Virtual Fixture Guidance for Robotic Assisted Surgery

Checkpoint Presentation

2019.03.28

Group 3: Anurag Madan, Zhaoshuo (Max) Li

Mentor: Dr. Mahya Shahbazi, Dr. Russell H. Taylor

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Motivation

- Many anatomies are fragile and close to surgical field during operation. Therefore, we want to propose a **virtual fixture** (VF) guided paradigm to extend the surgeon's capabilities during **robotic-assisted surgeries**.

Outline

- Confocal endoscopic imaging for retinal surgery
  - Background
  - System design
  - User study result
- Virtual fixture guidance for skull drilling
  - Background
  - Design Approach
  - Deliverable
  - Responsibility and Management Plan
  - Timeline
  - Dependencies

Confocal endoscopic imaging for retinal surgery

Background

- Retinal detachment is a vision threatening condition. Success following surgical repair depends on a myriad of factors, including the duration of detachment [1].
- Probe-based confocal laser endomicroscopy (pCLE) enables real-time imaging and *in-vivo* characterization of tissues at the cellular level for enhanced diagnosis [2][3].
- pCLE is, however, limited by its field-of-view and micron-scale optimal range of focus (Fig. 1), making manual image acquisition extremely challenging due to physiological hand tremors

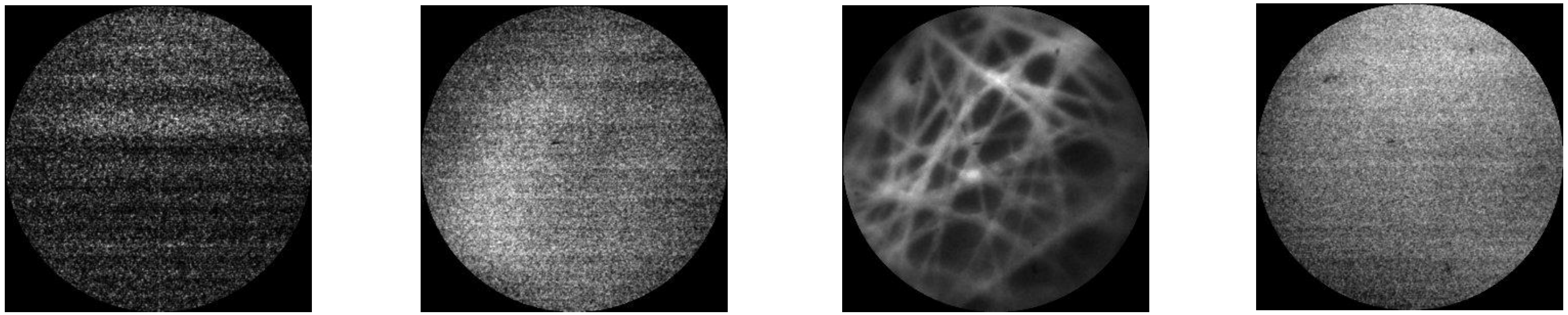
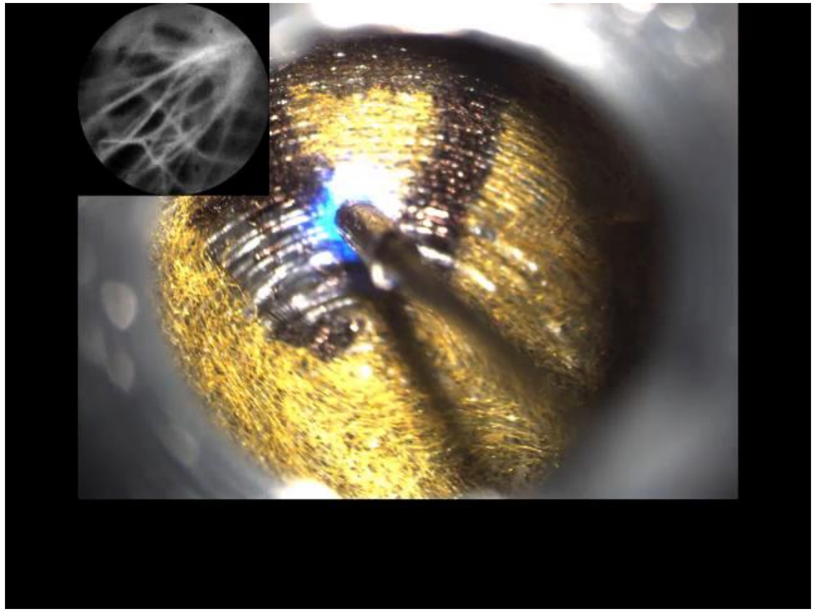


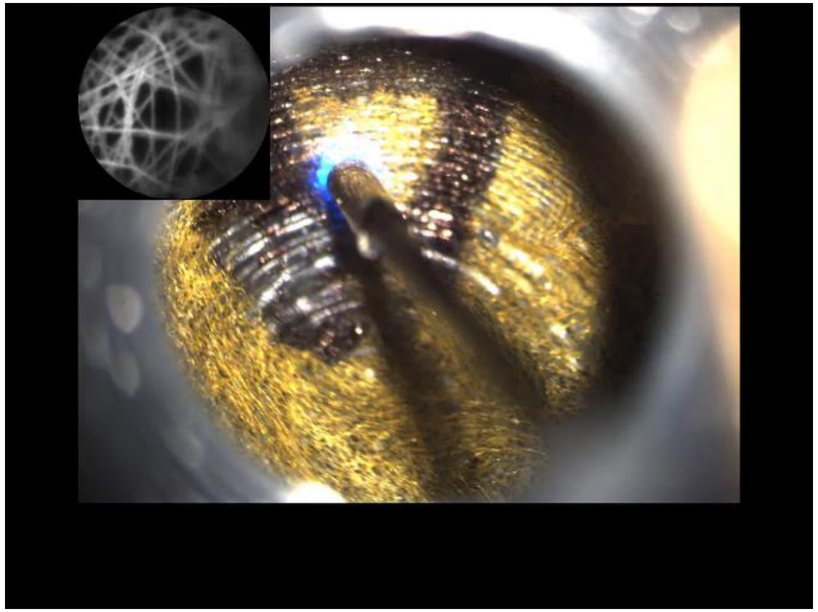
Fig. 1. Sample pCLE views. (a) Out-of-range, 2.34mm probe-tissue distance; (b) Back-focus, 1.16mm probe-tissue distance; (c) In-focus, 0.69mm probe-tissue distance; (d) Front-focus view, probe fully in contact with the tissue

Background (Cont.)

- A shared-control framework is proposed for semi-autonomous endomicroscopy scanning.
- User study video



Video 1, Cooperative



Video 2, semi-autonomous

System Design

- Image quality can be quantitatively measured by Crete-Roffet (CR) score [5]
- Gradient-based search
  - T_1 < CR → out-of-range focus; surgeon can control the depth.
  - T_1 < CR < T_2 → a stochastic gradient ascent approach is used by taking into account the past states of the image scores and the robot motion.
  - T_2 < CR → the optimal view has reached; axial motion is stopped.

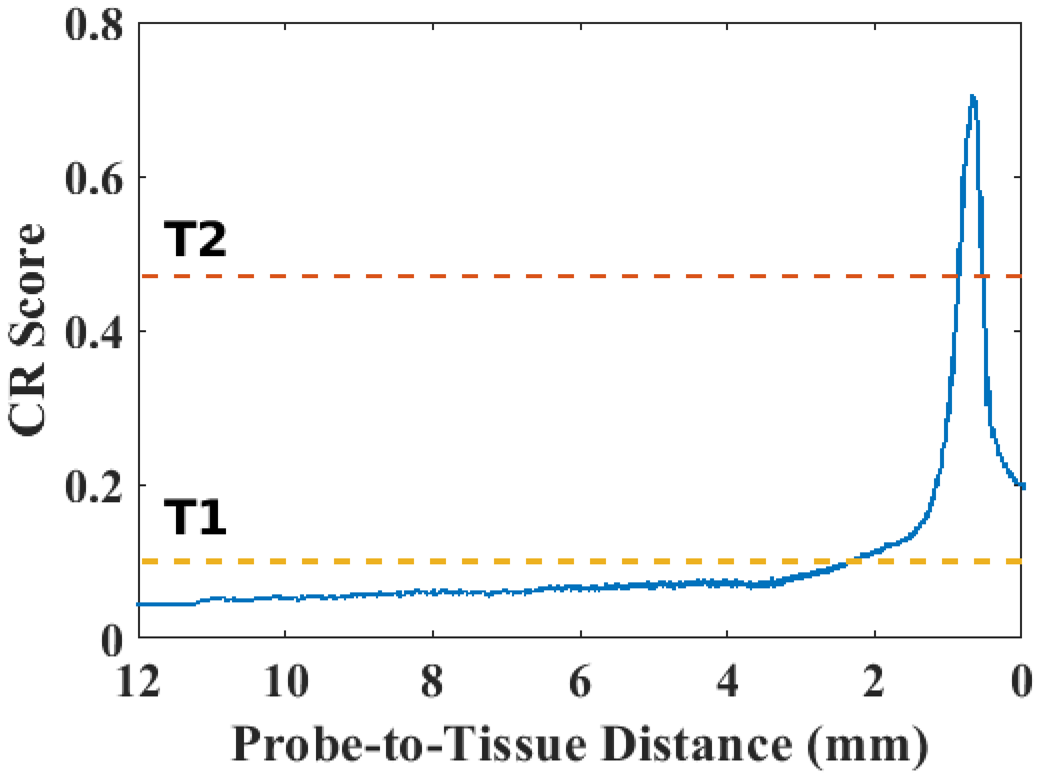


Fig. 2. CR score with respect to the probe-to-tissue distance.

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System Design (Cont.)

- Hybrid Cooperative Control – Mid-level Controller
  $\dot{x}_{des} = K_c \dot{x}_{des,c} + K_a \dot{x}_{des,a}$
- Hybrid Cooperative Control - Block Diagram

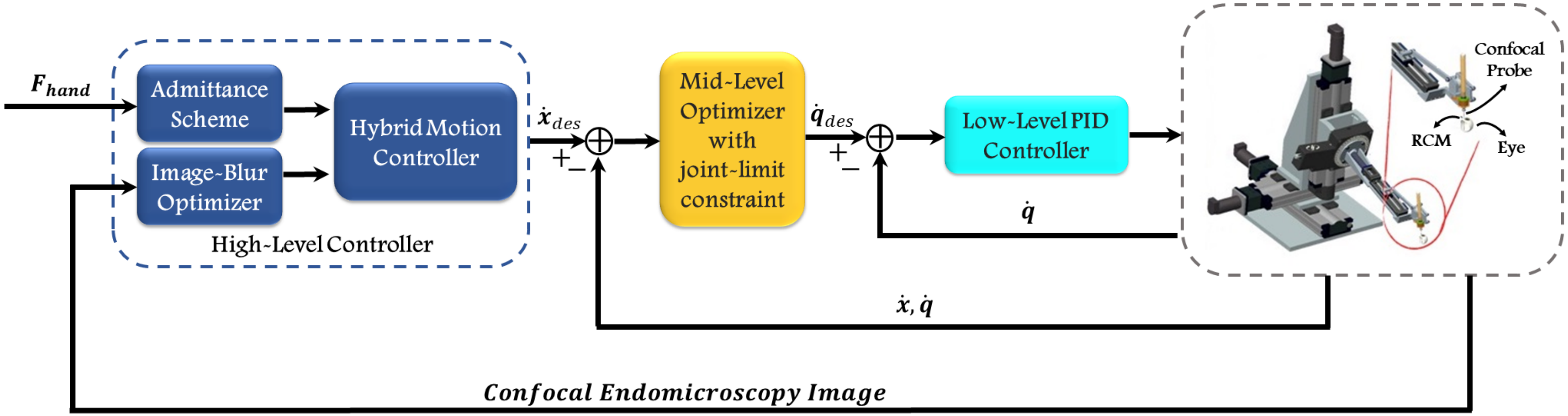

Fig. 3. General schematic of the proposed hybrid control strategy

User Study Result

- 9 subjects participated in the study

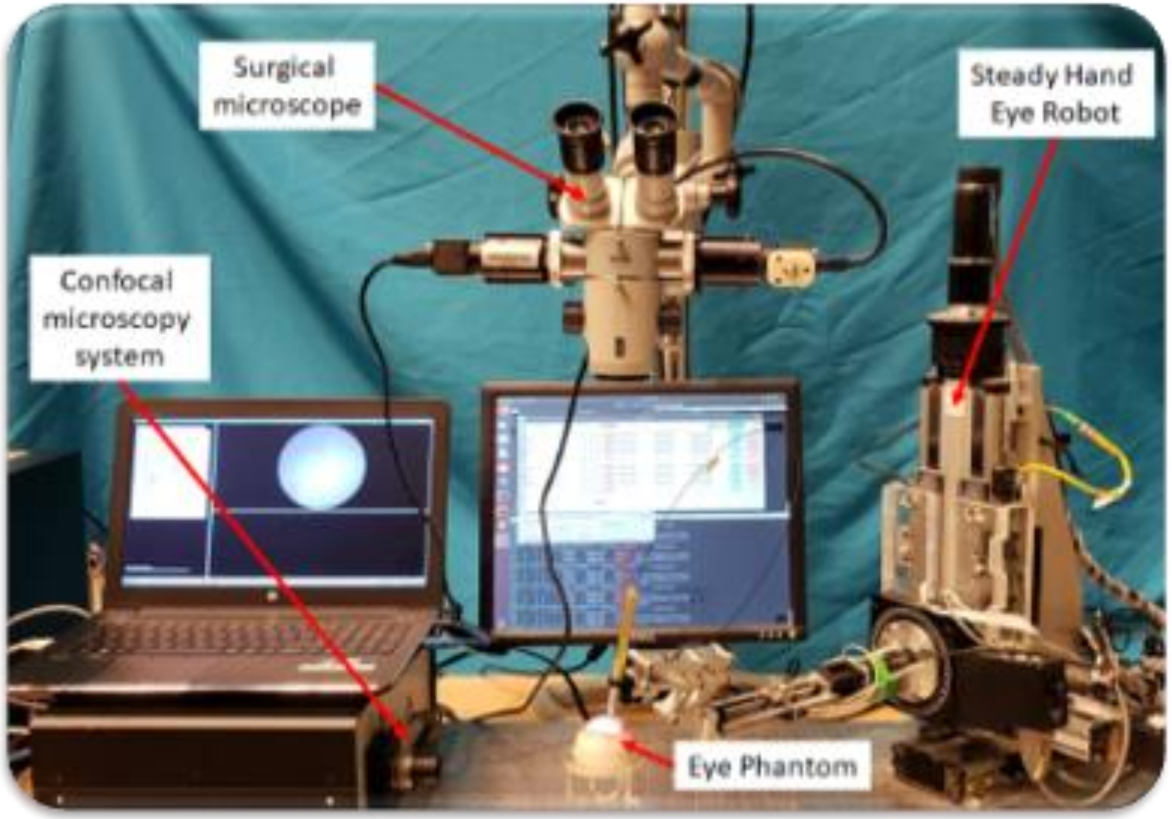

Fig. 4. Experimental setup showing the confocal endomicroscopy system, steady-hand eye robot, surgical microscope, and an artificial eye phantom.

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User Study Result

- Semi-autonomous framework improved in CR score, Duration of In-focus View and Motion Smoothness (MS)

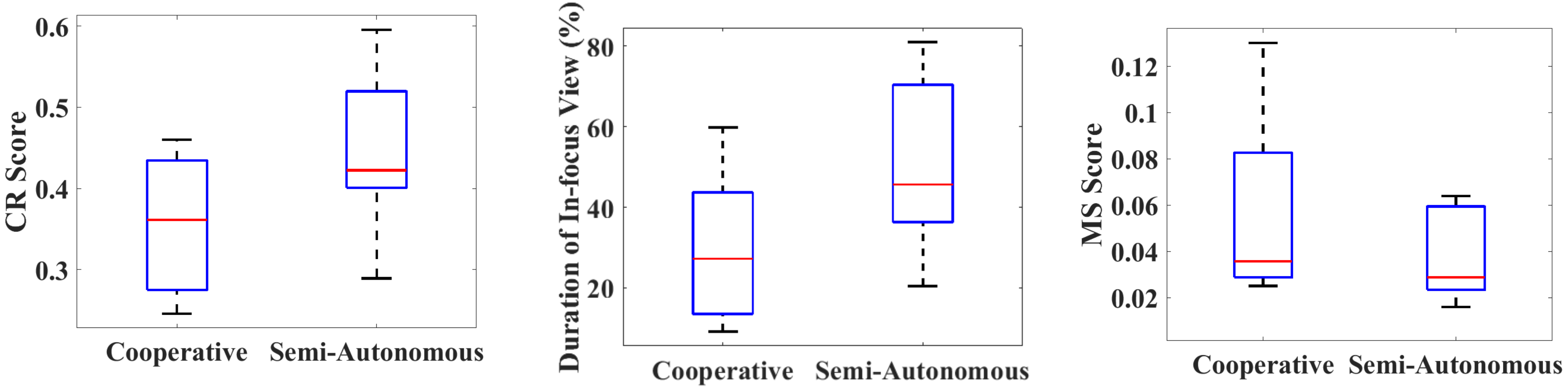

Fig. 5. Results of the user study

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Virtual fixture guidance for skull drilling

Background

- A **mastoidectomy** is a surgical procedure that removes diseased mastoid air cells, which can be used to remove infected air cells, and drain middle ear
- However, underlying anatomy is fragile, such as the facial nerve

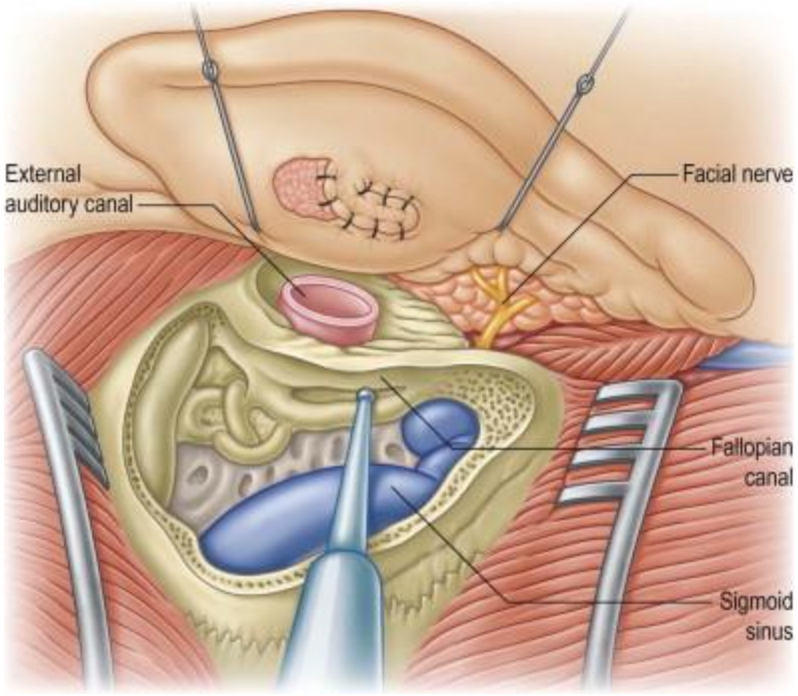

Fig 6. An overview of mastoidectomy procedure (source link)

Background (Cont.)

- Galen Mark I design
  - Parallel link robot
  - 5 DOF
  - Stable force sensor
- Current FK computation
  - Currently uses a polynomial approximation for Forward Kinematics calculations
- Current Jacobian computation
  - Currently calculates the inverse of the inverse Jacobian

Project goals

- Implement simple and complex virtual fixtures for hand-over-hand control of the Galen Mark I surgical robot.

Design Approach

- Correct Jacobian and Forward Kinematics of the Galen Robot
- Implement simple virtual fixtures like plane constraints using the already developed constraint optimization solver
- Prototype logic for implementing complex virtual fixtures like 3D surfaces of known geometry, where the surface equation might not be known
- Test complex virtual fixtures
- Iterate and improve

Design Approach (simple fixtures)

- Use known constraints for simple virtual fixtures [8],[9]
  - Plane: $\vec{n}.\vec{X} - \vec{n}.\vec{p} \geq 0$
  - Path Following: $min_{dq}||(J_T * dq - (g_{Trans} * Trans((g_{orth} * dx_{orth} + g_{adj} * dx_{adj})) + g_{Rot} * Rot(dx_P))||^2$
  - Axis: $min_{dq}|| J_H * dq - dx_{ins} ||^2$

Design Approach (surface fixture)

- Approach 1
  - Break the surface into multiple planes, and utilize the plane constraint optimizer, dynamically shifting between different planes.

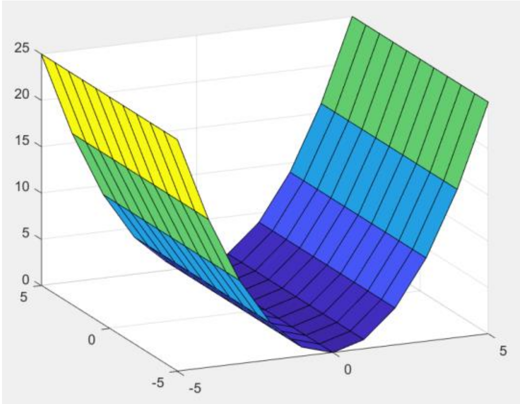

Fig 7. Surface modelling

- Approach 2
  - Fit a polynomial through the surface and have the high-level controller compute the distance of the tool tip to the surface itself.
  - This distance can then be written in the form of an objective function that the mid-level controller can optimize

Deliverables

- Minimum
  - Framework for simple virtual fixtures. Fixtures would be
    - Plane constraints
    - Path following
    - Insertion along an axis
- Expected
  - Framework for more complex virtual fixtures like constraints for 3D surfaces
  - Framework for automated switching of modes from virtual fixtures to free motion depending on location of tool tip
- Maximum
  - Framework to compute virtual fixture constraints based on CT scan data

Responsibilities and Management Plan

- Since most of the project relies on coding, both team members can work together on different parts. But based on expertise and preference, the tasks were divided as follows.
  - Max
    - Forward Kinematics validation
    - Simple virtual fixture implementation
  - Anurag
    - Jacobian correction
    - Surface constraint logic
- Management plan:
  - Code will be stored on BitBucket
  - Documentation will be prepared separately on OneDrive

Milestones

Accomplishment	Estimated Date	Status
Jacobian and FK correction	Apr 1	Incomplete
Simple Virtual Fixture implementation	Apr 7	Incomplete
Surface virtual fixture Logic	Apr 12	Incomplete
Surface virtual fixture implementation	Apr 20	Incomplete

Dependencies

Dependency	Plan to resolve	Estimated resolution date
Access to Galen Mark I	Schedule with Dr. Taylor	Resolved
Access to CT (if necessary)	Coordinate with Dr. Taylor	April 15
Access to phantom skull (if necessary)	Coordinate with Dr. Taylor	April 15

References

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