Teleoperation for Ophthalmic Surgery: from the Eye Robot to Feature Extracting Force Feedback

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Abstract

We describe a teleoperation system, the “Eye Robot”, which enhances the dexterity of an ophthalmic surgeon by permitting extremely smooth and precise (resolution <5 microns) manipulation of an instrument that penetrates the eye. This system is based on a six degree-of-freedom parallel manipulator and computer controller. An application to micropuncture of retinal blood vessels is described. In present use, the surgeon controls the robot through a trackball interface, and feedback is strictly visual. We go on, however, to consider the addition of force feedback to such a system. After discussing the problem of “competing effects” associated with constant gain force feedback, we introduce “feature extraction”, in which artificial emphasis is placed selected features in the force signal. A variety of feature extractors intended to aid either an operator’s perception of an event, or his reaction to an event, are introduced in the context of puncture. We describe a set of experiments which serve to illustrate the strengths and weaknesses of these different approaches.

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1 Introduction

The last few years have seen a dramatic increase in robotic tools applied to medicine. Robots are now being developed and used on an experimental basis, for example, for non-invasively yet selectively irradiating complex cancerous tissue volumes which lie within healthy tissue (Schweikard, et al., 1993), for aiding the orthopedic surgeon in the precise positioning of tools used in joint replacement surgery (Kienzle, et al., 1993), and for other applications such as telesurgery and single cell manipulation (Hunter, et al., 1989).

Ophthalmic surgeons are now becoming interested in expanding their surgical capabilities with the aid of robotics — to be able to guide tools through tasks with great smoothness of motion and then to be able to manipulate something else while the tools remain motionless where they were placed. Natural physiological tremor should no longer define the limit on the delicacy of the tasks that can be undertaken. Furthermore, after robotic tools are introduced to expand the domain of procedures that can be taken on (unfortunately removing the surgeon's tactile sense from the loop in the process), it will be incumbent upon the robotics community to then restore the "feel" of tool manipulation to the surgeon in spite of the "distance" between the hand and the actual tool.

In this paper we first introduce an appropriate robotic tool to be used in micro-ophthalmic surgery. We then deal with the restoration of the "feel" of surgical instrument manipulation to the surgeon once the robotic tool is in place.

2 Background and Motivation

Hemodynamic research of the retinal circulation in our laboratory has prompted the development of methods and tools allowing extremely precise positioning of various instruments at the retinal surface. Current research requires a spear-like 2-3 μm glass micropipette to be placed within the lumen of retinal vessels (60-120 μm) of the live anesthetized cat for several minutes while pressure measurements are taken or drugs are injected (Attariwala, et al., 1994, Glucksberg and Dunn, 1992, Glucksberg, et al., 1993). The size of retinal vessels, fragility of the micropipette tip and physiological tremor (Charles, 1994a) preclude performing this procedure by hand, thus necessitating a mechanical manipulator. Although mechanical manipulators for ophthalmic procedures have been described previously (Allf and Jr., 1987, Glucksberg, et al., 1993, Guerrouad and Vidal, 1989, Pournaras, et al., 1991), limitations in accuracy, flexibility and size have
motivated the development of the “Eye Robot” specifically for the task of retinal vascular micropuncture.

In order to better explain the design constraints imposed on a manipulator for retinal vascular micropuncture, a typical procedure is outlined here. A trocar made from a thin-wall 18g needle is inserted through the sclera, creating a portal for positioning instruments within the eye. A rigid glass micropipette is inserted through the sclera via the trocar and advanced until the tip protrudes beyond the end of the needle. While viewing the interior of the eye through a plano-concave lens placed over the cornea and an operating microscope, the micropipette is guided towards various sites on the retina. This is accomplished by pivoting the hypodermic needle and micropipette about the scleral puncture point, that is, the point of intersection between the needle and the wall of the eye. By keeping the needle nearly stationary at the point where it passes into the eye's interior, damage to and movement of the wall of the eye is minimized. Once in the proper orientation, the micropipette is advanced through the needle until it penetrates the target vessel and the tip rests within the lumen. Thus there are three degrees of freedom (DOF) required for retinal micropuncture, two for pivoting the micropipette about the scleral puncture point and one for moving through it.

Because most commercially available micromanipulators move in Cartesian (X-Y-Z) coordinates and are not capable of the puncture centered motion required for retinal procedures, several custom ocular manipulators have been constructed (Allf and Jr., 1987, Glucksberg, et al., 1993, Guerrouad and Vidal, 1989, Pournaras, et al., 1991). Motion constraints are typically maintained by two curvilinear tracks having common centers of curvature or by a single curvilinear track pivoting about a central axis. Attaching an instrument to the device such that the instrument passes through the common center guarantees the instrument will pivot about a fixed point. Such micromanipulators tend to be bulky because the mechanical tracks span the entire range of motion at all times, prohibiting the accommodation of multiple simultaneous entries into the eye. Another point of functional inflexibility is that the center of spherical motion can not be moved with respect to the base of these manipulators due to the fixed radii of the mechanical tracks. As an alternative to these gimbal-type devices which are physically constrained to the desired "puncture-centered" movement, a multiple DOF device can be constrained mathematically by its computer controller. The advantage is not only the versatility gained by redundant degrees of freedom, but also that of compactness, allowing multiple manipulators to be used simultaneously on a single eye when necessary.

At least one group has approached this problem using a six DOF serial manipulator,(Charles, 1994b). The inherently high stiffness to weight ratio of a parallel manipulator, however, offers an attractive alternative (Hunter, et al., 1993, Jensen, et al.,
The mechanical design of the Eye Robot (Fig. 1) is based on a variation of the Stewart platform (Stewart, 1965) originally presented by Merlet (Merlet, 1992a, Merlet, 1992b) and is detailed elsewhere (Jensen, et al., 1994). The assembly is roughly 12 cm in diameter by 24 cm in length and is capable of operating within a 30 degree cone emanating from the scleral puncture point onto the retina.

An instrument attached to the robot’s end effector platform may be positioned and oriented with six DOF within the working range of the actuators. Six legs connect the end effector platform to linear slides via ball-joint connections. The linear slides are actuated by dc-torque motors through ball-screw transmissions while ball-screw rotation is monitored using laser rotary encoders. Each end effector pose (combination of position and orientation) maps to a unique combination of linear slide extensions determined and maintained by a computer controller.

The operator controls the position of the instrument within the eye using a hand-held trackball attached to the computer controller. Even though the robot is capable of moving the instrument with six DOF, the motion for ocular surgery is constrained mathematically to allow only the two pivotal and one plunge degrees of freedom described previously. Buttons on the trackball are used to enable instrument motion and to switch between pivotal and plunging motion of the instrument when the trackball is rolled. With only the enable button held down, rolling the trackball will result in a pivotal motion of the instrument about the scleral puncture point. The two rolling DOF provided by the trackball map intuitively to the resulting two pivotal DOF of the instrument and make positioning the instrument within the eye a simple task. Pressing both the enable and the plunge button will fix the instrument orientation and move the instrument into and out of the eye through the scleral puncture point as the trackball is rolled. If no buttons are pressed, then a roll of the trackball will result in no motion of the instrument.

The Eye Robot is used to routinely perform retinal vascular micropuncture for the injection of drugs or measurement of pressures within the retinal vessels of a live anesthetized cat. While currently used only for research purposes, the micropuncture technique may prove viable in a clinical setting for the treatment of conditions such as retinal vein occlusion. No treatment for retinal vein occlusion currently exists (Becker and Post, 1951), however, using micropuncture to lyse the occlusion with thrombolytic agents may prove worthwhile.
3 Force Feedback in Microsurgery

The "distancing" of the surgeon from the tool has had the positive effect of protecting the eye, for these micro-scale operations, from unpredictable tremor, fatigue, and so forth, of the surgeon. Inherent in such a buffered system, however, is the attenuation, or in this case complete removal of, the surgeon's haptic sense that normally would have accompanied direct manipulation of the tool. While it is not possible to remove the robot and allow the surgeon the direct manipulation of the tools for these microscopic tasks, it is possible to reconstruct the force feedback path that has been eliminated.

Figure 2 shows the progression schematically from (a) direct manipulation of the tool, to (b) remote manipulation of the tool via micromanipulator, to (c) restoration of the “feel” of tool use by force feedback. This last step involves equipping the micromanipulator (slave) with sensors and endowing the joystick (master) with the ability to "push back" so that force (or motion) which results from the feedforward path may be reflected to the surgeon in the feedback path. Systems incorporating both feedforward and feedback pathways are called “bilateral”.

Of course, simply completing the feedback path to the master does not guarantee usefulness of the resulting tool. The ultimate goal in much of the literature is the realization of a device which can reflect to the user every subtlety occurring at the slave with such fidelity that remote and direct manipulation are indistinguishable. Yet we suggest that “unfaithful” reflection of reality can yield improved performance, especially for micro-scale tasks like those of eye surgery.

To study this idea, we developed a simple single-degree-of-freedom test system which will be the focus of the remainder of this paper. It consists of a haptic display or “manipulandum” (which can push back on the user), a small actuator which can hold a tool such as a hypodermic needle, and a computer for implementing the bilateral control scheme.

This force reflecting controller scales down the motion of the master to command the motion of the slave (feedforward path) and scales up the forces that arise in slave/task interaction for reflection to the operator (feedback path). It is reasonable to assign constant values to these scaling factors, but consider some of the pitfalls of this approach.

3.1 Shortcomings of Constant Gain Controllers

If the task of interest involves two or more subtasks with very different mechanical behaviors (herein referred to as “impedances”), the controller designer may face the tradeoff of offering the user either insufficient haptic sensitivity or
uncomfortably high reflected force levels. To illustrate, in preliminary experiments set up so that the user could remotely puncture plastic film via the slave’s hypodermic needle, it was found that high force gain in the feedback path to the master could cause a very distinct sense of contact between needle tip and membrane, a potentially valuable piece of information. The operator knew when contact had occurred before any damage was done to the membrane. However, the price of having this information became evident upon puncture attempts which required uncomfortable force levels to be attained by the operator at the master. The alternative was to sacrifice the distinct contact for more comfortable puncturing force levels.

To reconcile these “competing effects”, consider a controller which monitors the derivative of the force at the slave (either spatial or temporal) in an effort to exploit the suddenness of the force change. The next sections more carefully develop this idea of force feature extraction.

3.2 Feature Extraction

In performing a task with a tool, whether or not it is an active bilateral manipulation tool, the person doing the manipulating usually interacts with a variety of impedances. A wrench is pushed through the air and engaged with a steel nut. Before contacting the nut, the wrench movement produces no sudden force changes. A tightening stroke of the wrench produces a potentially large change in force, but over a long time period. The transition from one of these impedances to the other, non-contact to contact, however, can produce sudden large force changes because it involves crossing an impedance boundary.

It is suspected that the majority of the cues in manipulation come from such changes in impedance, not from impedance magnitude itself. While constant scaling amplifies all forces encountered at the slave, sometimes it is appropriate to be more discriminating in choosing what to amplify. The selective artificial emphasis of the force change that arises from traversing a boundary of dissimilar impedances will be termed feature extraction.

4 Experiments

4.1 Methods

Figure 3 shows a block diagram implementing a temporal torque-differentiating feature extractor (within the dashed box) working within a standard bilateral constant-gain controller. Since we wish to determine experimentally whether or not various types of
feature extraction can be of benefit, we will compare task performance using a non feature extracting controller (which will be called mode 0) with task performance using three feature extracting controllers (modes 1, 2, and 3). The chosen task is puncturing plastic film with a hypodermic needle. The modes of feature extraction are described below. Torque feedback gain (\(\lambda_{up}\)) will be chosen by an informal set of preliminary experiments to find an average comfortable level which yields good performance without feature extraction. All experiments will be repeated using a second value for torque feedback gain in an effort to illuminate the effect of this variable.

### 4.1.1 Mode 0

This controller is the reference controller and incorporates no feature extraction. All other modes represent modifications of mode 0 (i.e. additions of feature extractors). This mode can be represented by the block diagram (see Fig. 3) without the feature extraction portion included.

The gain \(\lambda_{dn}\) which attenuates master motion to yield desired slave motion has been set to unity (the units are: slave radians/master radians). In terms of endpoint arclength, the hypodermic needle is constrained to move about 1/3 the distance that the master handle does. The gain \(\lambda_{up}\) which amplifies slave/task interaction torque was determined by a preliminary experiment (described later).

### 4.1.2 Mode 1

Mode 1 represents the first of the feature extractors to be appended to the reference controller. The detection scheme is based on thresholding of the differentiated slave torque signal. The action taken is "natural recombination" (addition of the scaled differentiated torque signal to the "normal" torque signal commanded to master). When a feature is detected, the recombination action occurs for 800ms during which time no other features may be detected. The user feels the slave torque, which has been amplified by the torque feedback gain, with an additional high frequency signal of 800ms duration superimposed. The expected advantage of this mode was chiefly perceptual. When operating with a low torque feedback gain, mode 1 was expected to improve the user's perception of puncture and not to aid in reaction.

### 4.1.3 Mode 2

Just as in mode 1, the differentiated slave torque signal is thresholded to detect features. The action taken is "packet recombination" (addition of a predetermined packet of torque to the "normal" torque signal commanded to master). In this case, the torque
packet is a constant retarding torque which lasts 800ms. When the system detects puncture, the user feels a strong force withdrawing the hand in the direction opposite to puncture. Because the master and slave remain connected in the same way before and after puncture, the needle also withdraws when the user's hand does. Mode 2 is designed to aid in reaction to puncture rather than the perception of it.

4.1.4 Mode 3

In mode 3, once again the differentiated slave torque signal is thresholded to detect features. Action taken here, however, is overlay of a virtual fixture on the master. In this case, the virtual fixture is a wall (consisting of a stiff grounded virtual spring) set up just before the site of puncture (that is, the user is suddenly one encoder count inside a virtual wall after puncture is detected by the system, and is therefore arrested). Mode 3 was also designed to aid in reaction rather than perception. Where mode 2 culminated in an active "kick" to the operator's hand, mode 3 produced a reaction that felt passive to the user, like running up against a mechanical stop. Hence, mode 3 did not feel as though energy was being added to the system by the manipulandum as did mode 2.

4.2 Apparatus

4.2.1 Master

The system master consists of a six inch crank mounted on the shaft of a brushless d.c. motor. Also connected to the motor shaft are a rotary viscous damper and a high-resolution optical encoder (~900,000 counts/rev). Torque due to the rotary viscous damper is measured and output to the computer controller along with the shaft position information. The crank handle is mounted on bearings so that one may grip the handle firmly and give the shaft multiple turns without a sliding interface between palm and handle. Details of this manipulandum's design can be found in (Brown, 1995, Kuyper, 1993).

4.2.2 Slave

The slave actuator is a moving coil, permanent magnet, non-commutated rotary arm (a modified hard disk drive). This actuator has been retrofit with a 2 inch aluminum arm and an optical encoder resulting in about 1600 counts over the full 40 degree range of motion. The puncture implement is a 25 gauge hypodermic needle attached to the end of the slave arm.
4.2.3 Controller

The basic controller style consists of the open loop master commanding the position-velocity servoed slave (Fig. 3). A Micron 90 MHz Pentium machine serves as the controller. Commercially available encoder, D/A, A/D, and digital I/O ISA cards allow communication with the master and slave. Digital filters and the control code are all written in C.

The encoder-generated position signals from the master and slave are read by the encoder decoder card in the computer and digitally differentiated and low-pass filtered to give master and slave velocity. In addition, the voltage corresponding to the torque applied to the shaft by the viscous damper is read by the A/D and digitally filtered. The rationale for the appropriate addition of physical damping and its subsequent virtual removal for performance enhancement is discussed in other papers (Colgate and Brown, 1994, Colgate, et al., 1993). Finally, the torque to the master and slave amplifiers is commanded via a D/A card in the computer.

Fig. 4 schematically illustrates the physical layout of the experiment components. The experimenter is between the subject and the slave. The subject is therefore without visual feedback of the puncture task. The subject stands at the manipulandum. The master handle is just below chest height. The subject is able to see the computer monitor by looking slightly to the right.

4.3 Protocol

After signing a consent form containing an overview of the experiment and a discussion of the risks and compensation involved, each subject was familiarized with the experimental apparatus. They performed punctures and were familiarized with the video output which would provide information such as performance on each puncture as well as the time constraints under which they would be required to work. Subjects were read a script describing each experiment in great detail, and were reminded that their compensation would be commensurate with performance. They were also shown the headphones through which music would be played for the masking of ambient sounds.

A practice session followed. Headphones were not used so that experimenter/subject dialog was possible. Subjects were presented with 4 different controller modes for each of two torque feedback gains in a predetermined order, giving 8 controller cases per subject. For each of these 8, they performed 7 punctures. After each puncture, their performance measure was displayed on the computer screen. These data were not recorded.
After the practice session and a brief rest period, subjects were fitted with headphones which blocked the sounds of the master motor and the actual puncture of the plastic film. They were then presented with the same 8 cases in the same order as in the practice session. For each of the 8 cases, subjects performed 3 punctures for refamiliarization with the particular controller, followed by 10 punctures for which overshoot and timing data was recorded. As in the practice session, subjects received an immediate indication of their performance for each puncture from the computer display. Following the puncture trials, each subject was interviewed and qualitative data recorded. The entire session took approximately 1 hr/subject.

4.3.1 Shortcomings of the Protocol

Some unisolated variables that may affect the data follow. The first group of differences between subjects falls under the heading of kinematics. People of various heights participated in the experiment. No compensation was made for this variation. Elbow bend was therefore different. Also, two of the subjects were left-handed. The direction of puncture was not reversed for them. It is possible that, although most of the same areas of the hand were touching the handle in both left-handed and right-handed cases, that the difference in the load-bearing areas could have affected the uniformity of the data (all other variables being equal).

Another area of variability was subject strength. As a percentage of full arm strength (in the motion tested) the maximum puncture force may have varied considerably. While this does not affect the comparison of task data for any one subject, it casts some doubt on the validity of comparing across subjects.

Half of all punctures were practice. Learning (performance improvement over a set of ten punctures using any given controller) is not apparent in the data. Nevertheless, a small percentage of the trials were done over a large range of torque feedback gains. Subjects may perform slightly differently when switching from a heavy tool to a light tool than when switching from a light to a heavy tool. In all experiments, torque feedback gains were varied gradually in an effort to minimize this effect.

There was a tradeoff to consider regarding randomization of controller types. Presentation of the various modes and gains in random order helps to remove effects of fatigue and learning from the data. On the other hand, so disparate were the techniques for use of the various tools, both in perception and reaction, that each change of mode required a period of refamiliarization, rendering any randomization impractical.

The music which was used to mask sounds of the master motor and of puncture may have had variable distraction effects on the subjects. One subject suggested that he
may have performed better without it, due to the attention it drew. Others claim not to have been distracted by the music at all.

4.4 Preliminary Experiments

4.4.1 Autonomous Puncture

This experiment did not involve human subjects. To better characterize puncture detection and the variability thereof, the master and human were removed from the loop. The computer controller was programmed to perform punctures autonomously. The speed of puncture was set to be just slightly higher than the average speed of puncture when performed by a human subject.

One may argue that if automated puncture yields the best performance, then it should be used rather than human-operated bilateral manipulator. The counter argument is that the supervisory role of the operator can not be discarded in most cases, especially in the case of multiple degree-of-freedom path planning in unstructured, dynamically changing environments. The judgement and adaptability of the operator is impossible or at least difficult to replace with a computer controller. For certain procedures, however, a compromise may be appropriate in which the task is divided into segments, some of which require the complex supervisory control of a human, and some of which may be turned over to a program to control.

4.4.2 Torque Feedback Gain Optimization

This was an investigation of performance as a function of torque feedback gain. A group, consisting of two people, deviated from the described protocol in that they worked only with mode 0 (no feature extraction) over 9 torque feedback gains (0.1, 0.2, 1, 2, 3, 4, 5, 10, 20). Other elements of the protocol were as described. They were asked to minimize overshoot with the time constraint of 8 seconds.

The data for the torque feedback gain optimization is summarized in Fig. 5. Recall that no feature extraction was used here. Subjects used mode 0 over a large range of torque feedback gains. The greater the torque feedback gain, the greater was force required at the manipulandum handle to perform the puncture. The plot shows a minimum (optimal performance) near the torque feedback gain of 1. The minimum occurs because below this value, the puncture was difficult to detect and lead to rapidly deteriorating performance. Above this value, subjects had an increasingly difficult time reversing the manipulandum handle direction in a short time. This information was used to choose the
torque feedback gains ($\lambda_{up}$) to ensure a fair comparison of mode 0 with the feature extracting modes. The low and high values for torque feedback gain were chosen to be 1 and 3.

4.5 Standard Experiments

4.5.1 Minimize Overshoot, Untimed
The first experiment involved 3 subjects whose goal was to minimize overshoot. No time limit was given.

4.5.2 Minimize Overshoot, Limited Time
The remaining seven subjects were asked to puncture, minimizing overshoot under a fairly relaxed time constraint (8 seconds). Most subjects did not choose to take more than about half of the allowed time (timing data is presented in the next section).

4.5.3 Minimize Time, Limited Overshoot
In an effort to ascertain how much care was being given to the task done with the different controllers, two subjects were rewarded for speed of puncture completion with a moderate overshoot constraint (0.100 radians) over the same set of 8 cases.

5. Results

5.1 Effect of Mode on Overshoot
All of the data from the standard experiments can be summarized in two plots (Fig. 6, 7). The first shows average overshoot as a function of controller type for all three standard experiments. The second shows the corresponding timing data for those same trials.

We can now compare each controller mode with mode 0. Use of feature extraction modes 1, 2, and 3 all enabled subjects, on average, to reduce their overshoot penalty from that of mode 0 (which involved no feature extraction) with only one exception. With the higher torque feedback gain, addition of mode 1 feature extraction was not beneficial.

In the main experiment, it is clear that mode 1 was not as helpful as modes 2 and 3 for reducing overshoot. In fact, for low torque feedback gain, mode 0 and mode 1 resulted in average performance values which are not different enough for one to have confidence,
just from inspection, in the apparent improvement offered by mode 1. A statistical t-test was performed on the data for mode 0 and mode 1 from the main experiment. The t-test used assumes equal variances of two normal distributions. As explained in (Berenson, et al., 1988), the t-test is not very sensitive to departures from normality, and equal variances is a reasonable assumption. The null hypothesis is that the actual population mean overshoot for modes 0 and 1 are equal. Setting the level of significance $\alpha = 0.005$ for a fairly strict test, the critical value is $t_C = 2.576$ and the test statistic is $t = 4.460$. Since $t > t_C$, the null hypothesis is rejected. The means are distinct. The addition of mode 1 feature extraction therefore provided a measurable improvement in performance over mode 0.

5.2 Effect of Mode on Timing

Timing data gives an indication of how much attention each controller required for successful completion of the task (Fig. 7). Mode 2 consistently consumed the least time regardless of torque feedback gain in the main experiment. However, in the time-minimization experiment, the advantage of mode 2 was lost.

5.3 Effect of Torque Feedback Gain on Overshoot

For the overshoot minimization experiments, low torque feedback gain was better than high torque feedback gain in modes 0 and 1 where it was up to the subject to stop the needle, and high gain was better where the controller contributed the majority of the retarding torque (Fig. 8).

5.4 Effect of Torque Feedback Gain on Timing

Time taken to puncture was consistently greater for high torque feedback gain during the main experiment (Fig. 7). In the speed experiment, however, there is little statistically significant difference from one gain to the other.

6 Discussion

6.1 Perceiving and Reacting

For our purposes, perception requires that a signal resulting from the feature has made its way to the operator's brain causing the operator at least to respond (if not to be conscious of it). Reaction is energetic input to the slave that can come from two possible
sources: (1) the operator moves the master, and/or (2) the controller moves the master. If the perception cue is augmented by the controller and no other action is taken, reaction is left entirely up to the operator and can happen no more quickly than the active human bandwidth will allow. If more rapid reaction assistance is offered by the controller (such as a retarding torque or virtual fixture), then the necessity of perception by the operator seems to be omitted. If reaction aids preclude the necessity for perception, then why not abandon perception aids altogether?

One reason is that the feature of interest may signal completion of only one of many subtasks within a complex task. The task may be sufficiently forgiving to allow success with only a perception aid and therefore may be done more quickly and easily without having to, for instance, reset a virtual fixture to continue with other subtasks.

A second reason is that success with reaction aids may not be easily extrapolated to multiple degree-of-freedom systems. By using the technique of providing high-frequency perception aids and low-pass filtering the feedforward path, coupling between different degrees of freedom can be minimized for perception aids. With reaction aids, however, the substantial torques required to alter the trajectory of the operator's limb (as opposed to those required just for tactile perception) require consideration of coupled stability problems for multiple degree-of-freedom systems. Such problems can be quite complex, providing another argument for seriously considering the benefits of perception aids in spite of their poorer performance in these single degree-of-freedom experiments.

Finally, in poor signal-to-noise situations, it may be difficult for the controller to distinguish between impedance boundaries of interest and other torques that arise from bearing stiction or environment vibrations. In such a scenario, the operator may receive many false indications of features, and will have to rely on visual feedback and other cues to further discriminate. It is easy to imagine the problems which would arise from establishing a virtual fixture on every false feature and having to reset each one.

6.2 Subject Interviews

The user's personality plays a role in specifying the appropriate controller for a bilateral manipulation task. Some people trust the properties of the tool more than others. For example, about half of the subjects claimed that they would choose the relatively violent mode 2 tool if they were required to perform a critical surgery in spite of the fact that they do not have much control over the trajectory of the tool after puncture. They know that their performance metrics are good when they use that tool and, in light of that information, do not feel that they need to be in control of the tool at all times. The other half requires the sense of being in control of the trajectory of the implement at all times, and therefore prefer the mode 3 virtual wall in spite of poorer
performance metrics from use of that tool. As a result of his experimental work with virtual fixtures in and other perceptual overlays in bilateral manipulation, Rosenberg advocates the use of a controller which has a user interface from which the operator can choose perceptual overlay elements (Rosenberg, 1994). Such a system could accommodate differences in personal preference and personality and is heartily endorsed.

7 Conclusions

This paper has considered the use of force feedback in microsurgery. We began, however, by discussing a telesurgery system which incorporates no force feedback. The Eye Robot has proven to be a very effective tool for micropuncture of retinal vessels because it provides precise, smooth motion and because visual feedback is sufficient to guide the necessary motions. The Eye Robot is also much simpler and much less expensive than would be a system incorporating force feedback. Nonetheless, there are many foreseeable microsurgical scenarios in which visual feedback will be impaired or obscured, and restoration of the surgeon’s feel will become essential.

Yet, due to “competing effects”, constant gain force feedback may not be the best way to restore feel. We demonstrated this in an informal experiment in which the competing effects were the feel of contacting a membrane, and the feel of puncturing it. Observation of this difficulty led to the idea of “feature extraction” in which the transversal of impedance boundaries is detected and used to trigger useful feedback. Three feature extraction modes were considered here in the context of puncture. They may be summarized as follows:

**Mode 1:** This perception aid serves to improve overshoot performance when the natural task feedback is near the margins of the user’s perception ability, but otherwise is of little value. It is generally not as assistive as the other modes as it leaves reaction completely to the operator. It is recommended where the superior performance offered by the reaction aids can be traded for the perception aid's greater freedom and greater reliance on the supervisory skill of the operator through visual feedback. It would also be preferred where reaction to the feature is further manipulation, not just stopping as with puncture.

**Mode 2:** In contrast to mode 1, this constant torque packet gives the operator the least control over reaction and, generally speaking, the best performance metrics. It utilizes the master actuator's superior frequency response. The mode 2 constant retarding
torque is the least portable of the feature extraction modes since it is most sensitive to the individual's style of tool use. For example, the level of torque can only be set appropriately after considering momentum of the master at the time of feature detection and the torque used to accomplish the task by the particular user, while the virtual fixture is more user-invariant.

Mode 3: This is the best compromise between good performance metrics and control left to the operator. It reacts quickly but seemingly passively, and offers the option of leaving the needle inserted in the punctured material.

While feature extraction has been used successfully, this work must be considered preliminary. In future work, it will be important to explore alternate forms of feature detection (such as spatial differentiation of torque, which is more closely related to impedance change than temporal differentiation), and the use of feature extraction in more complex, multi-degree-of-freedom tasks.

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Fig. 1. The Eye Robot.
Fig. 2. Originally, the surgeon feels reaction forces from the surgical tool. Addition of a micromanipulation tool breaks the force feedback path. Implementation of a bilateral manipulation scheme restores the feel of the environment to the surgeon.
Fig. 3. Detailed block diagram of the experimental controller. The basic bilateral controller is represented by the solid lines. The feature extractor is represented by the dashed lines.
Fig. 4. Schematic of the experimental setup.
Fig. 5. Overshoot as a function of torque feedback gain with no feature extraction implemented.
Fig. 6. Overshoot as a function of controller type and torque feedback gain.
Fig. 7. Time taken to puncture as a function of the controller mode and torque feedback gain.
Fig. 8. Shows that higher torque feedback gain is detrimental where the subject must react to the feature, and beneficial where the controller is chiefly responsible for the reaction to the feature. Data is from experiment #2 (main experiment).