Report Seminar Presentation

-Saurabh Singh

Project- Force Control Algorithms for Schlera Eye Surgery
Team Members- Ankur Gupta and Saurabh Singh
Team- 20

Project Objective:

The first step is to collect data from surgeons and based on that data devise a function from the force scaling mode of the co-operative control to the full RCM mode. Currently, the surgeon based on his experience cancels out the possibility of translational motion after reaching certain depth in the eye. Therefore, it is proposed to devise experiments which will capture the behavior of several surgeons to learn about their surgical procedure. Based on that collected data and according to current depth of tool from sclera restrict the surgeon from making movements which are detrimental to sclera. The collected data will help us to learn:

- Transition function
- Lower and Upper depth bounds of sclera where the operating modes switch
- β , the parameter which reduces degree of freedom

Papers Reviewed:

For the seminar presentation, I read two papers. They are:

- Xingchi He∗, James Handa, Peter Gehlbach, Russell Taylor and Iulian Iordachita*," **A Submillimetric 3-DOF Force Sensing Instrument With Integrated Fiber Bragg Grating for Retinal Microsurgery**".[1]*

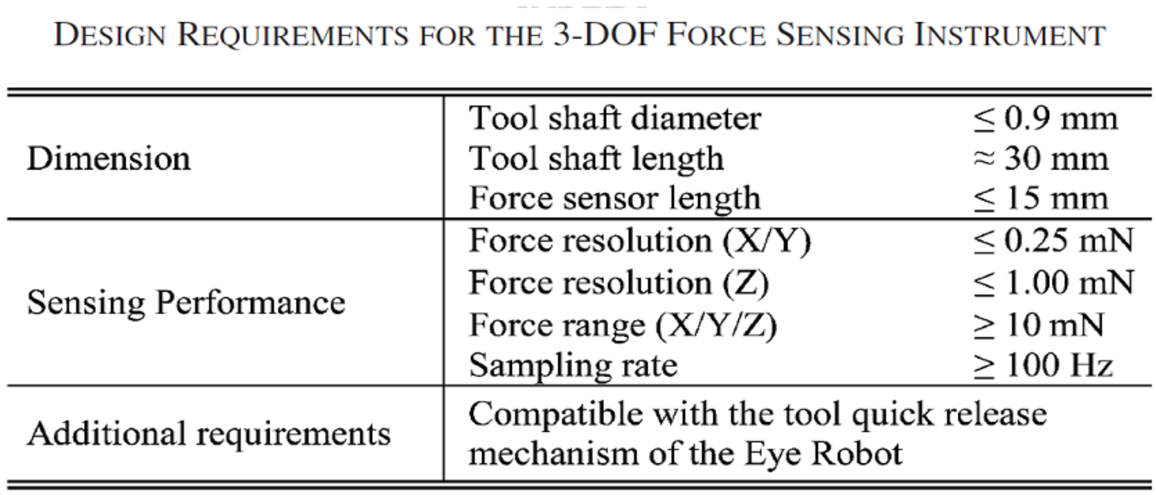
- Marc D. de Smet, Thijs C. M. Meenink, Tom Janssens, Valerie Vanheukelom, Gerrit J. L. Naus, Maarten J. Beelen, Caroline Meers, Bart Jonckx, Jean-Marie Stassen*,"**Robotic Assisted Cannulation of Occluded Retinal Veins**."[2]*

Since my project is to develop control algorithms for forces that are of millinewton order I chose paper 1 to learn how these millinewton forces are being calculated by the tool, Moreover, the paper 1 shows how the development of tool that we are using in project took place. The choice of paper 2 was done to learn and present how Robot assisted retinal eye surgery helps in the treatment of Retinal Vein Occlusion.
The rest of the report presents summary, conclusions and results of the paper presented and read.

Paper- I

Objective: The goal of the authors writing this paper was to develop a submillimetric 3-DOF force sensing pick instrument based on FBG sensors. The work also focused on the incorporation of high force sensing sensitivity along axial direction and maximize the decoupling between axial and transverse force sensing.

Design of the force sensing tool: The researchers have stated in literature that a force sensor should be present at the tip of the tool for measuring the tip forces at the eye. The tool should have high force sensitivity in axial direction of tool. The surgical tool should have resolution of millinewton order for axial forces and quarter millinewton for transverse forces. Moreover, the tool length should be less than 15 mm to avoid double puncture in the eye.



DESIGN REQUIREMENTS FOR THE 3-DOF FORCE SENSING INSTRUMENT

Dimension	Tool shaft diameter	≤ 0.9 mm
	Tool shaft length	≈ 30 mm
	Force sensor length	≤ 15 mm
Sensing Performance	Force resolution (X/Y)	≤ 0.25 mN
	Force resolution (Z)	≤ 1.00 mN
	Force range (X/Y/Z)	≥ 10 mN
	Sampling rate	≥ 100 Hz
Additional requirements	Compatible with the tool quick release mechanism of the Eye Robot	

Table 1. Shows the design requirements of the surgical tool

The two design aspects have been considered to achieve high sensitivity axial and transverse force sensing:

1) FBG sensor configuration.

2) Flexure design for instrument shaft.

FBG sensors reflect a narrow spectrum spike with the Bragg grating. The Bragg wavelength, at which the reflection occurs, depends on the strain in the FBG segment. It can be used to measure strain precisely. 4 FBG Sensors have been used for the design of the tool. Three FBG sensors were attached longitudinally along instrument shaft with 120◦ intervals. One FBG sensor placed in center of the tubular instrument (along the instrument shaft axis). This chosen configuration maximizes decoupling of axial and transverse force measurements. The inner fourth FBG sensor measures the strain from axial forces. The three outer FBG sensors measure the transverse forces. FBG sensors have one 3 mm FBG segment with center Bragg wavelength of 1545 nm.

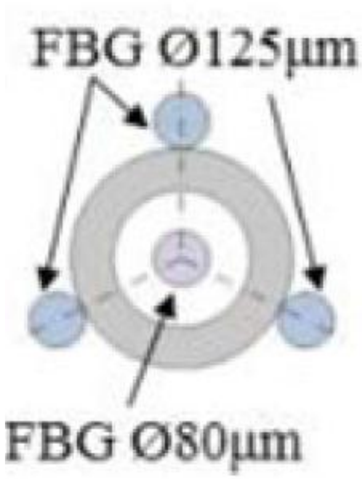


Fig. 1 Shows the configuration of the 4 FGB sensors

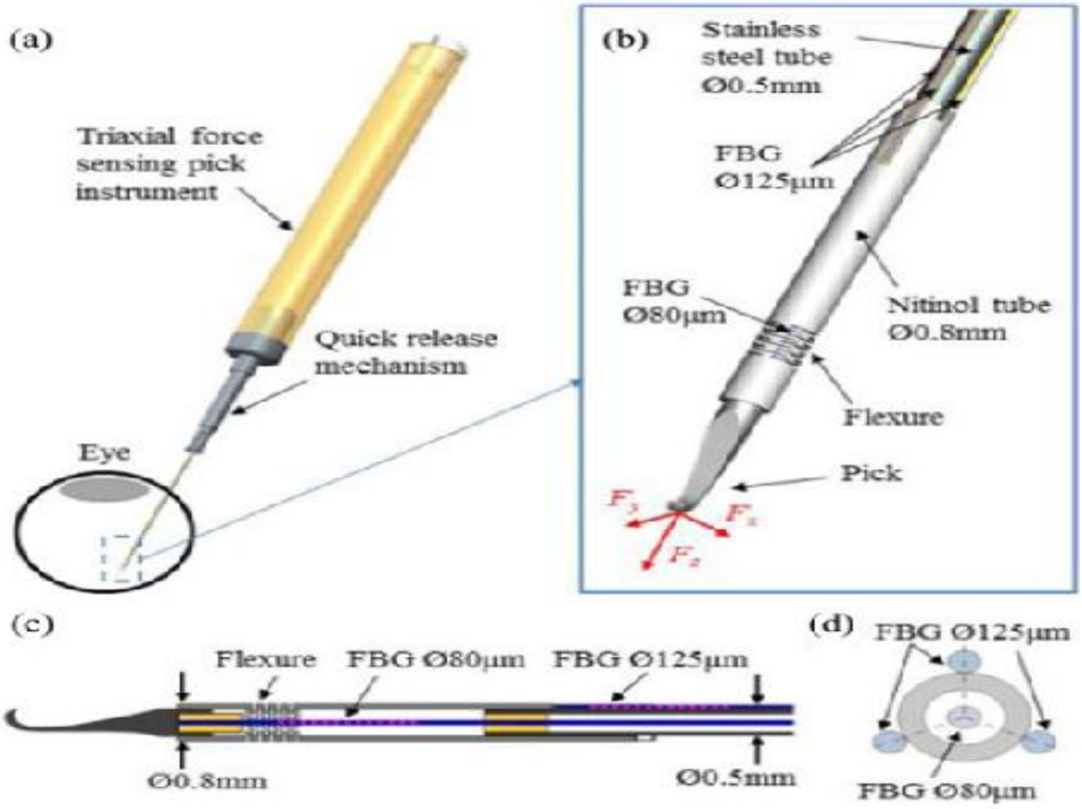


Fig. 2 Shows CAD model of the 3-DOF force sensing. (a) Pick instrument, (b)Close up (c) Section view of the distal force sensing portion, (d)Section view of the FBG sensor configuration.

To increase axial force sensitivity, stiffness of instrument shaft in axial direction was reduced by selecting appropriate material and creating a flexure segment. Nitinol was used for the flexure design as it is super elastic has low Young's modulus - 41 Gpa and is biocompatibility.

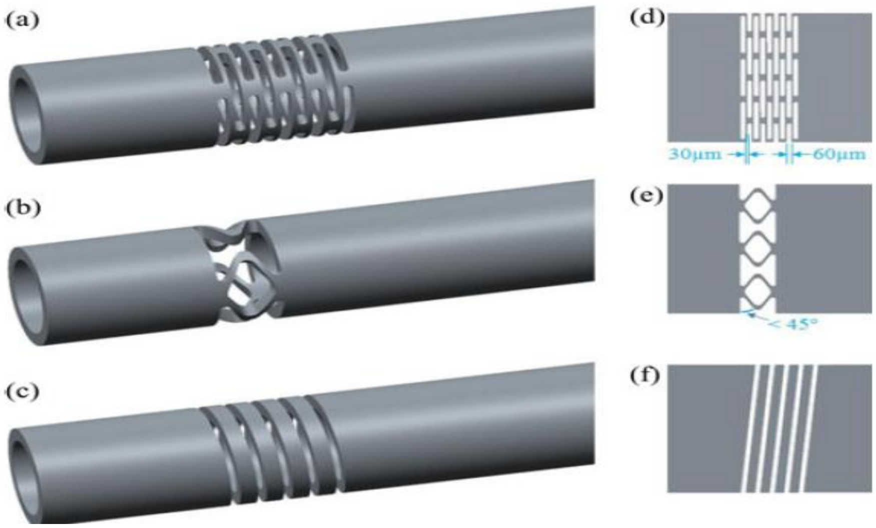


Fig. 3 Shows Flexure concept: (a), (b) and (c) to increase sensitivity of axial force sensing . Corresponding 2-D unfolded flexure pattern are shown in (e), (f) and (g).Tube outer diameter is 0.8 mm, and inner diameter is 0.6 mm.

The flexure design of Concept (a) provides good elasticity, fabrication feasibility and design flexibility and hence it was chosen by authors by tool manufacturing.

Force Calculation Algorithm:

Transverse Force Calculation: The strain is linearly dependent on the moment and thus proportional to the transverse forces applied at the tool tip. The relation between strain and force and moment is given by :

$$\varepsilon = \frac{M}{EI} r = \frac{F_t d}{EI} r$$

The shift in Bragg wavelength of the FBG sensors is linearly dependent on local strain and temperature change and it is given by:

$$\Delta\lambda = k_{\varepsilon}\varepsilon + k_{\Delta T}\Delta T$$

Common mode of all three FBGsensors is due to the strain attributed to axial forces and temperature change. The subtraction of the mean of Bragg wavelength shifts of all three FBG sensors gives differential mode sensor reading:

$$\Delta s_i = \Delta\lambda_i - \Delta\lambda_{\text{mean}} = k_{\varepsilon i}\varepsilon_i - \frac{1}{3}\sum_{i=1}^{3} k_{\varepsilon j}\varepsilon_j k_{\Delta T}$$

The equation to relate FBG sensor readings to the transverse forces:

$$\hat{F}_t = K_t \Delta S_t$$

Estimated transverse forces applied at the tool tip F_t are transverse forces K_t is calibration matrix and ΔS_t are sensor reading.

Axial Force Calculation:

- **Linear Method:** Axial force sensing can be linear in a local region. Equation to relate Bragg Wavelength shift to axial forces :

  $$\hat{F}_z = K_z \Delta\Lambda$$

  Bragg wavelength shifts of FBG sensors- $\Delta\Lambda = [\Delta\lambda_1 \quad \Delta\lambda_2 \quad \Delta\lambda_3 \quad \Delta\lambda_4]^T$

  F_z is the estimated Axial Force.

- **Non- Linear Method:** Nonlinear Axial method based on Bernstein polynomials. F_z is the estimated force in the axial direction

  $$\hat{F}_z = \sum_{i=0}^{n}\sum_{j=0}^{n}\sum_{k=0}^{n}\sum_{l=0}^{n} c_{ijkl} b_{i,n}(\Delta\lambda_1^*) b_{j,n}(\Delta\lambda_1^*) b_{k,n}(\Delta\lambda_3^*) b_{l,n}(\Delta\lambda_4^*)$$

  The order of chosen Bernstein is 2, where F_z is force in the axial direction, c_{ijkl} is the constant coefficients, b_{ijkl} are the Berstein basis polynomials and $\Delta\lambda_t$ is scaled change fiber bragg grating between (0,1). A more compact form given by:

  $$\hat{F}_z = \sum_{i=0}^{2}\sum_{j=0}^{2}\sum_{k=0}^{2}\sum_{l=0}^{2} c_{ijkl} B_{ijkl} = \bar{B}C$$

  Thermal drift of the inner FBG sensor and that of the common mode of the three outer FBG sensors are linearly correlated.

  $$\Delta s_4 = \Delta\lambda_4 - \kappa \frac{1}{3} \sum_{i=1}^{3} \Delta\lambda_i$$

  The axial force calculation with temperature compensation is given by:

  $$\hat{F}_z = \sum_{i=0}^{n}\sum_{j=0}^{n}\sum_{k=0}^{n}\sum_{l=0}^{n} c_{ijkl} b_{i,n}(\Delta s_1^*) b_{j,n}(\Delta s_2^*) b_{k,n}(\Delta s_3^*) b_{l,n}(\Delta s_4^*)$$

Tool Calibration:

The automated calibration system consists of: (a) Robot with additional rotary stage, (b) Precision scale: Resolution-1mg and Repeatability- 2mg, (c) Calibration weight -21 mN, (d)FBG interrogator- Micron Optics, (d) Computer (e)Calibration chamber

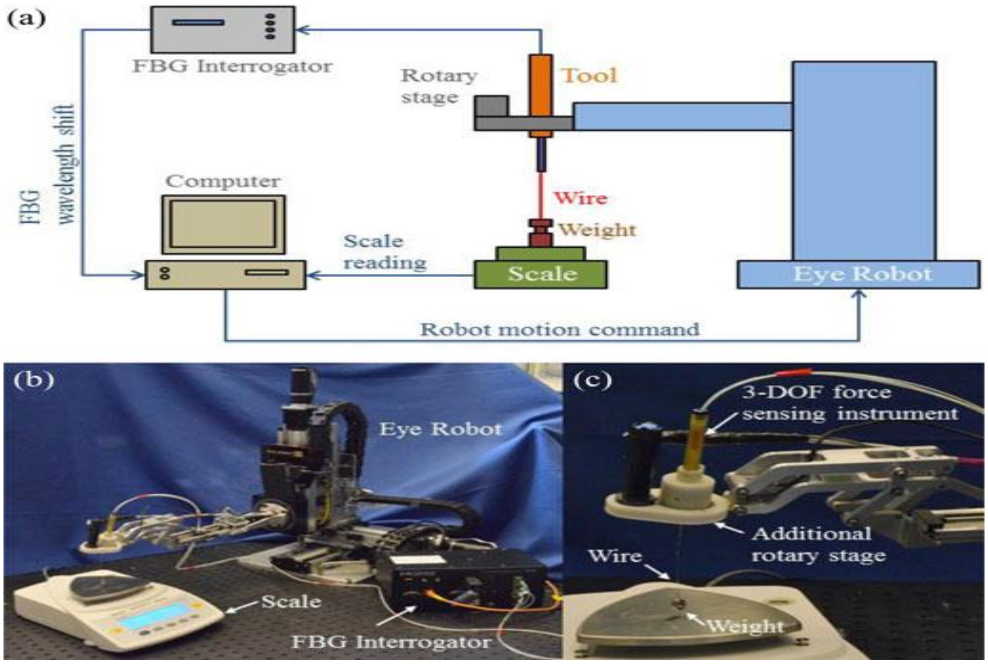


Fig 4 Shows the Calibration Procedure

Computer reads in Bragg wavelength shifts from the FBG interrogator and scale weight, and commands the robot to translate and rotate the instrument to adjust the magnitude and the direction of the force load. Equations for the force calculation: where α is the roll angle and β is the pitch angle

$$\begin{aligned} F_x &= \|F\| \sin\alpha \sin\beta \\ F_y &= \|F\| \cos\alpha \sin\beta \\ F_z &= \|F\| \cos\beta \end{aligned}$$

Linear Calibration for transverse and axial forces is done by Least Square Fitting Method. Nonlinear Calibration for Axial Forces is done by Bernstein Polynomial Global Method.

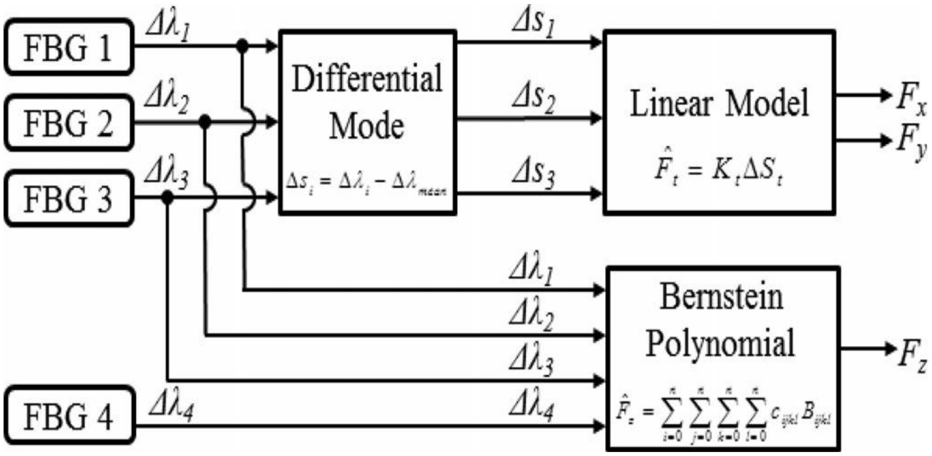
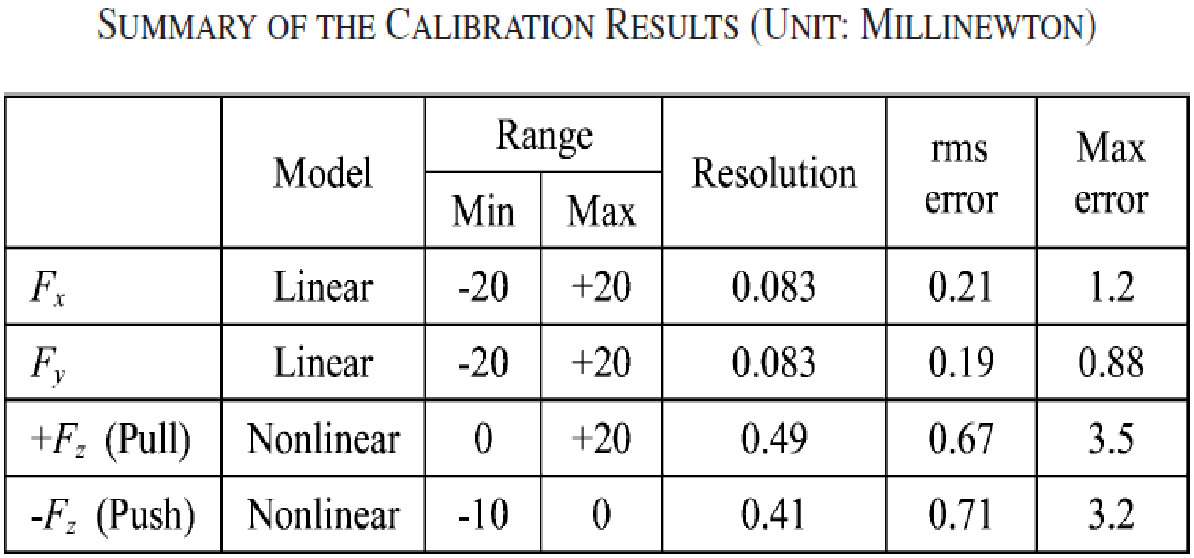


Fig. 6 Shows the flowchart of the sensor data collection and axial and transverse force calculation



SUMMARY OF THE CALIBRATION RESULTS (UNIT: MILLINEWTON)

	Model	Range		Resolution	rms error	Max error
		Min	Max			
F_x	Linear	-20	+20	0.083	0.21	1.2
F_y	Linear	-20	+20	0.083	0.19	0.88
$+F_z$ (Pull)	Nonlinear	0	+20	0.49	0.67	3.5
$-F_z$ (Push)	Nonlinear	-10	0	0.41	0.71	3.2

Table 2: Shows the calibration results for the proposed force calculation algorithms

Results:

- Developed tool has resolution of millinewton for axial forces and quarter millinewton for transverse forces.
- The proposed linear model for calculating transverse forces provides accurate global estimate.
- The proposed linear model for calculating axial forces is locally accurate within a conical region with a 30◦ vertex angle or when axial forces are relatively larger than the transverse forces.
- The proposed second-order Bernstein polynomial curve fitting model provides global estimate for axial force.

- The authors developed automated calibration system for repeatability testing, calibration, and validation.
- Experimental results demonstrate a FBG sensor repeatability of 1.3 pm.

Paper- 2 : Robotic Assisted Cannulation of Occluded Retinal Veins

Objective: Development of methodology for cannulating porcine retinal venules using a robotic assistive arm.

Retinal Vein Occlusion: Retinal Vein Occlusion(RVO) is the second most common cause of vision loss after diabetic retinopathy. Retinal vein branches are blocked by a blood clot in RVO. Cannulation is a process simple act of injecting saline or a balanced salt solution in a cannulated vein which can dislodge a clot. Cannulation of veins gives access for treatment.

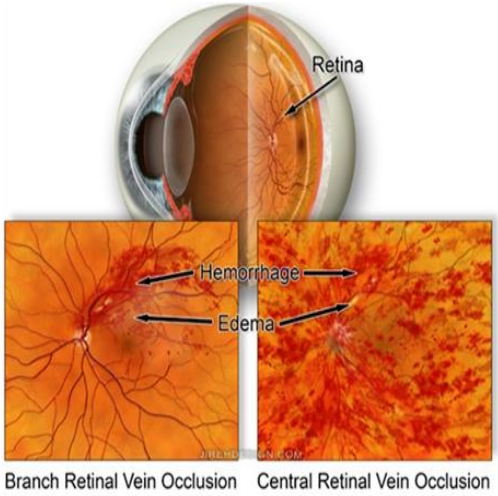


Fig 6. Retinal Vein Occlusion

Fig. 7 Blurry Vision a cause of RVO

Preceyes System

The system consists of motion Controller (MC) for hand motion input by the surgeon and Instrument Manipulator (IM) holding the surgical instrument. A clutch on MC activates the coupled motion between MC and the IM.

Design:

- Double parallelogram mechanism with 4DOF(Back Drivable)
- This mechanism constrains the pivoting access point to the eye
- Incase of power failure the manipulator can be manually moved by surgeon owing to its light weight.
- Tip motion resolution: 1-10 μm.

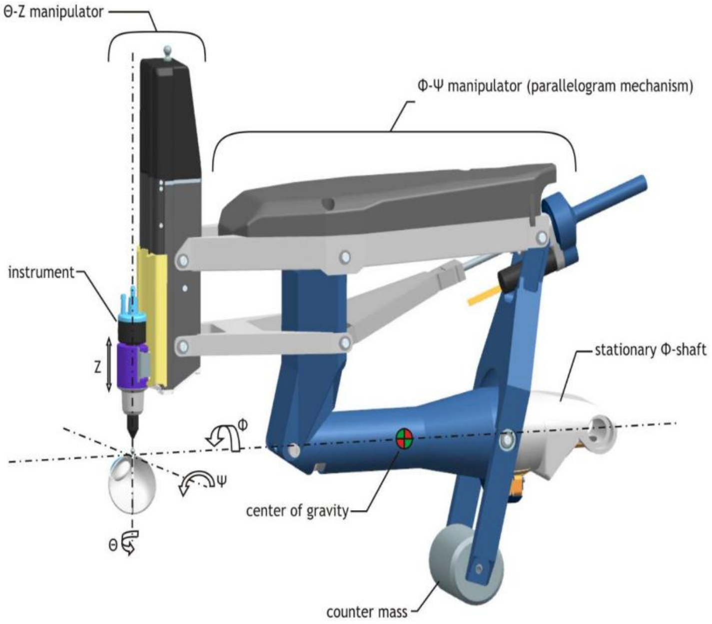


Fig. 8 Preceyes System

Method Used:

- Test Veins: Porcine retinal veins (Ø 80-300 μm) size close to human retinal veins
- Induce retinal vein occlusion by injecting rose bengal and exposing the vein to laser light (wavelength: 532 nm).
- Cannulation was done by a glass catheter tip. (Ø 30 μm and beveled tip)
- Injection of balanced salt solution by a syringe pump. (14 μL/min)
- 2 test cases:
  (1) Manual cannulation
  (2) Automated piercing protocol to avoid double puncture

Results:

1. Cannulation of venules using a robotic microassistive arm can be achieved with consistency, provided the piercing is robotically driven.
2. Manual method: 24/52 attempts were successful. (48% success rate)
3. Automated piercing: 9/9 eyes were successful.

Limitations: This paper does not clearly explains the technique used for finding RCM. Moreover, no information provided on alignment of RCM.

References:

- Xingchi He∗, James Handa, Peter Gehlbach, Russell Taylor and Iulian Iordachita*,"* ***A Submillimetric 3-DOF Force Sensing Instrument With Integrated Fiber Bragg Grating for Retinal Microsurgery***".

- Marc D. de Smet, Thijs C. M. Meenink, Tom Janssens, Valerie Vanheukelom, Gerrit J. L. Naus, Maarten J. Beelen, Caroline Meers, Bart Jonckx, Jean-Marie Stassen*,"****Robotic Assisted Cannulation of Occluded Retinal Veins****."*