Virtual Fixture Guidance for Surigcal Robots of Complex Geometry

Computer Integrated Surgery II

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Anurag Madan and Zhaoshuo Li,

under the auspices of Professor Russell H. Taylor, Dr. Mahya Shahbazi and Dr. Niravkumar Patel

1. Introduction

- In many surgical procedures, patient's critical anatomies are close to the surgical field and exposed to the surgical tool. Any contact could lead to surgical complication.
- Mastoidectomy is such an example, where facial nerves are close to the drilling location. The process requires high surgical skills, full concentration of surgeons, and carful maneuvering of the surgical tool.
- Virtual fixture has been used in surgical robotics to provide necessary constraint of user's movement to reduce the risk [1].
- However, virtual fixture as a constraint optimization can be computational expensive for the controller, which causes lagged motion and instability.
- The goal of this project is to develop virtual fixture guidance with optimized data structures to improve real-time performance for the Mark I robot from Galen Robotics.

2. Solution

Two virtual fixtures are developed in this project - multiple plane constraint and multiple mesh constraint.

Multi-plane Constraint

- Plane constraint is a primitive constraint, which can be formulated as an inequality constraint [1]

$$N \cdot J\Delta q \leq \frac{d}{\Delta t}$$

  where N is the unit normal of the plane, J is the Jacobian of the robot, Δq is the incremental joint position, d is the signed distance from the plane to the robot tip and Δt is the period of the robot run loop.
- Multiple plane constraints can be used to approximate complex convex shape. In our project, a cylindrical constraint is created using multiple plane constraints.

Multi-mesh Constraint

- However, only using plane constraint is a problem when having a concave shape, Fig 1. illustrates such a case.
- Using triangle meshes can approximate any shape, and the constraint can be formulated the same as plane constraint.
- The normal direction can be different depending on where the closest points are on triangle meshes, which are illustrated in Fig 2.:
  - Points within the triangle → mesh normal
  - Points on edges and only found on one mesh → do not include in the optimization problem when there are other mesh constraints active,
  - Points on edges and shared with multiple meshes → averaged normal direction from different

Real-time Improvement

- Bounding box around tool tip is used for fast rejection of far away meshes, where bounding box length is the velocity of robot in one iteration.
- Covariance tree [2] is used to facilitate the search for closest points on meshes that intersect with the bounding box of tool tip.

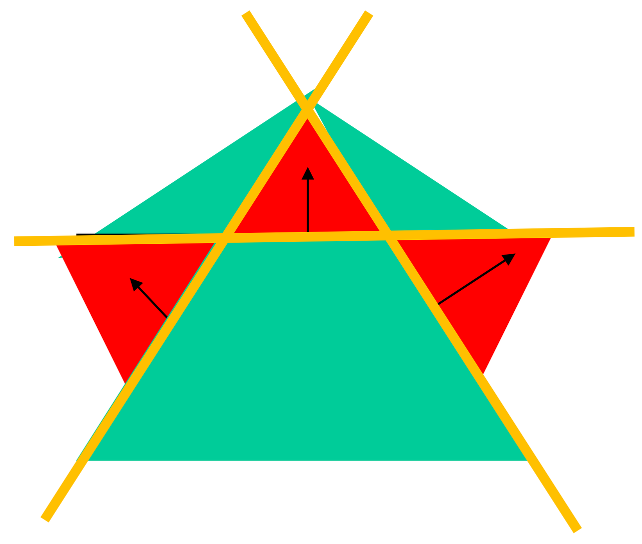


Fig 1. Multi-plane constraint fails for a convex shape. *Orange lines*: planes; *Arrows*: normal direction; *Green regions*: optimization is feasible; *Red regions*: optimization fails.

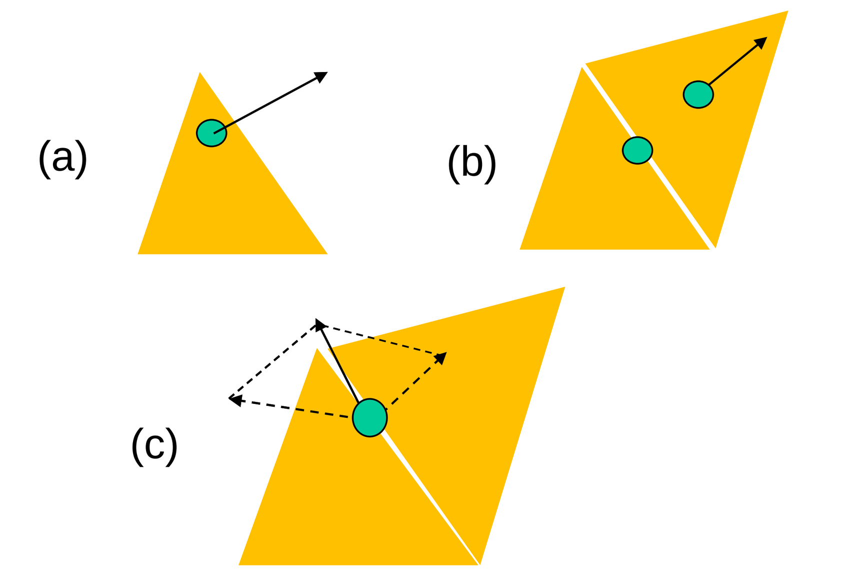
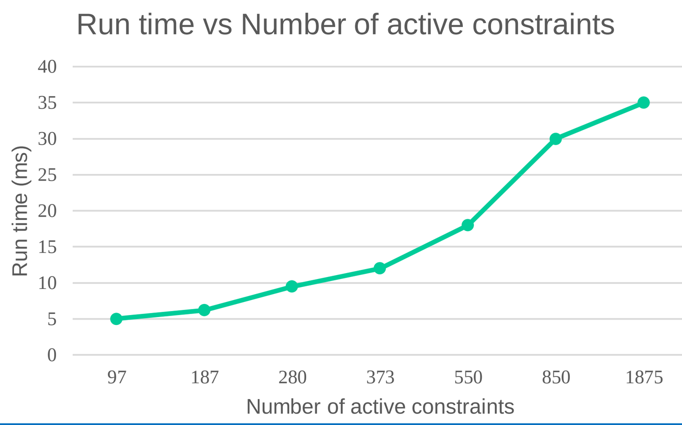


Fig 2. Three cases for multi-mesh constraint, (a) Point within mesh, (b) Point on edge - found by one mesh, (c) Point on edge - found by multiple meshes. *Orange triangle*: meshes; *Dashed arrows*: mesh normal; *Solid arrows*: final direction; *Green dot*: closest points.

3. Outcome and Results

Preliminary experiment result is shown in plot below.



4. Future Work

- The positional error given the virtual constraint needs to be evaluated.
- The software needs to be generalized to 6 DoF on Mark I.
- Error recovery needs to be added.
- Zhaoshuo Li will continue this project in 2019 Fall term.

5. Credits and Lessons Learned

Credits

- Anurag Madan: Optimization formulation, testing
- Zhaoshuo Li: Covariance tree, testing

Lessons Learned

- Cannot brute-force through mesh constraints

6. References

[1] A. Kapoor. Motion Constrained Control of Robots for Dexterous Surgical Tasks. PhD thesis, Johns Hopkins University, September 2007.

[2] J. P. Williams, R. H. Taylor, and L. B. Wolff, "Augmented KD techniques for accelerated registration and distance measurement of surfaces," in Computer Aided Surgery: Computer-Integrated Surgery of the Head and Spine, Sep. 1997, pp. 1–21

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