Methods for Haptic Feedback in Teleoperated Robotic Surgery

Paper Review

Jessie Young

Group 5: Haptic Interface for Surgical Manipulator System
March 12, 2012

Paper Selection:

A. M. Okamura. "Methods for Haptic Feedback in Teleoperated Robotic Surgery." Industrial Robot: An International Journal, Volume 31, Number 6, 2004. Pp. 499-508

Project Summary

Our project, the Haptic Interface for Surgical Manipulator System, aims to create an intuitive haptic interface for controlling a snake-like surgical manipulator. By creating a system that allows the surgeon to more easily navigate the interior of an osteolytic lesion during total hip replacement surgery, we hope to increase the procedure's efficiency as well as volume coverage within the lesion. Through user trials we will evaluate how well various forms of haptic feedback and other forms of sensory feedback (such as auditory and visual) enhance the user experience.

Necessary Background

Osteolytic Lesions in Total Hip Anthroplasties: The number of total hip anthroplasties, the surgical replacement of hip joints, is projected to exceed 174% over the course of the next 20 years. Component wear and osteolysis, the active breaking down of bone, release of minerals, and subsequent transfer of calcium from the bone fluid to the blood, are the primary causes for this replacement. Osteolytic lesions around the implant, if not removed, may lead to complications such as bone fracture, component loosening, or component disconnection.

Traditional Minimally-invasive Approach: Traditional manual minimally-invasive procedures for replacing the polyethylene liner of the implant consists of accessing the lesion through pre-existing or newly drilled screw holes within the implant. This aims to preserve the acetabular and femoral components of the THA to subsequently reduce the risk of bone fracture. The surgeon may then explore or clean the lesion using a variety of instruments inserted through the hole.

Two main challenges associated with this approach are one: the ability to coverage all relevant regions within the lesion using the instrument, and two: the lack of visualization during the procedure. Traditional manual procedures have demonstrated approximately less than 50% coverage of the lesion volume.

A Robotic Solution: The Johns Hopkins University, in collaboration with the Johns Hopkins Applied Physics Lab, has developed a highly dexterous snake-like robot to access the interior of the lesion. The manipulator consists of a hollow cannula through which an instrument such as a curette may be inserted. Two cables threaded through the cannula of pull to bend the tip within a single plane. A stage upon which the manipulator is mounted provides the robot two additional degrees of freedom, translation and rotation. Path-planning simulations have demonstrated 85%-95% coverage of the interior of a phantom lesion, a significant improvement over traditional manual procedures.

Our Project's Goal: The manipulator system lacks an intuitive method of control. The bend, rotational, and translational degrees of freedom were each controlled using keystrokes in MATLAB. As a result, haptic feedback (or the sense of touch and force) is missing. Our goal, therefore, is to create an easy-to-use interface that incorporates both intuitive control as well as haptic feedback through the use of a PHANTOM® Premium 6 degree of freedom haptic device as well as force input from two load cells on the manipulator.

Paper Purpose and Relevance

The purpose of the author's paper was to define the problem of the lack of haptic feedback in robotic assisted minimally invasive procedures and characterize the different types of haptic feedback that may help improve accuracy and efficiency. The author begins by outlining the current limitations of teleoperation. First, the loss of haptic information to using bilateral teleoperation systems such as the da Vinci Surgical System for procedures involving fine dexterous tasks such as cardiac suturing. This often contributes to operations that are longer and more technically challenging. Second, the steep learning curve, even for experienced surgeons, suggests that other modalities, perhaps haptic feedback, may be incorporated to shorten learning times and increase ease of use.

The paper describes the variety of experiments to characterize the problem and the trials used to discover an optimal means of providing haptic feedback to improve the effectiveness of the surgery. Taking into practical constraints such as cost, complexity, and biocompatibility, the paper sought to find a method of force feedback that would be the most realistic and beneficial to implement in an operating room.

I selected this paper to review because goals of this study to justify the use of haptic feedback in robot-assisted surgery and to compare the efficacy of different methods of feedback matched our goal of creating an intuitive haptic interface for a surgical robot. Our goal is to demonstrate, as she did in her study, that force feedback provides better performance compared to both traditional manual and robotic-assisted procedures supplying *no* force feedback. Furthermore, her study of how the cost and sensor-technology limitations affected or failed to affect performance helped us in designing a control scheme that maximized performance given our limited budget and the number of available force sensors providing haptic feedback on the device.

Methods

Testing Accuracy and Repeatability: To evaluate different methods of incorporating force feedback, the author compares the efficacy of using the hand (Figure 1 a) and instrument with force feedback (b), and fully robotic graspers with no force feedback (c) by measuring the magnitudes of force generated in the suture thread. The suturing of cardiac tissue is a highly dexterous task in which force generation at the instrument is crucial; enough tension must be applied to properly knot and tighten the suture, but not enough to break the delicate thread or damage sensitive tissue. The instrument used was a modified stylus with embedded strain gauges and the robotic ties were performed using the da Vinci console. The hypotheses were evaluated using paired student's t-tests.

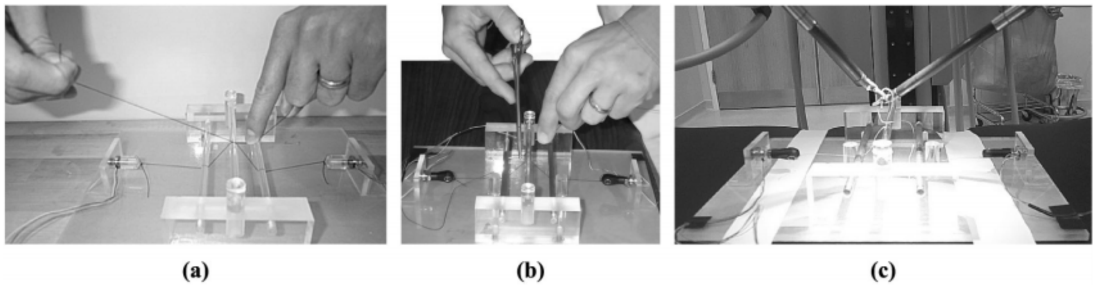

Figure 1: Measuring suture tension to determine forces applied using hand, instrument, and robotic ties

The experiment also compared the coefficient of variation (CV) of force (standard deviation as a percentage of the average force level) among hand ties, instrument ties, and robot ties.

Control Laws: The author implemented a tested several methods of control schemes between the master device (which the surgeon controls) and the remote robot (which operates on the patient). A test was devised to assess the efficacy of using impedance control, in which virtual impedance forces connect the master to the slave manipulator and cause them to track each other. The author outlines the several problems with this approach. If force sensors, which are not necessary for this method, are not used, the forces conveyed to the surgeon's hand will not be the forces the surgeon wishes to feel; instead of transferring interaction forces with the environment, the body wall and friction forces at the trocar (the pointed instrument used inside the cannula to introduce the port) will be displayed, which is not desirable. On the other hand, using force sensors in impedance control whose degrees of freedom do not match up to the degrees required for manipulation (6 or more DOF for position and orientation, plus 1 more for gripping) could limit the information available to the surgeon and the haptic interaction will feel strange and non-intuitive.

To assess the effect of limiting the degrees of freedom provided in the force feedback, the author experimented with sensing only the bending forces on a blunt dissection tool, and performed artery extraction to evaluate how grip force feedback affects task performance. Both experiments were performed using modified PHANTOM® haptic devices, as shown in Figure 2.

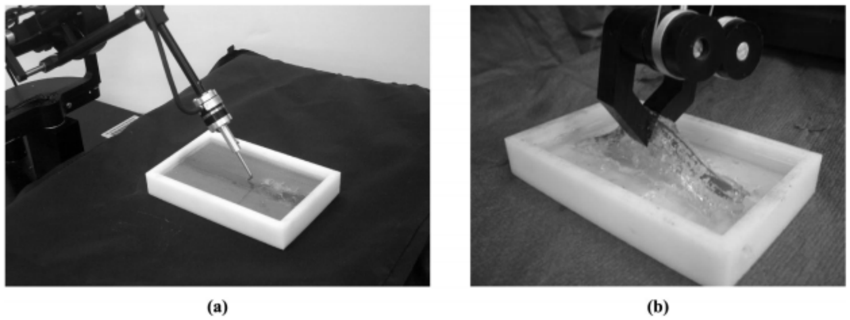

Figure 2: (a) A blunt dissection task performed with a missing degree of freedom of force feedback along the tool axis. (b) An artery extraction task performed with a missing gripper force feedback

<u>Sensory Substitution:</u> Since complete and realistic haptic feedback is not practical due to cost and biocompatibility reasons, the author examine alternative means of supplementing available haptic information with other modalities such as visual (Figure 4, a) feedback, audio feedback, and a combination of both. The author tested for both accuracy and repeatability in these trials using Dunnett's test to determine whether any form of feedback was better than none. The second hypothesis, also evaluated using Dunnett's test, proposed that the coefficient of variance of forces generated using sensory feedback was indistinguishable from the ideal baseline variances using hand ties.

The experiment measured the tension felt in the sutures during the first throw of a surgical suture knot by the left and right da Vinci instruments. The auditory feedback (AF) outputted a single tone when an "ideal" tension (obtained from hand ties) was reached. The visual feedback (VF) included an overlay of the force levels in the form of two colored, graphical bars that resized their height and shade according to the measured tensions in each hand. The combination of audio and visual feedback (AVF) simply meant both audio and visual cues were provided simultaneously.

Results and Discussion

The experiments found that forces could be applied more accurately with resolved force feedback than without. A hand tie without robotic assistance was used as the ideal baseline for determining what levels of forces to apply during the suture, as measured by suture tension. 63% of trials revealed a difference between the instrument (with force feedback) tie and the hand tie and 73.3% revealed a difference between the robot tie and the hand tie. This confirmed the hypothesis that tactile information or amplified force feedback increased the accuracy of ties as compared to ties made without force feedback.

The author also found that the instrument ties had a CV most similar to the hand ties', which suggested that repeatability might be improved with the inclusion of force feedback. Figure 3 shows how a single subject's forces varied with different methods, using a variety of suture thread materials.

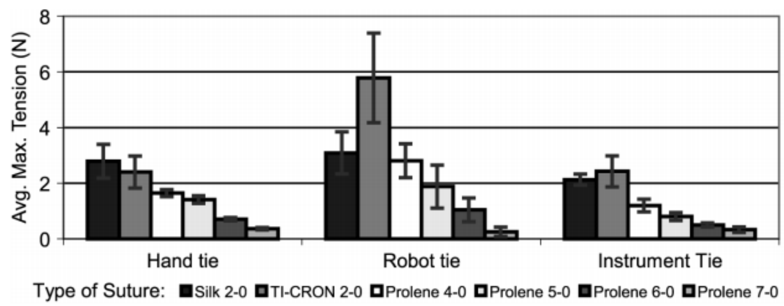

Figure 3: Data summary for a single subject showing variability in forces applied

The experiments testing the omission of various degrees of freedom revealed that missing axial forces did not create a statistically significant difference in the level of applied forces in comparison to complete 3D force feedback with all degrees of freedom intact, suggesting that bending forces along may be sufficient for tasks such as blunt dissection. The gripper experiments showed that the additional of gripping forces do not greatly affect the user performance, and therefore may not be necessary in tasks such as artery extraction. The author did not provide any numbers or figures for this set of experiments.

The tests for various means of sensory substitution revealed that any sort of sensory substitution was better than having none. The second hypothesis, that forces generated using sensory feedback was indistinguishable from forces from hand ties, was not completely satisfied; audio and visual feedback did not improve precision in knot-tying with a robot-assisted surgical system.

The third hypothesis, which proposed that any sort of feedback improved precision compared to no feedback, was proven true. A Duncan's multiple range test (Figure 4) showed that precision improved by 50.2% with audio feedback, and by 84.1% with visual feedback, which was calculated using the coefficients of variance of each of the methods.

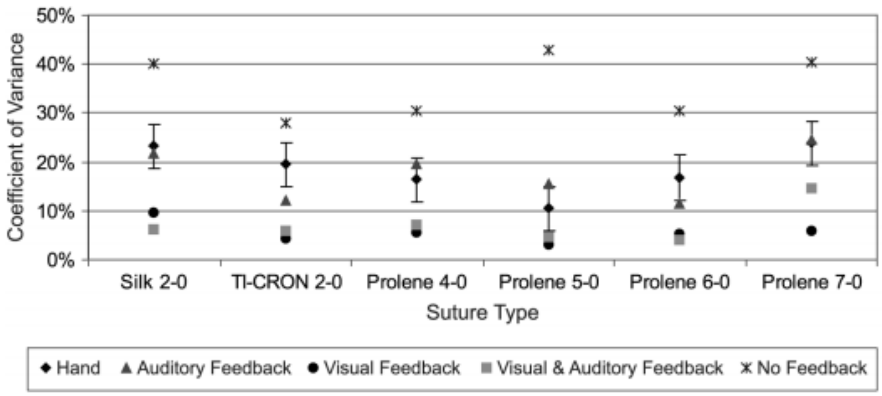

Figure 4: Comparing the coefficient of variance of various feedback methods to that of the hand data. The error bar corresponds to the critical difference for Dunnett's multiple range test

Personal Assessment

Using the task of suturing to compare the effects of force feedback was both a timely and effective method: previous research had focused on haptic feedback in teleoperation for non-medical systems and this allowed for easily measurable and repeatable functional outcomes.

The author's conclusion that force feedback is the factor which contributes to correctly and consistently generated forces is based on the assumption that viewing a stereo image through da Vinci console for the robotic ties, as opposed to viewing the workspace directly for the hand and instrument ties, does not affect performance. She mentions that since the stereo display system is of sufficient speed and resolution, this result is minor. A study citing the minimal effects of this indirect vision, or inclusion of this factor into her experiments, would strengthen her argument.

The author addresses the limitations of current control laws, in particular impedance control, in allowing for truly realistic haptic feedback. By distinguishing between different uses of haptics in minimally-invasive surgery and their effects, she identifies applications where haptic feedback are not required and may even convey to users the wrong information. For example, she addresses the issue of sensor-actuator asymmetry, which occurs when the degree of freedom of the master controller does not match the degree of freedom of the sensors on the remote manipulator. However, after performing experiments with these “missing” degrees of freedom, she concluded that certain forces do not significantly improve performance. This conclusion is important in order to correctly and practically implement haptic feedback in a real clinical setting; considering that the da Vinci tools are designed to be disposable, the addition of unnecessary or misplaced sensors would increase the prices of each tool, which may make the incorporation of force feedback cost-prohibitive.

After assessing different modes of suturing control and sensory substitution, the author concluded that haptics does in improve performance, but is careful to qualify the statement by adding that it is applicable to highly dexterous, complicated procedures and not general minimally-invasive procedures. She also limits her findings to the area of force feedback, where forces are resolved to a single point, rather than full haptic feedback, which includes the sense of touch. Tactile displays, she says, are not likely to meet the size and weight constraints for multi-degree-of-freedom systems in the near future, which neatly allow her to exclude them from her current investigation.

It would have been useful to see her revisit the second main problem of teleoperated surgical systems that she mentioned in the introduction, the steep learning curve, to bring the discussion full circle. By expanding the discussion a little on why the system is so difficult to master initially, she could have perhaps suggested that the lack of force feedback is what contributes primarily to the learning curve. She discusses the potential of haptics to provide data for more realistic surgical simulations. Perhaps making the connection between better training software and decreased learning times would further justify the use of haptics in minimally-invasive surgery.