

NORTHWESTERN UNIVERSITY

**Kinematic Design of an
Ophthalmic Surgery Robot
and
Feature Extracting Bilateral Manipulation**

A DISSERTATION

SUBMITTED TO THE GRADUATE SCHOOL
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

for the degree

DOCTOR OF PHILOSOPHY

Field of Mechanical Engineering

By

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EVANSTON, ILLINOIS

June 1995

ABSTRACT

Kinematic Design of an Ophthalmic Surgery Robot and Feature Extracting Bilateral Manipulation

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Part I of this work describes a parallel manipulator design aid. From the jacobian, which maps perturbations in joint space to resultant perturbations in endpoint coordinates, the *sensitivity vector* is derived. This is accomplished by concatenating the one-norms of the rows of the jacobian. The sensitivity vector can be monitored as geometric design parameters are varied, yielding a concise display of changes in end effector motion characteristics over a variety of kinematic configurations. The design procedure is applied to an ophthalmic surgery micromanipulator used for micropuncture of retinal vessels, but is sufficiently general for use in the design of any parallel manipulator.

Part II addresses issues in teleoperation. It is often suggested in the literature, with regard to force-reflecting bilateral manipulation, that the ideal bilateral controller would provide the operator with a sense of direct manipulation of the remote environment. This dissertation is one of a few recent works which suggest that unfaithful reflection of slave/task interaction to the master manipulator can lead to a more useful teleoperation tool yielding greater remote task success for the operator. Several *feature extractors*, which recognize and react to the traversal of task impedance boundaries, are presented here.

Results of human subject experiments, which compare puncture task performance using a bilateral manipulation tool with and without feature extractors, show superior task success metrics with the feature extractors in place.

ACKNOWLEDGMENTS

I wish to thank my advisor, Professor Ed Colgate, for his encouragement and of course for his ideas and instruction both in design and in the study of tool use. Thanks to Professor Matt Glucksberg for introducing me to the important and fascinating world of surgery research, and to Professor Michael Peshkin for bringing new ideas to the table and participating as a subject in the experiments.

I greatly appreciate the willingness and flexibility of all the subjects whose data appear herein, and to Ed Kuyper, Paul Millman, Beeling Chang, and Mike Brown who invested so much in the design, construction, and programming of the manipulandum.

Thanks to Mike Stanley for bringing me up to speed on the VME bus system for the preliminary experiments, and to Professor Blake Hannaford for donating the disk drive used as the slave manipulator.

Last, but certainly not least, thanks to my wife Betsy, my parents, and my siblings for their support and confidence in me.

The micromanipulator research was made possible by the
Margaret W. and Herbert Hoover Jr. Foundation.

To Betsy

without whose loving support this would not have been possible

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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 cancerous tissue volumes which lie completely within healthy tissue [54], for aiding the orthopedic surgeon in the precise positioning of tools used in joint replacement surgery [39], and for other applications such as telesurgery and single cell manipulation [34].

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.

This is a two part dissertation which deals with the issues introduced above. The first part focuses on the details of designing an appropriate robotic tool to be used in but not necessarily limited to micro-ophthalmic surgery. In fact, the principal idea presented is a kinematic evaluation technique which is sufficiently general for use with any parallel robot design. The completed prototype is presented and its first application described.

The second part deals with the restoration of the "feel" of surgical instrument manipulation to the surgeon once the robotic tool is in place. Here, again, the ideas presented are portable tools that may be used in applications well removed from ophthalmic surgery.

PART I

DESIGN OF A MICROMANIPULATOR FOR OPHTHALMIC SURGERY

1. BACKGROUND AND MOTIVATION

An active area of research is the treatment of retinal venous occlusion by delivery of anticoagulant drugs directly to blood clots in retinal vessels [1, 2, 24]. Shortcomings of micromanipulators currently being used in such research have motivated the development of new tools. In order to better explain the design constraints, some steps which are included in a typical procedure are outlined here. A hypodermic needle is inserted through the wall of the eye to gain access to the interior surface. A rigid glass micropipette is inserted through the hypodermic needle far enough that its tip protrudes beyond the end of the needle. The micropipette is guided to various injection sites on the retina by pivoting the hypodermic needle about its 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 the wall of the eye is minimized. A third allowable degree of freedom is movement along the axis of the hypodermic needle since it does not deform the wall of the eye at the puncture point significantly.

Most commercially available micromanipulators are not useful for guiding the hypodermic needle in the way described, since they exhibit Cartesian movements. The spherical movement needed can be found in some commercially available micromanipulators, and some have been constructed for this type of research [48], but they are circular track serial devices, (Fig. 1), which are mechanically constrained to move on a spherical surface.

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.

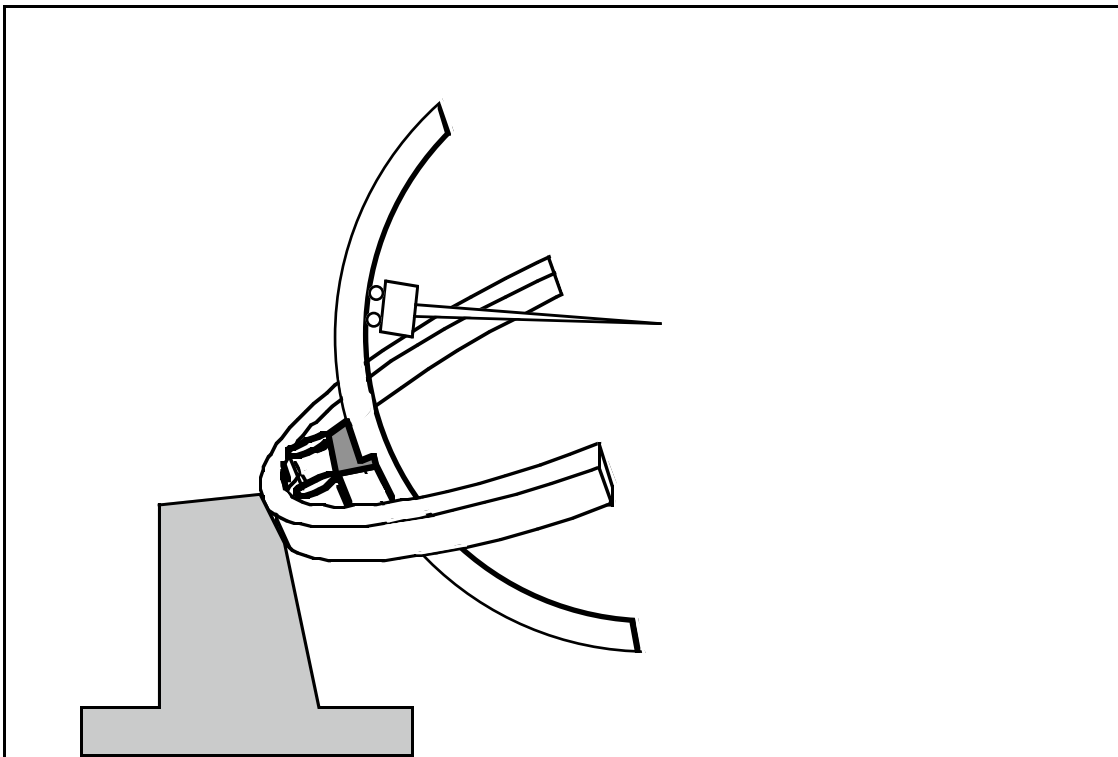


Fig. 1. Schematic of a traditional spherical-movement micromanipulator.

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. A desirable size and shape

for the device is that of a human wrist and hand gripping a slender tool. This will allow multiple manipulators to be used simultaneously on a single eye when necessary.

At least one group has approached this problem using a serial manipulator [10]. The inherently high stiffness to weight ratio of a parallel manipulator, however, offers an attractive alternative. The initial operation mode will be open loop wherein the operator will watch the end effector (through the pupil with the aid of a microscope) and guide it using a multi-dimensional joystick input device connected to a computer controller.

2. KINEMATIC DESIGN

Initial Choice

The Stewart Platform [56] parallel six DOF robot scheme (Fig. 2) was chosen as a starting point for its inherent stiffness and compactness. (Merlet has summarized several advantages not listed here [45].) Different geometries were evaluated through the definition of six quantities derived from the jacobian. Details follow.

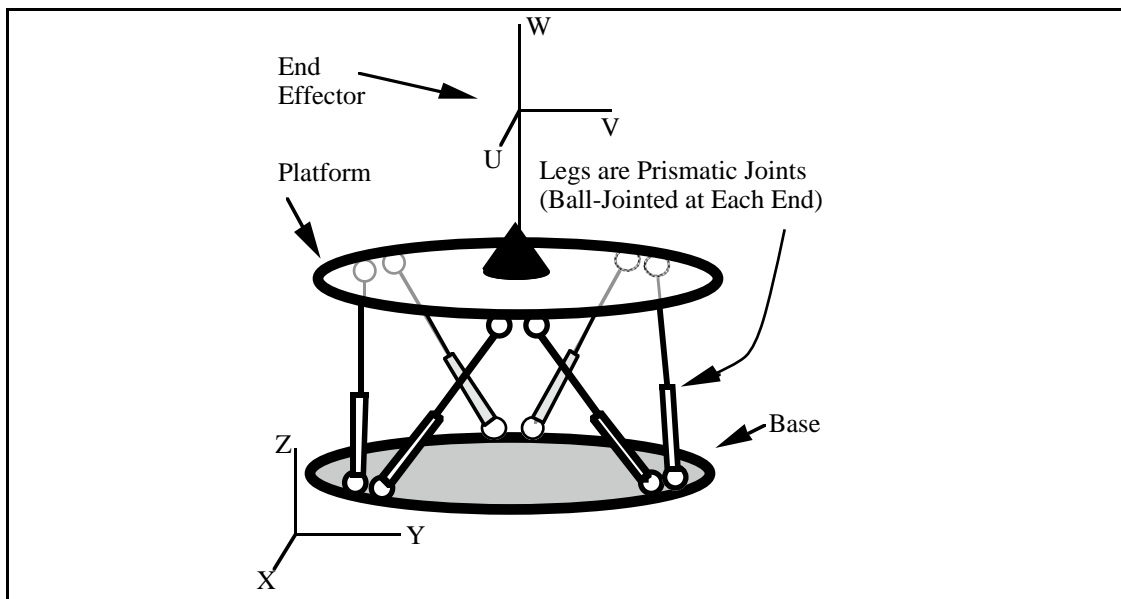


Fig. 2. Stewart platform schematic.

Coordinate Systems

The traditional scheme of specifying end effector orientation with three euler angles will be slightly modified to better examine each manipulator design's suitability for the task at hand. Imagine a third coordinate system $[U^*V^*W^*]$ in addition to those pictured in Fig. 2 whose origin is always coincident with the $[UVW]$ origin at the puncture point, and whose U^*V^* plane is always parallel to the XY plane. As the hypodermic end effector with rigidly attached system $[UVW]$ is placed in some arbitrary orientation, the position of the *tip* of the needle can be projected onto the U^*V^* plane. (Recall that the puncture point is *not*, in general, at the tip of the needle.) The two coordinates (u^*,v^*) necessary to describe this projected tip position make up two of the three orientation variables. The third will be the angle of rotation γ of the platform about the hypodermic. The position (x,y,z) of the puncture point in the $[XYZ]$ frame completes the set of six variables needed to fully specify the position and orientation of the end effector.

These choices were shaped by the microinjection task. During a procedure, the greatest part of the movement will be in the (u^*,v^*) coordinates, while rotation γ about the needle has little effect and therefore is of little importance for this application.

Sensitivity Parameters

One important requirement in choosing a specific kinematic design was low sensitivity of endpoint position to perturbations in leg length, because amplification of uncertainty in joint position is undesirable from the precision standpoint. Since the jacobian maps joint perturbations into endpoint perturbations, each Jacobian element can be thought of as a gain from joint to endpoint space.

$$\begin{array}{ccc}
 \begin{bmatrix} \delta x \\ \delta y \\ \delta z \\ \delta u^* \\ \delta v^* \\ \delta \gamma \end{bmatrix} & = & \begin{bmatrix} \frac{\partial x}{\partial q_1} & \cdots & \frac{\partial x}{\partial q_6} \\ \vdots & & \\ \frac{\partial \gamma}{\partial q_1} & \cdots & \frac{\partial \gamma}{\partial q_6} \end{bmatrix} \begin{bmatrix} \delta q_1 \\ \delta q_2 \\ \vdots \\ \delta q_6 \end{bmatrix} \\
 \text{Endpoint} & & \text{Jacobian} & & \text{Joint} \\
 \text{Change} & & & & \text{Change}
 \end{array}$$

The sum of the absolute values of all Jacobian elements in a single row, (or the one-norm of each row vector) is some measure of a "worst-case" gain, mapping a simultaneous unit perturbation in all joints to a perturbation in one of the six endpoint coordinates. For the first row of the jacobian, define the sensitivity S1 to be

$$S_1 = \sum_{i=1}^6 \left| \frac{\partial x}{\partial q_i} \right|.$$

The vector comprising all six such sensitivity measures will be called the sensitivity vector for convenience in this thesis. Since the sensitivity vector is different for each position and orientation of the end effector of a given design, a few key positions were chosen as representative and considered across all designs. It should also be noted that comparison of sensitivity vectors is not a purely quantitative task, since one geometry might yield high sensitivity in one degree of freedom and low in another while the converse might be true in a second geometry. Knowledge of the movements that would be most critical in the microinjection application shaped the judgments of which sensitivity measures to weigh more heavily, (such as (u^*, v^*)), and which to, in some cases, ignore completely (such as γ). Yet another important point to note is that, while the vectors can be compared to one

another, elements within one vector can not be directly compared. This is because the elements of the sensitivity vector corresponding to the rotational degree of freedom has units of (radians/length) while the translational DOF units are (length/length).

Mathematical Design Search Method

The approach, using the symbolic manipulation software package, Mathematica, was to leave the Stewart Platform geometry parameters of interest and the set of endpoint coordinates as variables, and then to solve the inverse kinematics problem of finding the joint positions (leg lengths) as a function of those variables. This is straightforward for a parallel manipulator, because once the coordinates of all leg attachment points are known in a single coordinate frame, leg lengths are found by vector differences. The inverse jacobian is then obtained by symbolically differentiating with respect to the joint positions. From this state, endpoint position and geometry values can be supplied, and the inverse jacobian evaluated and inverted to give the jacobian. Following this procedure, many geometries and endpoint positions can be examined without having to invert or differentiate with numerical methods.

Parameters to be chosen included the diameter, D_b , of the smallest circle circumscribing the leg attachments to ground (base size), a similar circle diameter, D_p , for the upper end leg attachments (platform size), and a nominal value, H , for the distance between platform and base.

Two general areas of investigation into geometry effects were the ratio $H:D_p$ (slenderness), and the ratio $D_p:D_b$ (conicalness). Fig. 3 shows a few examples of the effects of geometry on sensitivity vectors. The u^* and v^* values, which are of primary

importance for microinjection, are best when the manipulator is slender (row 4). The tradeoff is a significant degradation in x and y (using the first row as a reference). If the platform is large compared to the base (row 2), a similar but less severe tradeoff results. The third row shows a conical design in which the base is twice the diameter of the platform. The x and y sensitivities are better than in the case of the cylindrical design of row 1, and u^* and v^* are not significantly worse. This design was rejected, however, in favor of row 1 on the basis of range of motion (which always competes with low sensitivity).

Db	Dp	H	Sensitivity of					
			x	y	z	u^*	v^*	g
(in)	(in)	(in)						
2	2	2	5.94	5.21	1.07	0.71	0.77	3.01
2	4	2	7.48	7.67	1.24	0.86	0.76	1.74
4	2	2	3.42	3.81	1.28	0.86	0.80	1.61
2	2	6	12.11	12.43	1.01	0.67	0.72	8.48

Fig. 3. Effect of three geometry parameters on the sensitivity vector.

3. PHYSICAL DESIGN

Stewart Platform

Approaches to the physical design of a Stewart Platform can be divided into two classes: (1) legs either pull or push against an antagonistic force (i.e. a spring pushes the platform away from the base at all times while six variable length cables constrain it [43]), or (2) each leg is a linear actuator which can be commanded to a desired length.

In order to get a reasonable range of motion and good response characteristics using approach (1) above, a considerable amount of potential energy must be stored in the antagonistic system. Failure of a leg connection in such a system could have catastrophic results in ophthalmic surgery. With approach (2), the biggest problems are the actuator's overall length, length to stroke ratio, and diameter to length ratio. Most of these quantities are much larger than desired with commercially available linear actuators, leading to problems with leg collisions, high sensitivity values, and poor range of motion.

Variations on Initial Design

To circumvent some of these difficulties, a variation was devised (Fig. 4). This variation allows the linear actuators to remain fixed to ground rather than being ball jointed to ground, which in turn generates fewer problems with leg collisions and sensitivity

parameter goals. This same variation was presented by Merlet [44] with the difference that Merlet's platform-end leg connections occur in three coincident pairs, while Fig. 4 shows six distinct platform attachment points.

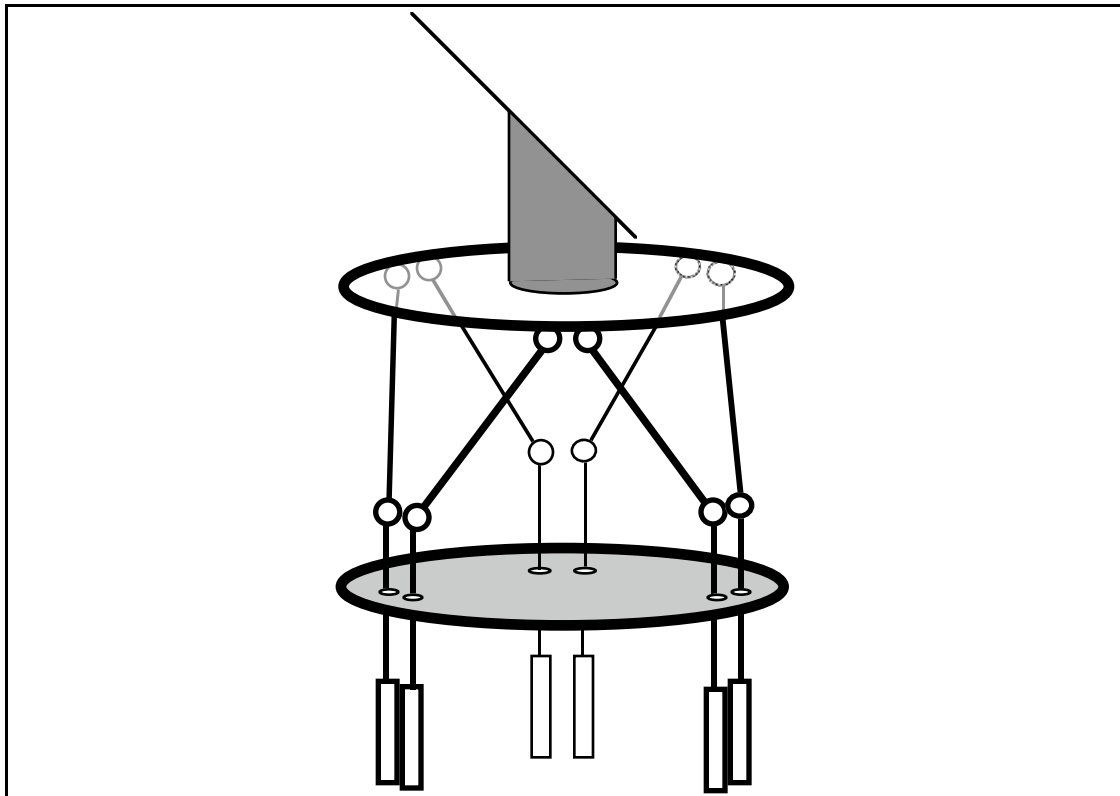


Fig. 4. Schematic of the modified parallel manipulator with 45 degree hypodermic needle end effector.

It was also decided that the needle should not be mounted perpendicular to the platform in order to avoid collisions between the back end of the micropipette and the legs. (Recall that the micropipette is rigid and must pass all the way through the hypodermic needle.) Mounting at 45 degrees not only avoids collisions but makes micropipette access much more convenient yielding a more functional design.

These variations on the earlier manipulator design were not without cost. The sensitivity vector suffered somewhat. After considering the sensitivities, range of motion and function, the final design now has leg length, platform diameter, and base diameter all of two inches, yielding a sensitivity vector of (5.31, 5.41, 1.50, 0.48, 0.89, 1.87).

4. COMPLETION OF THE DESIGN AND FABRICATION

The device has been designed and fabricated (see Fig. 5). It is now being used in a Northwestern University Biomedical Engineering research lab where it is regularly used to successfully hold and guide a micropipette to a retinal vessel puncture site. It presently uses a passive input device manipulated by the operator who depends solely on visual feedback through a microscope. Work in the ophthalmic research mentioned at the beginning of Part I is ongoing.

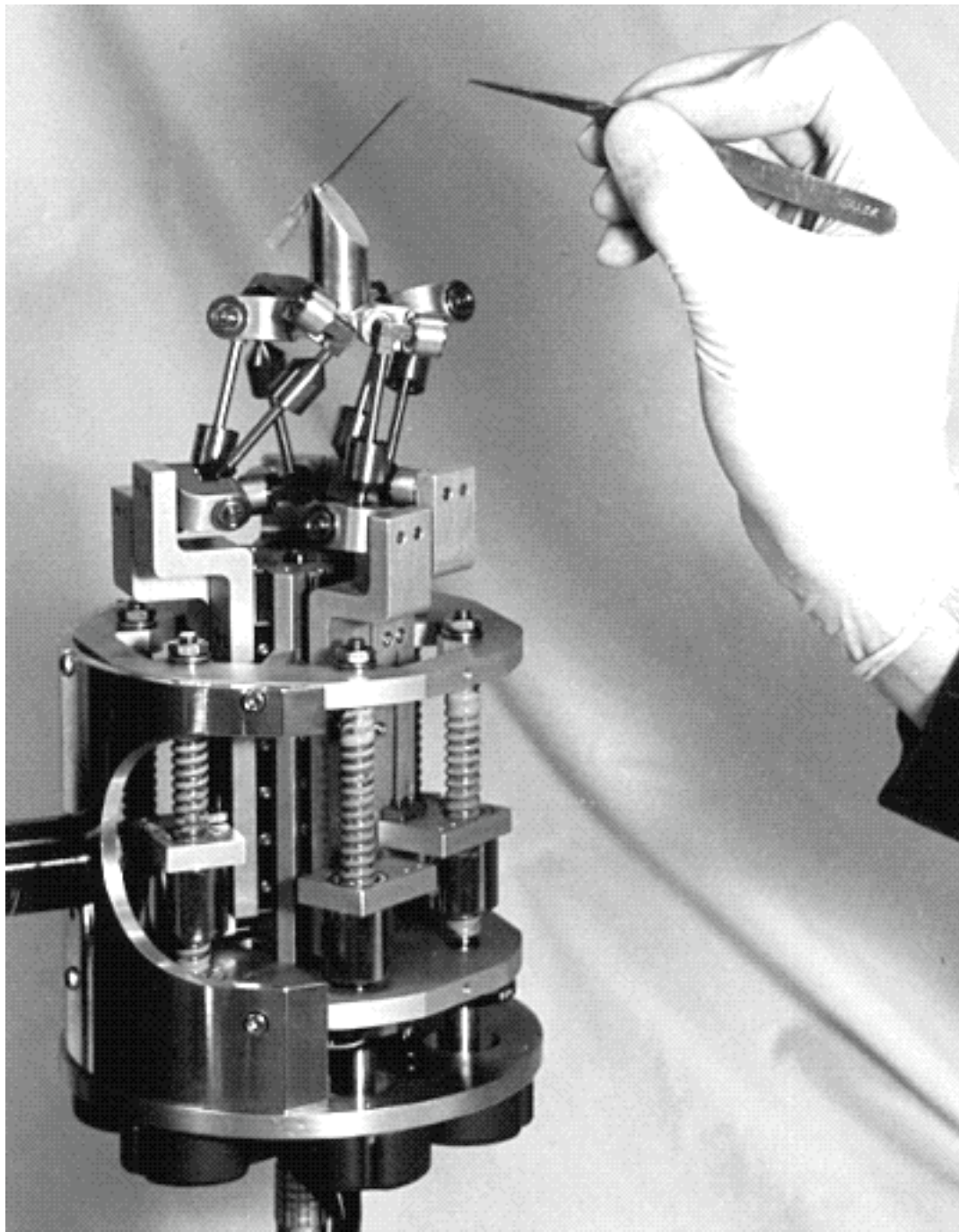


Fig. 5. Micromanipulator for ophthalmic surgery.

PART II

TOOLS FOR THE BILATERAL TELEOPERATOR DESIGNER

5. INTRODUCTION TO PART II

The "distancing" of the surgeon from the tool (as discussed in part I) has resulted in the protection of 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 micropuncture, it is possible to reconstruct the force feedback path that has been eliminated. This brings us to the subject of teleoperation.

6. MOTIVATION

Definition and Discussion of Terms

Let us begin by defining a few terms, some of which may seem quite familiar. They are included in spite of their common usage because they are often used casually and have evolved to have vague meanings.

Teleoperator - According to Sheridan[55], a teleoperator is a machine that extends a person's sensing and/or manipulating capability to a location remote from that person. Teleoperator is such a broad term that it extends even beyond the set of all hand tools. Consider some examples of systems that, most would agree, would appropriately be described as teleoperation systems:

- An astronaut sits within the space shuttle manipulating a passive joystick while watching an active extravehicular robot arm carry out satellite repair commands.
- A worker manipulates potentially harmful radioactive containers from the other side of a protective wall with a passive exoskeletal master and a kinematically similar passive slave connected by cables. The worker is only a few feet from the containers.
- While viewing through a microscope, a surgeon repairs the nerve connections in a finger that has been severed and reattached. A micromanipulator slave and force reflecting master are being used to enhance dexterity.

If the preceding are acceptable examples of teleoperators, then the definition of teleoperator must not require the system to be bilateral, computer mediated, active, mechanically linked, or even have user and task separated by a long distance as the term itself implies. If these, then why not a cable operated tree-pruning shear on the end of a pole, or a telephone system, or a pencil? What about public speaking, which uses a column of fluid as a tool to excite an eardrum fifty feet away upon energetic input from the user? The fact is that each system from this somewhat tongue-in-cheek list of examples has a counterpart from the more conventional list for which there is no significant mathematical difference.

Active bilateral manipulator - The term "active bilateral manipulator" will be used to describe the subset of teleoperators with which this proposal is concerned. All systems which fit this category have an active mechanical master and an active mechanical slave which communicate through a "signal-level" mediator. (Note: Nearly all bilateral manipulators referred to in this work will be active, so the word "active" will often be dropped.)

Signal-level mediator - In this proposal, the term "signal-level mediator" will refer to an active signal processor (analog electronic, digital electronic, or mechanical) which operates on signals which have power levels that are insignificant in magnitude compared to either the master/user interaction, the slave/task interaction, or both. In the case of the passive radioactive container manipulation system mentioned above, the cables that connect the master and slave transmit mechanical information at power levels comparable to the power transferred by the user to the master and by the task to the slave. The cables do NOT function as a signal-level mediator. The

same is true of a pencil which has a rigid connection between master (wherever it is gripped) and slave (the writing tip). Analog circuitry which operates at a Watt or two is signal-level when controlling a master actuator that typically reaches 100-200 Watts. In this case, even if the slave were small and operated on the level of one Watt or so, the system would qualify as an active bilateral manipulator. Note: There does exist a teleoperator, developed at the University of Minnesota by Kazerooni, called an “extender” [37, 38]. It behaves much like an active master/slave system, but is a hybrid of a passive lever which scales up human motions and an active force sensor/actuator system built into the lever which scales up human forces. Motion scaling is mechanically fixed, but force scaling is programmable. In the extender, “power and information signals transfer simultaneously at one point”, according to Kazerooni, which make its description inconsistent with the definition of active bilateral manipulator. Considering these facts, perhaps an appropriate classification of the extender might be termed “half active bilateral manipulator”. This work is not intended to exclude the extender or similar designs.

Proprioception and Kinesthesia - According to Kandel [36]: Limb proprioception is the sense of position and movement of the limbs. There are two submodalities of limb proprioception: the sense of stationary position of the limbs (limb position sense) and the sense of limb movement (kinesthesia).(p347)

Haptic - relating to human physical sensing of the environment, including tactile and proprioceptive and excluding auditory, visual, and olfactory senses.

Haptic display - the mechanical part of the total interface between human and either a signal-level simulated environment, or a slave which is in turn interacting with a real environment. Where the video display provides visual stimulation (with the ultimate goal of transferring information), the haptic display provides tactile and/or proprioceptive stimulation (with the ultimate goal of transferring information).

Macro-Mini-Micro-Telemanipulation - Blake Hannaford in notes for a 1993 IEEE ICRA workshop which is unfortunately unpublished, considers the position scale factor, λ , from master to slave and a survey of literature in defining the M-prefixes:

Macro-telemanipulation	$10^0 \leq \lambda < 10^3$
Mini-telemanipulation	$10^{-3} \leq \lambda < 10^0$
Micro-telemanipulation	$10^{-6} \leq \lambda < 10^{-3}$
Nano-telemanipulation	$10^{-9} \leq \lambda < 10^{-6}$

Bilateral - refers to the existence of BOTH a feedforward pathway from human through the teleoperator to the task AND a resulting feedback pathway from the task through the teleoperator to the human. Very commonly the feedforward and feedback variables are motion and force respectively. Not only may these be swapped, however, but they may be any pair of variables whose product is instantaneous power (such as the scattering variables "inwave" and "outwave"[13]).

Force Reflecting - makes specific the ambiguity intentionally left in the definition of "Bilateral". Motion is fed forward and force is fed back. In other words, the system and task are modeled as an impedance to the operator. "Force Reflecting"

implies "Bilateral". (Judging from its use in the teleoperation literature, this term is often used casually to be synonymous with bilateral instead of a special case of it.)

Macro/Micro Bilateral Manipulator (MMBM) - introduced by Colgate [11, 12, 13] and is an active bilateral manipulator in which the master is the size of a hand tool, and the slave operates on environments below the level of human dexterity. This term will be used to refer in general to master-slave systems where the slave operates on smaller scales than the master, without regard for the strictness of the M-prefix definitions above.

Bilateral Controller - a two-port controller. Each port consists of an input and an output, the product of which is power. One port communicates with the master and the other port communicates with the slave. Slave output is a function of master and slave inputs. The same is true of master output.

Telemanipulators - the subset of teleoperators formed by enforcing the restriction that there be haptic interaction at the master. While a survey of the literature does not seem to require a telemanipulator to be bilateral, usually they are.

Unilateral to Bilateral Manipulator

Schematically, this dissertation has followed the progression shown (Fig. 6). The last step in Fig. 6 is to equip the micromanipulator (slave) with sensors and endow 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.

The experiments in this work will deal chiefly with bilateral manipulators in which the master is easily used like a hand tool by the human, and the slave operates on environments below the level of human dexterity. This "Macro-Micro Bilateral Manipulator" (MMBM) platform has been chosen because the current needs of the projects in this laboratory are in micro teleoperation, but this is not meant to suggest that the usefulness of the results will be restricted to MMBM. On the contrary, it is hoped that the results will be independent of the platform being used.

Ideal Bilateral Manipulators

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. There seems to be a growing belief, however, that "ideal" bilateral manipulator is an ill-defined term. For many, "ideal" retains the meaning of providing the user with a realistic sense of manipulating the remote object directly. Yet for others, such realism would render the tool useless, either because they wish to toss a defective 20 ton steel I-beam into the discard heap [37, 47], or because they wish to feel the subtle differences between stretching a cancer cell and a healthy cell while watching under a microscope [34]. In either of these extremes, a one-to-one mapping could hardly be considered ideal.

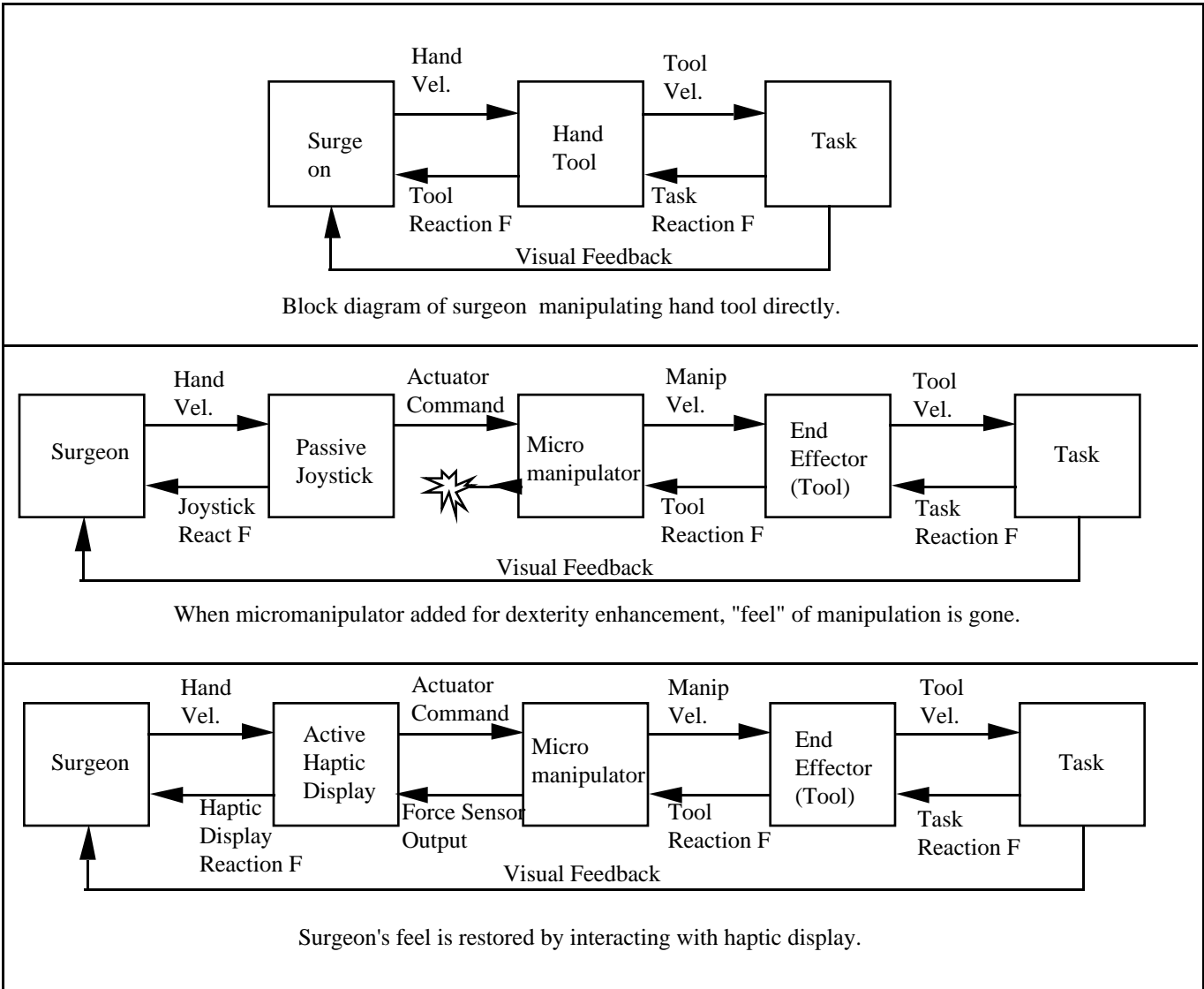


Fig. 6. Originally, the surgeon feels reaction forces from the surgical tool. Addition of a micromanipulation tool breaks the force feedback path. Implementation of a bilateral manipulation scheme restores the feel of the environment to the surgeon.

This work does not seek to develop a single controller suitable for all tasks, but to begin to build an arsenal of controller elements which can be selectively chosen to attack the particular task at hand.

Constant Gain Controllers

Non-Portability of Optimized Systems

Force reflecting MMBM controllers scale down the motion of the master to command the motion of the slave (feedforward path) and scale 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 so that the operator can become accustomed to the motion and force mappings of the system.

Furthermore, it is certainly reasonable and interesting to investigate how changes in constant scalings or system impedance affect task success. Raju's Ph.D. dissertation is an example of this type of work [49]. However, experiments which determine “ideal gains” or “ideal impedances” for a particular system in performing a particular task do not yield very portable results. While it is necessary to vary the motion and force scales initially to develop a useful test bed, less emphasis will be given to these results. This work will focus more on dealing with the following type of problem that can arise with constant-scaling MMBMs.

Shortcomings of Constant Gain Controllers

If the task of interest involves two or more subtasks with very different 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 with a macromaster and mini slave in which the slave wields a hypodermic for puncturing plastic wrap, it was found that high force gain in the feedback path to the master causes a very distinct sense of contact between needle tip and membrane, a potentially valuable piece of information. The operator knows when contact has occurred before any damage is done to the membrane. However, the price of having this information becomes evident upon puncture attempts which may require uncomfortable force levels to be attained by the operator at the master. The alternative is to sacrifice the distinct contact for more comfortable puncturing force levels.

Another related source of difficulty is a task which requires high forces to be generated and culminates in a relatively small impedance change indicating task completion. An example is engaging a pushbutton switch. Here, a heavy spring is compressed. The user knows that the switch is engaged by feeling a click at the end of the pushbutton's travel, which results in a subtle change of force. Using a bilateral manipulator, the slave forces can be amplified to allow the click to be felt at the master, but this could again require the user to generate high forces to compress the spring.

To reconcile the conflicting needs of the different modes of these tasks, 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.

7. FEATURE EXTRACTION

Impedance Boundaries

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 which needs an additional quarter turn of tightening. 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, can produce sudden large force changes because it involves crossing an impedance boundary. Not coincidentally, it is the success of this transition phase of the task which stands to suffer the most when the force feedback path to the one doing the manipulating is interrupted.

Definition of Feature Extraction

It is suspected that the majority of the cues in manipulation come from changes in impedance, not from impedance magnitude itself. While constant scaling in MMBM control 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*.**

Applications of Feature Extraction (Tasks)

Multiple Degree-of-Freedom Tasks

The following is a list of tasks which represent foreseeably common applications of MMBMs in medicine, microassembly, micromachining, etc. (Let us restrict the scope of this discussion to small scale tasks for the time being.)

- Place wrench on nut and tighten.
- Thread machine screw into tapped hole.
- Thread a needle.
- Inject drugs into tissue.
- Deburr a part.
- Paint or scrub a part with a brush.
- Immerse a part in a chemical bath and remove.
- Drill a hole.
- Pick up and carry an object with forceps (tight grip).
- Pick up and carry a delicate object with forceps (use slipping to determine minimum allowable grip force).
- Cut with scalpel.
- Cut with scissors (as in arthroscopic surgery).
- Stretch tissue or material.
- Scrape tissue or material.
- Cut threads in a hole with a tap.

Single Degree-of-Freedom Components

For simplicity, it is desirable to consider the benefits of feature extraction as applied to single DOF systems. The following list comprises a partial set of single DOF skills that would be beneficial to executing the tasks above.

- Puncture detection (and prevention of overshoot).
- Contact/non-contact detection.
- Detection of stick/slip action.
- Control of normal force of deburring or scraping tool.
- Detection of completing through-hole drilling.
- Control of scalpel incision force.
- Prevention of overshoot if stretched material breaks or slips from grasp.
- Prevention of overshoot if scraping tool loses its bite.
- Prevention of tap overtorque and breakage.

Definition of Catastrophic Tasks

It is useful, for classification of the above 1 DOF skills, to introduce the definition of catastrophic and noncatastrophic tasks. **Catastrophic tasks have, as part of the success of the task, some sudden change in impedance with a detectable signature in the force-time or force-position curves.**

Note that tapping a hole is noncatastrophic. If there is a sudden change of impedance during the tapping of a hole, it most likely indicates tap breakage, not task success as required by the definition.

Most punctures are examples of catastrophic tasks. The material being punctured gives way to the puncturing implement causing a sudden impedance change. The catastrophe is necessary for the success of the task. Consequently, the catastrophe provides a valuable cue to a feature extracting controller. The action taken after feature detection will be discussed in a later section.

Statement of the Mission

The contribution of this work is to provide the bilateral manipulation system designer with a few tools that may be incorporated into bilateral controllers to facilitate a certain class of tasks, namely, catastrophic tasks.

Implementation of Feature Extraction

Extraction Techniques

Feature extraction is a modular tool which may be implemented in any one of a variety of forms. In high pass filtering feature extraction, the high frequency components of the force or torque signal in the feedback path are isolated. The output of the filter is thresholded to distinguish noise from features of interest.

In differentiating feature extraction, the torque is differentiated either spatially or temporally and then thresholded. Another screening step checks the order and number of sign changes in the slope to determine whether or not the feature is “interesting”. If so, then the desired effect is produced.

Programmable Effects

The first of the effects that feature extractors may evoke is called natural recombination. Here, the output of the feature extractor is amplified (or attenuated) and added to the unfiltered signal. The operator feels an artificially great emphasis on the feature. When used with the high-pass filtering detection technique, this is the purest of all the effects to be discussed since the operator feels only a reshaping of the frequency response of the actual task impedance (similar to impedance shaping [13] except with the nonlinear thresholding added). In all other effects to be discussed, the feature extractor acts like a programmed conditional which evokes a completely artificial result instead of acting as a nonlinear filter as in natural recombination.

Closely related is packet recombination which uses the feature extractor to decide when to release a predefined packet of torque to the operator. This mode can be used like an audible alarm to alert the operator of some notable change of condition which otherwise would have been difficult to perceive, or to aid the user in reacting to the feature.

Next, there is the effect of virtual fixture addition. Rosenberg found significant improvement in bilaterally manipulated peg-in-hole tasks with the use of virtual fixtures [50]. However, virtual fixtures in the literature generally require prior knowledge of the structure of the environment with respect to ground. With feature extraction, though, virtual features can be set up relative to the end effector upon detection of a catastrophe in a task. Using single DOF puncture as an example, the program can construct a virtual wall 100 microns beyond the coordinate of the puncture (as detected by the feature extractor) to prevent over-insertion of the needle. This is much simpler than pre-task definition of such a protective device, which would require precise absolute coordinates of the puncture point as well as accurate models of tissue compliance, etc.

Another valuable effect that the feature extractor could be programmed to have is gain modulation. This could come in the form of a damping increase for post-catastrophic manipulation, or raising the force feedback scaling to provide a better “feel” after the most energetic part of the task is complete. (This is not far removed from the ideas of Salcudean et al., who attempted improving the haptic display of virtual hard contact by exaggerated damping in the “skin” of a virtual object [53]. Of course that does not involve actual slave/task interaction.)

The Niche of Feature Extraction

This proposal does not represent the first attempt at non-constant scalings in active bilateral manipulation. Hannaford, for example, proposed a generalized master-slave architecture that he called Bilateral Impedance Control [29]. This is a form of adaptive control in which "local control loops at the master and slave sides attempt to reproduce the impedance seen at the opposite end of the teleoperator". This controller is applicable only to same-scale bilateral manipulation. It has not yet been implemented. Fukuda et al.[23] implemented “impedance reflection” using a micro slave and reported it to be comparable in effectiveness to more traditional control schemes such as position-symmetric (to be discussed).

Work more closely related to feature extraction is "impedance shaping" presented by Colgate to specifically target MMBM control [11, 12, 13]. Impedance shaping was devised to deal with the micromanipulation problem associated with dissimilar scaling of inertial, dissipative, and compliance forces as size changes. In theory, impedance shaping bilateral manipulators can present the operator with an altered impedance that is more

"familiar" than a purely scaled version of the real microtask. Impedance shaping per se has not yet been implemented, although feature extraction grew out of those ideas.

There are also papers dealing with reaction to slippage in robot grippers and artificial hands [9] [46] [57]. Electromechanical sensors are mounted in the grippers. Minute vibrations in the early stages of slip evoke an increase in grip force. While these are not bilateral manipulation implementations, they do make use of a technique that resembles feature extraction. Extensions of that work do extend into constant gain bilateral manipulation. Most notably, the work of Kontarinis and Howe appends an accelerometer to the slave manipulator and reflects high frequency vibration information to the master via a voice-coil actuator [31, 32, 41]. The low frequency and high frequency force information come through parallel feedback pathways to separate actuators, each actuator reflecting the particular band of frequencies for which they are best suited. Such an enhancement of a bilateral manipulator has been shown experimentally to improve task success. It has the advantage of not requiring high bandwidth master and slave actuators. That system attempts to faithfully reproduce forces and vibrations at the slave in contrast to the feature extraction system which artificially accentuates or reacts to features.

The remainder of the literature to be mentioned consists of a number of papers on constant feedback scaling bilateral manipulation. First, the work coming from the Jet Propulsion Laboratory [3, 7, 20, 30, 40] comprises primarily one or two JPL Six DOF serial force-reflecting hand controllers coupled to non-backdriveable industrial robots such as PUMAs. High fidelity bilateral manipulation is not expected with such a system due to the low bandwidth frequency response of the slave. In contrast, work with the so-called "magic wrist" [52] involves relatively high-bandwidth magnetically levitated actuators.

The literature from Argonne represents the earliest papers on teleoperation [25, 26, 27, 28] along with Howell at Oak Ridge [33] and Jelatis [35]. Note that the year of Goertz's report entitled "A Force-Reflecting Positional Servomechanism" is 1952. Note also that this earliest active bilateral manipulator used a position servoed slave and a torque servoed master. (The block diagrams in the following section will help to visualize these.) As early as the mid-60's, Ferrell addressed the currently popular topic of transmission delay in bilateral control [21, 22].

In none of the literature cited has anything equivalent to feature extraction been attempted.

8. THEORY

Standard Block Diagrams of Servo Loops

This work will be concerned with systems which fit the general form shown in Fig. 7. The visual feedback path, while usually present, will not be explicitly shown in subsequent diagrams. All controller schemes discussed will ultimately be represented by a detailed version of this general form. Let us take care, however, not to strip intuition from

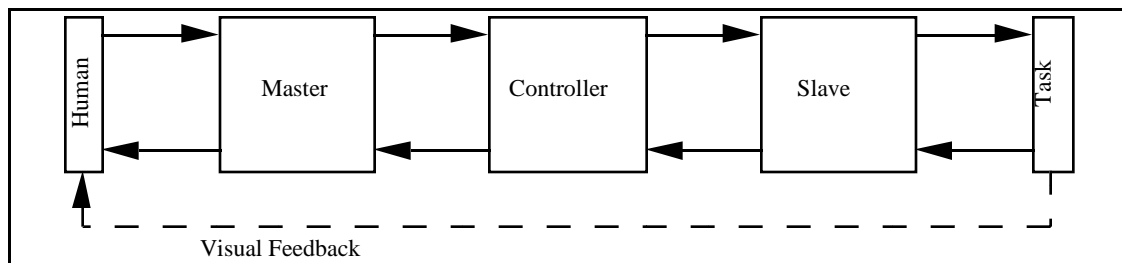


Fig. 7. General form of systems being considered. Visual feedback may or may not be present.

the process of casting possible controllers into the general form by first considering the master and slave in more familiar block diagram forms. In the case of designing a force reflecting bilateral controller, one way to begin is to close a position regulation feedback loop around the slave, but close no loop around the master. These two disjoint parts are shown in Fig. 8.

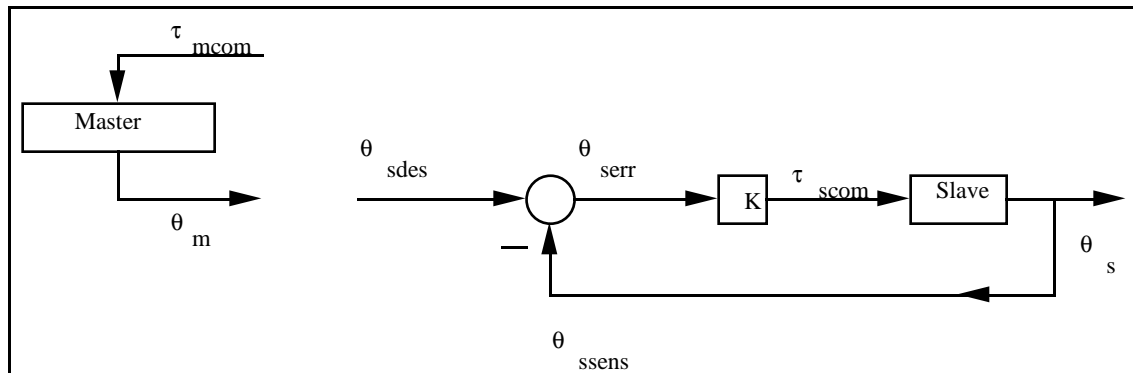


Fig. 8. Open loop master and position servoed slave before connection as force-reflecting bilateral manipulator.

The desired (or reference) position of the slave can then come from the position of the master. If the master and slave operate on very different position scales, the master position must be scaled down before it becomes an appropriate reference input to the slave position regulator. We would also like the master to be actuated in proportion to the endpoint force of the slave. This force applied to the slave by the task may be measured with strain gauges or some other type of force transducer. With an approximating assumption, however, such a sensor can be avoided altogether. Assume that the impedance of the slave is negligible compared to the impedance of the task. If this is the case, then the torque that the task is applying to the slave is almost exactly balanced by the torque commanded to the slave by its servo controller. For the slave used in this research, mass and damping are low and its commanded velocities and accelerations are typically comparatively low since it tracks a human's hand movement.

Fig. 9. is the same as Fig. 8. with the (light grey) addition of the human, task, feedforward and feedback paths. The λ_{dn} scales master position down into a reference command to the slave servo loop, and the λ_{up} scales up the estimate of the slave/task

torque to give a detectable torque to the human via the master. Note that a copy of the slave's commanded torque is being used as the slave/task torque estimate.

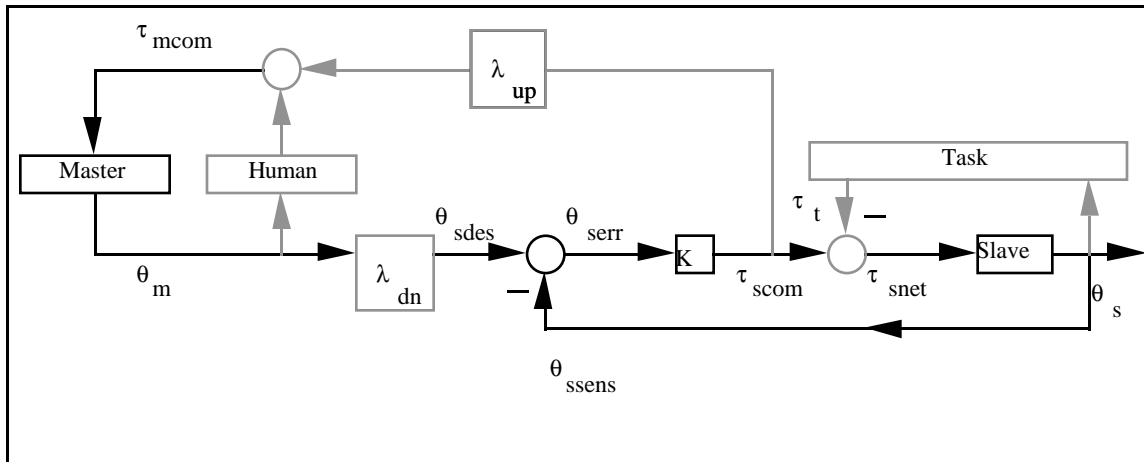


Fig. 9. Force-reflecting bilateral manipulator interacting with a task at the slave end and a human operator at the master.

General Bilateral Block Diagram Form

Now let us make the transition to the general form. First the portion of the block diagram which represents the human/master interaction is drawn in terms of impedances (denoted Z , motion input, torque output) and admittances (denoted Y , torque input, motion output). The same is done with the task/slave interaction. Since these parcels are elements of every bilateral manipulator block diagram that will appear in this dissertation, it is convenient to condense each into a single admittance as shown in Fig. 10.

To reproduce the block diagram of Fig. 9. using the newly defined equivalent admittances of Fig. 10., we add the servo controller at the slave end and the two scale factors between the master and slave ends (Fig. 11).

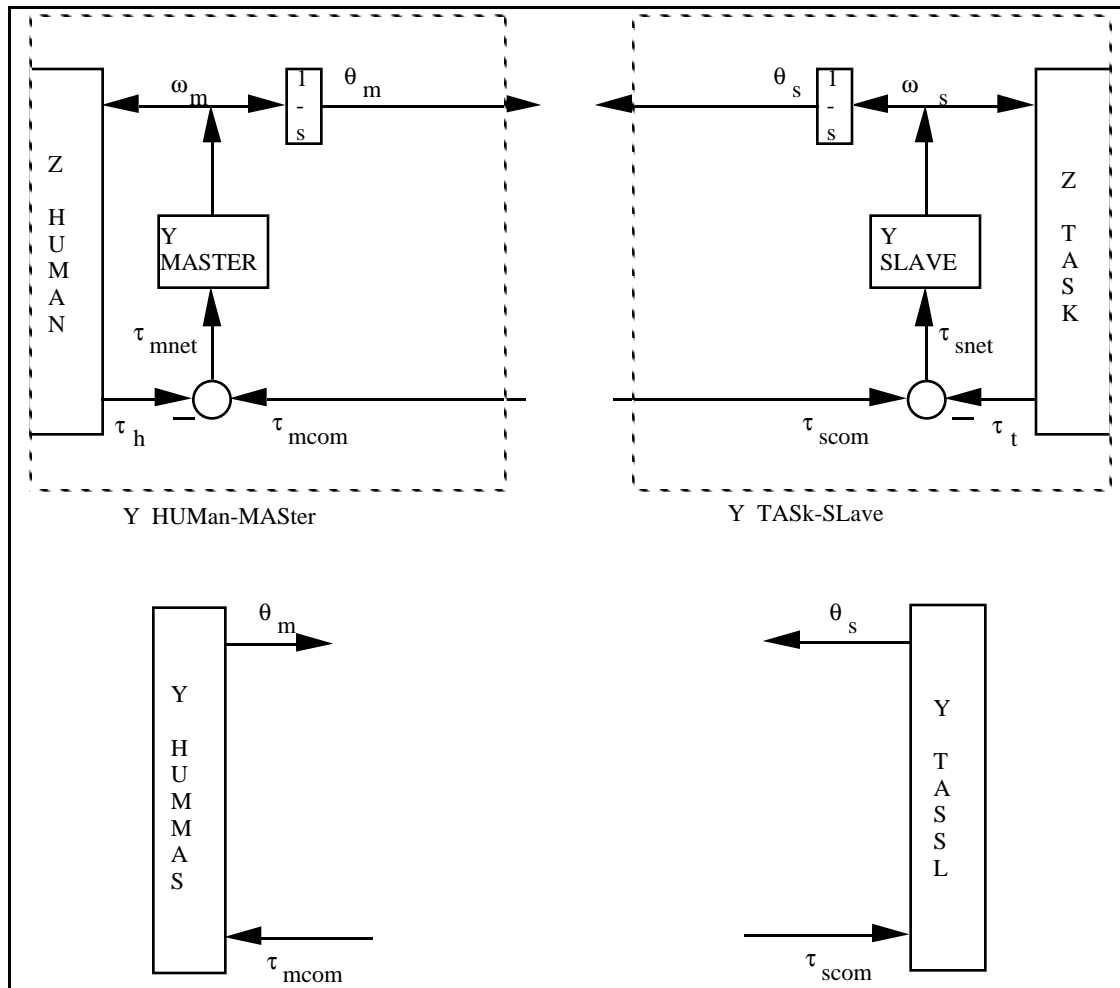


Fig. 10. Equivalent admittances of HUMAN/MASter interaction (left) and TASK/SLAVE interaction (right).

A mirror image of the Fig. 11 interconnection scheme can be used as well. Here, the position servo loop is closed around the master instead of the slave. The reference position signal to the master comes from the scaled up slave position sensor output (Fig. 12).

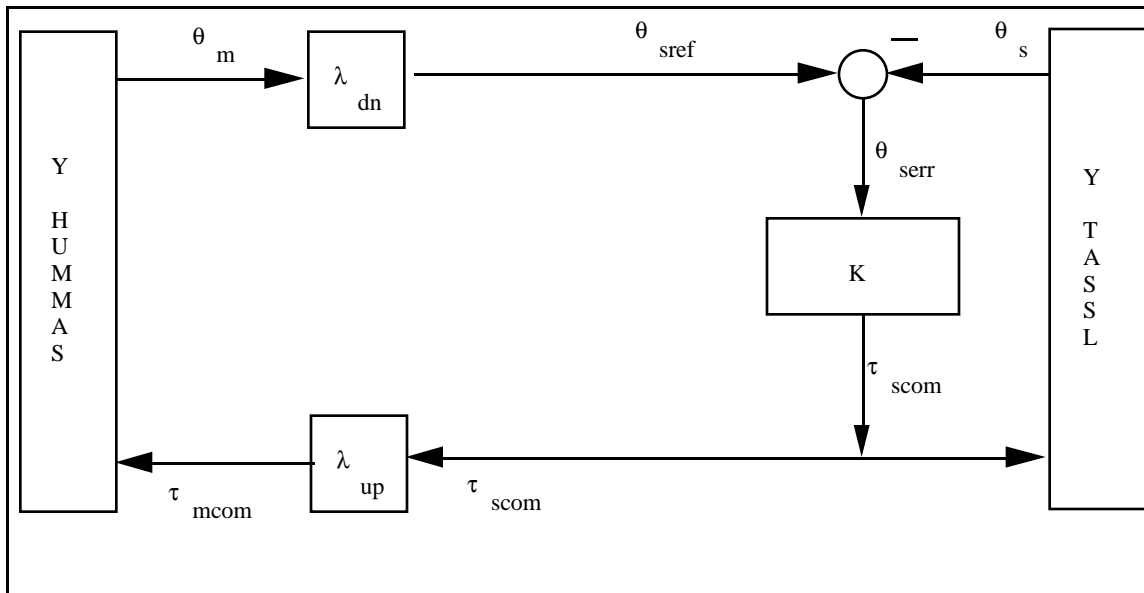


Fig. 11. Rearrangement of Fig. 9 into the general bilateral manipulator form. This is a position servoed slave and open loop master utilizing force reflection. Master and slave operate on different scales, requiring position scale-down and torque scale-up.

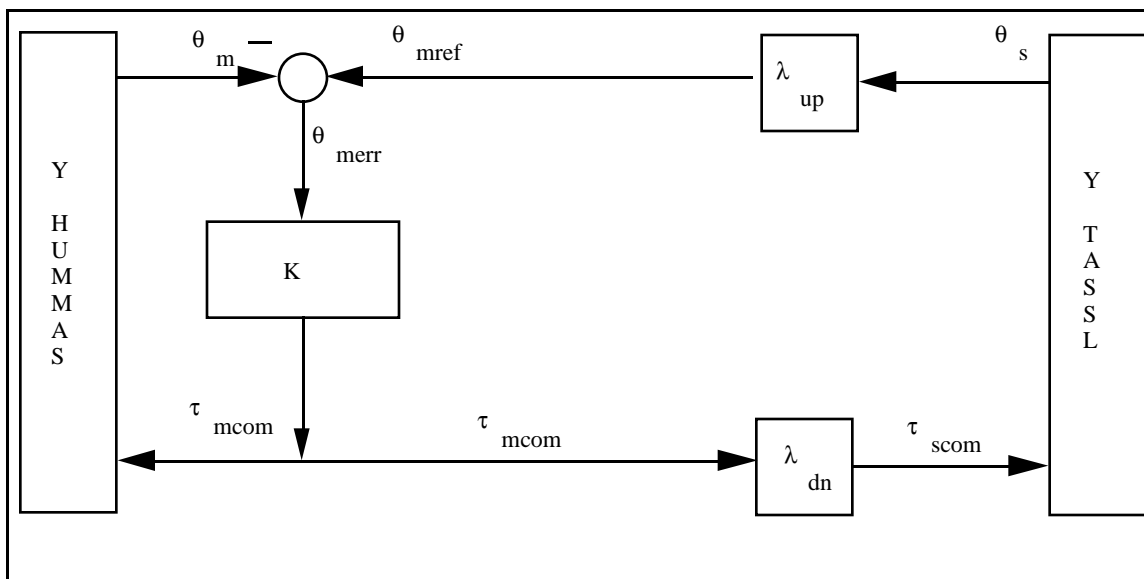


Fig. 12. Position servoed master and open loop slave.

Controllers from Lit in General Form

Naturally, there is an infinity of possible controllers. There are, however, a few that have been suggested with sufficient frequency that they have acquired names. The so-called "position symmetric" or "classical" bilateral control scheme is shown in Fig. 13.

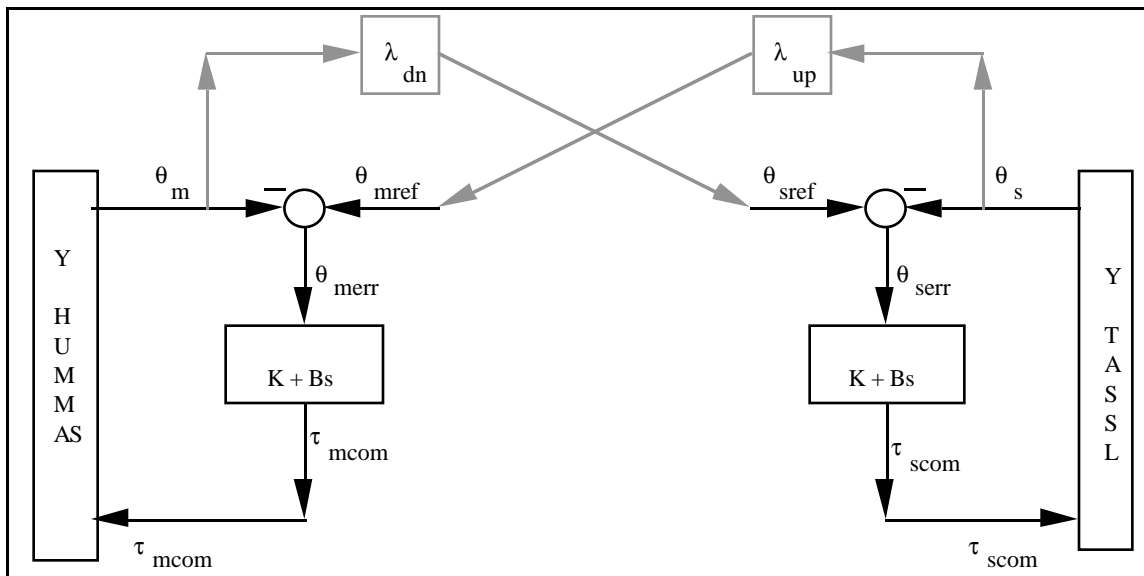


Fig. 13. "Classical" or "Position Symmetric" control scheme. Both master and slave are position-velocity servoed. In light grey, the master position is scaled to be the reference position of the slave servo loop, and vice versa. Torque is not explicitly fed forward or backward. The position difference between master and slave produces the torque at the master via the servo loop.

Note that the previous configuration stretches the definition of bilateral somewhat. Both forward and backward paths are motion paths (their product is not power as the formal definition requires).

Fig. 14. shows Colgate's robust impedance shaping controller manipulated into the general form. The block labeled $Z_{difference}$ contains an impedance representing the difference between the actual and desired impedance of the slave/task interaction.

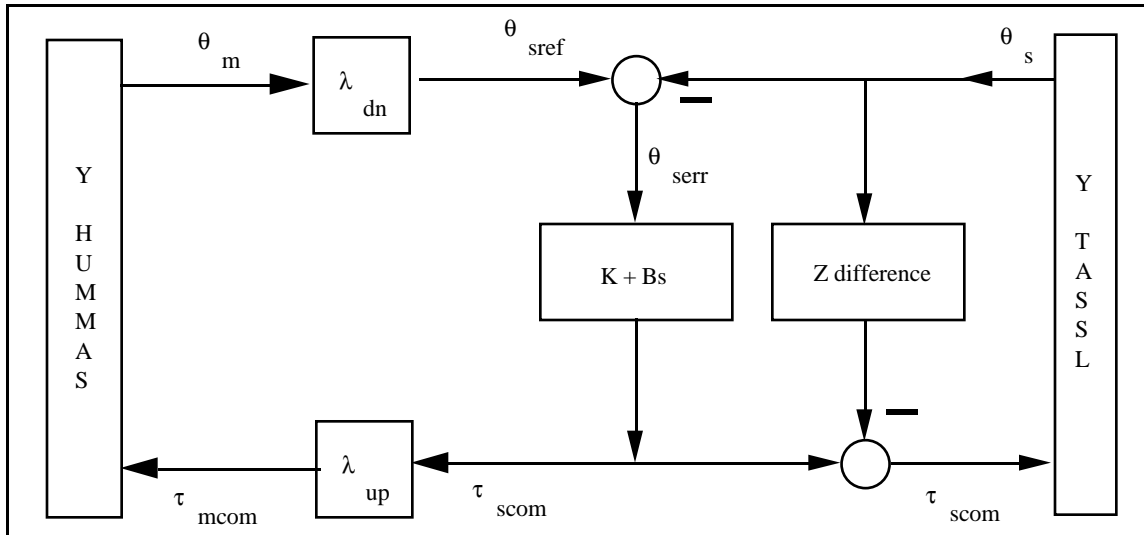


Fig. 14. “Robust Impedance Shaping” controller in general form.

Criteria for Basic Controller

Feature extractors are not complete controllers in and of themselves. It is convenient to think of them as components, retrofittable to any standard controller. Consequently, it is necessary to choose a constant scaling controller to which experimental feature extractors may be appended. This choice is arbitrary for the most part, restricted only by the following criteria. First, the controller must be stable, smooth, and quiet so that there is less likelihood of noisy signals which could be misinterpreted as features. Secondly, it is important for functional flexibility that the upward and downward scaling factors between master and slave be able to be set independently. (This second criterion excludes, for example, the position symmetric controller shown in Fig. 13. which requires the up and down scales to be reciprocals.)

Feature Extracting Controllers

Recombination

Recall that recombination involves monitoring the slave torque (either pre- or post-scaleup) for changes which indicate a change of task impedance, and adding a special torque back into the torque commanded to the master as shown in Fig. 15. The added special torque is intended to be beneficial to the user's manipulation facility in some way. It may enhance a real torque change so that it is more noticeable, or, with a predetermined artificial "packet" of torque, signal the user and/or energetically aid the user in reacting to the feature.

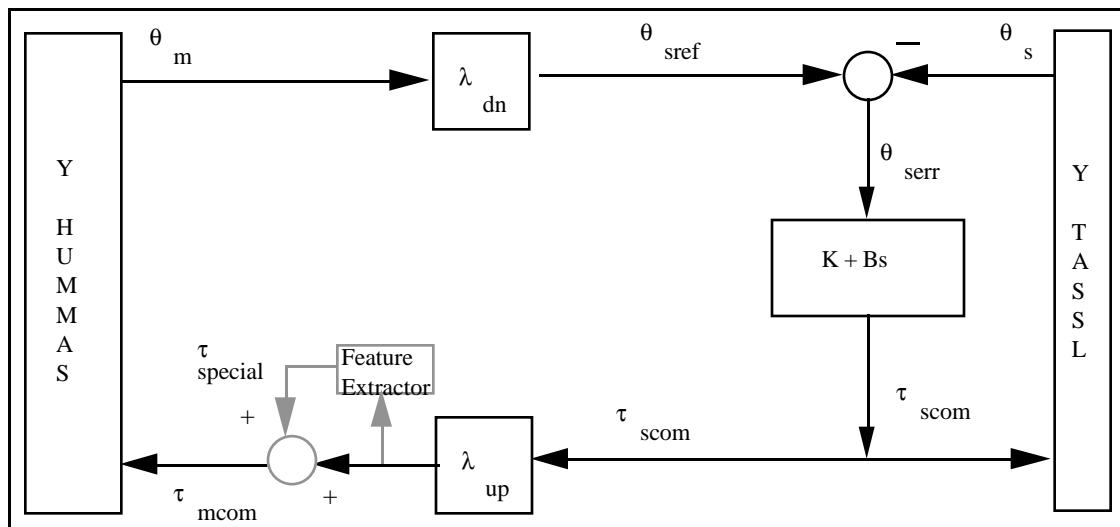


Fig. 15. Basic controller with recombining or haptic signaling feature extractor. The output of the feature extractor is added to the unfiltered torque signal.

The special torque adds more energy to the closed loop system which can contribute to instability. This concern motivates the next discussion.

Added Energy Compensation

Recombination involves adding energy to a feedback loop, a suspect practice from a stability standpoint. Three ways of compensating for this added energy are presented.

One attack on the potential stability problems introduced by the feature extractor is that of model-based removal of the special torque's effects (see Fig. 16.). If we assume that Y HUMMAS behaves as a linear admittance, then the motion output due to the original torque commanded to the master (without feature extraction) can be superimposed upon the motion output due to the special torque to arrive at the total motion output from Y HUMMAS. By modeling Y HUMMAS and sending a copy of the special torque through this model, we can, in theory, subtract the effects of the special torque altogether before the signal continues on to the slave.

The modeling of Y HUMMAS is especially difficult due to the fact that the human is included (see Fig. 10.). If the special torque is guaranteed to be high frequency compared to the upper limit of a human's frequency response, then the difficulty of modeling the human is lessened because voluntary response need not be included. A passive model of the human arm, while non-trivial, is much more tractable than an active model.

An alternative to modeling Y HUMMAS is to include enough physical viscous damping in the master that the energy added by the feature extractor is dissipated in the "filter" of Y HUMMAS. Considerable analysis is currently being done in this area and can be drawn upon [17] [15] [16].

Another attractive alternative to modeling Y HUMMAS is low-pass filtering the feedforward path. The feature extractor adds energy at high frequency. Subsequent low-pass filtering removes most of the added energy. The chosen method was to implement

both the addition of physical viscous damping and low-pass filtering the feedforward path. In this way, unstable regions of the controller were easy to avoid.

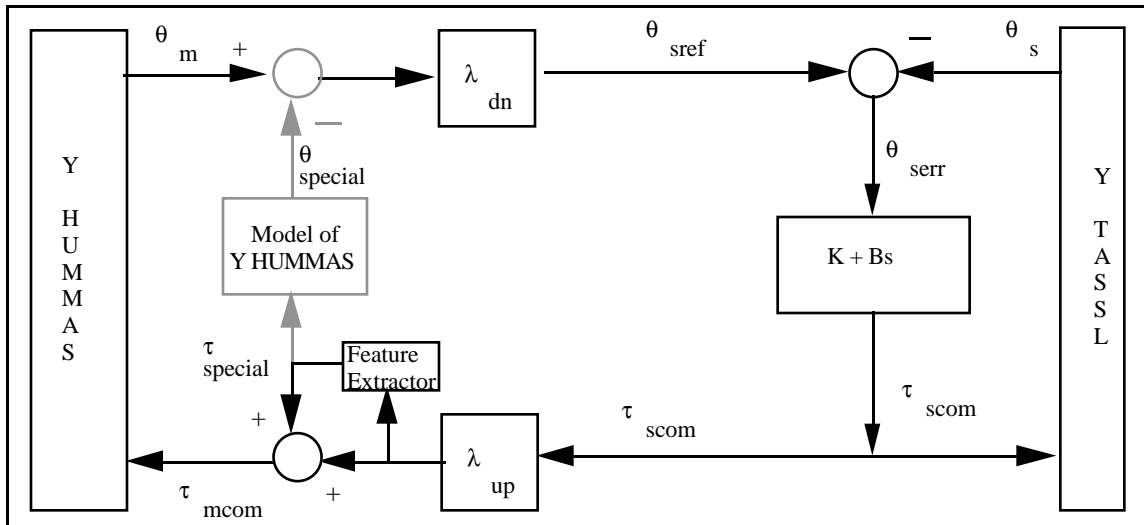


Fig. 16. Model based removal (light grey) of the effects of the feature extractor. Designed to inhibit propagation of a high frequency pulse in the feedforward path.

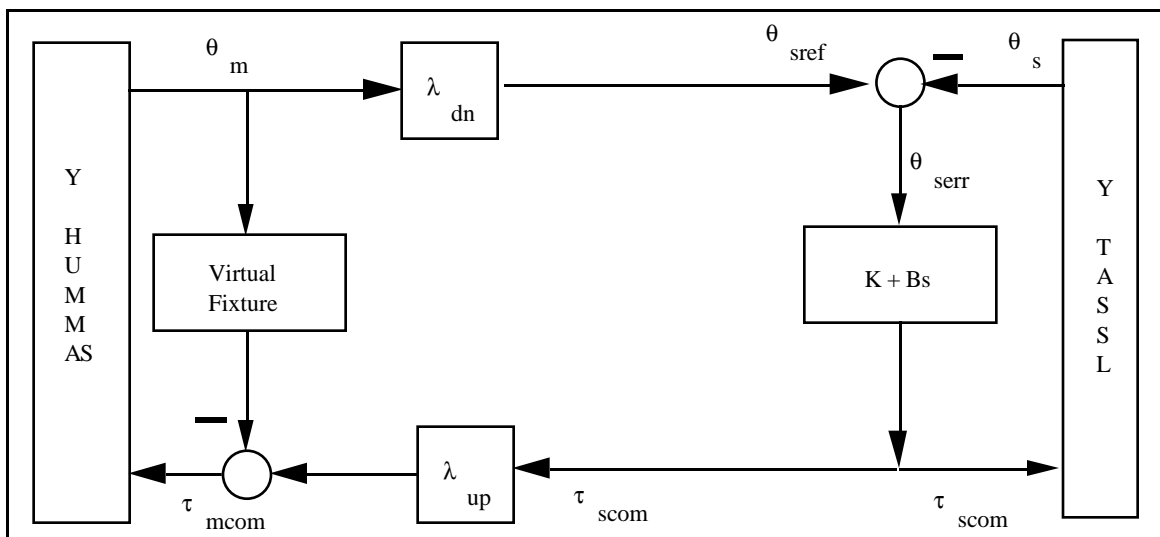


Fig. 17. In “virtual fixture addition” the feature extractor adds the virtual fixture upon recognition of the catastrophic event of interest.

Virtual Fixture Addition and Gain Modulation

Unlike recombination, it is difficult to express the next two controller effects in terms of a single block diagram. In virtual fixture addition and gain modulation, the feature extractor decides whether or not to *change* the block diagram. In the case of virtual fixture addition a new block is inserted, yielding the block diagram (Fig. 17).

In the case of gain modulation, the feature extractor simply changes λ_{up} , λ_{dn} , or the PD controller gains K and B.

9. EXPERIMENTS

Tasks

Of the MMBM tasks listed in a previous section, puncture was chosen for use in the human subject experiments. Most of the single DOF skills discussed are useful only when incorporated in a multiple DOF system. Puncture, on the other hand, is well suited to stand alone as a useful single DOF task, and does not require elaborate fixtures or end-effectors.

The micropipettes used in the retinal venous occlusion research discussed in Part I of this dissertation are ground to be so sharp (2 micron tip [24]) that they produce very small features compared to the hypodermic. For the first experiments, it was desirable to have an easily detectable feature for testing different types of controllers. Future experiments can address feature extraction in the face of poor signal-to-noise situations.

Preliminary tests with a single DOF PD controlled slave (no master) pushing a hypodermic needle through Saran Wrap show a torque "feature" as puncture occurs (Fig. 18). Time and commanded slave position are directly proportional in this experiment. It is also important to note that the assumption of slave/task interaction torque being the same as commanded slave torque is questionable here, since slave acceleration is comparatively high. Nevertheless, a detectable feature arises upon puncture (even if the actual torque values are subject to question). The signal-to-noise ratio is adequate for feature extraction.

System Components

Master

The LIMS single degree-of-freedom manipulandum was chosen as the system master. It 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 ($\sim 900,000$ 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 manipulandum design can be found in [5, 6, 8, 42] .

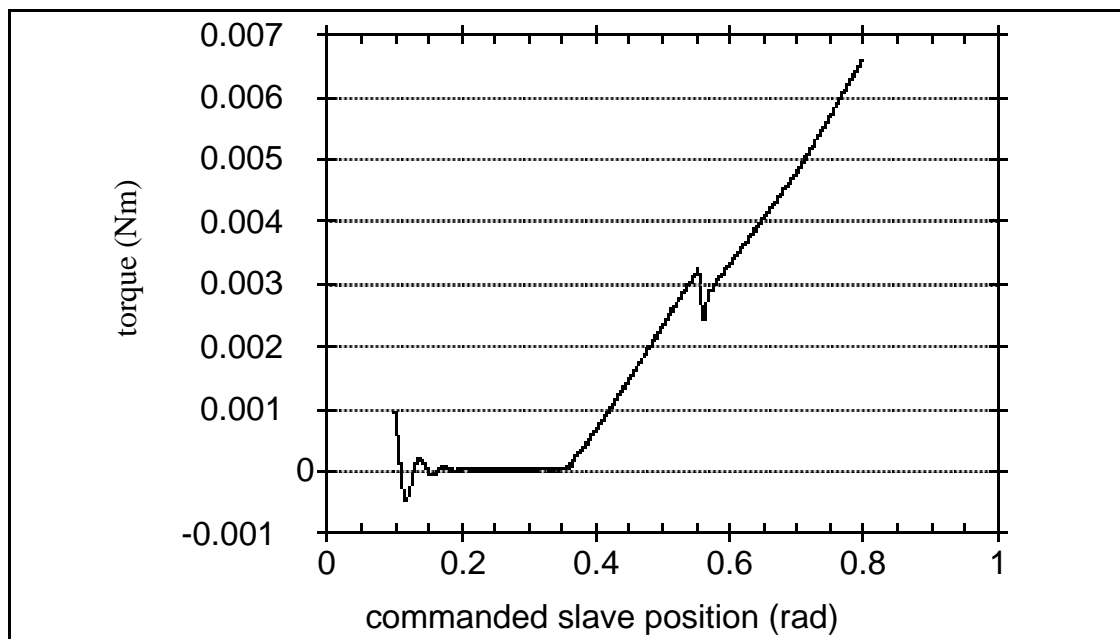


Fig. 18. Feature in the torque-position curve (commanded position is proportional to time in this plot) caused by a hypodermic needle puncturing Saran Wrap. The needle first touched the plastic membrane at about 0.36 rad.

Slave

It was decided that the device used to obtain the preliminary puncture characterization curve of Fig. 18 would be used in the bilateral setup. The slave actuator is a moving coil, permanent magnet, non-commutated rotary arm (a modified hard disk drive). This voice-coil 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 was a 25 gauge hypodermic needle attached to the end of the slave arm.

Controller

The basic controller style consisting of the open loop master commanding the position-velocity servoed slave has been chosen (Fig. 19). It behaved nicely in preliminary experiments and has no inherent restrictions on the feedforward and feedback scales.

A Micron 90 MHz Pentium machine serves as the signal-level mediator. 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 were all written in C.

The encoder-generated position signals from the master and slave were read by the encoder decoder card in the pc 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 was read by the A/D and filtered (the code for which was developed earlier [5, 6, 8, 42]). The research behind the appropriate addition of physical damping and its subsequent virtual removal for performance enhancement is discussed in other papers [18, 19]. Finally, the torque to the master and slave amplifiers was commanded via a D/A card in the computer.

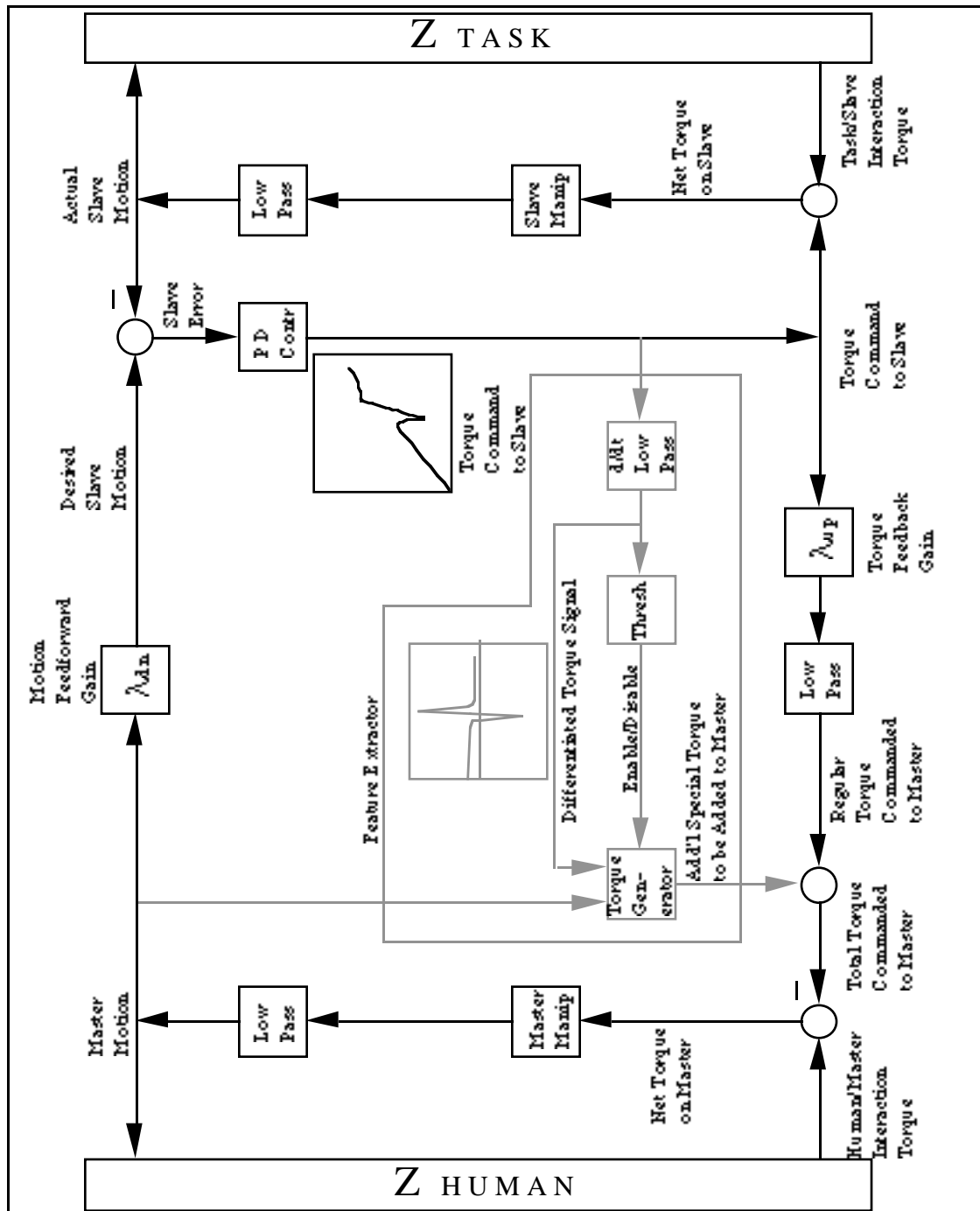


Fig. 19. Detailed block diagram of the experimental controller. The basic bilateral controller is represented by the dark print. The feature extractor is shown in light grey print.

Experimental Setup

The target consisted of two concentric plastic tubes, one just fitting inside the other. The i.d. of the inner was approximately 1.75 inches. The outer tube was clamped rigidly in a ring stand/clamp apparatus. The inner tube was covered at one end with a small piece of Reynolds brand Plastic Wrap and secured with a rubber band. The plastic was not taut, but was intentionally left unpreloaded to better model a wide range of puncturing tasks. Stretching the plastic film over the tube end results in more sudden failure of the material and hence is believed to be a less conservative model. The inner tube was slipped into the rigidly held outer tube. The end of the inner tube opposite the plastic target was accessible to the experimenter for rotating the target. The ring stand holding the concentric tube apparatus was then set up in relation to the slave so that the needle would puncture the plastic about 1/4 inch from the edge of the inner tube. In this way, a slight rotation of the inner tube about its axis of symmetry could expose a new puncture site to the hypodermic. It was possible to do on the order of 50 punctures with one target preparation.

It was found in preliminary experiments that the static friction during puncture between the plastic and the steel hypodermic needle served to naturally limit overshoot as did the rigid mounting of the needle to the slave arm. These issues were addressed by smearing general purpose cam grease on the plastic before using it as a target, and by using a flexible coupling between the needle and the slave arm. In these ways, the task of minimizing overshoot was made as difficult as possible for this model. Maximum overshoot was mechanically constrained to be 0.128 radians, or about 1/4" of needle travel

Fig. 20 schematically illustrates the physical layout of the experiment components. The experimenter was between the subject and the slave. The subject was therefore

without visual feedback of the puncture task. The subject stood at the manipulandum. The master handle was just below chest height. The subject was able to see the computer monitor by looking slightly to the right.

Feature Extraction Modes Used

Only a subset of the previously discussed feature extraction controllers were investigated experimentally. The chosen ones have been numbered for convenient reference. The intent of each of these designs can be divided into two categories: those which enhance user perception of the catastrophic event, and those which aid in the reaction to the detection. Note that the torques that arise from feature extraction are not scaled by the torque feedback gain.

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. 19) without the light grey feature extraction portion included.

The gain λ_{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.

Nine different values were assigned to the torque feedback gain λ_{up} during the course of the experiments, however the most commonly used were 1 and 3 (units of: master torque/slave torque). Rationale for these choices follows.

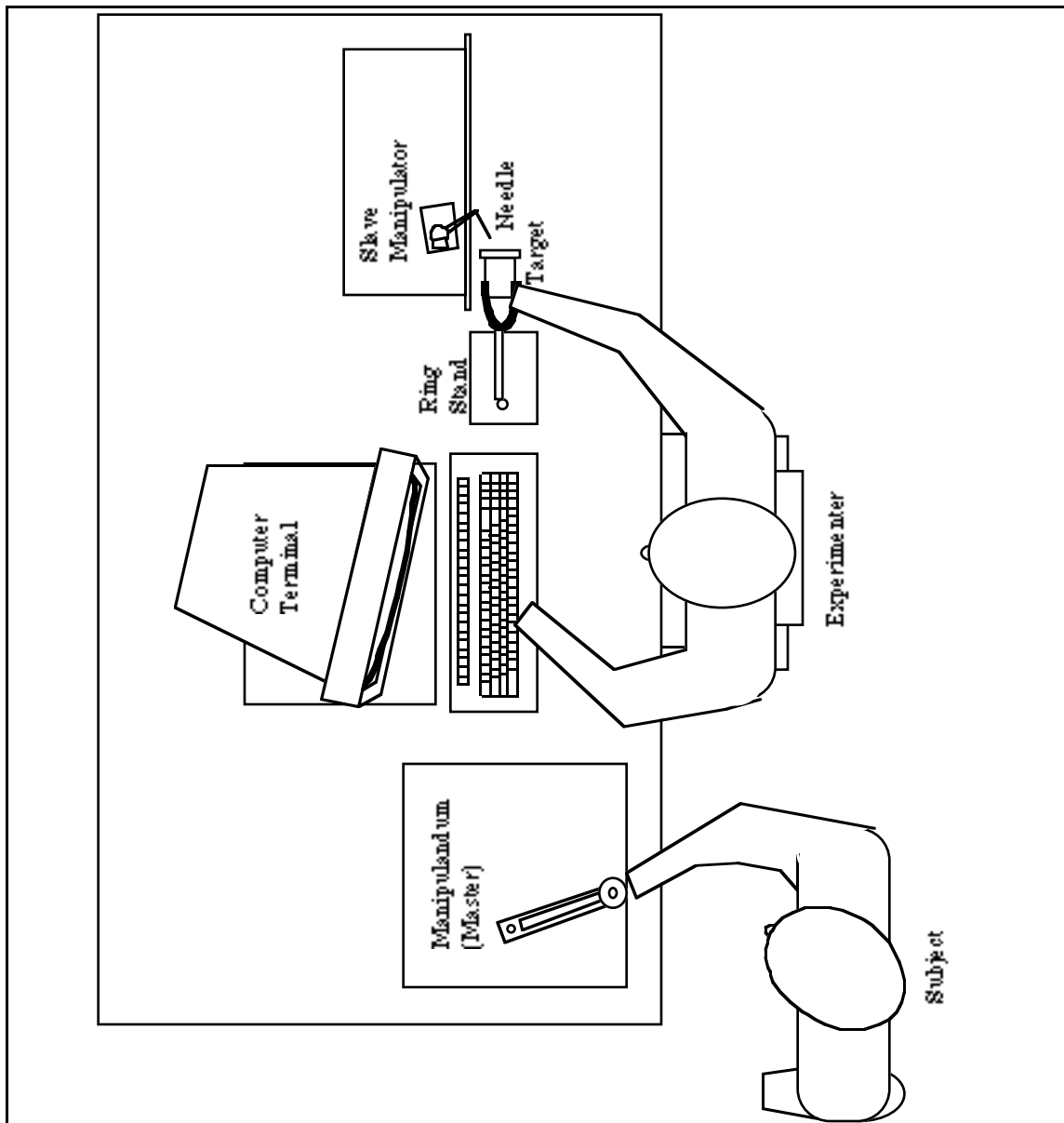


Fig. 20. Schematic of the experimental setup.

The amount of torque amplification from slave to master could have been chosen arbitrarily, but an informal set of data (taken on the experimenter) was used as a guide for finding a gain which would yield the best performance without feature extraction. It indicated that the highest achievable gain (which requires the user to apply forces on the order of several pounds to the handle to perform a puncture) yielded the poorest overshoot performance. Presumably, this is because it is difficult for a person to execute the necessary sudden reversal of a high applied force due to potential energy stored in the limb and limited active muscle bandwidth. Performance improved as the force required to puncture was reduced (by lowering the torque feedback gain) until the level where detection of puncture became the overriding problem. Performance deteriorated rapidly at extremely low gains. For the informal data set, the best performance occurred at a gain of about 3 (Master-Nm/Slave-Nm), near the low end of the range.

For the purpose of better understanding the potential advantages of enhanced detection of puncture, a gain of 1 (Master-Nm/Slave-Nm) was also chosen. The gains 1 and 3 will also be referred to as "low" and "high". This low gain, it was believed, would make the puncture harder to detect without feature extraction. The expectation was that natural recombination would enhance the detection portion of the task and lead to better performance, and that this improvement would be more dramatic with low torque feedback gain than with high. Note that the master arm is approximately 3 times as long as the slave arm when considering force scaling. A torque feedback gain of 3 (high gain) approximates a 1:1 ratio of endpoint forces. At a gain of 1 (low gain) the force at the master handle is about 1/3 of the actual puncture force. The following three modes represent the three feature extractors which were appended to the reference controller. They all threshold the differentiated slave torque signal for detecting features. The action taken varies.

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.

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 was designed to aid in reaction to puncture rather than the perception of it.

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 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.

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 was displayed on the computer screen providing immediate feedback. 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 immediate feedback as to their performance for each puncture from the computer display. Following the puncture trials, each subject was interviewed and qualitative data recorded. The whole session took approximately 1 hr/subject.

Shortcomings of the Protocol

It is impossible to isolate every variable in a human subject experiment. Some 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 quite a bit.

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 after moving from using a very heavy tool to a light tool than they would moving 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. At least 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.

The Five Experiments

The following describes the experiments in chronological order. The “standard” experiments all followed the protocol of the previous sections and were aligned with the original investigation intent of comparing feature extracting controllers to constant gain

controllers. The “auxiliary” experiments, on the other hand, were devised after the standard experiments were underway to shed light on questions that were arising.

Standard Experiment 1: Minimize Overshoot, Untimed

The first experiment involved 3 subjects whose goal was to minimize overshoot. No time limit was given.

Standard Experiment 2: Minimize Overshoot, Limited Time

In experiment 1, occasionally subjects were puncturing so slowly as to eliminate a feature altogether (15-20 seconds per puncture). To reduce the number of wasted trials in which no feature was detected and to expedite the data-taking process, the protocol was changed to have a time limit on each task. 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). Experiment 2 contains the bulk of the data that was taken and will be alternatively referred to as the “main” experiment.

Standard Experiment 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.

Auxiliary Experiment 1: Torque Feedback Gain Optimization

The decision was made to make a more formal investigation of performance as a function of torque feedback gain. The fourth group, consisting of two people, did not follow the standard 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 standard. They were asked to minimize overshoot with the time constraint of 8 seconds.

Auxiliary. Experiment 2: Automatic 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.

10. RESULTS & DISCUSSION

Autonomous Puncture

Results:

Let us begin with auxiliary experiment #2, as this data serves as a good benchmark for the best performance achievable (Fig. 21). It is considerably better than the average performance involving a human. In only one scenario did subjects do approximately as well as the autonomous performance. The data also shows the repeatability of puncture detection by the feature extractor. Note that the variability occurs in a few discrete steps about the median. These steps correspond to the distance between encoder counts on the slave.

Discussion:

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 roll 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

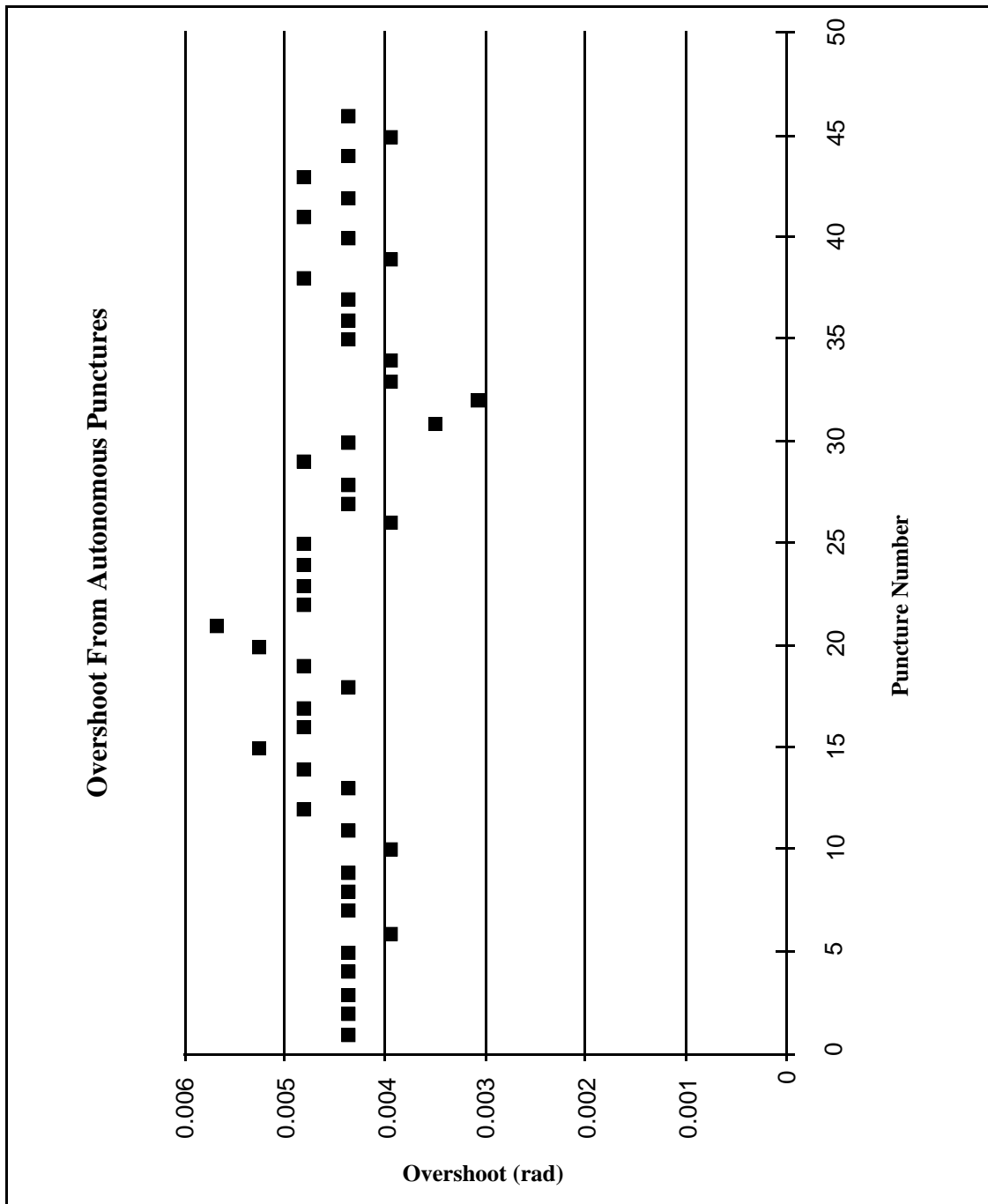


Fig. 21. Overshoot data generated by autonomous puncture tasks executed by the slave only. Discrete values are an artifact of encoder resolution.

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.

Torque Feedback Gain Optimization

Results:

The data for the torque feedback gain optimization (auxiliary experiment #1) is summarized in Fig. 22. Recall that no feature extraction was used here. Subjects used mode 0 over a large range of torque feedback gains. The plot shows a minimum (optimal performance) near the torque feedback gain of 1 (slightly different from the informal experiment described earlier which predicted 3 as the minimum).

Discussion:

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.

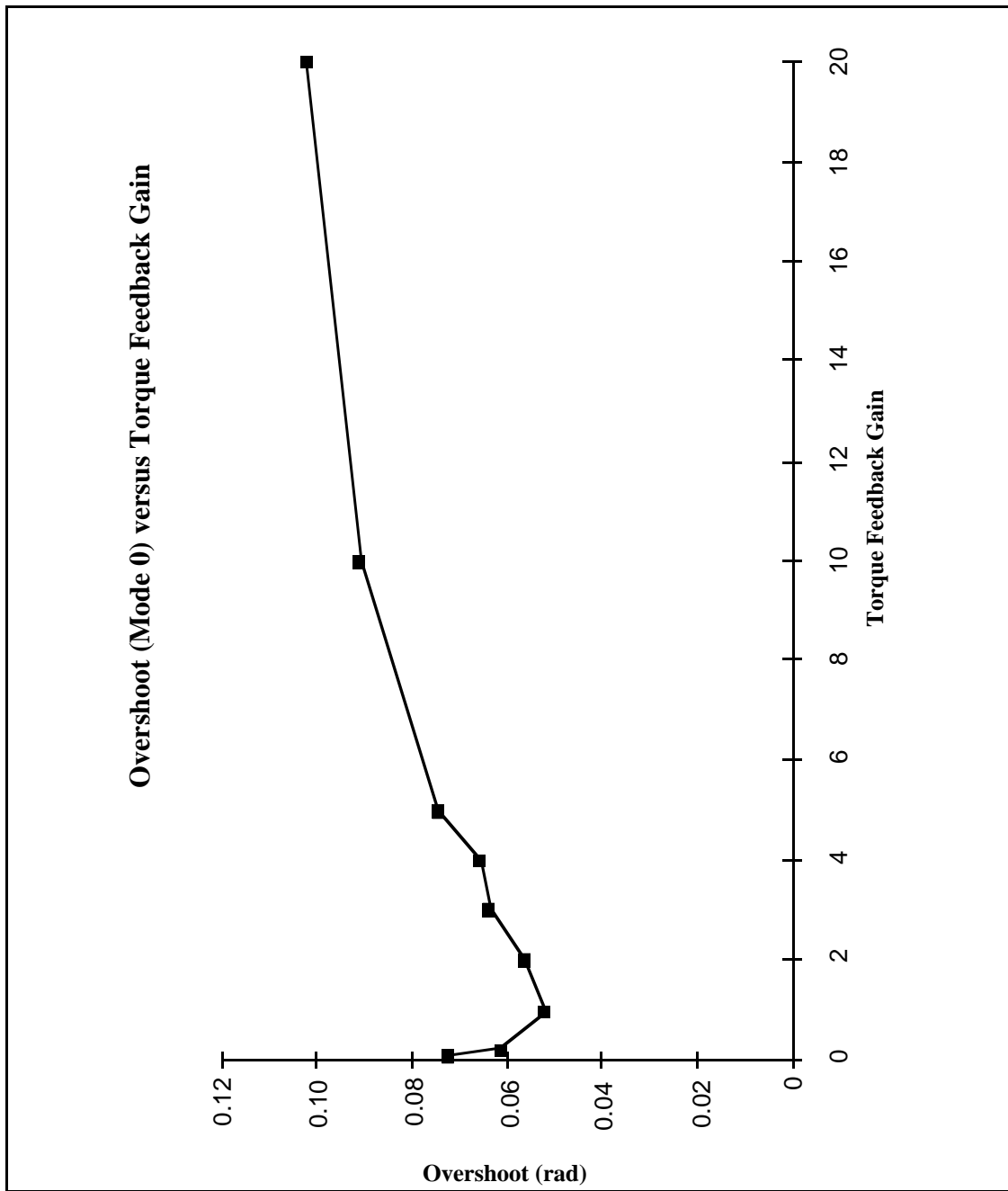


Fig. 22. Overshoot as a function of torque feedback gain with no feature extraction implemented.

Effect of Mode on Overshoot

Results:

All of the data from the standard experiments can be summarized in two plots (Fig. 23, 24). 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 (except that there exists no timing data for standard experiment #1).

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). In fact, all data showed the modes in order of increasing performance to be mode 0, mode 1, mode 3, mode 2, with only two exceptions.

The first exception is that in the main experiment (minimize overshoot, with time constraint) subjects did worse, on average, with mode 1 feature extraction than with mode 0 in the case of high torque feedback gain.

Discussion:

The most probable explanation for this is that at the high gain, the puncture was easily perceived by the subject without the aid of feature extraction. Additional emphasis of the feature did not cause improvement in overshoot performance. Furthermore, the added vibration of mode 1, designed to increase the perception of the puncture, was not only unnecessary, but detrimental. (Note that natural recombination results in both positive and negative torques being added to the "normal" feedback torque.)

Fig. 23. Overshoot as a function of controller type and torque feedback gain.

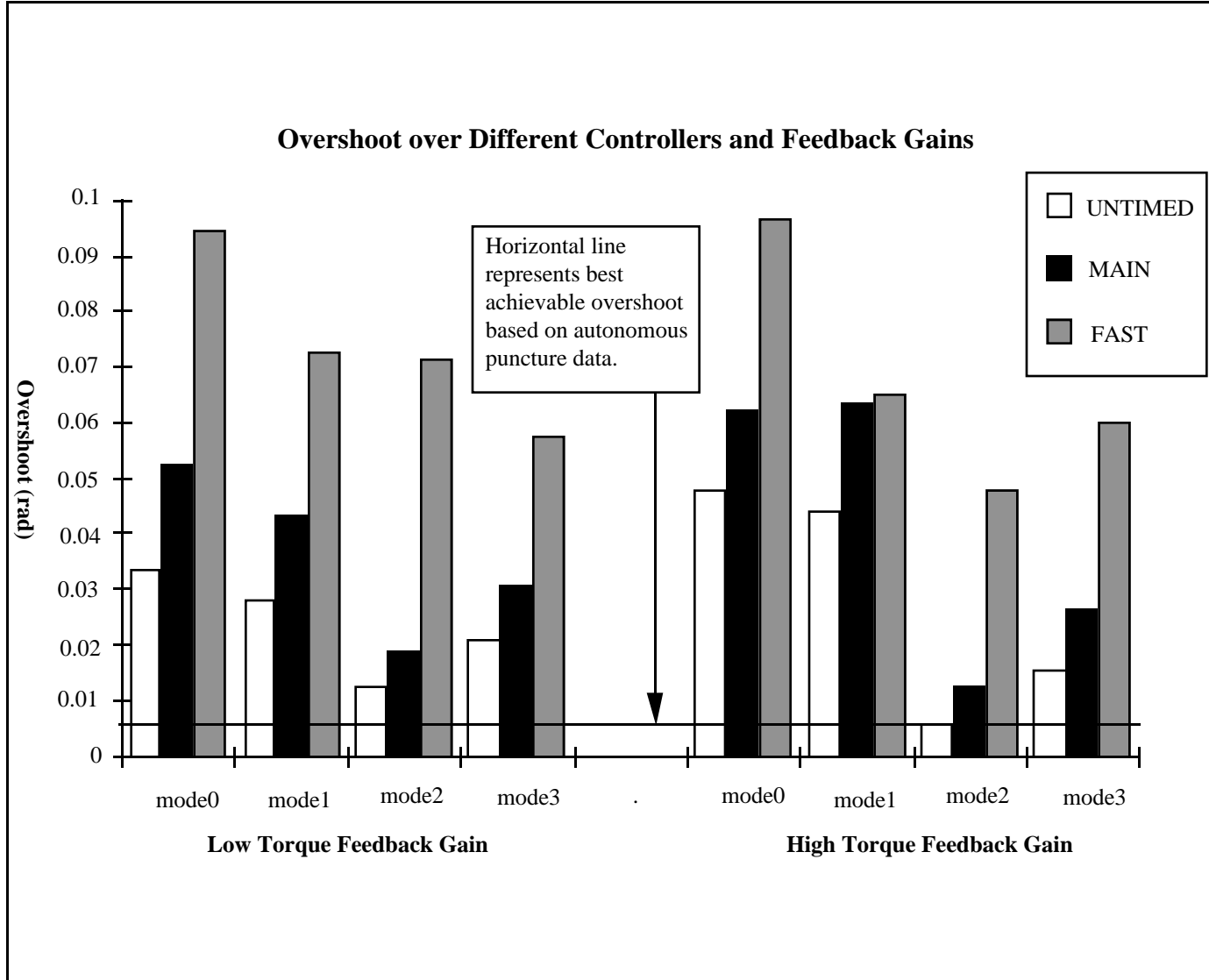
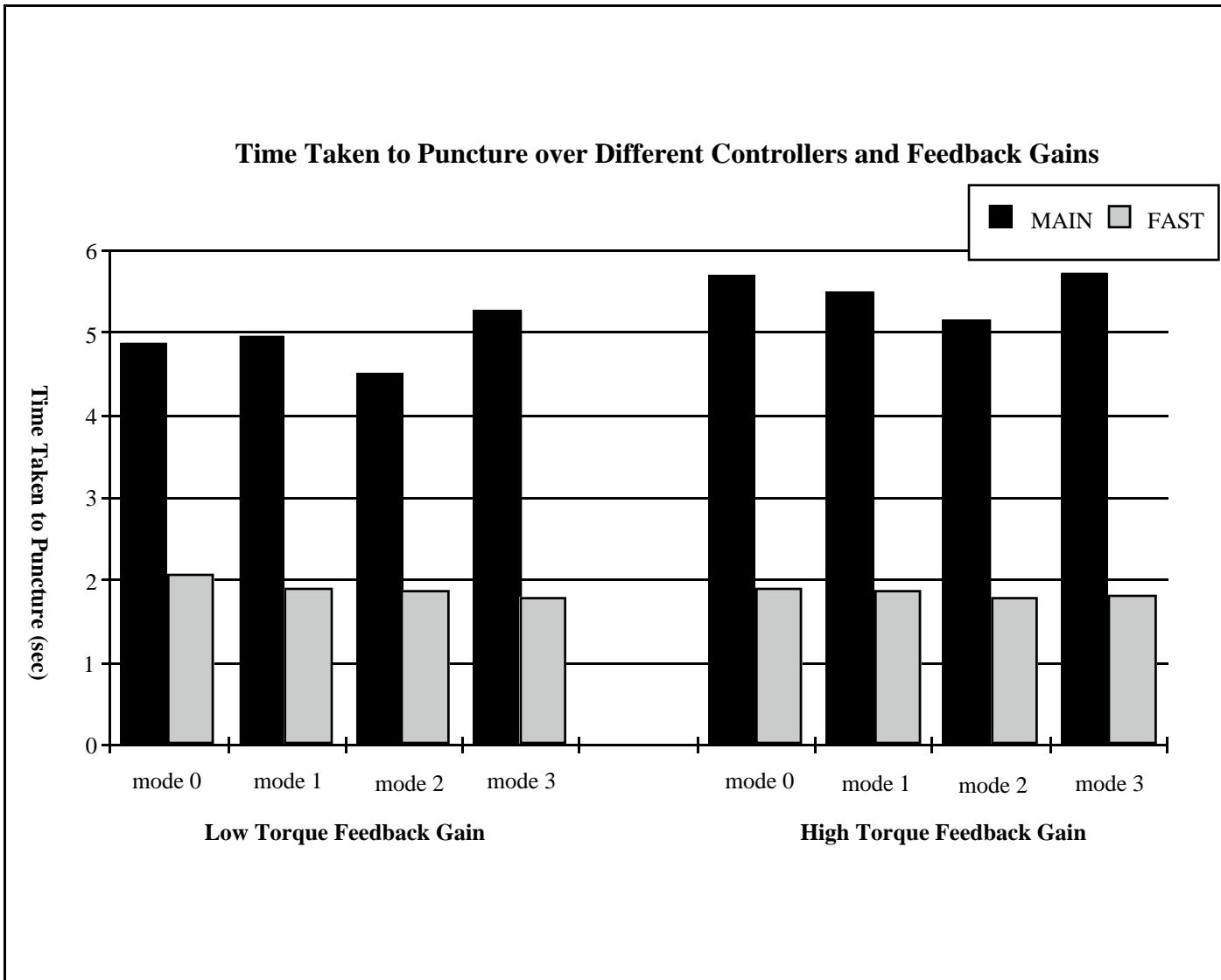


Fig. 24. Time taken to puncture as a function of the controller mode and torque feedback gain.



Results:

The second exception to the otherwise uniform trend observed in the overshoot performance data is that in the time-minimizing experiment (the bars labeled "fast" in Fig. 23), a virtual fixture (mode 3) yielded better performance than the strong retarding torque (mode 2) in the case of low torque feedback gain (in all other cases mode 2 was best).

Discussion:

A possible cause here stems from the fact that, in the time-minimization experiment, subjects were puncturing quickly and therefore hitting the target with some velocity. For low torque feedback gain, where the resistance that the subject feels from the actual puncture torque is low, the velocity of the hand was not slowed very much by the puncture. The constant torque was sufficient to give the best performance in all cases of slow puncture, but not when the subject was motivated to attain high momenta, where the constant torque became a smaller percentage of the torque required to stop the handle and subject's arm. In contrast, the virtual wall resulted in a retarding torque that rose sharply as the wall was entered and therefore became the best performer.

Results:

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. According to the statistics text used [4], 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 provided a measurable improvement in performance over mode 0.

Effect of Mode on Timing

Results:

Timing data gives an indication of how much attention each controller required for successful completion of the task (refer back to Fig. 24). 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.

Discussion:

Once again, we see that, in the high momentum cases (time optimization experiment), the advantage of the constant retarding torque disappears. This suggests a potential improvement to mode 2 for the bilateral manipulator designer of making the level of torque added after puncture dependent on the velocity of the slave at the time of puncture.

Effect of Torque Feedback Gain on Overshoot

Results:

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. 25).

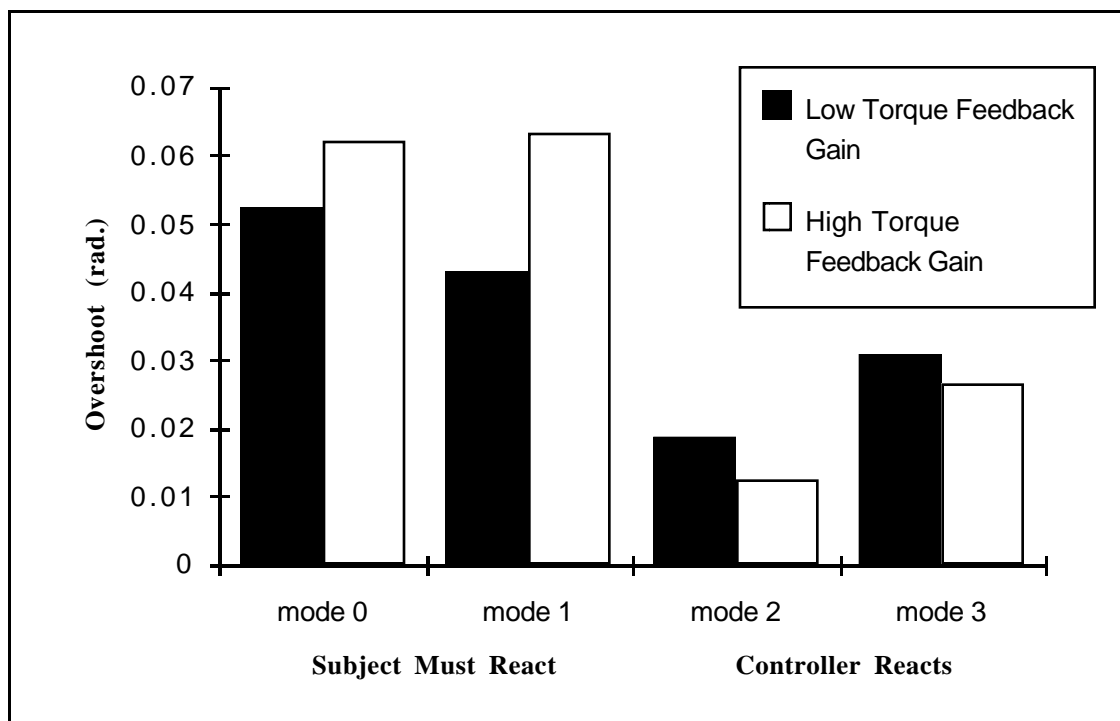


Fig. 25. Shows that higher torque feedback gain is detrimental where the subject must react to the feature, and beneficial where the controller is chiefly responsible for the reaction to the feature. Data is from experiment #2 (main experiment).

Discussion:

When the subject must stop the needle advance, the overriding detriment to performance is high potential energy in the arm (which comes with high torque feedback gain). When the controller contributes most of the retarding torque, high feedback gain appears to be advantageous. The reason for this effect is not well understood. It could be that the increased feedback gain provides the benefit of higher puncture torque which, in turn, acts to retard needle advance. The needle momentum for the punctures of the main experiment were small, however, making this a questionable explanation.

Effect of Torque Feedback Gain on Timing*Results:*

Time taken to puncture was consistently greater for high torque feedback gain during the main experiment (refer back to Fig. 24). In the speed experiment, however, there is little statistically significant difference from one gain to the other.

11. ADDITIONAL DISCUSSION

Perceiving and Reacting

For our purposes, perception requires that a signal resulting from the catastrophe 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?

First, 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.

Secondly, 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 significantly affect 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. (Work regarding stability criteria for multiple degree-of-freedom systems in contact with constraining environments appears in [14]). This is 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.

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 [51]. Such a system could accommodate differences in personal preference and personality and is heartily endorsed.

12. SUMMARY OF PART II

An augmentation of bilateral controllers has been set forth as beneficial for catastrophic tasks. This augmentation exploits the traversal of impedance boundaries (features) in assisting the user toward successful task completion. Several basic controller platforms, two styles of feature detection, and several modes of assistance have been suggested and discussed. In a set of human subject experiments, impedance boundaries were detected by temporal differentiation and thresholding of the torque commanded to the slave manipulator. The basic controller consisted of a position/velocity servoed slave and open loop master. Assistance was given in three forms and performance compared with the non-feature-extracting reference controller as the bilateral manipulator was applied to a puncture task with a variety of constraints. In addition, an exploration was made of reference controller performance as one parameter, the torque feedback gain, was varied.

This bilateral controller implementation was able to respond much more quickly to features than could the operator. All three forms of assistance resulted in improved performance in nearly all scenarios. The most beneficial was mode 2 (constant torque packet) in most cases, followed by mode 3 (virtual wall), and finally mode 1 (perception enhancement).

When feature extraction is not implemented, there is an optimal torque feedback gain for catastrophic task performance. It is believed that, below the optimal gain, the catastrophe is too difficult for the human to perceive, and above it the potential energy

stored in the user's limb and the limited active bandwidth of muscular actuation combine to reduce the human's ability to react to the catastrophe.

Mode 1: As hypothesized, 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 nicest 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. It may be less useful than a perception aid for tasks where trajectory is naturally constrained after the feature of interest such as in placing a wrench on a fastener and tightening it.

13. SUGGESTED FURTHER INVESTIGATION

Alternative Forms of Feature Detection

Spatial differentiation of the torque (presented earlier in this dissertation) is more closely related to impedance change than the temporal differentiation used, and could result in more pronounced features, a definite advantage for situations with poor signal-to-noise ratio for feature extraction. It would be interesting to see if spatial differentiation of the slave torque would yield more robust feature extraction.

Image Processing Techniques

It is also possible that techniques from image processing such as edge detection will offer yet other feature extractors. So far they have not yielded any usable ideas as the techniques surveyed to this point operate on fields of existing data, not on data gathered in real time.

Poor Signal-To-Noise Ratio

Before the application of feature extraction to real tools, it will be necessary to design tests for poor signal-to-noise ratio situations where the feature is a torque change on the order of those that result from the noise in the system (sensor noise, slave bearing stiction, etc.).

Non-Catastrophic Tasks

If this work is applied to the micropuncture described in Part I, it is likely that something other than a mechanical impedance boundary will be used as the feature, since micropuncture may not qualify as a catastrophic task. If the pressure differential from the outside to the inside of a vessel, for example, were used to detect puncture, then the perception cue would be completely synthesized. Some of what has been presented in this work can apply to non-catastrophic tasks provided that there is a substitute for the mechanical feature.

Gain Modulation

One of the discussed programmable effects of feature extraction was gain modulation. This can be divided into three sub-categories: changing the motion feedforward gain; changing the torque feedback gain; or adjusting the stiffness of the slave which in turn changes the stiffness of the whole bilateral manipulator. There are many potential advantages hiding in this one technique which has not been explored.

It has been suggested, for example, that the poorer reaction capabilities of the human may be compensated for by adjustment of the motion feedforward gain λ_{dn} . Consider the case of the puncture task again. The reaction time of the operator (that is the time between puncture detection and reversal of the needle direction) is not a function of the controller, but depends solely on the operator. However, the overshoot that occurs during that time (assuming no reaction aid has been implemented) does depend on the controller, particularly on the λ_{dn} . By lowering the motion feedforward gain to a small fraction, the amount of overshoot at the needle would be reduced because the master handle overshoot would then map to a smaller needle overshoot. In other words, lowering λ_{dn} gives the

operator a greater arclength in which to react and still achieve the same overshoot. The tradeoff to be dealt with is that navigation through a comparatively large workspace could be tiresome as it would require a great deal of master movement. Investigation of this would be an interesting extension of this work.

14. CONCLUDING COMMENTS

As the area of bilateral manipulation expands, it will be interesting to see what level of modularity and portability is attained. This work was an attempt to head in that direction by developing tools which could be applied to any bilateral controller. Success was partial, in that the feature extraction worked consistently and offered significant improvement in successful task completion, but still has an element of dependence on the torque feedback gain chosen, limiting its portability. Nevertheless, the ideas presented have the potential of contributing to the development of useful bilateral manipulators. The hope is that, in the not too distant future, knowledge of the inner workings of such a tool will not be a prerequisite for successful application.

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