Force Control Algorithm for the Sclera Eye Surgery

Group Number: 20

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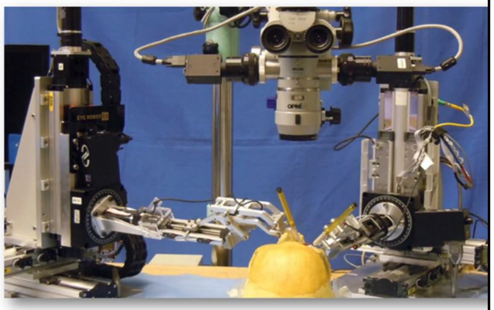
I. Background and Project Overview

The retina is an extension of the brain. It forms the interior lining of the eye and contains millions of light-sensitive nerve endings. Vitreous is a clear, gel-like substance that fills the cavity between the lens and the retina. The retina and vitreous can be affected by a large variety of conditions, including diabetic retinopathy, retinal vein occlusion and macular degeneration. Vitreoretinal Surgery is a procedure involving manipulation of these delicate tissues inside the eye. Desired forces that a surgeon should apply at the tip of his instrument are usually imperceptible to untrained humans. (typically, below 8 mN). Human finger on the other hand has a force sensing resolution of 500 mN. It can thus be concluded that any hand tremor and any kind of mismanagement in forces in the surgery is dangerous. Potential risks of not following the desired force behaviors include Retinal hemorrhage, Retinal Tear, Corneal Striae due to Sclera Bulge, loss of vision etc. In such surgeries, Real-time force measurements/feedback can be useful. To address such issues the Johns Hopkins University has been working to build/improve Eye Robot for the last 15 years.

Carefully following a force curvature along a path begs for variable admittance control. The problems to design a control algorithm for the eye robot are as below:

1. RCM is not fixed in the vitreoretinal surgery and can move up to 12 mm.
2. The eye robot in various situations blocks the view of the surgeon and makes it difficult to view the retina/sclera in the microscope.
3. To make the eyeball fixed the use of two sclerotomies is employed by the surgeons. It involves the use of two dual robot setups and the distance between the two incisions(sclerotomies) must be made fixed. This problem of eyeball motion becomes worse when the surgeon cannot feel the force exerted at the two sclerotomies.



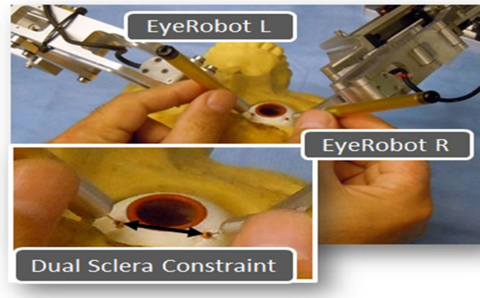


Fig.1 The dual eye surgery robot setup

Fig. 2 The dual sclera constraint

In such scenario, a surgical robot which can assist a surgeon to interact with the patient tissues i.e., by providing quantifications of the real-time interactions of the tissue manipulation at the tool tip and the contact between the tool shaft and sclerotomy comes in handy. These objectives in the current control methodology are gained by using the variable admittance control. Despite the effectiveness of the robot has been tested on the rabbits the various interaction parameters, force scaling parameters and the control methodology switch from the force scaling to the variable admittance control has a linear intermediate path. This path is not linear for the human operative conditions.

II. Problem

Skilled eye surgeons prefer not to move the surgical tool with translational degrees of freedom after certain tool depth inside the eye. Since, there is no available account at what depth the forces by the translational forces become detrimental to the sclera. This information becomes necessary for changing mode of operation of the Eye Robot 2.1 from the Experimental mode (6 DOF) to the Sclera mode (4DOF). The study of behavior and interplay between depth of the tool inside the eye (beyond sclera) and the vector of forces at those depths would be a first to be presented quantitatively. Hence, the focus of the project to investigate the following:

- Lower and Upper depth bounds of sclera: The lower depth bound of sclera is the depth up to which the robot can operate in the experimental mode while the upper bound depth of sclera is the maximum depth a tool can reach inside the eye.

- β, Parameter which reduces degree of freedom from the 6DOF to 4DOF at lower sclera depth to upper bound depth of sclera.
- Transition function: By transition function we mean the function which provides parameter β for every depth of the tool between the lower and the upper bound depth of sclera.

This is the first step to mimic the behavior of an expert surgeon. It is extremely helpful for training new surgeons and rating the skills and progress of learning surgeons (Language of Surgery). This can quicken the process of training new surgeons and make the entire process much more quantitative.

III. **Technical Approach**:

To understand the technical approach, it is important to be aware of the limitations and setup of the Eye Surgery Robot currently being used at our research lab.

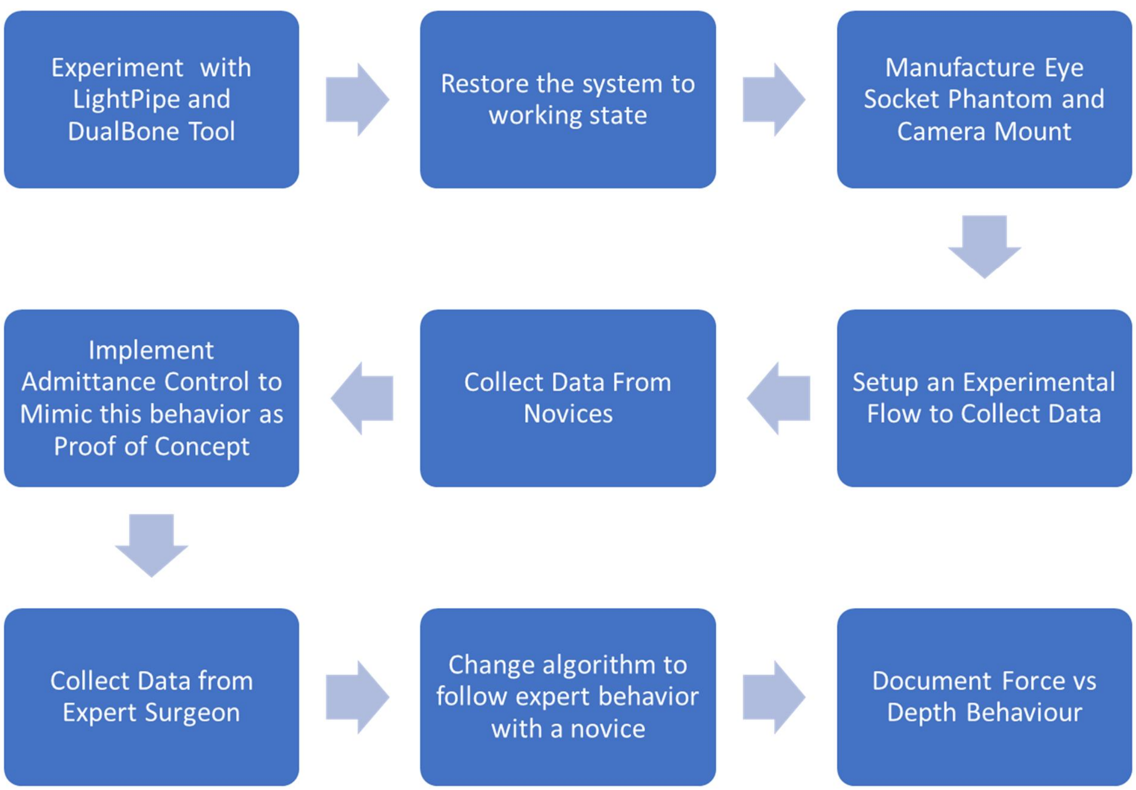


Fig.3 Flowchart of overview of steps taken for the project

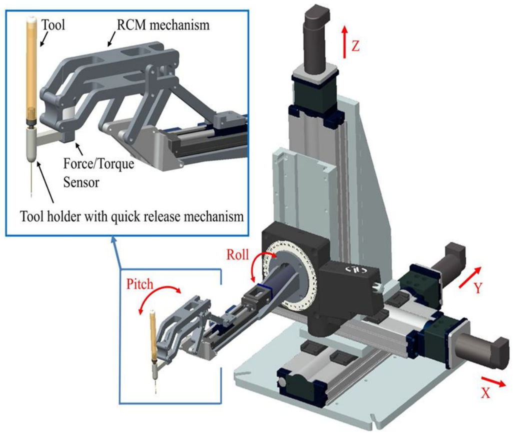


Fig 4. Eye Robot 2.1

A. Robot Structure: The eye robot 2.1 offers 5 DOFs. The 3 of the 5 DOF comes from the translation degrees of the freedom in terms of the motion of X, Y and Z motion of the platform of the robot. The remaining 2 DOF are the two rotational degrees of freedom which provide rotations to the robotic arm in form of roll and the pitch at the tool wrist. The robot is a passive rotational DOF at the tool. The complete kinematic model of the robot for the surgical process has been studied thoroughly from Xingchi He PhD thesis. The robot provides a pitch from -45 to +45 degrees at wrist for the motion of the RCM.

Now our main contribution apart from collecting the data is to design a control algorithm that mimics the recorded and desired behavior from a panel of expert surgeons. For this project, we have created a proof of concept system that acts according to data collected from novice users of the study. It can be easily be extended to follow any other behavior by simply plugging in another file collected from an expert.

B. Variable Admittance control: The robot used to work on the variable admittance control which is designed based on the force scaling and the admittance velocity controls.

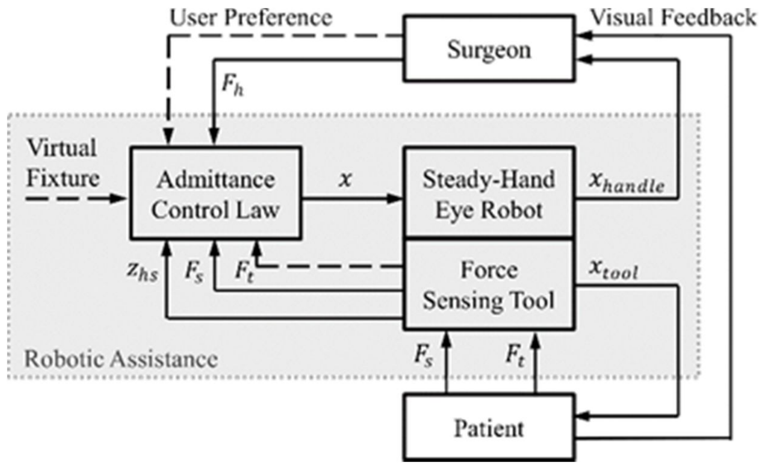


Fig. 5 Flowchart of the current control algorithm

The Solid lines in the above figure show the signal flow in current robot control algorithm, dashed lines show the signals that can also be incorporated into the control law. The constant admittance control is given by equations below.

$$\dot{x}_{hh} = \alpha F_{hh}$$

$$\dot{x}_{hh} = \alpha(F_{hh} + \gamma F_{hs})$$

The governing equation for variable admittance control is given by the equation below where it also incorporates the force from the sclera.

$$\dot{x}_{ss} = \alpha(A_{sh}F_{sh} + \gamma A_{ss}F_{ss})$$

Based on the task, necessity and depth of the tool inside the eyeball the tool admittance and the control model can be varied from the 6DOF to 4DOF by setting the motion guidance constraint such as the virtual RCM by setting the appropriate value of beta in the below given matrices.

$$A_{sh} = diag([1-\beta,\ 1-\beta,\ 1,\ 1,\ 1,\ 1]^T)$$

$$A_{ss} = diag([1+\beta,\ 1+\beta,\ 1,\ 1,\ 1,\ 1]^T)$$

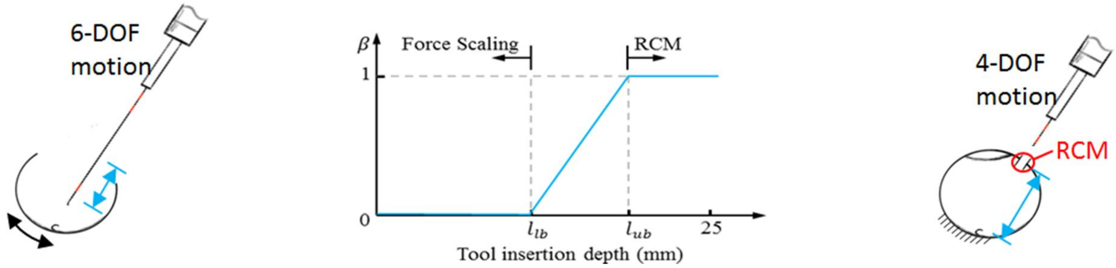


Fig 6 The linear profile between Force and depth implemented before this work

Our contribution is changing the beta variable in this equation. We have made beta as a function of depth which directly takes the value as ratio(γ) from the data collected from our experiment. A typical force vs depth behavior by a novice is depicted in Fig 6, as per the data collected by our experiments.

$$A_{sh} = diag([1-\gamma, 1-\gamma, 1, 1, 1, 1]^T)$$
$$A_{ss} = diag([1+\gamma, 1+\gamma, 1, 1, 1, 1]^T)$$
$$where\ \gamma = F_{desired} / F_{actual}$$

Here, $F_{desired}$ is a function of depth directly mapped from the collected data and F_{actual} is the force currently being exercised by the user. Clearly this way of handling will drive the robot to a velocity that will try to get the forces as close to desired value as possible in an infinitesimal time step.

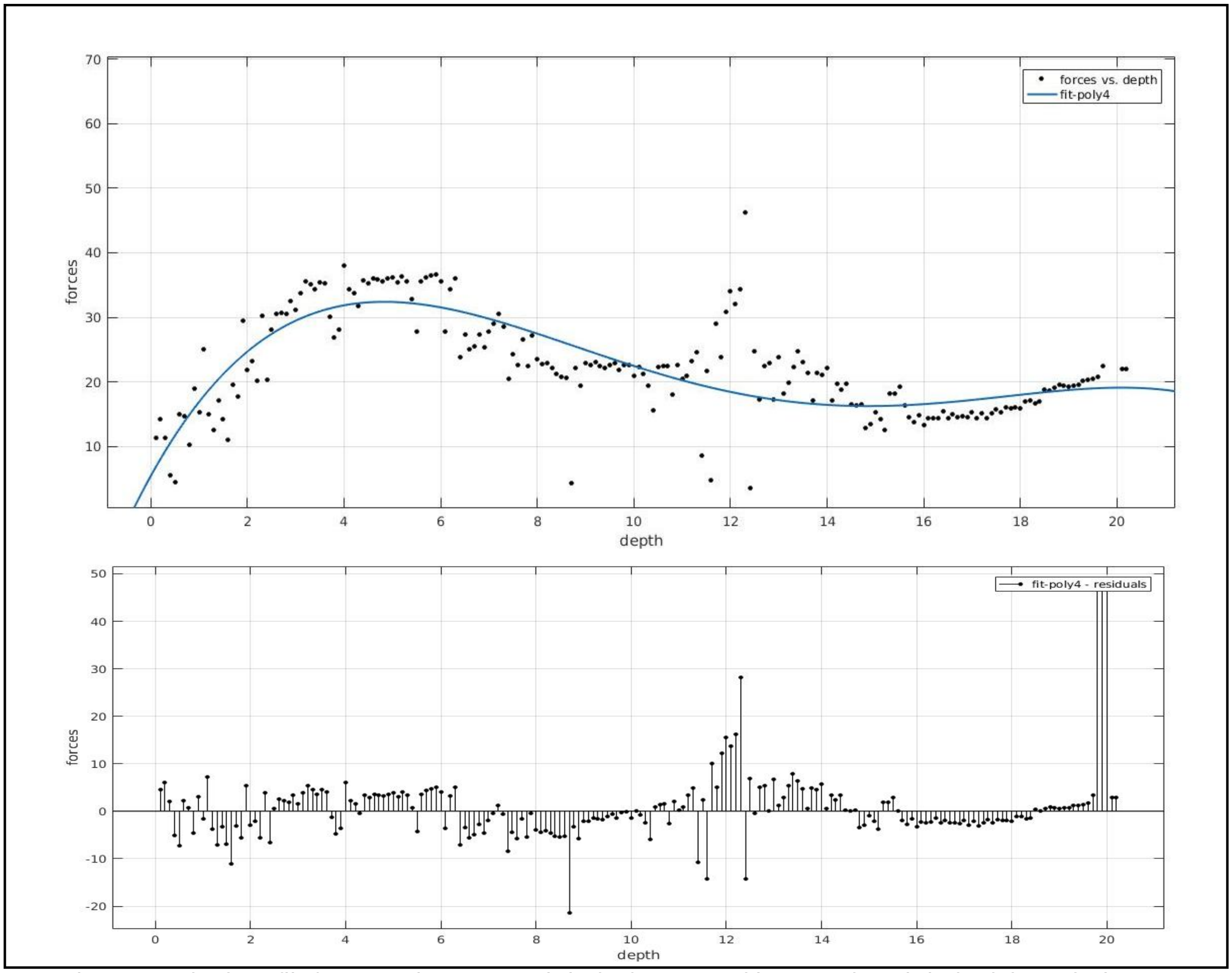


Fig 7. Force depth profile from a novice user. Y axis is the force exerted in mN and x-axis is depth beyond sclera in mm. (Top) Blue line is curve that fits polynomial of degree 4 (poly-4) to the data. (Below) Residuals of poly-4 vs the data

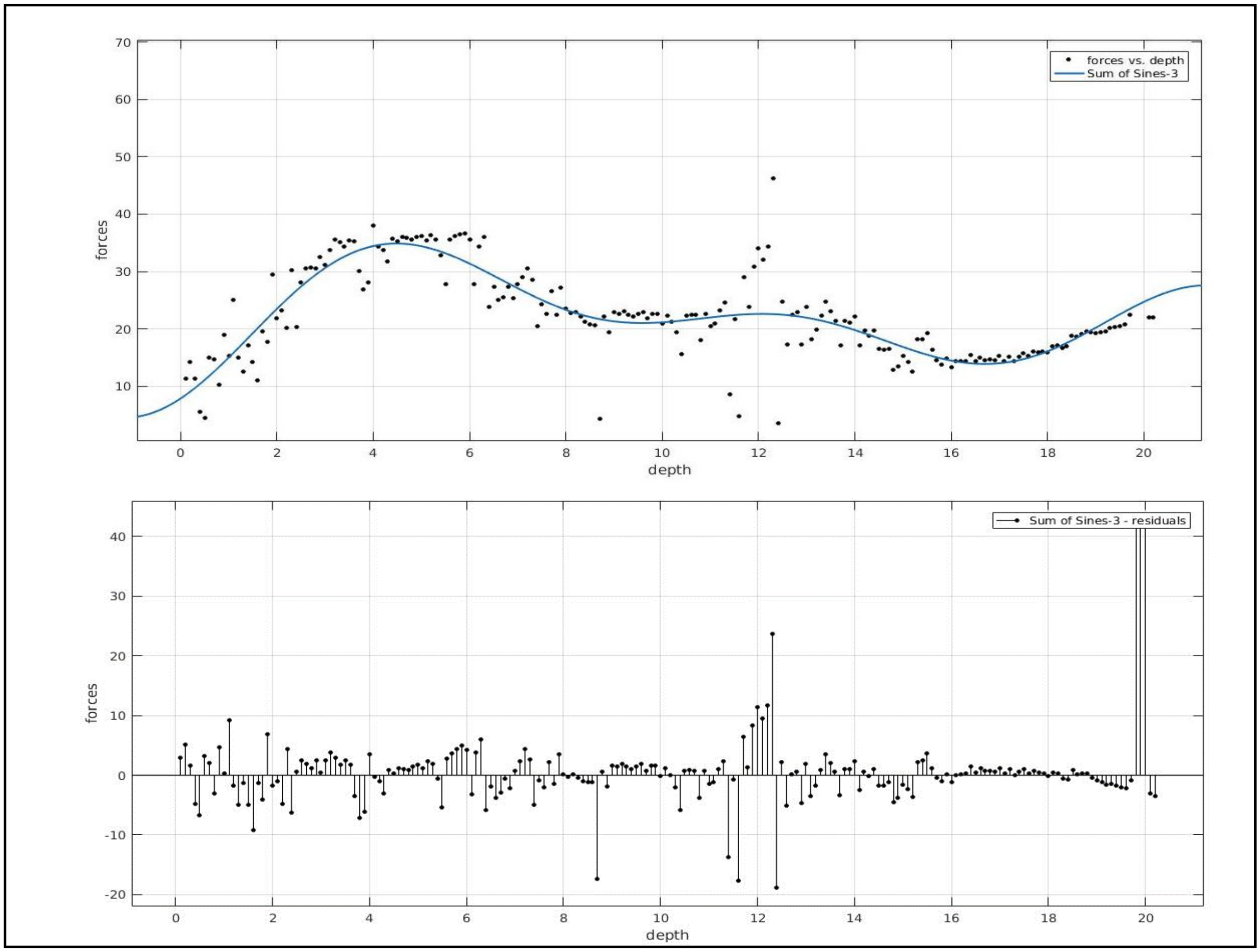


Fig 8. Force depth profile from a novice user. Y axis is the force exerted in mN and x-axis is depth beyond sclera in mm. (Top) Blue line is curve that fits Sum of 3 Sines (Sin-3) to the data. (Bottom) Residuals of Sin-3vs the data

As shown in Figures 7 & 8, we fit two curves to the data collected with the force sensing tool Dual-bone. The two are elementary curves such as sum of sines and polynomial. They were chosen to be such because though we want to fit the data as close as possible, but we do not the idiosyncrasies of a few subjects to affect the algorithm. This is commonly referred to, in Machine Learning parlance, as avoiding overfitting to avoid outlier fitting and improve generalization. We have also shown residual errors on the right of respective fits. Both these residuals are acceptable and allow the outliers to not affect minimization because we are using Tukey's biweight function to increase robustness.

Detailed analysis of the two functions and their parameters is as below:

1. Polynomial: Degree 4

   $f(x) = p1 * x^4 + p2 * x^3 + p3 * x^2 + p4 * x + p5$

   $Coefficients$ ($with$ 95% $confidence\ bounds$):

$p1 = -0.002346\ (-0.003169, -0.001524)$
$p2 = 0.1244\ (0.0908, 0.1581)$
$p3 = -2.193\ (-2.648, -1.738)$
$p4 = 13.53\ (11.25, 15.81)$
$p5 = 5.464\ (2.107, 8.822)$

$Goodness\ of\ fit$:
SSE: 0.4345
$R - square$: 0.7577
$Adjusted\ R - square$: 0.7527
$RMSE$: 4.696

2. Sum of Sines: Degree 3
$f(x) = a1 * \sin(b1 * x + c1) + a2 * \sin(b2 * x + c2) + a3 * \sin(b3 * x + c3)$
$Coefficients\ (with\ 95\%\ confidence\ bounds)$:
$a1 = 24.53\ (20.6, 28.45)$
$b1 = 0.0648\ (-0.1138, 0.2434)$
$c1 = 1.126\ (-2.707, 4.96)$
$a2 = 10.82\ (-112.3, 133.9)$
$b2 = 0.4929\ (-0.8027, 1.788)$
$c2 = -1.786\ (-17.48, 13.91)$
$a3 = 10.14\ (-123.9, 144.2)$
$b3 = 0.6369\ (-0.1923, 1.466)$
$c3 = -0.372\ (-10.25, 9.506)$

$Goodness\ of\ fit$:
SSE: 0.3482
$R - square$: 0.8058
$Adjusted\ R - square$: 0.7978
$RMSE$: 4.247

IV. Experimental Setup:

a. Challenges in the Experiment

The start of the project came with various challenges to setup and make the Eye Robot 2.1 run in its proper state. The challenges and the ways we overcame those challenges are given below:

1. Selection of Tool for the robot: The time we started our project, the robot was working with the tool named “Lightpipe”. We ran several sanity checks to ensure the force sensing ability and calibration of the tool were within accepted norms. The provided tool failed the below test. The reason for the tool failing the test could be the time for which it hadn’t been used and the calibration had gone bad with time. Moreover, the tool showed signs of worn out FBG sensors. Hence, we procured a new tool “DualBone” from our mentor Dr. Iordachita. After testing another procured tool, we ran sanity checks then we

went to setting up other components of the robot. The graphs for the sanity checks are provided in the fig. above. The tests we conducted are listed below:

i. Drift test: A known mass was hung from the tip of the tool to check if the force sensor readings of the tool drifted with time.
ii. Linearity of the sensor: A known mass was hung at increments of 1 mm from the tool tip to ensure that the tool provided correct sclera depth and the force sensing changed uniformly by varying the distance of the hung mass from the tool tip.
iii. Calibration test: The axis of the tool was changed by providing a manual rotation to tool and check in (b) was performed for that axis.

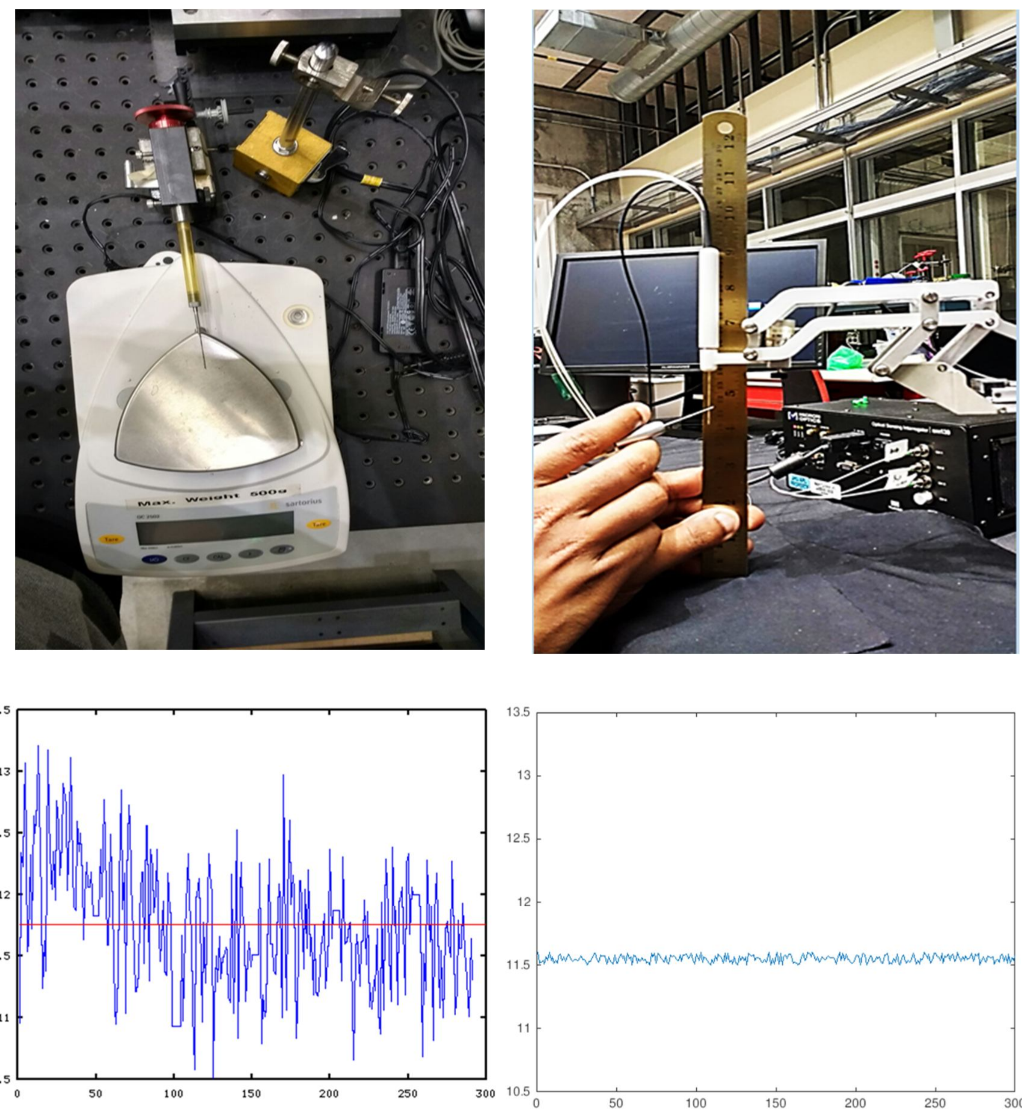


Fig 8. Top Left: Force consistency with rotation setup. Top right: Sclera Depth Consistency Setup Bottom Left: Sclera Depth Response from LightPipe for a fixed depth of 11.5 mm. Bottom Right: Same Response with Dual Bone. Clearly Dual Bone has much better response.

2. Low processing speed: The computer with which Eye Robot was running was too slow to work with and run our OpenCV codes. Hence, we ported codes from the old system to a system with much higher processing speed.

3. Development of the Phantom: The phantom that was previously used for the eye robot experiments offered huge friction and the forces required to move the eye in the eye ball socket were high enough to be detrimental to tool. Hence, we fabricated a new 3D printed eye ball socket and a laser cut podium was designed to raise the height of the eyeball from the table. Mineral oil and Ultrasound lubricating gel were the available lubricating agents present in the laboratory which have viscosity same as the eyeball fluid. We tested both the lubricating agents and mineral oil was used as the lubricating agent. Inside the eye, we placed 4 colored marks namely red, blue, green and black at the max operating angle limit of 30 degrees from the normal of the center of the eye in top, down, right and left direction as shown in the figure 9.

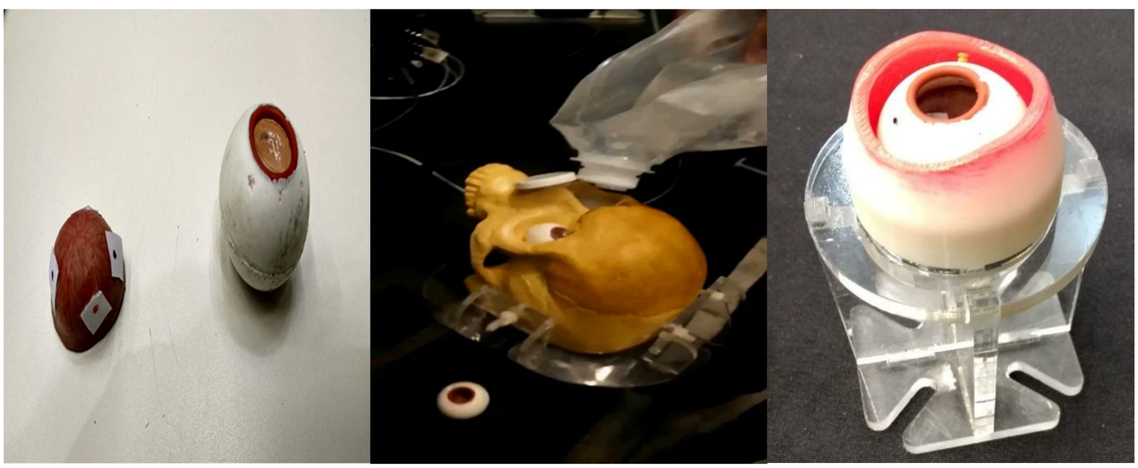


Fig 9. Eye Ball Phantom(Left). Friction Reduction by Ultrasound Gel (Middle). New Eye Socket Fabricated by 3D Printing

4. Camera and setting up the imaging system: While performing the eye surgery the doctors keep their eyes fixed at the monitor providing the real-time image of the eyeball motion. We placed a USB Camera from Logitech to capture the motion of the eye in the eyeball and the motion of the tool in the eye ball. To setup the camera we also designed the camera mount. Since, the workspace of the eye robot is not too large the mount was designed in such a way to capture the video of the operation with proper focus and no obstruction in motion of the robot. Hence, a camera mount, which supports the camera inside, was designed in the shape of a crank by 3D printing which was attached with a metallic vertical stand. The latency problem of the video capture was solved by

using a computer high processing speed. To start the experiment with nearly same state a blinking marker was generated from OpenCV libraries at the center of each captured frame of the camera. This helped the user to bring the center of the eye to this point and start the experiment to bring repeatability and the consistency in the trials.

b. **Description of the experiment**:

The designed experiment has the following steps:

Step 1: Align eye with the center point blinker displayed on the screen with the tool. This point is the home location.

Step 2: Make the tool tip go to the home position and touch it with the tool tip.

Step 3: Then follow the same procedure in the order:

Bring Yellow mark near the marker- Touch the yellow mark- Retract

Bring Red mark near the marker- Touch the Red mark- Retract

Bring green mark near the marker- Touch the Green mark- Retract

Since we have 3 colors (R, G, Y) inside the eye 6 possible permutations of the Step 3 task are possible. They are: YBR, YRB, BRY, BYR, RBY, RYB where R, B, Y denote the Red, Blue and the Yellow color. For each permutation of the color we logged the sclera depth, forces from FBG sensors and time taken to perform the trial. We performed 3 sets of trials of experiments with and without robot with Dr. Iordachita, 2 sets of trials of experiments with and without robot with Berk Gonenc and 1 set of trial of experiment with and without robot with Dr. Gelbach.

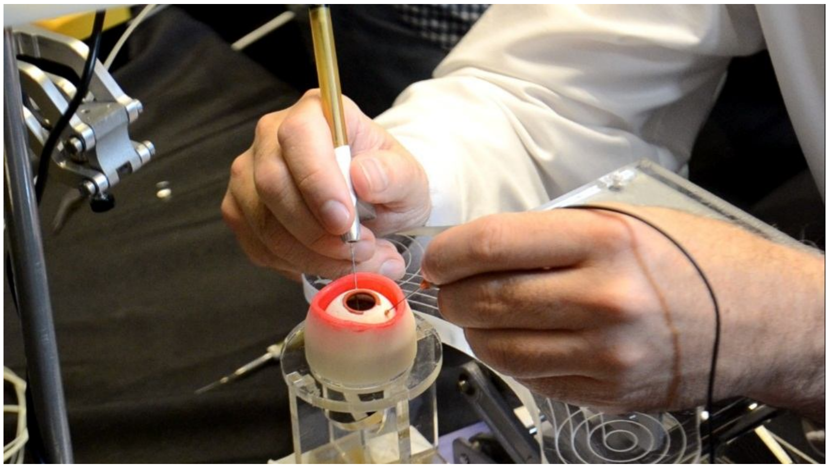


Fig. 10 Doctor performing trials for the designed experiment

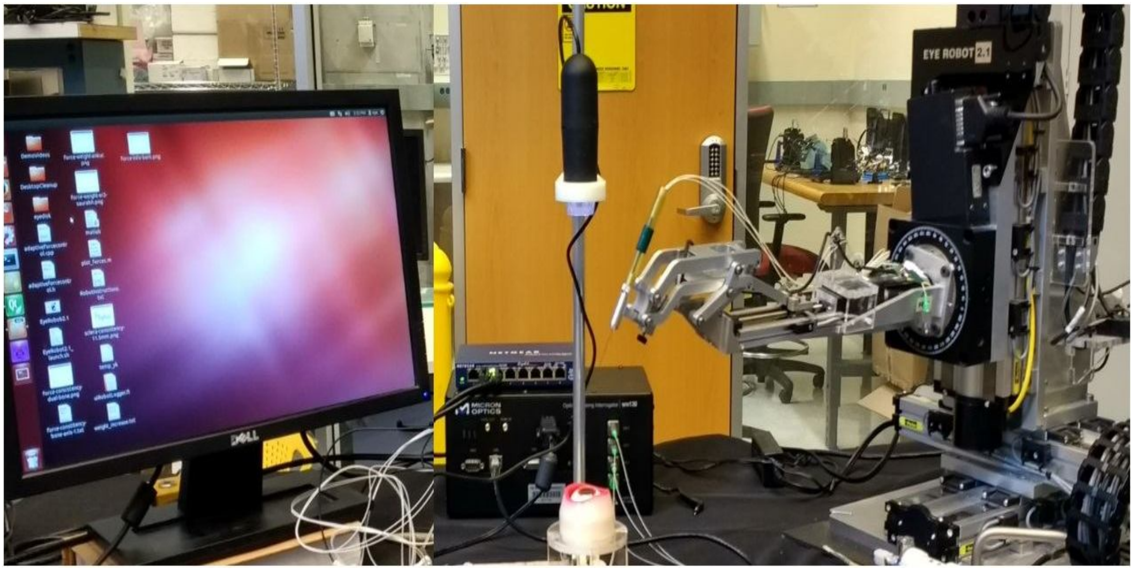


Fig 11. Shows the current state of the Eye Robot 2.1 after all experiment setup

V. **Significance**:

We were able to run validation experiments on two micro-force sensing instruments namely the DualBone and LightPipe. We studied and analyzed their behavior with depth, force norm and force direction consistency. Then we setup a highly robust and repeatable experiment for the inexperienced as well as the expert users for data collection. We were successfully able to collect more than 10,000 data points from novice users. Based on the depth vs force profile we collected, we also implemented the control algorithm that would follow the same behavior for a completely new user, following his/her commands on the way. This is a far-reaching development in microsurgery since it can be directly used to train new surgeons and/or assess their progress quantitively. This paradigm can be used to automatically guide any vitreoretinal surgeon to conduct surgery without the fear of exerting more force than required, thereby enabling him focus on the goal of the surgery thereby potentially reducing the risk in the process. This would have a direct impact on Quality of Life of the patients' post-surgery.

VI. **Limitations and Future Work**:

The experiments we ran for data collection and admittance control were all based on a single subject. We used a dry phantom for all data collection and controls. Therefore, future work could potentially involve multiple subjects and use more realistic phantoms to conduct data collection. This can greatly improve the quality of parameters for curve fitting.

Unfortunately, the tool that we finalized for the project is stopped function properly towards the very end of the trial thus prohibiting us from collecting expert surgeon's data. It is for this reason that, we can only hypothesis about the force profile changes with depth when done with a trained surgeon. That is why a crucial next task will be to test the control algorithm and the mechanism we developed with the data collected from the surgeon.

The surgeon typically uses two tools to guide and rotate the eyeball during a surgery. In our experiments one of the tools was fitted with force sensors, while the other was not. Since these tools were different(DualBone and conventional lightpipe), there was a stiffness mismatch during the eyeball manipulation by surgeon. The limitation was unavailability of two tools with the same Young's Modulus. Hence, the experiment trials with the tools of the same stiffness will provide accurate force variation trend.

VII. **Management Summary**:

A well-structured plan was made with the tentative dates by which we worked to meet the assigned goals. Weekly meetings were planned to give updates, discuss current progress, and get feedback for the project with our mentor Dr. Iulian Iordachita. The frequencies of our meeting increased to daily towards the last one and a half month of the project. The team worked to document the code they wrote so that it is readable to inexperienced users.

Ankur Gupta worked majorly on the software part of the of the eye robot. He developed the codes and developed customized functions and utilities to collect the required data from the trials. Based on his experience with OpenCV he implemented blinking point in the optical center of frames captured from the camera which could run in a separate thread thereby not affecting the performance of the robot. He also developed the imaging system for the doctor to visualize the camera output on the monitor.

Saurabh Singh worked on the hardware development and understanding the control algorithm of the eye robot system. He worked to fabricate the camera mount for the camera, worked on the phantom development and the eye lubrication.

Ankur and Saurabh worked together to develop the control strategy for the eye robot motion based on the depth of surgical tool inside the eye.

Lessons learned by both Ankur and Saurabh include the methodology and culture of a research group, exploration and integration of third party software and libraries, and building a large C++ application with Qt GUI and numerous dependencies with CMake. Apart from the software skills the project provided the knowledge of sensing forces of milli-Newton order.

VIII. **Acknowledgments**: We would like to thank Dr. Iulian Iordachita's AMIRO group at Johns Hopkins University, especially Berk Gonenc for their mentorship during this project. We would also like to thank Dr. Marin Kobilarov and Dr. Russell H. Taylor for guidance on the project. The team will like to show gratitude to ASCOL lab for providing lab equipment at odd hours.

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X. Appendix:

```
constraintControlAlgorithm.cpp
plot-depth-force.py(fast)
plot-depth-forces.m(slow)
CamCapture
CamCapture.pro
CamCapture.pro.user
Makefile
main.cpp
main.o
```