EN 601.656 Computer Integrated Surgery II
Background Literature Critical Review
Project 24: "*Evaluation of Virtual Remote Center of Motion for Minimally Invasive Surgery*"

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Paper selection

It was decided that a constrained optimization approach for implementing virtual RCM-based control of the UR5 robot manipulator will be used. There are few reasons for that. Firstly, the project technical requirement is that a robot inside AMBF simulator must follow the provided cartesian positions of the tool tip either pre-recorded or provided online using a real teleoperation robot like daVinci MTM. Secondly, there are available C++/Python libraries for optimization, particularly libraries for inequality constraint equations solving as sawConstraintController library.

There are two possible modes of virtual RCM based robot control: velocity and position control. In this report, the paper representing velocity control mode will be analyzed because initially velocity control mode for UR5 control was chosen to implement for RCM constrained control.

B. Mitchell et al. "Development and application of a new steady-hand manipulator for retinal surgery" Proc. IEEE Int. Conf. Robot. Autom. pp. 623-629 2007.

Relevance

This paper was chosen because it implements virtual RCM constrained velocity control of steady-hand manipulator for retinal surgery. Though it is a hands-on robot, i.e. the input of the system is an operator's force exerted on the handle, the formulation of vRCM in the paper can be adapted to vRCM formulation of our project where inputs are the tool tip positions. Moreover, it gives a general overview of what is virtual RCM, its difference from hardware imposed RCM, pros and cons of both. And the paper focuses on the specific application of virtual RCM, which gives motivation for me to realize the importance of the project.

Technical summary

The paper describes development of a steady-hand 5 degrees-of-freedom manipulator particularly designed for retinal surgery application. It is one of the first versions of the eye surgery steady-hand manipulators series in which compactness of the robot was favored in place of stability that could be achieved by implying RCM in the robot mechanical design itself. Due to the design, implementation of virtual RCM was necessary.

The name 'steady-hand' of the robot comes from the paradigm of the shared control of the tool between a surgeon operator and the robot by means of a force/torque sensor on the handle. It allows precise control of the needle which is highly required in eye microsurgery and helps to eliminate tremor.

The application that the robot was demonstrated on is retinal vein cannulation. It requires insertion of the needle into a retina vein. The insertion point on the eye sclera becomes a remote center of motion which creates a set of constraints on the robot's allowable motion in order not to damage the eye tissue.

The robot structure allows more compact design. It has 2 DoF responsible for rotation, (roll and tilt). Spin is not drivable and must be performed by an operator manually. Remaining 3 DoF are due to XYZ general translations. Elimination of tool insertion and spin related DoF's allowed to obtain thinner tool holder design and simplify interaction with a microscope workspace. Such design allowed virtual RCM implementation which requires 3 rotation axis intersecting at insertion point and the translation through the insertion point.

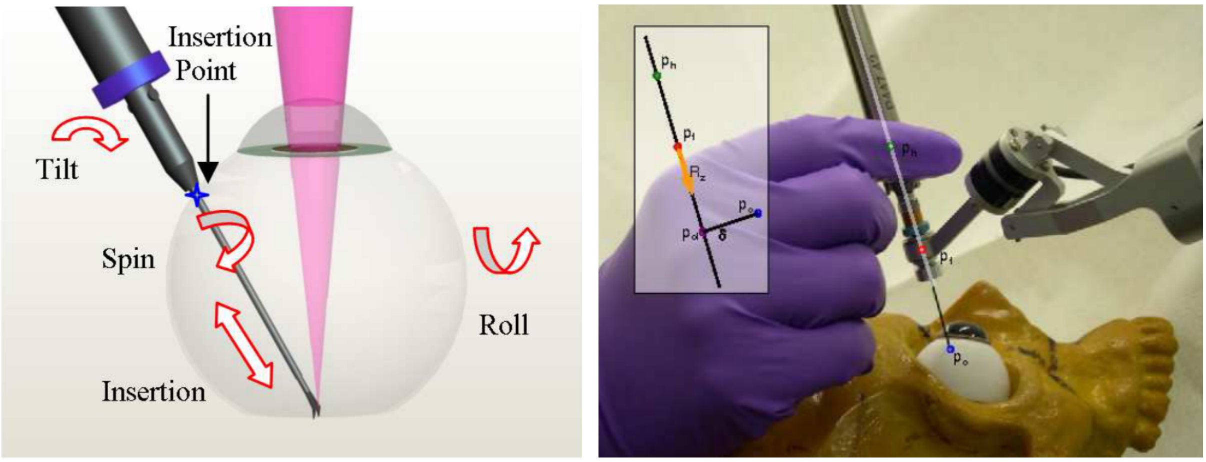

Figure 1. (Left) Rotations and translation allowed during RCM control. (Right) The real robot performing the needle insertion on the mock eye.

Next, virtual RCM implementation will be discussed. Admittance control guidance methods are used in order to control the tool. Firstly, forces and torques measured by the 6DoF force sensor are transformed to a tool 6x1 velocity screw by 6x6 matrix G as the following:

$$v = Gf$$

Here, entries of the matrix G represent relative gains of the input forces. It allows to tune the robot response to the applied forces/torques.
Then, a constrained optimization technique is used to implement the virtual fixture embodying RCM. So, the control algorithm aims to minimize the following distance:

$$||J_h(q)\Delta q - Gf||$$

while respecting RCM constraint at the same time:

$$||P_{cl} + J_{cl}(q)\Delta q - P_o|| \leq \epsilon$$

where q - joint states; J_h - manipulator Jacobian at the handle, J_{cl} - manipulator Jacobian at the point on the tool closest to the RCM, P_{cl} - cartesian position of the point on the tool closest to the RCM, P_O - cartesian position of this closest point.

This optimization algorithm outputs Δq values representing joint velocities such that the distance between input velocity vector, obtained by sensed forces/torques transformation, and actual robot cartesian velocities vector (v and w) at the handle is minimum.

Results summary:
The steady-hand robot was successfully designed and tested on the animal eye. The experiment of insertion of the needle to 80 micrometers sized vein with minimal damage and high precision proves the correctness of the implemented control algorithm with RCM constraint and the intended targeted design.

Critical analysis
The control algorithm described in the paper puts control response to the input forces to the first priority because it optimizes in terms of velocities while RCM is implemented as the inequality constraint with some allowable value of epsilon. It might cause some deviations from the desired RCM which is a real insertion hole on the human sclera. And the values on G entries and epsilon are not mentioned, though it might be important to know forces in which direction are playing more role in the robot tool control. Such choice of prioritization of input forces tracking over aiming to RCM satisfaction during control algorithm implementation might be due to the importance of the robot's responsiveness and tool placement precision over possible tension on the sclera caused by deviations from the imposed RCM.

The paper describes qualitative results mostly. Though it provides robot performance specifications in the tabular form, the only quantitative result thoroughly described is a successful insertion of the needle to ~80 μm OD vein. Though it states that the robot assisted control of the needle insertion is tremor-free and precise it does not reveal quantitative results for vibration of the tool while being controlled by an operator.
As it was said, the control of the robot prioritizes human control over RCM. Thus it also would be interesting to see how precisely RCM constraints were followed.
User-study involving eye surgeons might also help to demonstrate the usability of the robot, learning period, etc.

Conclusion/Takeaways:
The method described in the paper does not have a proof of RCM constraint satisfaction and of robot stability, though it is very important to provide stability and precision guarantees in such delicate microsurgery tasks as eye retina vein cannulation.
<u>Pros:</u>

- Detailed description of the mechanical design, technical specification
- Provides real experiment focusing on vein cannulation of animal eye

<u>Cons:</u>

- Reliance on the knowledge of the previous work related to constrained optimization and admittance control

- Lack of mathematical proof of the robot stability and RCM satisfaction

Overall, the paper helped me to understand the history behind the emergence of RCM and virtual RCM, in particular. It gave me the vector on how to implement vRCM on the basis of constraints optimization.

References:

[1] B. Mitchell et al. "Development and application of a new steady-hand manipulator for retinal surgery" Proc. IEEE Int. Conf. Robot. Autom. pp. 623-629 2007.
[2] A. Kapoor, M. Li, and R. H. Taylor, “Constrained control for surgical assistant robots,” in Proc. ICRA, 2006, pp. 231–236.