A Microsurgical Assistant for Retinal Surgery

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Goal: Human-machine partnership to fundamentally improve interventional medicine

Slide credit: Marcin Balicki
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Vitreoretinal Microsurgery

- 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

• 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

3D Display with Overlays
Stereo video Microscope
OCT Display
EyeRobot2
Audio Output
FBG Interrogator
Force and OCT sensing tools
In-Vivo Experiments

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

Surgical Workstation

- Visualization & display
- Real time image and sensor processing
- 3D modeling and information fusion
- Task representation
- Safety monitoring
- Manipulation assistance and "virtual fixtures"

Preoperative images
Other patient data
Procedure plans
Procedure logs

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

- 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

Optical chain
- Zeiss microscope
- Dual channel beam splitter
- Zeiss to C-mount coupler
- C-mount Camera

Microsurgical Workstation Computer
- Video card
- X11 library
- svlImageRectifier
- svlImageResizer
- svlImageFileWriter
- svlImageWindow
- X11 interface
- SVL libraries
- cisstStereoVision pipeline
- CISST libraries
- Software application
- Display
- DVI cable
- Linux DC1394 library
- PCIe IEEE1394B interface board
- Linux IEEE1394 Raw library
- PCIe IEEE1394B interface board
- PCIe IEEE1394B interface board
- PCIe IEEE1394B interface board
- PCIe IEEE1394B interface board
- PCIe IEEE1394B interface board

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
Surgical Workstation

- Visualization & display
- Real-time image and sensor processing
- 3D modeling and information fusion
- Task representation
- Safety monitoring
- Manipulation assistance and "virtual fixtures"

Stereo video

Stereo video

OCT & Spectroscopy System

multi-spectral light source

Hand-held active tremor reduction (MICRON)

Steady hand microsurgical robots

OCT & Spectroscopy System

Modular control & sensing interfaces

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

Active Programmable Multispectral Illumination

Surgical Workstation

High Resolution 3D Video Display

Serial Port Interface

Camera Trigger

PWM

Light Source Control Box

RGB/IR LEDs

Fiber-Optic Coupler

Fiber-Optic Light Pipe

Retina
Synthetic full color from multiplexed illumination

<table>
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<tr>
<th>Red:White Frame Ratio</th>
<th>Multiplexed</th>
<th>Reconstructed</th>
<th>Ground Truth</th>
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Surgical Workstation
- Visualization & display
- Real time image and sensor processing
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- Task representation
- Safety monitoring
- Manipulation assistance and “virtual fixtures”

20-25 gauge tools & sensors (proximity, force, ischemia, OCT, other)
JHU Steady Hand “Eye Robot”

- 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

Stay within volume
Trace a circle
MICRON active tremor cancellation device
Cameron Riviere, Robert McLaughlin, B. Becker et al. (CMU)

Surgeon Results


Surgeon Results

Laser Photocoagulation on Porcine Retina
MICRON active tremor cancellation device
Cameron Riviere, Robert McLaughlin, B. Becker et al. (CMU)

Laser Photocoagulation on Porcine Retina: Results

<table>
<thead>
<tr>
<th>Unaided (2.0 Hz repeat)</th>
<th>Aided</th>
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<tr>
<td>![Unaided image]</td>
<td>![Aided image]</td>
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**Surgeon Results**


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**Hand-held active tremor reduction (MICRON)**

- Steady hand microsurgical robots
- 20-25 gauge tools & sensors (proximity, force, ischemia, OCT, other)

**Modular control & sensing interfaces**

- OCT & Spectroscopy System
- Multi-spectral light source

**Surgical Workstation**

- Preoperative images
- Other patient data
- Procedure plans
- Procedure logs

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Engineering Research Center for Computer Integrated Surgical Systems and Technology
Force Sensing Surgical Instruments

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

2-DOF Force Sensing Tools

- 2-DOF Pick Tool
- 2-DOF Forceps Tool

Fiber Bragg Grating (FBG sensors)

He et al. 2012
3-DOF Force Sensing Pick Tool

Distal force sensing segment

Quick release mechanism

10mm

Stainless steel tube Ø0.5mm

Flexure

Pick

1mm

Nitinol tube Ø0.8mm

FBG Ø125 μm

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

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Engineering Research Center for Computer Integrated Surgical Systems and Technology

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

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Engineering Research Center for Computer Integrated Surgical Systems and Technology
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
Functional OCT based on spectrum

**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 function of oxygenated and de-oxygenated blood.

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 versus position for (c) oxygenated layer; (d) de-oxygenated layer.

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**Stereo video**

**Multi-spectral light source**

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**Hand-held active tremor reduction (MICRON)**
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

- 25-35 Medical students, residents, and ophthalmologists
- 5 Membrane peels w/o auditory feedback
  - 10 Peels with warning and alarm sounds
  - 10 Peels with alarm sounds only
  - 10 Peels with alarm sounds only
  - 5 Peels w/o auditory feedback
  - 5 Peels w/o auditory feedback

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

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**Results**

- **B. Freehand**: Tip Forces [mN] vs. Time [s]
  - Audio vs. No Audio
- **C. Proportional Velocity**: Tip Forces [mN] vs. Time [s]
  - Audio vs. No Audio
- **D. Force Scaling**: Tip Forces [mN] vs. Time [s]
  - Audio vs. No Audio
- **E. Velocity Limiting**: Tip Forces [mN] vs. Time [s]
  - Audio vs. No Audio

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.

Peeling angles converge to 45°
A. Uneri, M. Balicki et al.
Submitted to BioRob2010

Resulting motion pattern resembles commonly used capsulorhexis technique.
Dual Force Sensor

(a) Eye Robot

(b) Dual Force Sensing Tool

Eye Robot

Pivot Point

Dual Force Sensor

Dual Force Sensing Instrument

FBG-II

FBG-I

FBG-III

Ø 0.5 mm

FBG-I
Dual Force Sensor

Follow the Motion of the Eye

X. He, Marcin Balicki, P. Gehlbach, J. Handa, R. Taylor, and I. Iordachita

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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

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Engineering Research Center for Computer Integrated Surgical Systems and Technology
OCT of Rabbit Retina with Micron-held Probe

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

M-Scan

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


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

1st Generation

2nd Generation

3rd Generation
Safety Barrier

Sensor Guided Incision

On

200µm
Depth ~100µm

(b)

Incision Depth [µm]

0 50 100 150 200 250 300

Lateral Position [µm]

Off

200µm
Depth ~100-250 µm

(d)

Incision Depth [µm]

0 50 100 150 200 250 300

Lateral Position [µm]
SMART Micro-Injector

Smart Micro-Forceps

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Engineering Research Center for Computer Integrated Surgical Systems and Technology
Other JHU Work: Automatic layer segmentation of macular OCT data
A. Lang, A. Carass, …, J. Prince (NIH R21EY022150)

Segmentation of 9 layers

GCL+IPL thickness analysis for multiple sclerosis

Consistent segmentation between scanners

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

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Engineering Research Center for Computer Integrated Surgical Systems and Technology
Other possible targets: ENT & Neurosurgery

Surgical Workstation

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Modular control & sensing interfaces

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Information-Intensive Interventional Suite

- Data Logging & Summary
- Logistics & scheduling
- PACS, other patient databases

- 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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