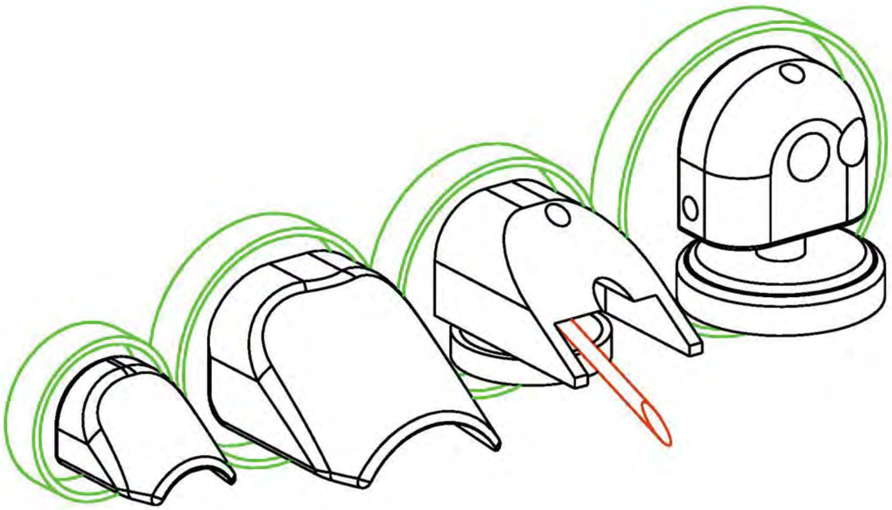
Inchworm locomotion

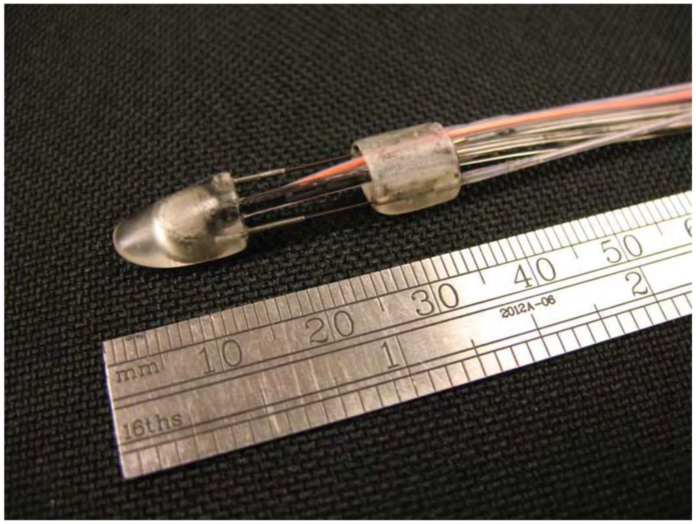






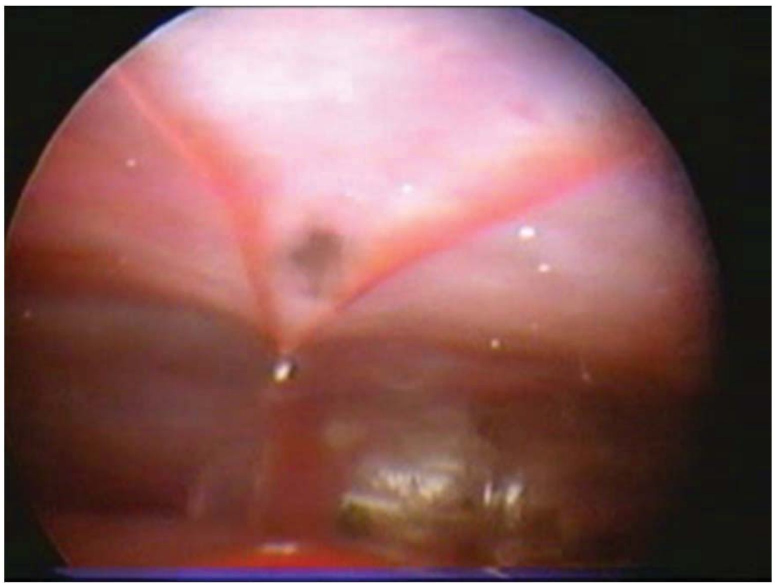
Prototypes

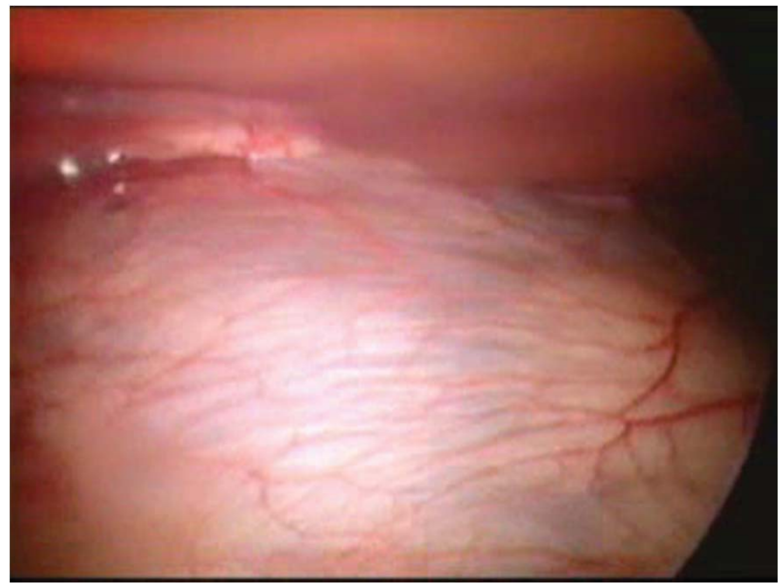




Intrapericardial locomotion *in vivo*

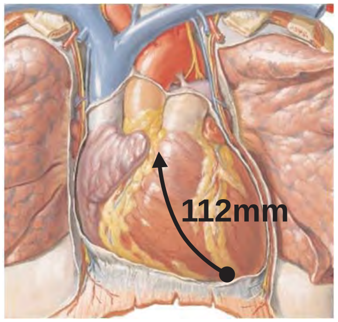
in porcine model





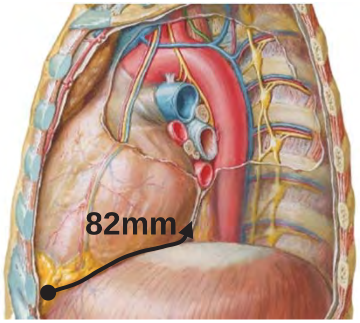
Carnegie Mellon
THE ROBOTICS INSTITUTE

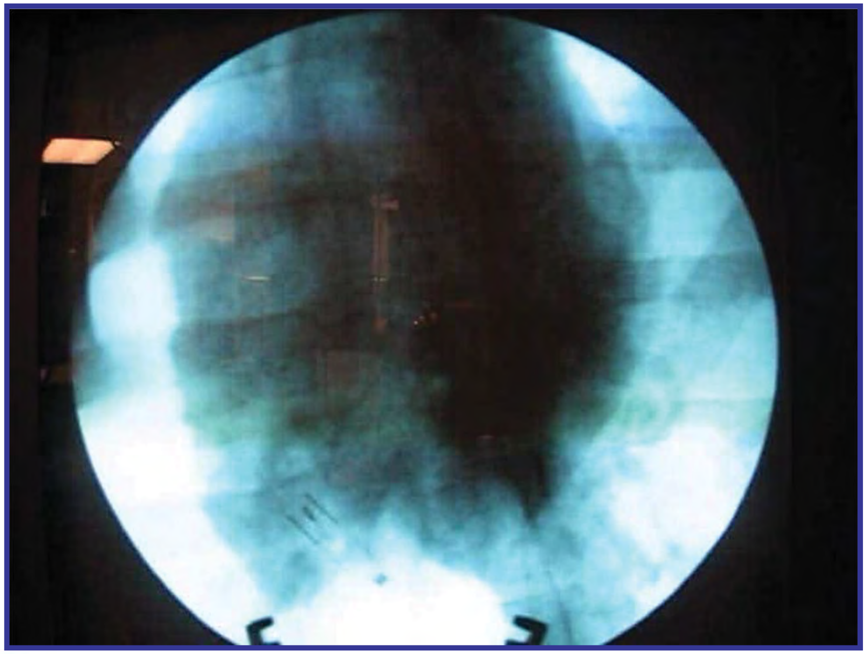
Locomotion: Anterior and Posterior Surfaces

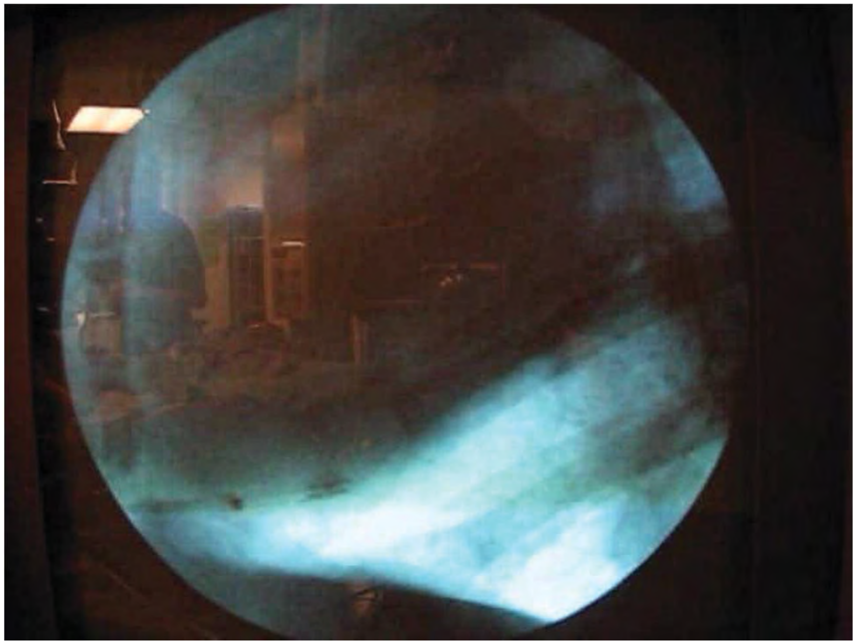


Anterior Right Ventricle

Posterior Left Ventricle



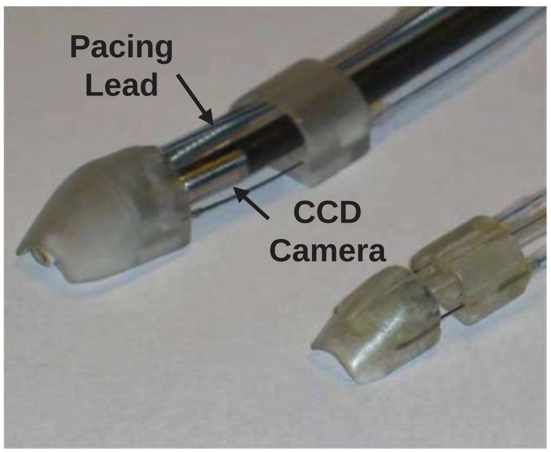


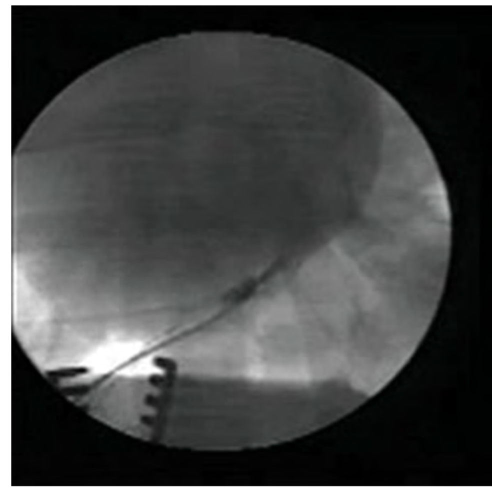


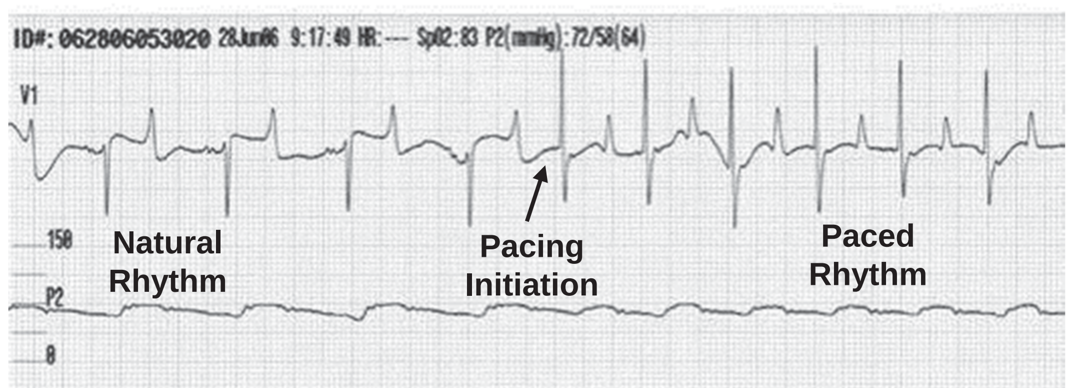
Epicardial lead placement

via subxiphoid access

- Successful lead placement on posterior left ventricle

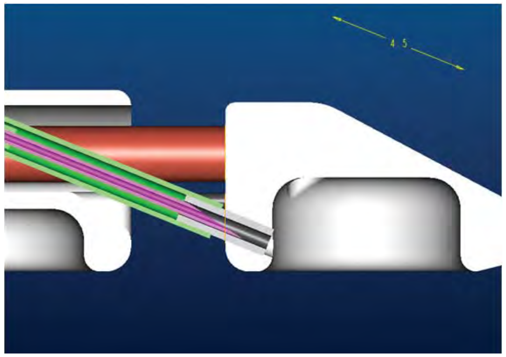


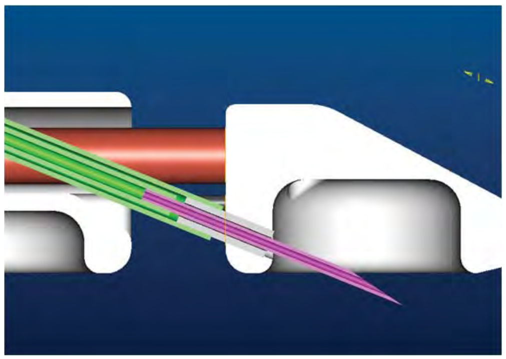


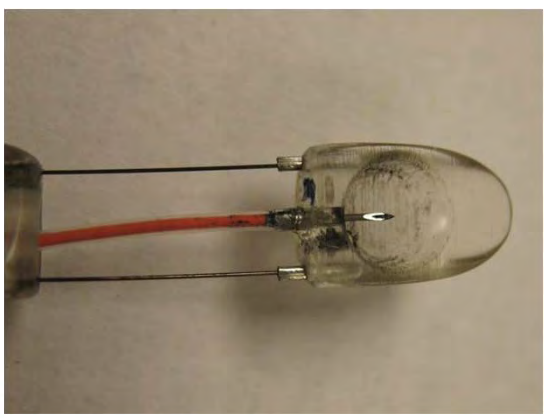


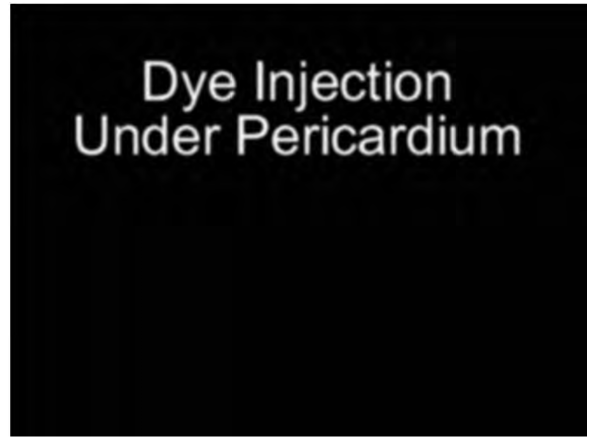
Dye Injection

via subxiphoid access

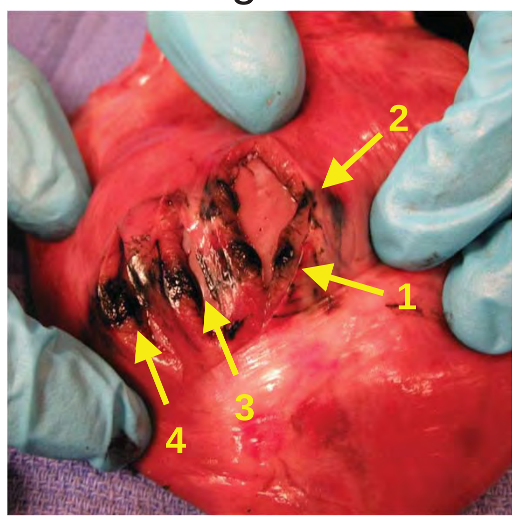




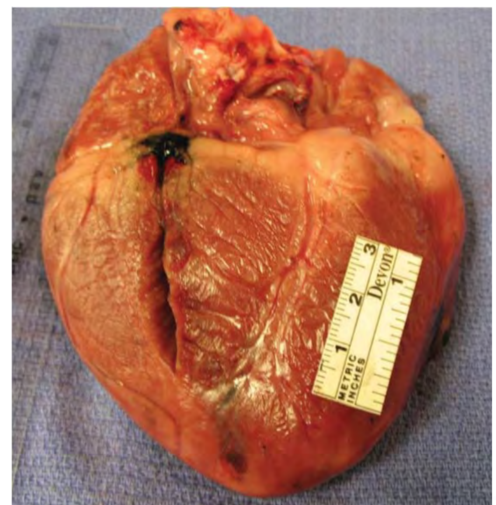




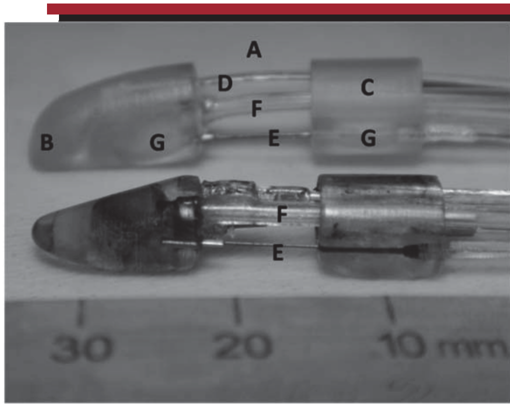
Anterior Right Ventricle



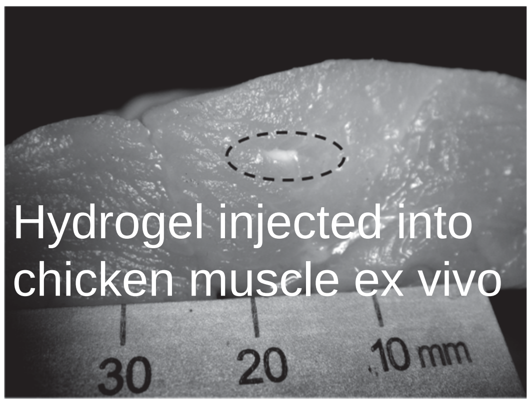
Posterior Left Ventricle

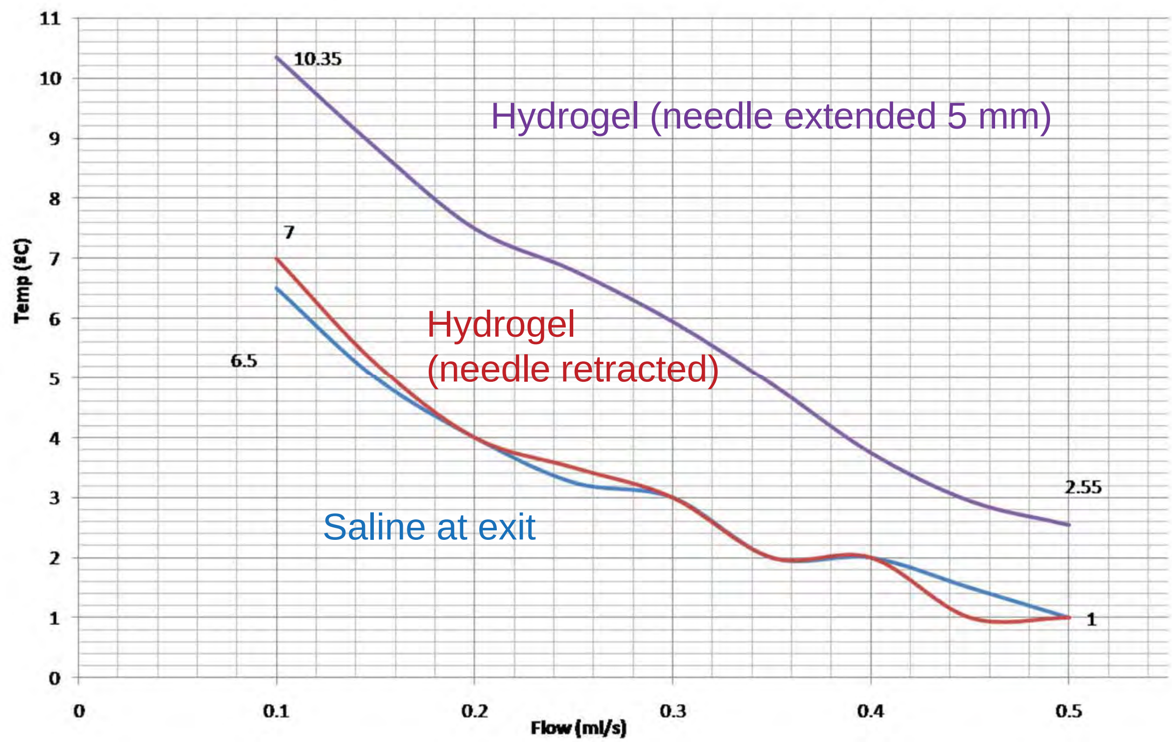


Injection of cooled anti-remodeling hydrogel



A. HeartLander
B. Front foot
C. Rear foot
D. Injection needle
E. Drive wires
F. Front suction line
G. Suction chambers





Clinical advantages

…over conventional surgery

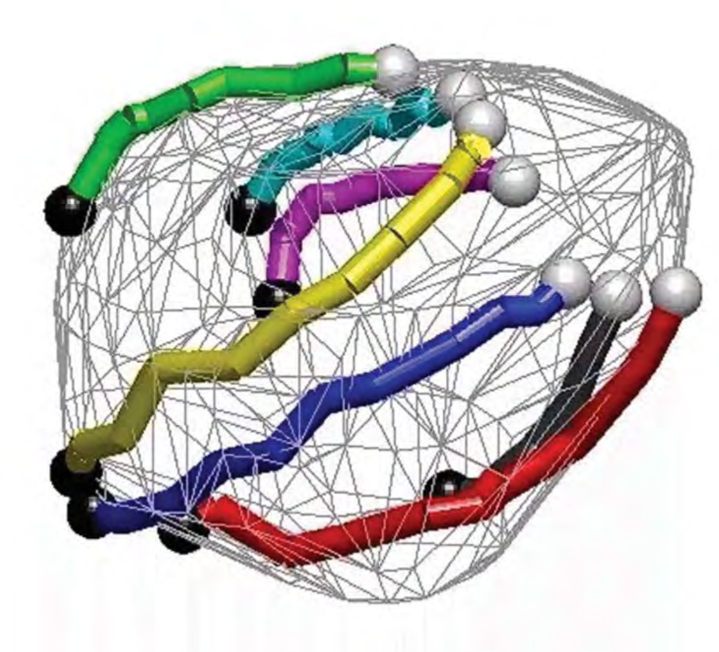
- no sternotomy
- no cardiopulmonary bypass

…over current MIS

- no immobilization of heart
- inexpensive, possibly disposable
- no lung deflation
- obviates general endotracheal anesthesia
- **outpatient heart surgery?**

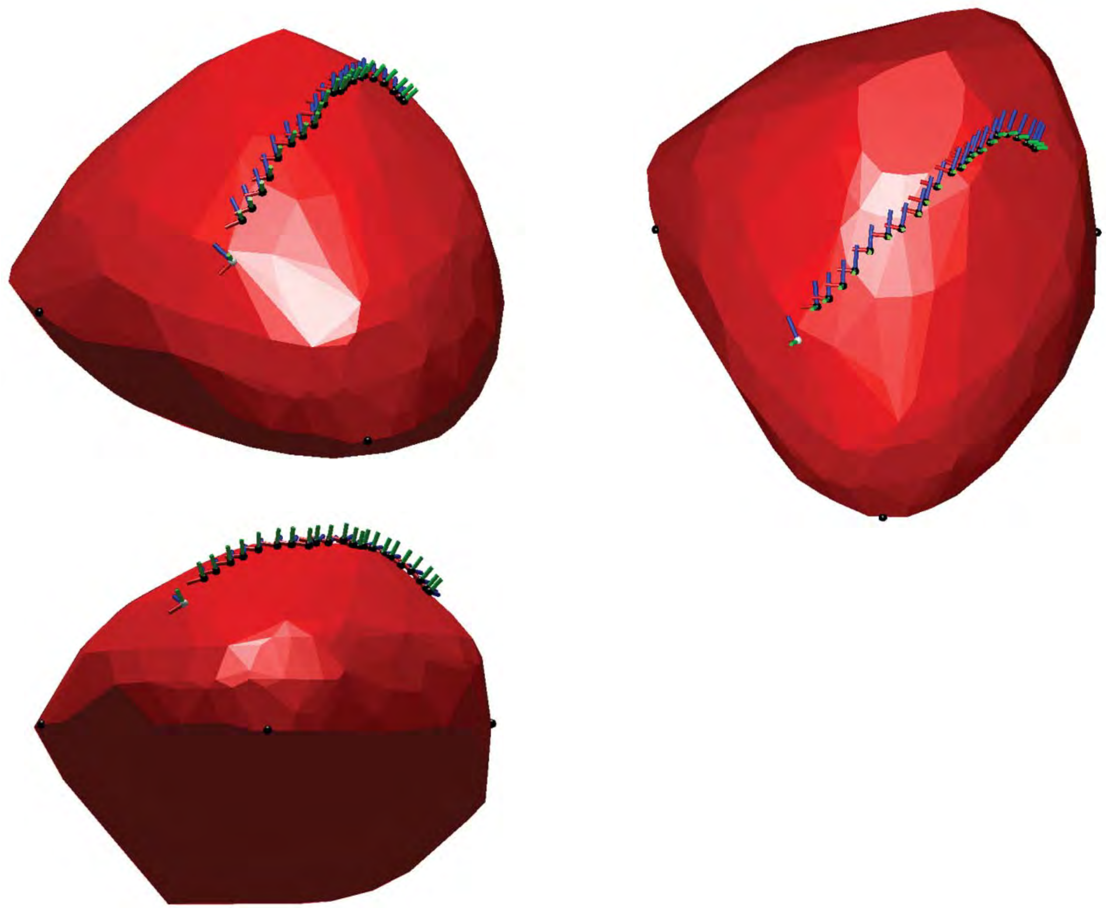
Access to all aspects of heart

Trial No.	Anatomical Location	Path Length (mm)	Time (s)	Average Speed (mm/min)	Number Of Steps	Step Efficiency (%)
3 (*green*)	anterior midline	73	50	88	8	45
6 (*yellow*)	right wall	100	84	71	13	38
4 (*cyan*)	left lateral	52	77	40	12	21
7 (*blue*)	right lateral	110	63	104	10	54
8 (*magenta*)	left lateral	61	77	48	12	25
9 (*red*)	right posterior	115	99	70	15	38
2 (*black*)	left posterior	53	22	143	4	65
mean		81	67	81	11	41
st. dev.		27	25	35	4	15

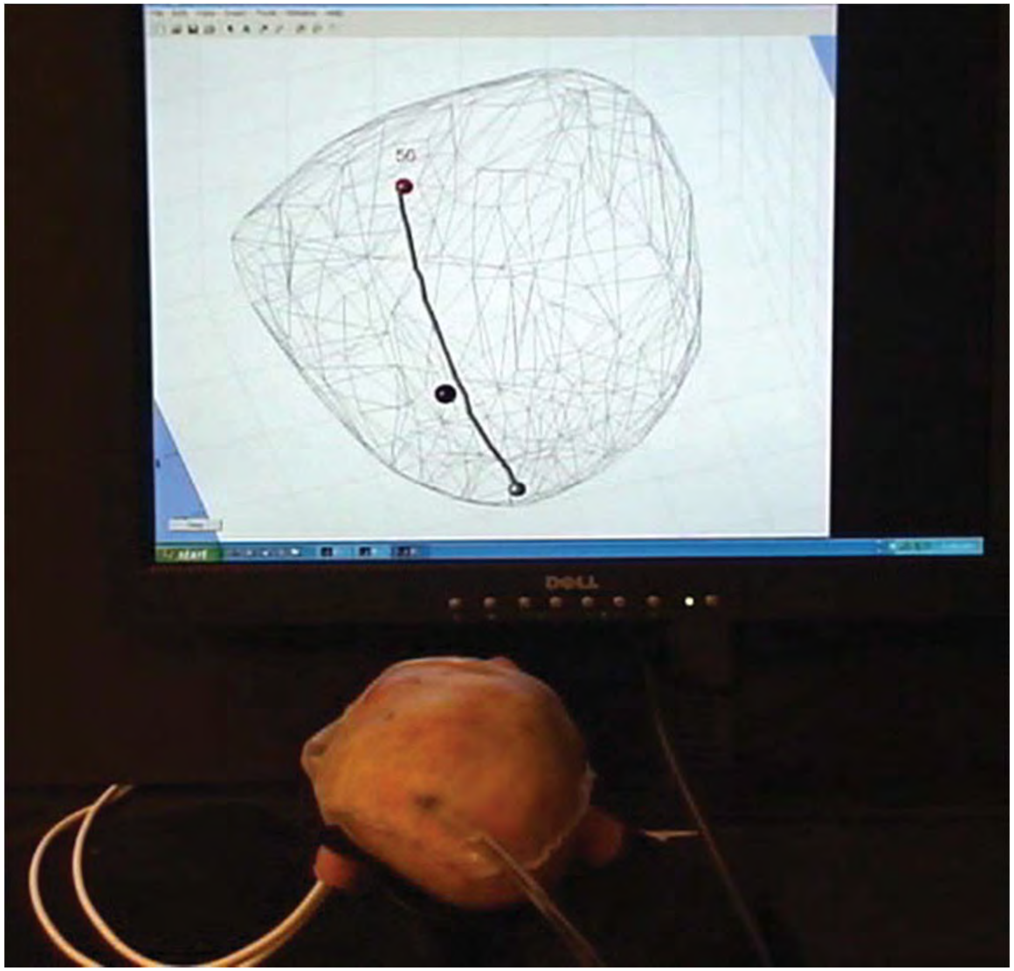


Carnegie Mellon
THE ROBOTICS INSTITUTE

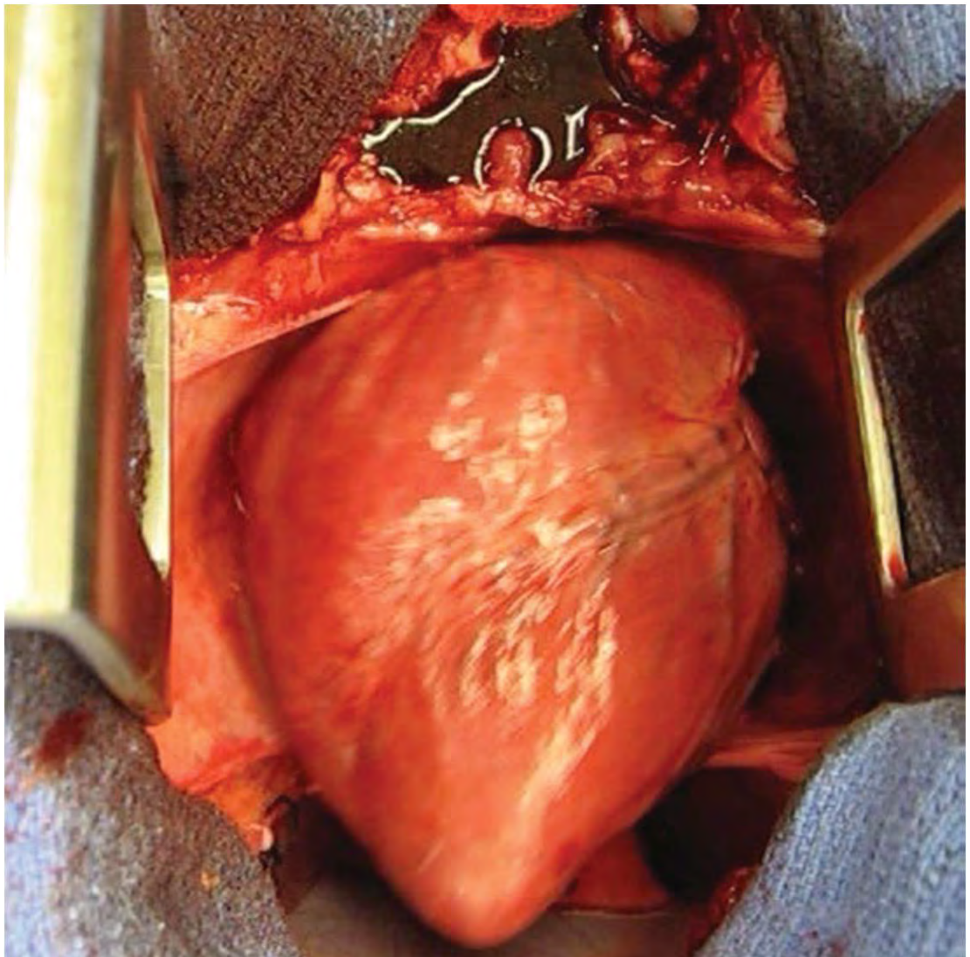
Lateral locomotion on beating heart phantom

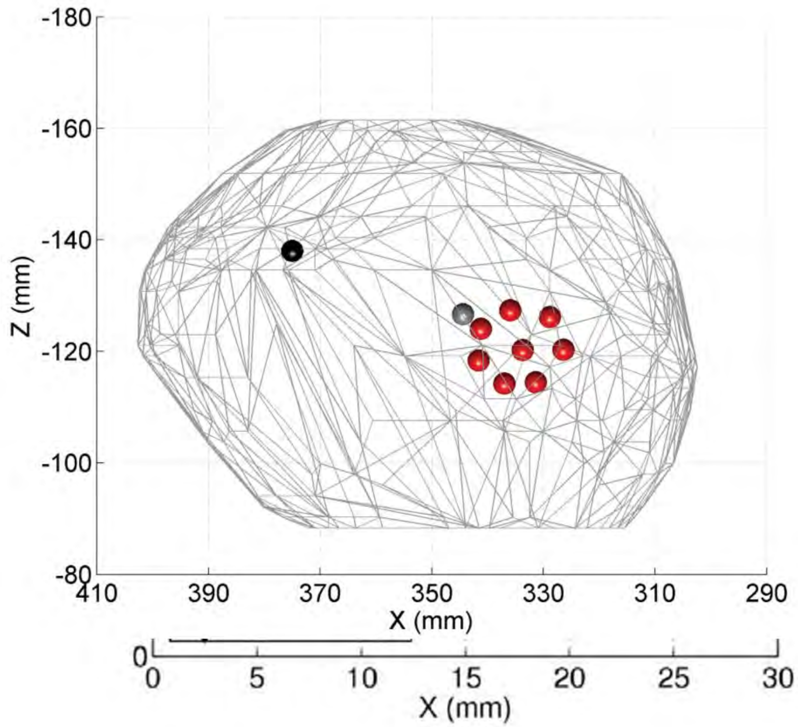


Locomotion accuracy/path following
closed loop



Fine Positioning: Posterior Surface





Overall error = 1.7 ± 1.0 mm

Carnegie Mellon
THE ROBOTICS INSTITUTE

Efficiency Improvement

- Locomotion efficiency < 50% due to slippage
- Intrapericardial pressure varies significantly due to physiological cycles
- Approaches:
  - Synchronization: Detect phase of physiological cycles and synchronize stepping with minimum intrapericardial pressure
    - Extended Kalman-filter-based model of physiological motion
  - Improved traction: Apply gecko-foot-inspired adhesive fibers (Prof. M. Sitti) in combination with suction

Physiological Motion Modeling

Measurement

=

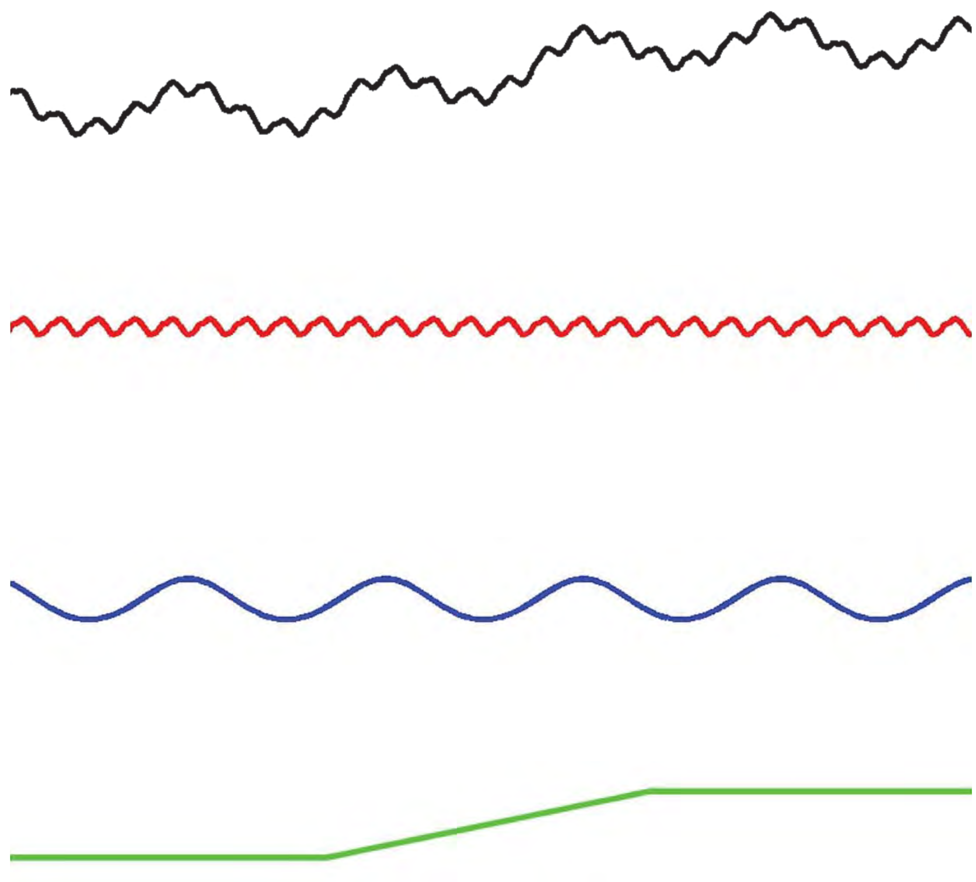
Cardiac Motion

+

Respiratory Motion

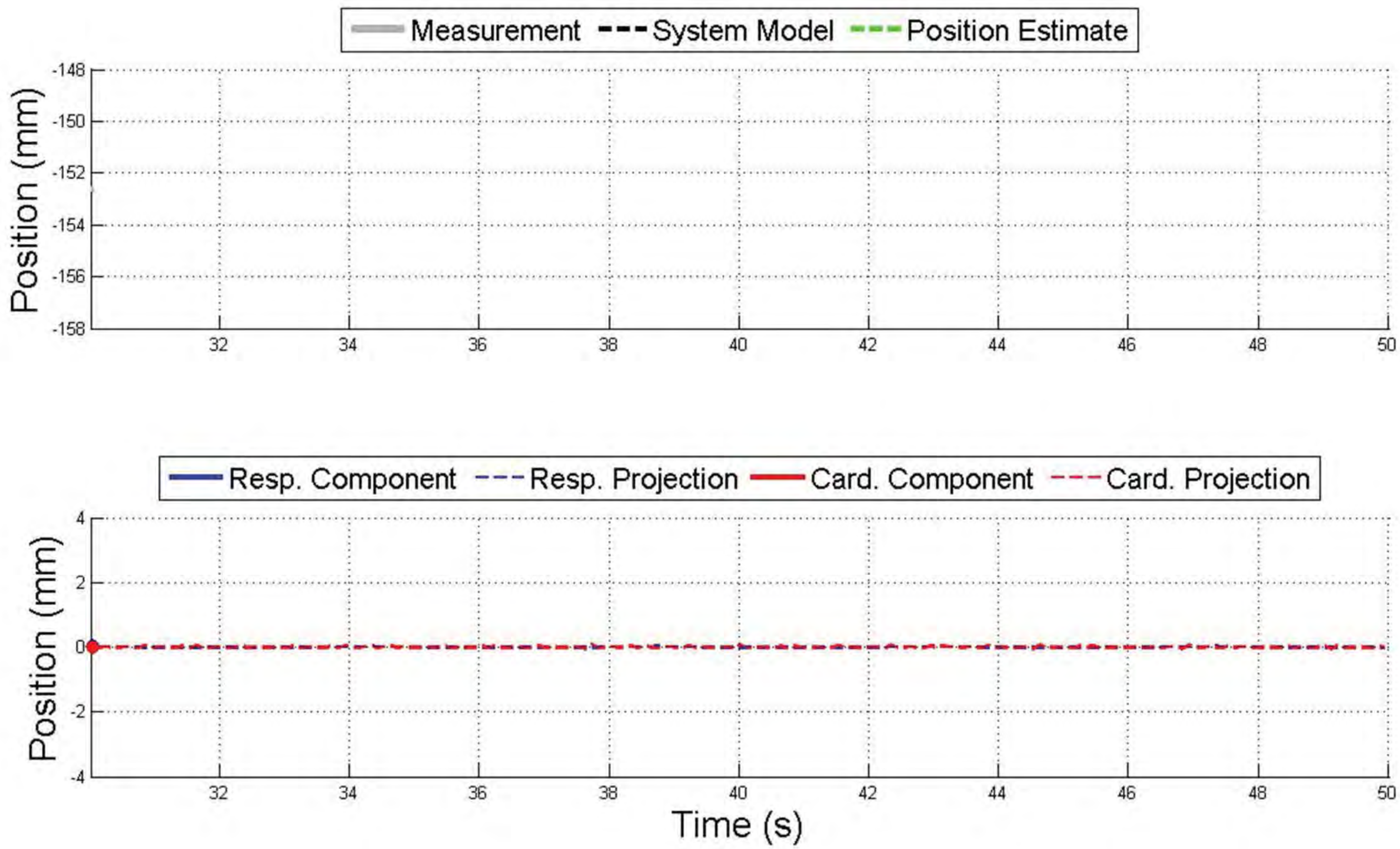
+

Robot Position



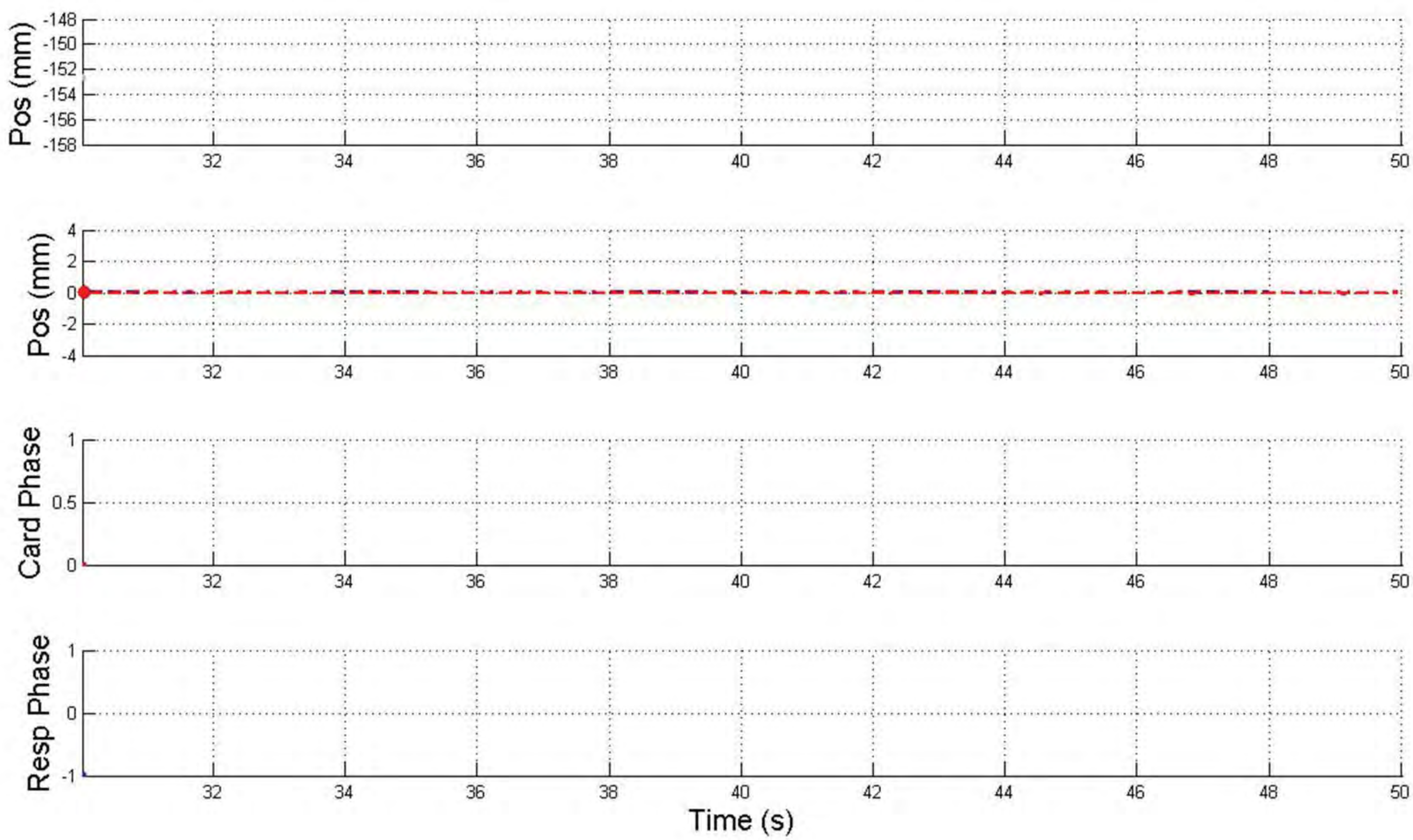
Performance – Live Model

Fourier model similar to Poignet et al.

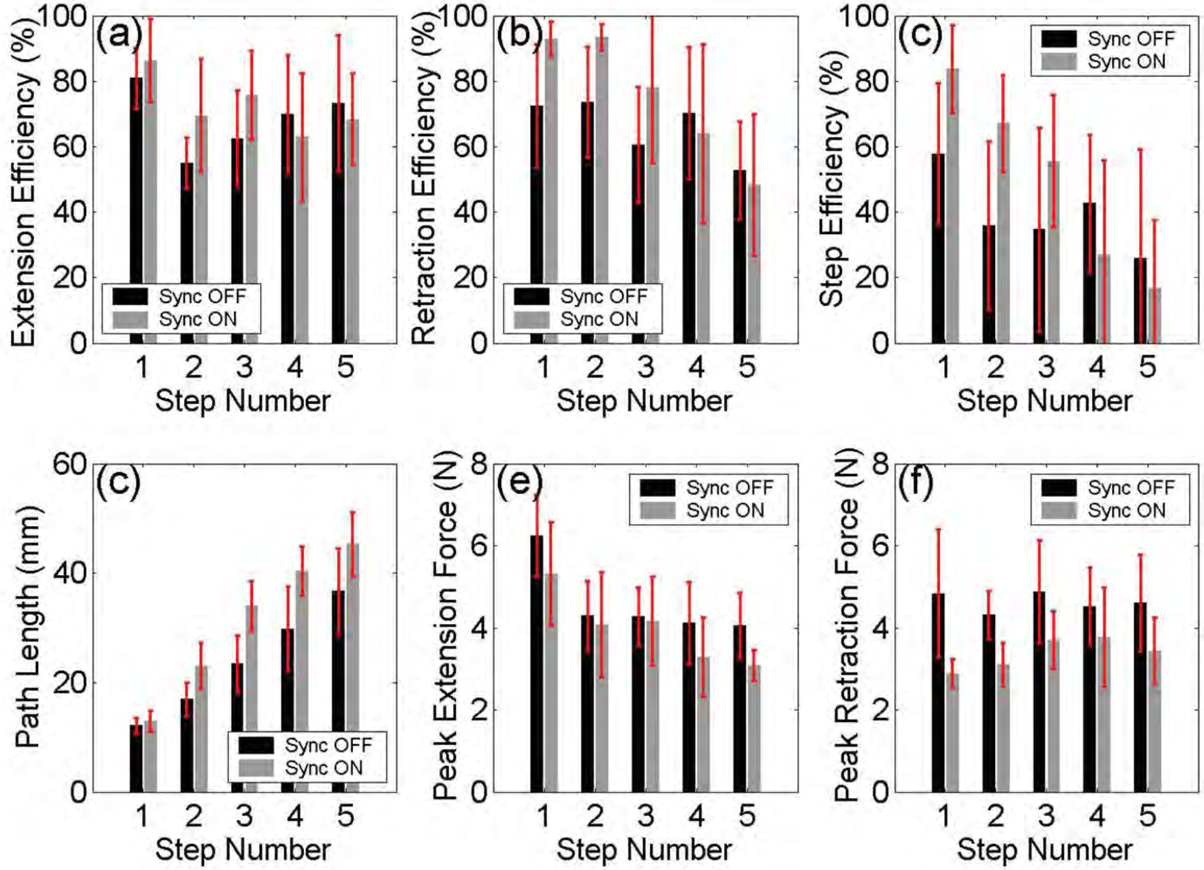


Carnegie Mellon
THE ROBOTICS INSTITUTE

Results – Phase Estimation

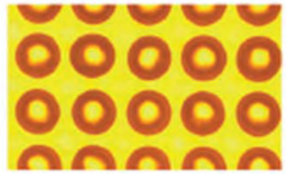


Efficiency Improvement with Synchronization

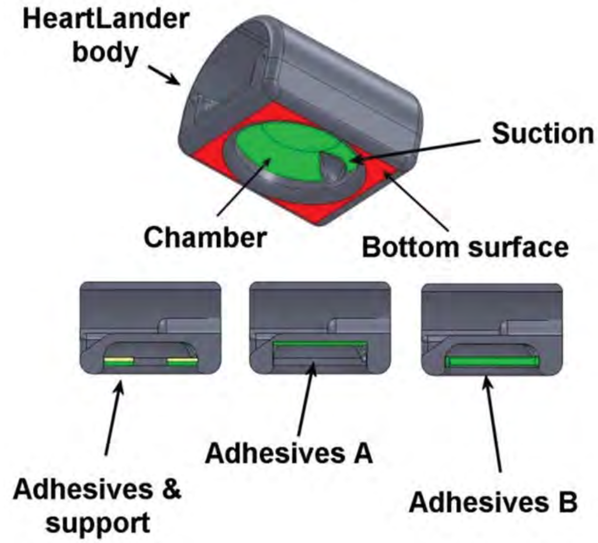


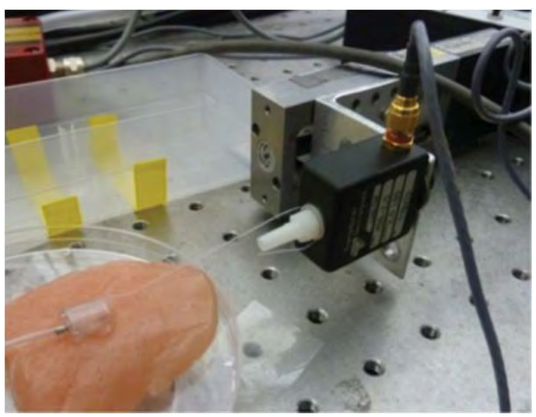
Bio-inspired adhesive to improve traction

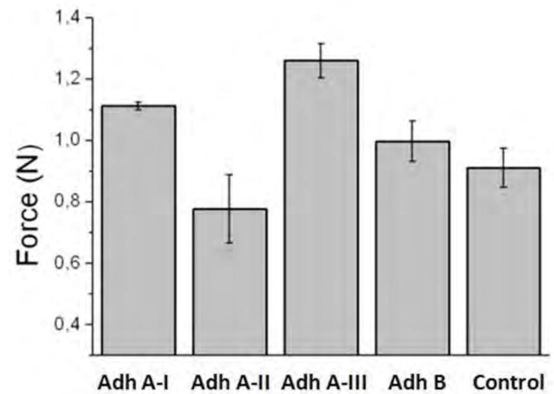
Microscopy side view



Microscopy top view







Tortora et al., EMBC 2012.

Carnegie Mellon
THE ROBOTICS INSTITUTE

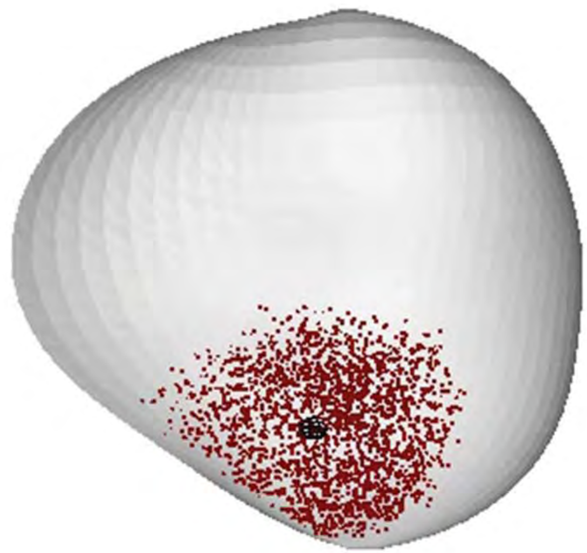
Localization on the Beating Heart

- Given a preoperative dynamic map and a series of noisy position observations in the world frame, T_R^W
- Solve for:
  - Registration
  - Localization
  - Cardiac Phase

$$s = \begin{bmatrix} T_M^W \\ T_R^M \\ \phi \end{bmatrix}$$

- Particle filter implemented for state estimation:
  - Initialized to region near initial tracker reading
  - Surface constraints
  - Exploit structure / constraints to limit # particles

Localization on the Beating Heart



Acknowledgments

Collaborators

Robert MacLachlan
Brian C. Becker, Ph.D.
Sungwook Yang, M.S.
Louis Lobes, M.D.
Gregory Hager, Ph.D.
Iulian Iordachita, Ph.D.
James Handa, M.D.
Peter Gehlbach, M.D.
Nathan Wood, M.S.
Kevin Fok
Marco Zenati, M.D.
David Schwartzman, M.D.
Giuseppe Tortora, Ph.D.
Metin Sitti, Ph.D.
Arianna Menciassi, Ph.D.
Marcin Balicki
Russell Taylor, Ph.D.
Jin Kang, Ph.D.
Xuan Liu

Funding

R01 EB000526
R01 EB007969
R01 HL078839
R01 HL105911

American Society for Laser Medicine and Surgery