Force Sensing Instrument for Vitreoretinal Surgery

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Outline

• 3-DOF Force Sensing Tool, Version 1

• 3-DOF Force Sensing Tool, Version 2

• Dual Force Sensing Tool
Vitreoretinal surgery
Vitreoretinal surgery

• Epiretinal membrane (ERM) peeling
  – Peel a 2-100µm thick scar tissue away from the retina (hand tremor > 100 µm)
  – High risk of retinal tears (vision loss) due to exertion of excessive or incorrectly applied forces

• Challenges in vitreoretinal surgery
  – Freehand manipulation of delicate 1-100µm structures
  – Forces are well below human tactile sensation
  – Force attenuation from tool–trocar interaction
  – Involuntary physiological hand tremor is significant
  – Limited by poor visual and kinesthetic feedback
  – Miniature instrumentation
  – Fatigue from prolonged operations and poor ergonomics
  – Patient movement

ERM
Force Sensing Techniques

- Optical Fiber Sensors
  - Fiber Bragg Grating (FBG)
  - Fabry-Perot Interferometer
- Strain gauge
- Linear Variable Differential Transformer
Prior Work

Design Specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Requirement</th>
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</thead>
<tbody>
<tr>
<td>Tool shaft diameter</td>
<td>&lt; 1mm</td>
</tr>
<tr>
<td>Tool shaft length</td>
<td>≥ 30mm</td>
</tr>
<tr>
<td>Force resolution (xy)</td>
<td>~ 0.25mN</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>&gt; 100Hz</td>
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</table>

Iordachita et al.
3-DOF Force Sensing Tool
version 1
3-DOF Tool Conceptual Design
Flexure Design

• Reduce axial stiffness, generate larger deformation under axial force load

• Decouple axial and lateral force?
Calibration setup

FBG Interrogator

Robot motion command

Computer

Scale reading

Eye Robot

Precision scale

FBG wavelength shift

Wavelength shift

Rotary stage

Tool

Wire

Weight

Scale

Eye Robot
Calibration setup
Calibration: first try

- Magnitude 0 – 20 mN
- 56 directions
- $\alpha$: -135° : 15° : 180°
- $\beta$: 0° : 15° : 90°
Linear Calibration Fx & Fy

Fx

Calculated force Fx(mN)

-25 -20 -15 -10 -5 0 5 10 15 20 25

Actual force Fx(mN)

-25 -20 -15 -10 -5 0 5 10 15 20 25

RMS error = 0.535 mN

Fy

Calculated force Fy(mN)

-25 -20 -15 -10 -5 0 5 10 15 20 25

Actual force Fy(mN)

-25 -20 -15 -10 -5 0 5 10 15 20 25

RMS error = 0.539 mN
Calibration Fz – Bernstein N=2

RMS error = 0.797 mN
## Calibration and Validation: Fz

<table>
<thead>
<tr>
<th>$\beta \setminus \alpha$</th>
<th>-135°</th>
<th>-90°</th>
<th>-45°</th>
<th>0°</th>
<th>45°</th>
<th>90°</th>
<th>135°</th>
<th>180°</th>
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<tbody>
<tr>
<td>0°</td>
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<td>75°</td>
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<td></td>
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<tr>
<td>90°</td>
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</table>

Calibration data set

Validation data set

### X-Y plane

- $\alpha = 0°$
- $\alpha = 45°$
- $\alpha = 90°$
- $\alpha = 135°$
- $\alpha = 180°$

### X-Z plane

- $\beta = 30°$
- $\beta = 45°$
- $\beta = 60°$
- $\beta = 75°$
- $\beta = 90°$
Calibration data set
(32/56 poses)

Validation data set
(24/56 poses)

RMS error = 0.776 mN

RMS error = 0.899 mN
Validation
three complete runs, each 56 poses

RMS error = 0.966 mN

RMS error = 0.930 mN

RMS error = 0.835 mN
Calibration: second try

- Magnitude 0 – 20 mN
- 168 directions
- $\alpha$ (spin about Z): [-135° : 15° : 180°]
- $\beta$ (Roll about Y): [0° : 15° : 90°]
Linear Calibration $F_x$ & $F_y$

RMS error = 0.21 mN

RMS error = 0.19 mN

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Calibration Fz – Bernstein N=2

RMS error = 0.787 mN
Axial Force RMS Error

- Overall RMS error with 2\textsuperscript{nd} order Bernstein polynomial: 0.787 mN
- How good is the fitting at each pose?
  - Min RMS: 0.52 mN
  - Max RMS: 1.45 mN
  - 89 poses (53\%) < 0.75 mN
  - 147 poses (88\%) < 1 mN
Axial Force RMS Error

- Overall RMS error with 2\textsuperscript{nd} order Bernstein polynomial: 0.787 mN
- How good is the fitting at each pose?
  - Min RMS: 0.52 mN
  - Max RMS: 1.45 mN
  - 89 poses (53\%) < 0.75 mN
  - 147 poses (88\%) < 1 mN
Validation with random forces

- Forces with random magnitude and direction
- \( N = 12 \)
- \( \alpha: 5.7° - 171.5° \)
- \( \beta: 10.3° - 86.2° \)
- Force magnitude:
  - \(-7.2 \text{ to } -18.6 \text{mN}\)
Random Force Validation

RMS error = 0.21 mN

RMS error = 0.20 mN
Random Force Validation $F_z$
Discussion and Conclusion

• We designed and built a 3-DOF force sensing tool for retinal microsurgery

• Force measurement RMS error
  – Fx and Fy: $\sim0.2$ mN (with linear fitting)
  – Fz: $\sim0.8$mN (with 2$^{nd}$ order Bernstein polynomial)

• Future work
  – More random force data to validate Fz calculation
  – Temperature compensation for axial force sensing
3DOF Force Sensing Tool version 2
Problem

• Flexure amplifies axial deformation, AND bending
• The axial FBG is not perfectly aligned with neutral axis
• Difficult to exclude lateral force induced strain from axial FBG
• Absolute displacement 1:30 under the axial/lateral force of same magnitude
New Flexure Design

• Design a flexure that can
  – amplify axial displacement & minimize lateral displacement
Tool Concept: FBG
Tool Assembly: FBG

(Lateral FBGs are not shown)

Flexure  FBG active segment  Optical fiber  1 mm
Fabrication

- Laser cutting
  - Tubing
  - Minimum feature size 25µm
  - Stainless steel
- Photochemical etching
  - Flat flexure part
  - Minimum feature size ~thickness
  - Brass, copper, aluminum
Flexure Assembly

1 mm
Flexure Assembly
3-DOF Tool, version 2
Bernstein Fitting (N=2)

X

Y

Z

Measured Force (mN)

Actual Force (mN)

Actual Force (mN)

Measured Force (mN)

Actual Force (mN)
Conclusion and Discussion

• A new flexure design that provides improved axial force sensing linearity

• Future work
  – Calibration
  – Temperature compensation
  – Hybrid 3-DOF force sensing based on Fabry-Perot and FBG
Dual Force Sensing Tool
Motivation
Motivation

• Robot stiffness reduces user perceived level of the forces between tool shaft and sclera
• Excessive forces on the sclera can also cause serious complications
• Sclera force information can provide vital feedback in robot assisted eye surgery, e.g.:
  – View adjustment
  – Tool coordination
  – Patient motion
  – Bimanual robot assistance
  – Teleoperation
Conceptual Design

FBG 2
FBG 1
Fx
Fy
Fx
Fy

Ø 0.50
Ø 0.15

0.16
0.16

40

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Force Calculation

Strain: \( \varepsilon = \frac{M}{EI} \) \( r = \frac{F_d}{EI} \) 

Wavelength shift: 
\( \Delta \lambda = k \varepsilon \varepsilon + k \Delta T \Delta T \)

Sensor reading: 
\( \Delta s_{\text{t}} = k_{\lambda} \varepsilon \varepsilon + k_{\text{mean}} \) 
\( \sum_{j=1}^{3} k_{\varepsilon j} \varepsilon j \)

Sensor reading: (Tip FBG) 
\( \Delta S_{\text{t}} = K_{\text{tt}} F_{\text{t}} \) 
\( \Delta S_{\text{t}} = \left[ \Delta s_{\text{t}1}, \Delta s_{\text{t}2}, \Delta s_{\text{t}3} \right] \) 
\( F_{\text{t}} = \left[ F_{\text{tx}}, F_{\text{ty}} \right]^T \)

Sensor reading: (Sclera FBG) 
\( \Delta S_{\text{s}} = K_{\text{ss}} F_{\text{s}} + K_{\text{st}} F_{\text{t}} \) 
\( \Delta S_{\text{s}} = \left[ \Delta s_{\text{s}1}, \Delta s_{\text{s}2}, \Delta s_{\text{s}3} \right] \) 
\( F_{\text{s}} = \left[ F_{\text{sx}}, F_{\text{sy}} \right]^T \)

Tip Force: 
\( F_{\text{t}} = K_{\text{tt}} F_{\text{t}} + \Delta S_{\text{t}} \)

Sclera Force: 
\( F_{\text{s}} = K_{\text{ss}} F_{\text{s}} + (\Delta S_{\text{s}} - K_{\text{st}} F_{\text{t}}) \) 
\( = K_{\text{ss}} F_{\text{s}} + (\Delta S_{\text{s}} - K_{\text{st}} K_{\text{tt}} F_{\text{t}}) \)

Sensor reading: 
Strain: 
Wavelength shift: 
Sensor reading:
Calibration – Step 1

Tip FBG

Sensor reading (pm) vs. Fx (mN)

Sensor reading (pm) vs. Fy (mN)

Sclera FBG

Sensor reading (pm) vs. Fx (mN)

Sensor reading (pm) vs. Fy (mN)
Calibration – Step 2

 Tip FBG

 ![Graphs showing sensor readings for Tip FBG](image)

 Sclera FBG

 ![Graphs showing sensor readings for Sclera FBG](image)

25 mm
Experiment Setup

- **Eye Robot**
- **Dual force sensing instrument**
- **Phantom**
- **Instrument tip**
- **Rubber band**
- **Bandage strip**

Dimensions: 25mm
Experiment Results

• Freehand:
  – human perceivable sclera force level
• Robot w/o force feedback
  – Robot stiffness attenuates force perception
• Robot w/ force feedback
  – Significant reduction of sclera forces

<table>
<thead>
<tr>
<th>Method</th>
<th>Max. force (mN) applied on the “sclera” before stop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>Freehand</td>
<td>34.81</td>
</tr>
<tr>
<td>Robot w/o FS</td>
<td>215.33</td>
</tr>
<tr>
<td>Robot with FS</td>
<td>6.59</td>
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