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Review of

Constrained Control for Surgical Assistant Robots

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Group 2: Constructing a Model of the Cochlea from OCT Images

Project Statement

The aim of this project is to create a robotic system to assist surgeons in performing cochlear implant surgery. A cochlear implant is a medical device used to restore hearing in deaf or hard of hearing patients. The implant includes an external microphone and transmitter and an internal electrode array, which is inserted into the cochlea by the surgeon. Current procedure calls for the surgeon to insert the electrode array freehanded, with no visualization inside the cochlea. It is therefore very difficult to ensure that the electrode array is inserted into an optimal position and that it does not damage the fragile hairs inside the cochlea during insertion. A robotic system would ideally help the surgeon to insert the electrode array into its prime position through the use of virtual fixtures, which are found by modeling the cochlea using OCT images.

Summary

Virtual fixtures are “algorithms which provide anisotropic behavior to surgeons’ motion commands in addition to filtering out tremor to provide safety and precision”[1]. This paper examines specific limited goals of virtual fixtures and how these individual goals can be combined to create more complex virtual fixtures. It also discusses how soft and hard constraints can be used differently in the preferred, safety, and forbidden regions. The paper establishes a weighted constrained optimization framework for robot-assisted surgery.

Paper Selection and Relevance

Virtual fixtures are extremely important tools in developing a robotic system for assisting in cochlear implant surgery. After imaging, they are the primary goal of the Cochlear Implant project, as they provide the insertion guidance that is missing in the conventional approach to cochlear implant surgery. In the case of cochlear implant surgery, the goal of virtual fixtures is to help insert the electrode array along the axis of the cochlea to the correct depth. The virtual fixtures should help the surgeon to avoid bumping the walls of the cochlea with the electrode array and to avoid inserting the electrode array too deep or not deep enough. Of the five “task primitives” of virtual fixtures presented in this paper, “stay on a point,” “maintain a direction,” “move along a line,” “rotate around a line,” and “stay above a plane,” the first three are especially relevant to the Cochlear Implant project. Combining these goals will create virtual fixtures which will help the surgeon position and move the electrode array into the cochlea along

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[1] Kapoor, et al. 231.

its center axis.

Problem

In order to use virtual fixtures in robot-assisted surgeries, we need an algorithm to implement these virtual fixtures. This paper provides that algorithm, which is customizable to different types of surgery and could be adapted for cochlear implant surgery, among other applications. The paper also discusses the pros and cons between linear approximations and nonlinear constraints in the constrained optimization problem.

Experiment Methods

The JHU Steady-Hand robot was used in the experiments for this paper. The robot moves in response to the force applied by an operator to a tool held by the robot, giving the operator control over the robot's motion. The prescribed motion of the tool was a virtual sinusoidal curve, shown on a monitor. Virtual fixtures were created by combining task primitives on the tool tip from and the tool shift frame. The tool tip frame has an origin at the tip of the tool and is oriented parallel to the robot's tool holder. The tool shift frame is also oriented parallel to the robot's tool holder. Constraints are implemented such that the tool tip moves along the virtual sinusoidal curve and the tool stays moving along the same direction. Individually, these are task primitives, but together they create a more complex virtual fixture.

Results

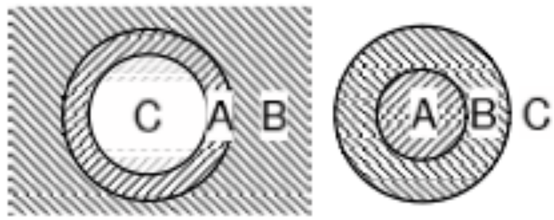
Solving least squares problems with linear constrains is more time-efficient than solving nonlinearly constrained problems. However, if the linear approximation is to closely model the nonlinear constraints, more linear constraints must be used. As the number of linear constraints increases, so does the computation time for solving the problem. This can be seen in the table below. Nonlinear constraints give better accuracy than linear approximations, even when a large number of hyperplanes are used, but computation time is generally greater when nonlinear constraints are used. There is an overall tradeoff between computation time and accuracy between linear approximations and nonlinear constraints.

Time for Computation[2]

# Hyperplanes	4	8	16	32	Nonlinear
Time(ms)	2.2680	4.1225	7.2842	14.3549	9.4017

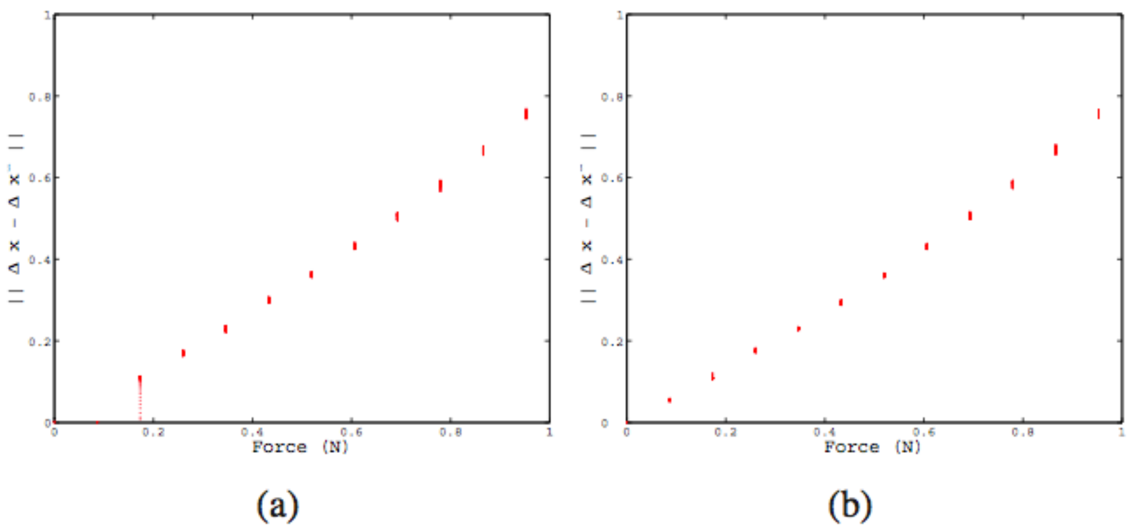
The notion of "soft" virtual fixtures is also studied in this paper. Soft virtual fixtures provide some resistance to the surgeon's movement, but do not stop movement altogether. Soft virtual fixtures may be especially useful in safety regions, where the tool may be moved for a short time outside of the preferred region. On the other hand, in forbidden regions, where the tool should never be moved for safety regions, hard virtual fixtures are used which completely stop movement of the instrument with no give. Examples of the spacial relationship between the different safety regions are shown in the picture below.

[2] Kapoor, et al. 235.



Examples of the relationship between (A) preferred region,
(B) safety region, and (C) forbidden region[3].

The difference between hard and soft constraints is demonstrated in the behavior of the objective function, which measures how closely the movement of the instrument is related to the force used by the surgeon. The larger the value of the function, the more resistance there is against the surgeon's movement. In the case of soft virtual fixtures, the value of the objective function increases significantly only once it reaches a threshold of error. This means that the surgeon can move with some freedom inside the safety region, but moving too far will create resistance and constrained motion. With hard virtual fixtures, the objective function increases with any movement, causing a prevention of movement in the forbidden regions. The difference in the behavior of the objective functions for soft and hard constraints is shown in the graphs below.



Graphs of the objective function for (a) a soft constraint and (b) a hard constraint. For the soft constraint, the value of the objective function rises significantly only after a given movement threshold[4].

[3] Kapoor, et al. 231.
[4] Kapoor, et al. 236.

Analysis

This paper is important in presenting a specific framework for creating complex virtual fixtures. The provided framework breaks most virtual fixtures, regardless of complexity, into the five "task primitives" which can be combined in many ways to create a final virtual fixture. In the case of cochlear implant surgery, the main task primitives used will be staying on a point, maintaining a direction, and moving along a line. A combined virtual fixture will guide the electrode array into the cochlea along its axis. A more complex virtual fixture must be enacted at the first basal turn, when the electrode array must not continue straight into the cochlea, but turn into the spiral. As shown by the curved path used in the experiments of this paper, this curved virtual fixture can also be created by combining the five task primitives.

The paper also is significant for distinguishing between soft and hard constraints and their different uses. Three different regions are defined, the preferred, safety, and forbidden regions. Different types of movement and virtual fixtures are appropriate for each. In the preferred region, the robot provides free motion with no resistance. This is the path along which the instrument is supposed to move. In the safety region, the tool has limited movement to allow for anatomical variations or registration errors that require the surgeon to vary motion from the prescribed path. Soft constraints are best used in the safety region. In the forbidden region, the tool must be prevented from moving at all for safety regions. Hard constraints are best used in the forbidden region. The relationship of the regions in cochlear implant surgery is most similar to the second of the example pictures shown on page 3 of this review. The preferred region, the axis of the cochlea, is in the center, surrounded by the safety region, where the electrode array may go with limited movement, and on the outside is the forbidden region, which the electrode array should not move into, lest it risk bumping the side of the cochlea. These distinctions are important in creating the virtual fixtures and deciding what type of movement should be allowed in which areas of the cochlea.

This work provides a good basis for creating soft and hard virtual fixtures. Future work might expand experimentation beyond the JHU Steady-Hand robot to other surgical robots, including the cochlear implant surgical system. In addition experimentation should be done with tools that change form, such as some electrode arrays, which go from straight to curved as they go around the first basal turn. The experiments discussed in this paper imply the use of a tool with a static tip, which remains in the same position relative to the robot. It must be investigated how the algorithm changes if the tip of the tool moves or the tool changes form. Besides the curling electrode array, other examples of this might be tools that open and close (e.g. scissors), or tools that advance and retract.

This paper is well written, and presents its ideas clearly. The paper shows the familiarity of the authors with the subject and is readable by someone with knowledge of the underlying mathematics, but limited experience with virtual fixtures. The use of tables and figures further clarifies the defined framework and results of the experiments. Overall, this will be a helpful paper in creating virtual fixtures for electrode array insertion during cochlear implant surgery.

Bibliography

Kapoor, A., Li, M., & Taylor, R. (2006). Constrained control for surgical assistant robots. *Proceedings of the 2006 IEEE International Conference on Robotics and Automation,* Orlando, Florida.