1990-12

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https://hdl.handle.net/10945/29689

Report Number: NPS69-90-06

NAVAL POSTGRADUATE SCHOOL

Monterey, California

ADAPTIVE CONTROL OF DIRECT DRIVE DEXTEROUS ROBOTIC HAND WITH BILATERAL TACTILE SENSING

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DECEMBER 1990

Final report for period 9/20/89 - 9/30/90

Approved for public release; distribution unlimited

Prepared for:

Naval Ocean Systems Center, Adaptive Systems Branch
ailua, HI 96734

NAVAL POSTGRADUATE SCHOOL
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This report was prepared by:

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1a REPORT SECURITY CLASSIFICATION: Unclassified
1b RESTRICTIVE MARKINGS:
2a SECURITY CLASSIFICATION AUTHORITY:
2b DECLASSIFICATION / DOWNGRADING SCHEDULE:
3 DISTRIBUTION / AVAILABILITY OF REPORT:
4 PERFORMING ORGANIZATION REPORT NUMBER(S): NPS69-90-06
5 MONITORING ORGANIZATION REPORT NUMBER(S):
6a NAME OF PERFORMING ORGANIZATION: Naval Postgraduate School
6b OFFICE SYMBOL *(If applicable)*:
7a NAME OF MONITORING ORGANIZATION: Naval Ocean Systems Center
6c ADDRESS *(City, State, and ZIP Code)*: Monterey CA 93943
7b ADDRESS *(City, State, and ZIP Code)*: Kailua, HI 96734
8a NAME OF FUNDING / SPONSORING ORGANIZATION: Naval Postgraduate School
8b OFFICE SYMBOL *(If applicable)*: ME
9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: O&MN, Direct Funding
8c ADDRESS *(City, State, and ZIP Code)*: Monterey, CA 93943
10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO

11 TITLE *(Include Security Classification)*: Adaptive Control of Direct Drive Dexterous Robotic Hand with Bilateral Tactile Sensing
12 PERSONAL AUTHOR(S): Morris R. Driels
13a TYPE OF REPORT: Final
13b TIME COVERED: FROM 9/20/89 TO 9/30/90
14 DATE OF REPORT *(Year, Month, Day)*: 90/12/19
15 PAGE COUNT:
16 SUPPLEMENTARY NOTATION:

17 COSATI CODES

FIELD	GROUP	SUB-GROUP

18 SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*: Robot hands, haptics, sensing,teleoperation

19 ABSTRACT *(Continue on reverse if necessary and identify by block number)*

The work addresses the problem of identifying objects using a remote teleoperator. The application of the research is part of the development of demonstration technologies for the next generation of ROV's currently under development by the US Navy. Two related research issues are developed. The first deals with determining how a teleoperator would remotely probe an unidentifed object, and attempt to determine what the object is based only of force feedback through the teleoperator mechanism. Haptic models are tested against experimental data. The second issue addressed is the design of a dexterous, direct drive end effector for use on a teleoperator system. Results concerning the mechanic design of a small scale mechanical hand are discussed.

20 DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS
21 ABSTRACT SECURITY CLASSIFICATION: Unclassified
22a NAME OF RESPONSIBLE INDIVIDUAL: Morris R. Driels
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22c OFFICE SYMBOL: ME/Dr

DD Form 1473, JUN 86 *Previous editions are obsolete* SECURITY CLASSIFICATION OF THIS PAGE

S/N 0102-LF-014-6603

Introduction

This research area is intended to contribute towards the development of the next generation of remotely operated vehicles (ROV's) currently under development by the US Navy. A concept for one such design is shown in figure 1. In these vehicles, the operator does not operate traditional controls (switches, joysticks, levers) in order to operate the vehicle, but experiences complete visual, auditory, force, and touch feedback directly from the remote environment in which the vehicle is operating. If the fidelity of the sensory feedback is high enough, the operator experiences 'telepresence' or 'virtual reality', a state in which the operation of the vehicle become more natural to the operator, thereby reducing operation time and increasing task effectiveness.

It is known that many, if not most, diving operations are conducted in conditions of little or no visibility, and human divers accomplish much of their work based on what they can feel rather than what they can see. It follows that if the ROV has to operate in similar conditions, we need to know how this blind touch probing would be perceived by the operator on the surface, and what strategies would be employed in order to accomplish certain tasks. It is in this area of probing by means of touch, commonly called haptic probing, that the PI is involved.

This final report covers research into several aspects of haptic sensing, and in particular, investigations of the way the haptic system may be used in conjunction with a teleoperator system to identify remote objects. The work proceeded in two main directions. Firstly, experimental data obtained by the PI while working as an ONR Fellow at NOSC was analysed, and several hypotheses regarding the mechanics of human haptic probing were evaluated. In the second area, the design of a multi-degree of freedom mechanical hand is undertaken. Such a device will be required to achieve the necessary dexterity expected of a system capable of achieving telepresence on the part of the operator.

Haptic Probing

In the summer of 1989, the PI had the oportunity to work with the Adaptive Systems Branch, NOSC in order to begin preliminary work in this area. The branch had a CRL force reflecting telemanipulator (see fig 2) on which experiments were performed. In the ten weeks allocated to the fellowship, only preliminary experimental procedures could be designed and executed. In the fall of 1989 the PI researched some of the physiological background to this subject and proposed simple models for the operation of the human haptic system when used in conjunction with a bi-lateral force reflecting telemanipulator. These findings have been written up in one conference paper (appendix A) and one journal paper (appendix B), currently accepted for publication, though not yet in print.

In order to continue this research, a CRL manipulator has been purchased and will be delivered in December 1990 to NPS. This will allow further extensive testing of hypotheses on haptic probing in conjunction with telemanipulator devices. It is expected that this work will lead to a basic understanding of the mechanics of haptic probing and object recognition, and the development of computer assisted aids to enhance operator recognition.

End-Effector Design

Figure 1 shows that the remote robot arm is fitted with a human-like (anthropomorphic) end effector capable of manipulating hand and power tools. Although such devices exist in the laboratory, their mechanical design is somewhat complex due in part to the remote actuation of the finger joints by means of tendons. This leads to frequent failures in heavy use of the hand. The PI has developed a novel approach to the design of such hands in which the actuator, consisting of a miniature DC motor and gearbox, is built directly into the finger unit itself. A prototype finger based on this design is shown in figure 3. Part of the project was to further develop the design of this end effector to decrease the size shown in figure 3 to one which approaches that of the human hand.

Commercial gearmotors were identified for this task and a prototype finger joint was constructed. This reduced the size from about 3 x human size to approximatly 1.5 x human size. Appendix 3 includes some of the drawings on which the new design is based.

Unfortunatly, work in this area had to be suspended until FY1990 due to the redirection of funds towards the purchase of the CRL telemanipulator mentioned previously. Work has re-started on this topic with a graduate student investigating the control system for the finger unit.

Conclusions

Good progress has been made in both the areas described, although it has taken a year to establish a laboratory facility in which the work can be performed. With the delivery of the CRL arm imminent, and several graduate students interested in many aspects of the research, progress is expected to continue in 1991.

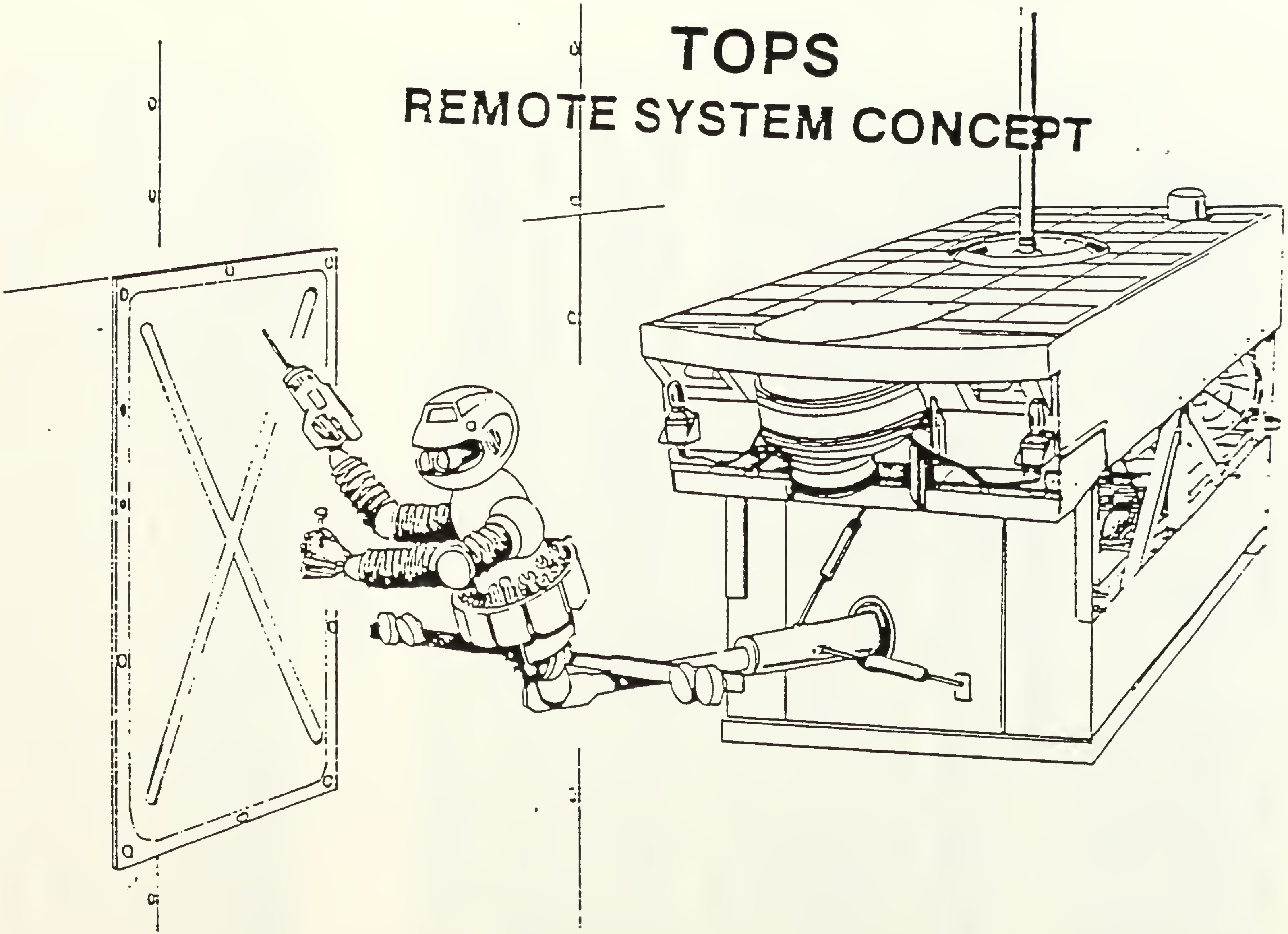

Figure 1.

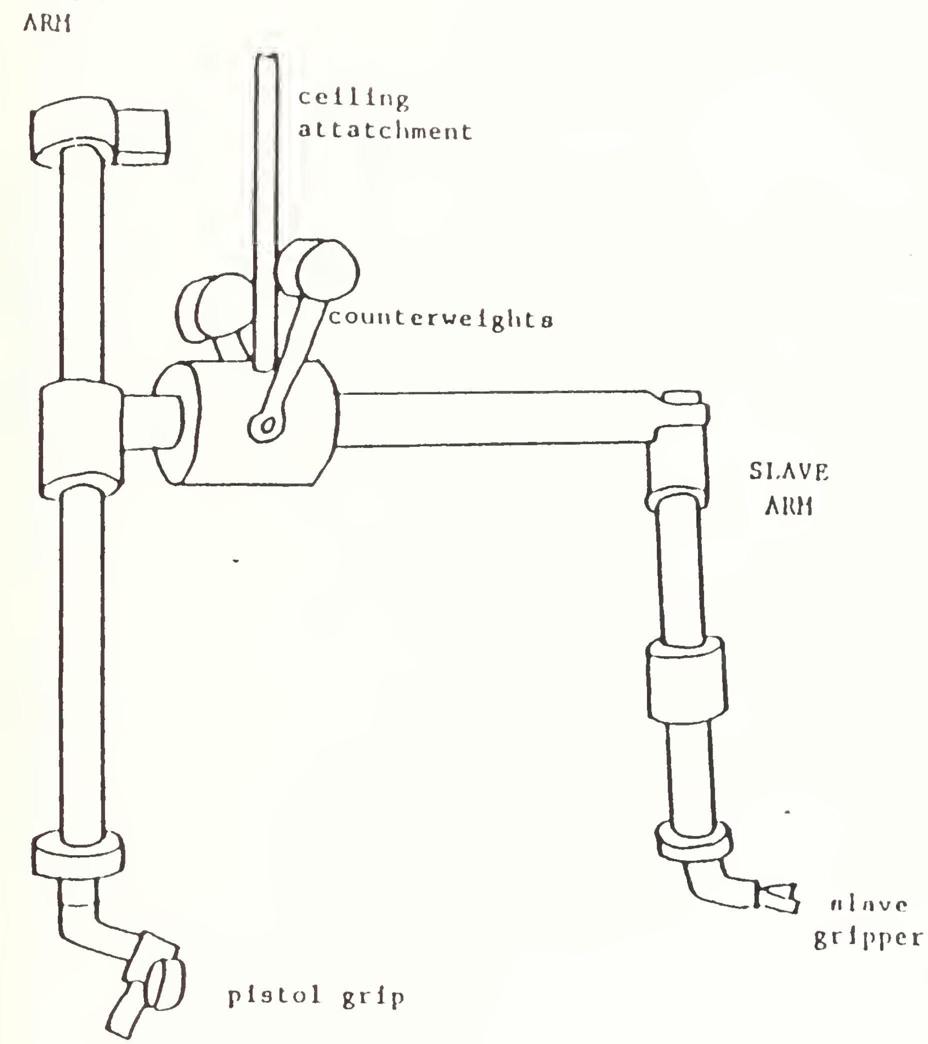

FIGURE 2 FORCE REFLECTING TELEMANIPULATOR

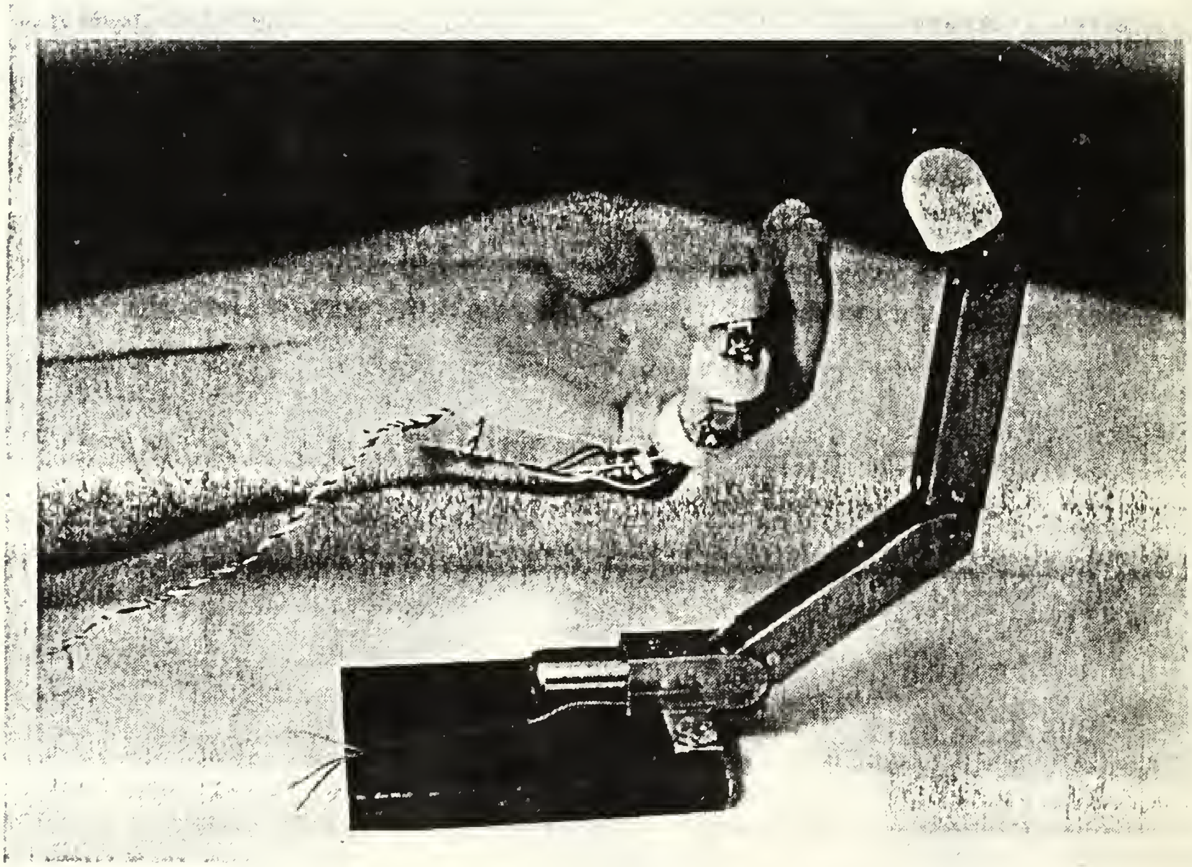

Figure 3: Prototype Finger and Teleoperator

APPENDIX A

Ergonomics of Hybrid Automated Systems II
W. Karwowski and M. Rahimi (Editors)

HAPTIC RECOGNITION THROUGH REMOTE TELEOPERATION

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Abstract

In this work, we are concerned with the role that the haptic system plays in teleoperation i.e. the exploration and manipulation of objects by a human operator using a remote robot arm. The approach is to incrementaly enhance the remote touch-sensing capability beyond kinesthetic force feedback to include contact data and local re-perception and compare the time to identify quasi-two dimensional objects with that of a directly held probe. Results obtained indicated that friction between the remote probe and the environment made the feedback signal "noisy" leading to conflicting and inaccurate hypotheses by the operators. Sensory feedback improved the signal to noise ratio giving performance levels approaching those of direct, as opposed to remote, probing.

Introduction

In this paper we are interested not so much in direct manipulation of objects, but in remote manipulation using a mechanical teleoperation device. The placement of a telemanipulator between the operator and the task to be performed acts as a kind of filter to many kinds of sensory feedback, including touch, and in most cases degrades the operator's ability to accomplish tasks that would be quite simple if performed directly. Nevertheless, the study of telemanipulative tasks is of considerable interest since this is a common way of separating humans from hazardous environments.

Contemporary telemanipulation facilities usually contain many sensory feedback paths to assist the operator in the accomplishment of some task. The manipulator itself may have force-feedback capability allowing the operator to sense the presence of an obstacle or constraint. Force feedback is usually of the terminus type, as shown in Figure 1, where only end-point forces at the control handle are felt, although some manipulators implement anthropomorphic feedback in which shoulder, elbow, wrist, hand and finger forces are sensed through an exo-skeletal structure worn by the operator. Visual feedback is obviously important, and this may be accomplished either directly through a viewing window, or by using a camera and video display for more remote applications. Audio and touch feedback are also significant contributors to performance and are complimentary in many ways, since sound produced by tapping an object provides confirmation of contact in the absence of direct touch sensing by the remote probe. For the work reported here, particular attention is focussed on the sense of touch. The reason for this is, firstly, that many fine motion manipulations, such as assembling an electrical connector, utilize touch feedback more than any other sense, and secondly there are many operational tasks where visual feedback is either impaired or totally absent. It is known, for example, [1] that underwater divers rely more on what they can feel rather than what they can see, particularly in turbid water. Discussion of the sense of touch introduces the concept of haptics, which recently has been used to imply greater meaning than Gibson's [2] "purposive touch" contained in his original definition. We define the haptic system to comprise many parts including:

Figure 1: Operator Handle on Terminus Tele-Manipulator

1. Tactile (localised) sensing of fine features
2. Proprioceptive (kinesthetic) sensing of coarse position
3. Other sensing systems such as temperature and pain
4. A two-way communication channel between the central nervous system and the brain
5. Perception processes to formulate hypotheses about the environment
6. Motor control mechanisms to re-distribute the primary sensor systems

Previous work in this area has concluded that although the haptic system may be used to recognize three dimensional objects both accurately and quickly, two dimensional object recognition is accomplished less successfully. In the tests reported by Lederman, Klatzky and Barber [4], raised two dimensional profiles were traced and recognition was attempted, resulting in poor performance. In other work on three dimensional object recognition reported by Klatzky, Lederman and Metzger [3] blindfolded subjects were allowed to pick up one of a set of 100 common objects and attempt recognition. In these tests, good results were obtained with only 4% of the tests resulting in mis-classification. Lederman, Klatzky and Bajcsy [4] report other published work which supports their conclusions that the haptic system is poorer at recognizing two dimensional shapes compared to its abilities regarding three dimensional objects.

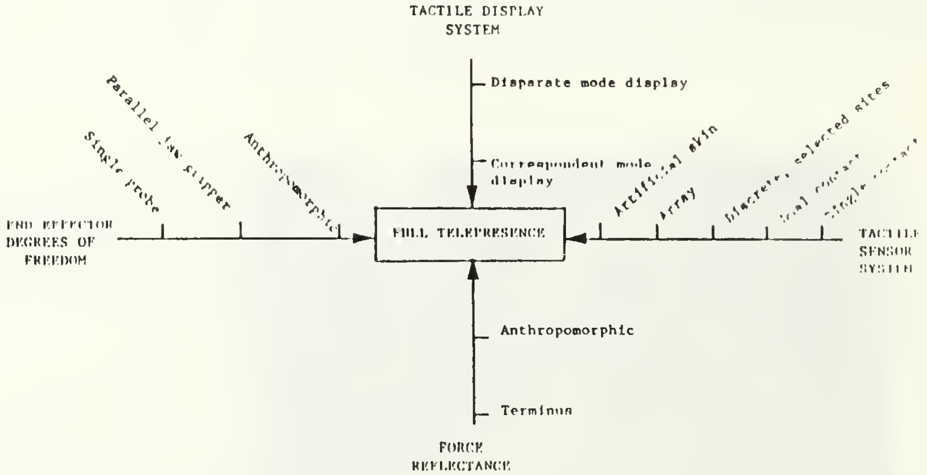

Figure 2: Independent Variables of Haptic Perception

In the work reported here, we have investigated further the abilities of the haptic system to explore and recognize essentialy two dimensional shapes using a telemanipulator.In addressing the problem of emulating the human haptic system in machines, much attention has been focussed on the area of tactile sensing. Machine haptics obviously has contributions from a much larger collection of components than just sensing. By considering the current status of teleoperation, and the efforts to improve this status so that the operator actually feels as though he or she is in the remote workplace (telepresence), some of the other mechanisms which impact teleoperator performance can be identified. Our research has identified four such mechanisms, which we propose to define as haptic variables. They directly influence the ability of teleoperators to perform complex tasks. These haptic variables are (1) tactile sensing (2) tactile display (3) force reflectance and (4) end effector dexterity. Although these mechanisms are also present in the human haptic system, they are less variable for the purposes of experimentation. These independent variables are represented in Figure 2, which also indicates examples of discrete componenents of each technology beginning with the most simple in the periphery of the diagram and increasing in complexity towards the center, which is the goal of full telepresence. A system comprising components located near the center of the diagram would be expected to have capabilities approaching those of the human hand. Note that for mechanical teleoperator systems with man in the loop control, the definition of haptic variables is consistent with the definition of the components of the haptic system given earlier, since the human operator provides the information transmission, cognitive and motor control functions directly through the manipulator.

Method

The objective behind the experimental work reported in this section is to investigate object recognition through remote haptic probing alone, and to determine which haptic variables will produce the most significant improvement in performance. In selecting the object set that operators would be asked to identify, it was decided to use wooden letters of

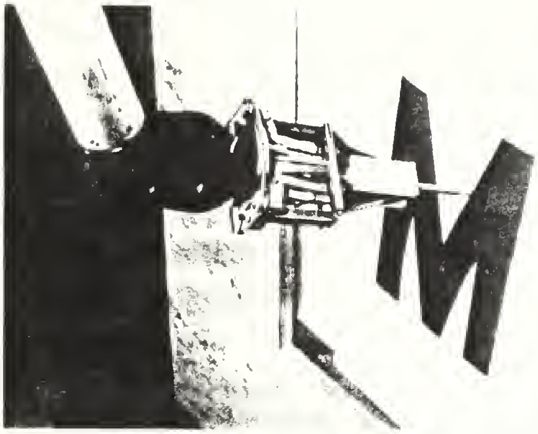

Figure 3: Remote Tele-Manipulator Probe

the alphabet about six inches tall and one inch thick. For each trial, a letter was selected at random from the set of 26 and attached in a random orientation to a metal taskboard. The manipulator used was a CRL force reflecting unit of the terminus type, which means that only forces at the controller handle are sensed. Force reflection is achieved mechanically through antagonistic cables operating each degree of freedom of the manipulator. The remote probe consisted of a 1/4 inch diameter steel tube about 6 inches long. Figure 3 shows the manipulator probing a test character. The operator handle is constructed in the form of a pistol-type grip (see figure 1). For all tests operators wore earplugs and headphones connected to a pink noise source so that all audible cues were masked. The operator was prevented from directly viewing the taskboard and remote probe by a curtain.

A total of three operators were used in each of four experiments. For each experiment, some twenty trials were performed . Although each operator had prior experience using the teleoperator system, the trials for each of the experiments were performed in a random sequence to equalize the effects of increasing familiarity with the equipment over the course of the experiment. The four experiments all involved the recognition of a randomly selected, randomly oriented letter of the alphabet, but differed in the sensory feedback provided to the operator during his probing. The specific conditions relating to each experiment were as follows.

Experiment 1:	Force feedback only, audio and visual masking.
Experiment 2:	As above but with edge contact feedback.
Experiment 3:	Same as Experiment 1, but with observation of hand controller movement permitted.
Experiment 4:	No telemanipulator, tracing using hand held probe

Experiment 2 allowed the operator to observe when the remote probe was in contact with the edge of the letter. To achieve this, each wooden letter had aluminum foil tape wrapped

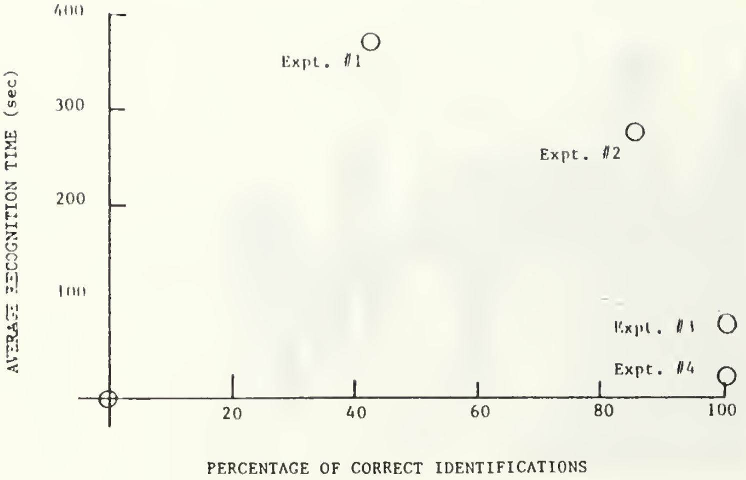

Figure 4: Experimental Results

around the edge, and a battery connected to it. The other battery terminal was connected to the remote probe so that when the probe was in contact with the edge of the letter a circuit was completed and a small light emitting diode (LED) was illuminated. The LED was placed into a small hole drilled into the mask worn by the operator so that edge contact confirmation was made available to him directly in front of his right eye. Prior to each test session, the operator was allowed to view a copy of the font used for the characters so that subtle differences could be observed, such as the difference between an M and inverted W, or an N and a Z. Operators were asked to provide a running commentary of what they thought was happening during the test. Operator comments and remote probe activity were recorded onto the same video tape. The operator was instructed to emphasize accuracy of identification rather than speed, and to make a clear identification at the conclusion of the probing. Operators were told if they made an incorrect identification, and the test continued. A time limit of ten minutes for recognition of a single letter was enforced, and the number of trials resulting in non-identification after this period was recorded. A second performance measure was the elapsed time required for correct identification, which was then averaged over all trials for the experiment.

Results

The results are shown in Figure 4 which indicates both the average time for character identification and the number of times identification was not possible within the permitted time period.

Discussion

The results of Experiment 1, together with the commentary provided by operators for the cases where no successful identification was achieved, provide insight into the process of teleoperation, and how performance may be enhanced. The main ambiguity observed by operators was the inability to distinguish contact forces between the probe and the letter from frictional forces between the probe and the taskboard. This was observed during the tests when the probe appeared to be following an edge quite accurately, but when a corner occurred, the probe continued to move in a straight line along the taskboard, constrained only by the end-point frictional forces. The operator was unaware of the situation until the length of the perceived edge became larger than his *a priori* expectations about the longest real edge, and a re-exploration of the taskboard occurred. This leads to the concept of a signal to noise ratio for haptic data where the signal in this case is the probe letter contact force and the noise is the probe taskboard frictional force. In situations such as Experiment 1 where the signal is relatively small compared to the noise, many ambiguities arise making the identification of simple primitives such as edges or corners difficult. Frequently, even contact itself was incorrectly assumed to have occurred and haptic probing took place totally in the presence of noise only.

The generation of end-point frictional forces at the probe is closely linked to the levels of internal frictional forces within the telemanipulator itself, as indicated by the following example. Suppose the control handle can be moved in any direction in space, but to cause such movement a static frictional force of say 5N has to be overcome. No obstacle in the path of the remote probe can be detected until a force greater than 5N is exerted. If one considers the general strategy of probing a letter, the operator attempts to conceptualize the location and orientation of the taskboard and then tries to move the probe lightly over the board until contact with the letter is made. Then, still minimizing the contact force between the probe and the taskboard, the probe is traced around the letter building up individual primitives into features and spatially mapping them into a recognizable object. Light contact with the taskboard is required to minimize the generation of end point frictional forces thereby increasing the signal to noise ratio during the probing phase. The internal friction of the manipulator however determines the magnitude of the friction force at the probe tip through the equation of static friction:

$$F = \mu R$$

where F is the frictional force along the plane of the taskboard, μ is the coefficient of static friction for the pair of materials comprising the task board and probe, and R is the force applied normal to the task board by the operator. If P is the internal static frictional force of the manipulator in a direction normal to the task board, it can be seen that

$$F > \mu P$$

Higher internal frictional forces therefore require larger contact forces in order to distinguish end point friction from object contact, and the search is characterised by clumsy, sometimes sudden movements when the probe leaves the object. Large excursions of the probe inhibit accurate relocation on the object and generally degrade the spatial mapping of primitives already identified.

Lower frictional forces allow delicate probing to take place, small, subtle features to be identified, and a general decoupling of the end point and contact forces. Object contact sensing seemed more dependent on the rate at which force was detected rather than the absolute level of force itself. Operators used this effect to detect objects by tapping the edge of the object with the probe. Although the sound of tapping could not be heard by the operator, the mechanical coupling of the probe and control handle had sufficient high frequency bandwidth to pass impulsive components of force to the control handle. This has significant implications for teleoperated systems connected electrically, rather than mechanically, since high bandwidth transmission over substantial distances may be more difficult to achieve. Experiment 1 indicates that due to the relatively high level of friction present in the telemanipulator, ambiguities due to end point friction had a significant effect on performance, resulting in only 40% of the trials ending in success. In those that failed, operators reported little idea of what the letter might be and that further probing probably would not have aided in recognition. This situation represents standard telemanipulator tasks in a frictional environment, with an average recognition time for the task of 390 seconds. Two mechanisms were tested as potential aids to object recognition. In the first of these, Experiment 2, object contact information was supplied to the operator, and resulted in a substantial improvement in performance by allowing the operator to discount apparent boundary information generated by end point friction. Observed probe motion was still somewhat clumsy but operators reported better conceptualiztion of the letter shape due to noise rejection. In these tests, recognition times were dramatically reduced to an average of 84 seconds, and no failures in recognition were reported.

In Experiment 3, the process of re perception [5] allowed operators to visualize object primitives by direct observation of the control handle, as well as the determination of the spatial relationship between these primitives. This also reduced object recognition times to an average of 265 seconds and the failures to identification, although the effect was not as great as the reduction in signal to noise ratio. Experiment 4, in which the operator held a geometrically similar probe to the one attached to the telemanipulator but stood directly in front of the taskboard and attempted to identify the letter, produced the best performance of all, with no failures and an average recognition time of only 15 seconds.

It is not clear at this stage why the human system is more than an order of magnitude better than what seems to be an equivalent mechanical system. Before discussing the differences between the systems, it is useful to recall their similarities. Both systems do not have any form of tactile sensing or display and both rely only on proprioceptive feedback. In both cases, probing took place with the hand in the same position with respect to the probe, which was made of the same materials. Possible mechanisms which might account for the disparate results of the human and machine based systems include friction, inertia, compliance and kinematic redundancy. In all cases, the manually-coupled probe was able to trace the object boundary at high speed, often making little or no contact with the taskboard. From previous arguments, this is indicative of a system with very little internal friction, which seems to be the case with any biological system. The different frequencies of mechanical vibration generated by taskboard and object contacts were clearly discernable with the manually held probe, but were absent with the mechanical system presumably due to mechanical filtering by the manipulator and transmission structures. The mechanical probe acceleration was less than the manual probe due to the considerable inertia of the manipulator. This precludes rapid tracing, and results in loss of contact when a sharp corner is encountered. The slow data rate imposed by the inertial effect also degrades the spatial mapping of object primitives by the process outlined earlier. It was also noticed that the human arm could generate variable compliance in different directions relative to the taskboard. In the exploratory procedures observed, the probe was very compliant normal to the board, which also assisted in reducing the sudden build up of end point fricional forces, yet was stiff in any direction parallel to the board so as to generate a rapid rate of change in contact force if motion other than along the object boundary were to take place. This may have been achieved because the human arm is, by definition, anthropomorphic, while the manipulator operates on a terminus force control principle. Finally the manipulator arm kinematics are not redundant as is the human arm. This means that the human arm, unlike the manipulator may re-position the major limbs without changing the end effector (the hand). This may provide flexibility when directional compliance is required for certain tasks.

Conclusions

Comparative tests with a telemanipulator system in common use indicate that haptic probing in order to identify objects belonging to a wide, though well defined set, results in relatively poor performance. One reason suggested for this is the effect of end-point friction between the probe and the taskboard on which the object is mounted. End point friction is in turn related to the level of internal friction present within the manipulator arm.

Sensory feedback improves performance, and two types of feedback were investigated. The effect of re-perception assisted the conceptualization of object primitives and their spatial relationships to each other and resulted in a reduction in the number of recognition failures and in the reduction of object recognition times. The availability of unambiguous object contact information reduced the haptic signal to noise ratio and resulted in all objects being recognized, again with a further reductin in recognition times.

Results obtained using direct probing by a human operator indicated substantial improvements in performance, and it is suggested that this is the result of differences in friction, inertia, compliance and kinematics between the human and mechanical systems.

Acknowledgement

This work was performed with the partial support of an ONR Summer Faculty Research Fellowship, and the assistance of the Advanced Systems Division, Naval Ocean Systems Center, Hawaii Laboratory, to whom grateful acknowledgement is made.

References

[1] Pepper R. "Diver Task Description and Analysis for TOPS Project" Naval Ocean Systems Center Technical Report, Advanced Systems Division, December 1986.

[2] Gibson J. "The Senses Considered as Perceptual Systems", Houghton Miffin, publishers, Boston 1966.

[3] Klatzky R., Lederman S. and Metzger V. "Identifying Objects By Touch", Perception and Psychophysics, Vol 37, No. 4, April 1985, pp 299-302.

[4] Lederman S., Klatzky R. and Bajcsy R., "Haptic Exploration in Humans and Machines", Report 87-01, Office of Naval Research, Arlington VA, January 1987.

[5] Kearst S. and Howard J., "Memory Psychophysics For Visual Area and Length", Memory and Cognition, Vol 6, 1978, pp 327-335.

APPENDIX B

PERCEPTION OF TWO DIMENSIONAL SHAPES USING HAPTIC FEEDBACK

by

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Introduction

In this paper we are interested not so much in direct manipulation of objects, but in remote manipulation using a mechanical teleoperation device. The placement of a telemanipulator between the operator and the task to be performed acts as a kind of filter to many kinds of sensory feedback, including touch, and in most cases degrades the operator's ability to accomplish tasks that would be quite simple if performed

Abstract

In this work, we are concerned with the role that the haptic system plays in teleoperation i.e. the exploration and manipulation of objects by a human operator using a remote robot arm. The approach is to incrementaly enhance the remote touch-sensing capability beyond kinesthetic force feedback to include contact data and local re-perception and compare the time to identify quasi-two dimensional objects with that of a directly held probe. Results obtained indicated that friction between the remote probe and the environment made the feedback signal "noisy" leading to conflicting and inaccurate hypotheses by the operators. Sensory feedback improved the signal to noise ratio giving performance levels approaching those of direct, as opposed to remote, probing.

Relavence of Work

Experimental work is described which investigates the way humans identify objects using the sense of touch (haptics) only, in conjunction with a remote teleoperator mechanism. The work impacts what may be achieved through telepresence in the control and use of remotely operated vehicles (ROV's) particularly for sub-sea operations where visual data may not be available.

Keywords

Teleoperation, Haptics, Sensory Feedback, Force Reflection, Recognition.

6. Motor control mechanisms to re-distribute the primary sensor systems

Although the above does not provide a formal definition of haptics, it allows the use of terms such as haptic recognition to mean that part of the haptic system dealing with the cognitive or perceptive phase of touch. Similar definitions of haptic sensors or haptic probing follow from the above list. In our work, we are primarily interested in recognizing objects using essentially proprioceptive information, with little emphasis on tactile data about smaller, local features. The object set to be recognized has to be selected carefully, since we assume that the operator has some previous experience with and knowledge of the objects, yet there is sufficient variation in the set to provide a reasonably challenging task given the capabilities of the telemanipulator. Previous work in this area has concluded that although the haptic system may be used to recognize three dimensional objects both accurately and quickly, two dimensional object recognition is accomplished less successfully. In the tests reported by Lederman, Klatzky and Barber (1987), raised two dimensional profiles were traced and recognition was attempted, resulting in poor performance. In other work on three dimensional object recognition reported by Klatzky, Lederman and Metzger (1985), blindfolded subjects were allowed to pick up one of a set of 100 common objects and attempt recognition. In these tests, good results were obtained with only 4% of the tests resulting in mis-classification. Lederman, Klatzky and Bajcsy (1987) report other published work which supports their conclusions that the haptic system is poorer at recognizing two dimensional shapes compared to its abilities regarding three dimensional objects.

In the work reported here, we have investigated further the abilities of the haptic system to explore and recognize essentialy two dimensional shapes using a telemanipulator. While acknowledging the previous work referenced above, it was felt that in some respects the object sets selected for the two and three dimensional exploratory testing were disparate in their familiarity to the subjects, and other factors may be equally significant. For example, compare the task of identifying a contour profile of South America with that of recognizing a toothbrush, two examples given in Lederman (1987). One might argue that subjects would be more familiar with a toothbrush than with the map which is, after all a representation of another actual object. Further, in handling a real object, other sensory mechanisms are at work, such as explorations of weight, compliance, temperature, surface texture and so on. In the first case of the map, an exploratory procedure would probably be employed which builds primitives into features, and relates features to objects as indicated by Stansfield (1986) except that proprioceptive data rather than tactile data would be spatially integrated. The acquisition of data for this task would be much slower than closing one's hand around a toothbrush, and since the haptic recognition system works essentially with dynamically refreshed data it might be expected that the toothbrush would be identified first. Some significance may also be attributed to the relative role of propreoceptive and tactile sensing in the two tasks. In the map tracing task, tactile sensing serves only to guide the finger along the contour and provides no information about the object to be recognized. Tactile sensors may indicate that the contour is plastic or wood, smooth or rough however none of these are attributes of South America. For this task, proprioceptive (kinesthetic) probing is the dominant mode. In the second task using three dimensional objects, their size was selected so they could be held in the hand which suggests that tactile sensing dominated kinesthetic sensing. While it is not clear what the quantitative effect of the propreoceptive/tactile data ratio is, the above tests seem to have substantially different values. An interesting experiment, perhaps offering a more appropriate comparison with the two dimensional profile experiments, would be to have subjects explore larger three dimensional objects such as a kitchen range, or a personal computer using one finger only.

In addressing the problem of emulating the human haptic system in machines, much attention has been focussed on the area of tactile sensing. Machine haptics obviously has contributions from a much larger collection of components than just sensing. By considering the current status of teleoperation, and the efforts to improve this status so that the operator actually feels as though he or she is in the remote workplace (telepresence), some of the other mechanisms which impact teleoperator performance can be identified. Our research has identified four such mechanisms, which we propose to define as haptic variables. They directly influence the ability of teleoperators to perform complex tasks. These haptic variables are (1) tactile sensing (2) tactile display (3) force reflectance and (4) end effector dexterity. Although these mechanisms are also present in the human haptic system, they are less variable for the purposes of experimentation. These independent variables are represented in Figure 1 which also indicates examples of discrete componenents of each technology beginning with the most simple in the periphery of the diagram and increasing in complexity towards the center, which is the goal of full telepresence. A system comprising components located near the center of the diagram would be expected to have capabilities approaching those of the human hand. Note that for mechanical teleoperator systems with man in the loop control, the definition of haptic variables is consistent with the definition of the components of the haptic system given earlier, since the human operator provides the information transmission, cognitive and motor control functions directly through the manipulator.

Method

The objective behind the experimental work reported in this section is to investigate object recognition through remote haptic probing alone, and to determine which haptic variables will produce the most significant improvement in performance. In selecting the object set that operators would be asked to identify, it was decided to use wooden letters of the alphabet about six inches tall and one inch thick. For each trial, a letter was selected at random from the set of 26 and attached in a random orientation to a metal taskboard. The manipulator used was a CRL force reflecting unit of the terminus type, which means that only forces at the controller handle are sensed. A schematic diagram of this manipulator is shown in figure 2. Force reflection is achieved mechanically through antagonistic cables operating each degree of freedom of the manipulator. The remote probe consisted of a 1/4 inch diameter steel tube about 6 inches long. The operator handle is constructed in the form of a pistol-type grip. A detail of the operator handle is shown in figure 3, while the probe is shown in figure 4. For all tests operators wore earplugs and headphones connected to a pink noise source so that all audible cues were masked. The operator was prevented from directly viewing the taskboard and remote probe by a curtain.

A total of three operators were used in each of four experiments. For each experiment, some twenty trials were performed. Although each operator had prior experience using the teleoperator system, the trials for each of the experiments were performed in a random sequence to equalize the effects of increasing familiarity with the equipment over the course of the experiment. The four experiments all involved the recognition of a randomly selected, randomly oriented letter of the alphabet, but differed in the sensory feedback provided to the operator during his probing. The specific conditions relating to each experiment were as follows.

Experiment 1:	Force feedback only, audio and visual masking.
Experiment 2:	As above but with edge contact feedback.
Experiment 3:	Same as Experiment 1, but with observation of hand controller movement permitted.
Experiment 4:	No telemanipulator, tracing using hand held probe

Experiment 2 allowed the operator to observe when the remote probe was in contact with the edge of the letter. To achieve this, each wooden letter had aluminum foil tape wrapped around the edge, and a battery connected to it. The other battery terminal was connected to the remote probe so that when the probe was in contact with the edge of the letter a circuit was completed and a small light emitting diode (LED) was illuminated. The LED was placed into a small hole drilled into the mask worn by the operator so that edge contact confirmation was made available to him directly in front of his right eye. Prior to each test session, the operator was allowed to view a copy of the font used for the characters so that subtle differences could be observed, such as the difference between an **M** and inverted **W**, or an **N** and a **Z**. Operators were asked to provide a running commentary of what they thought was happening during the test. Operator comments and remote probe activity were recorded onto the same video tape. The operator was instructed to emphasize accuracy of identification rather than speed, and to make a clear identification at the conclusion of the probing. Operators were told if they made an incorrect identification, and the test continued. A time limit of ten minutes for recognition of a single letter was enforced, and the number of trials resulting in non-identification after this period was recorded. A second performance measure was the elapsed time required for correct identification, which was then averaged over all trials for the experiment.

Results

The results are shown in figure 5 which indicates both the average time for character identification and the number of times identification was not possible within the permitted time period.

Discussion

The results of Experiment 1, together with the commentary provided by operators for the cases where no successful identification was achieved, provide insight into the process of teleoperation, and how performance may be enhanced. The main ambiguity observed by operators was the inability to distinguish contact forces between the probe and the letter from frictional forces between the probe and the taskboard. This was observed during the tests when the probe appeared to be following an edge quite accurately, but when a corner occurred, the probe continued to move in a straight line along the taskboard, constrained only by the end-point frictional forces. This is shown in figure 6 where the probe moves from A to the corner B, but continues in the direction C. The operator was unaware of the situation until the length of the perceived edge became larger than his *a priori* expectations about the longest real edge, and a re-exploration of the taskboard occurred. This leads to the concept of a signal-to-noise ratio for haptic data where the signal in this case is the probe-letter contact force and the noise is the probe-taskboard frictional force. In situations such as Experiment 1 where the signal is relatively small compared to the noise, many ambiguities arise making the identification of simple primitives such as edges or corners difficult. Frequently, even contact itself was incorrectly assumed to have occurred and haptic probing took place totally in the presence of noise only.

The generation of end-point frictional forces at the probe is closely linked to the levels of internal frictional forces within the telemanipulator itself, as indicated by the following example. Suppose the control handle can be moved in any direction in space, but to cause such movement a static frictional force of say 5N has to be overcome. No obstacle in the path of the remote probe can be detected until a force greater than 5N is exerted. If one considers the general strategy of probing a letter, the operator attempts to conceptualize the location and orientation of the taskboard and then tries to move the probe lightly over the board until contact with the letter is made. Then, still minimizing the contact force between the probe and the taskboard, the probe is traced around the letter building up individual primitives into features and spatially mapping them into a recognizable object. Light contact with the taskboard is required to minimize the generation of end point frictional forces thereby increasing the signal to noise ratio during the probing phase. The internal friction of the manipulator however determines the magnitude of the friction force at the probe tip through the equation of static friction:

$$F = \mu R$$

where F is the frictional force along the plane of the taskboard, μ is the coefficient of static friction for the pair of materials comprising the task board and probe, and R is the force applied normal to the task board by the operator. If P is the internal static frictional force of the manipulator in a direction normal to the task board, it can be seen that

$$F > \mu P$$

Higher internal frictional forces therefore require larger contact forces in order to distinguish end point friction from object contact, and the search is characterised by clumsy, sometimes sudden movements when the probe leaves the object. Large excursions of the probe inhibit accurate relocation on the object and generally degrade the spatial mapping of primitives already identified.

Lower frictional forces allow delicate probing to take place, small, subtle features to be identified, and a general decoupling of the end point and contact forces. A somewhat different effect is due to internal compliance of the telemanipulator. Operators felt that if the remote probe came into contact with a rigid object and then deformed under the action of a form of torsional stiffness, the control handle did not reflect the existence of the object very precisely. Object contact sensing seemed more dependent on the rate at which force was detected rather than the absolute level of force itself. Operators used this effect to detect objects by tapping the edge of the object with the probe. Although the sound of tapping could not be heard by the operator, the mechanical coupling of the probe and control handle had sufficient high frequency bandwidth to pass impulsive components of force to the control handle. This has significant implications for teleoperated systems connected electrically, rather than mechanically, since high bandwidth transmission over substantial distances may be more difficult to achieve. Experiment 1 indicates that due to the relatively high level of friction present in the telemanipulator, ambiguities due to end point friction had a significant effect on performance, resulting in only 40% of the trials ending in success. In those that failed, operators reported little idea of what the letter might be and that further probing probably would not have aided in recognition. This situation represents standard telemanipulator tasks in a frictional environment, with an average recognition time for the task of 390 seconds. Two mechanisms were tested as potential aids to object recognition. In the first of these, Experiment 2, object contact information was supplied to the operator, and resulted in a substantial improvement in performance by allowing the operator to discount apparent boundary information generated by end point friction. Observed probe motion was still somewhat clumsy but operators reported better conceptualiztion of the letter shape due to noise rejection. In these tests, recognition times were dramatically reduced to an average of 84 seconds, and no failures in recognition were reported.

In Experiment 3, the process of re-perception (Kearst 1978) allowed operators to visualize object primitives by direct observation of the control handle, as well as the determination of the spatial relationship between these primitives. This also reduced object recognition times to an average of 265 seconds and the failures to identification, although the effect was not as great as the reduction in signal to noise ratio. Experiment 4, in which the operator held a geometrically similar probe to the one attached to the telemanipulator but stood directly in front of the taskboard and attempted to identify the letter, produced the best performance of all, with no failures and an average recognition time of only 15 seconds.

In interpreting the results of these experiments, it is worthwhile remembering that one of the dominant effects in haptic recognition is the speed at which information is gathered and retained by the sensory and cognitive systems. The ability therefore to distinguish signal from noise is useful by itself, but since it will allow exploratory procedures to be performed much more rapidly, it will increase the likelihood of recognition. A nonlinear effect may be expected in the reduction of recognition times as the haptic process is aided by sensory feedback due to this rate of signal acquisition.

It is not clear at this stage why the human system is more than an order of magnitude better than what seems to be an equivalent mechanical system. Before discussing the differences between the systems, it is useful to recall their similarities. Both systems do not have any form of tactile sensing or display and both rely only on proprioceptive feedback. In both cases, probing took place with the hand in the same position with respect to the probe, which was made of the same materials. Possible mechanisms which might account for the disparate results of the human and machine based systems include friction, inertia, compliance and kinematic redundancy. In all cases, the manually-coupled probe was able to trace the object boundary at high speed, often making little or no contact with the taskboard. From previous arguments, this is indicative of a system with very little internal friction, which seems to be the case with any biological system. The different frequencies of mechanical vibration generated by taskboard and object contacts were clearly discernable with the manually held probe, but were absent with the mechanical system presumably due to mechanical filtering by the manipulator and transmission structures. The mechanical probe acceleration was less than the manual probe due to the considerable inertia of the manipulator. This precludes rapid tracing, and results in loss of contact when a sharp corner is encountered. The slow data rate imposed by the inertial effect also degrades the spatial mapping of object primitives by the process outlined earlier. It was also noticed that the human arm could generate variable compliance in different directions relative to the taskboard. In the exploratory procedures observed, the probe was very compliant normal to the board, which also assisted in reducing the sudden build up of end point fricional forces, yet was stiff in any direction parallel to the board so as to generate a rapid rate of change in contact force if motion other than along the object boundary were to take place. This may have been achieved because the human arm is, by definition, anthropomorphic, while the manipulator operates on a terminus force control principle. Finally the manipulator arm kinematics are not redundant as is the human arm. This means that the human arm, unlike the manipulator may re-position the major limbs without changing the end effector (the hand). This may provide flexibility when directional compliance is required for certain tasks.

Conclusions

Comparative tests with a telemanipulator system in common use indicate that haptic probing in order to identify objects belonging to a wide, though well defined set, results in relatively poor performance. One reason suggested for this is the effect of end-point friction between the probe and the taskboard on which the object is mounted. End point friction is in turn related to the level of internal friction present within the manipulator arm.

Sensory feedback improves performance, and two types of feedback were investigated. The effect of re-perception assisted the conceptualization of object primitives and their spatial relationships to each other and resulted in a reduction in the number of rcognition failures and in the reduction of object recognition times. The availability of unambiguous object contact information reduced the haptic signal to noise ratio and resulted in all objects being recognized, again with a further reductin in recognition times.

Results obtained using direct probing by a human operator indicated substantial improvements in performance, and it is suggested that this is the result of differences in friction, inertia, compliance and kinematics between the human and mechanical systems.

Acknowledgement

This work was performed with the partial support of an ONR Summer Faculty Research Fellowship, and the assistance of the Advanced Systems Division, Naval Ocean Systems Center, Hawaii Laboratory, to whom grateful acknowledgement is made.

References

Gibson J. 1966. The Senses Considered as Perceptual Systems, Houghton Miffin, publishers, Boston.

Kearst S. and Howard J. 1978. Memory Psychophysics For Visual Area and Length, Memory and Cognition, Vol 6, pp 327-335.

Klatzky R., Lederman S. and Metzger V. 1985. Identifying Objects By Touch, Perception and Psychophysics, Vol 37, No. 4, April, pp 299-302.

Lederman S., Klatzky R. and Bajcsy R., 1987 Haptic Exploration in Humans and Machines, Report 87-01, Office of Naval Research, Arlington VA, January.

Pepper R. 1986, Diver Task Description and Analysis for TOPS Project, Naval Ocean Systems Center Technical Report, Advanced Systems Division, December.

Stansfield S. 1986. Primitives, Features and Exploratory Procedures: Building a Robot Tactile Perception System, Proc. IEEE Robotics and Automation Conference, Raleigh NC, pp 1274-1279.

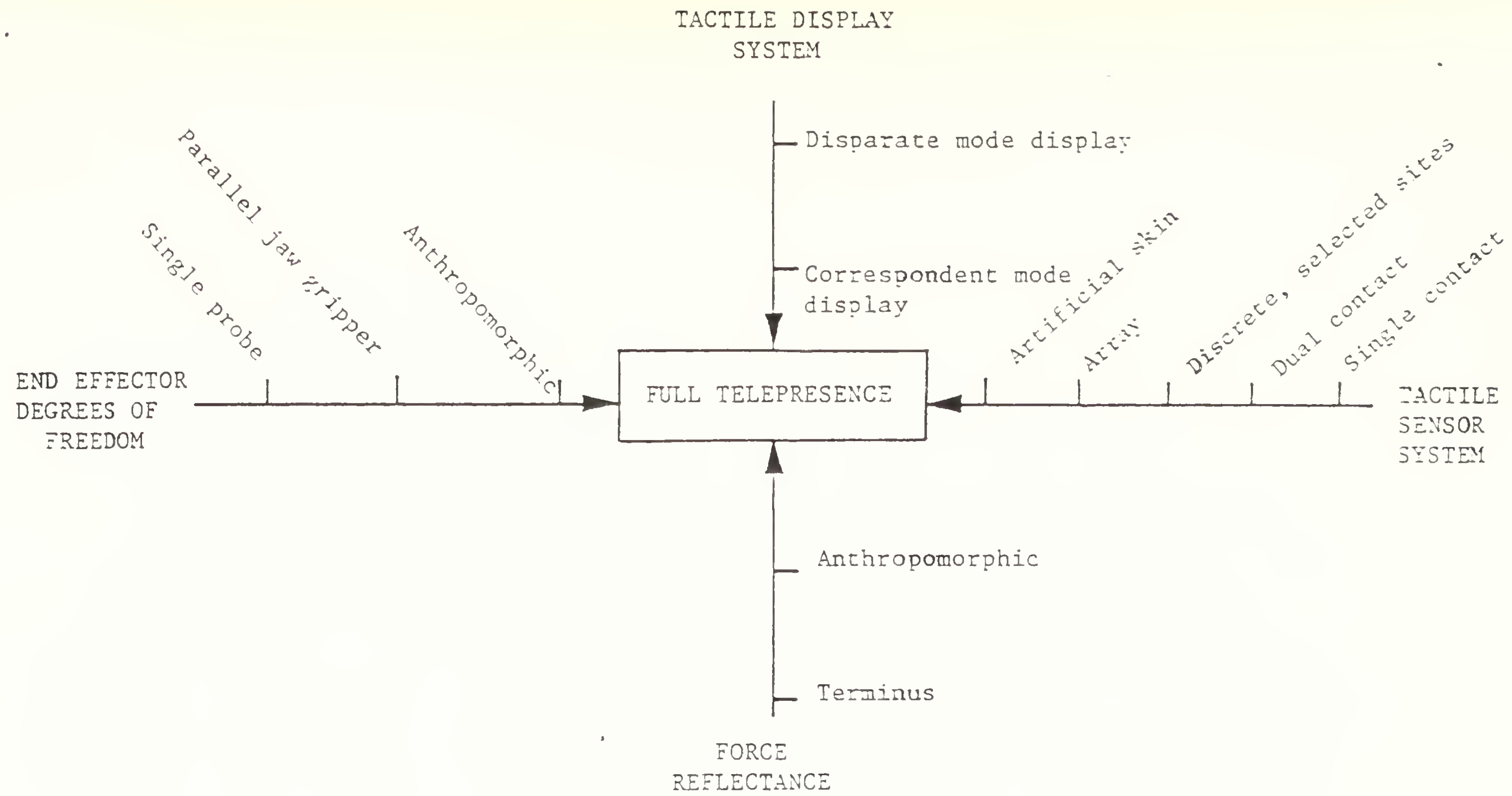


FIGURE 1 VARIABLES OF HAPTIC PERCEPTION

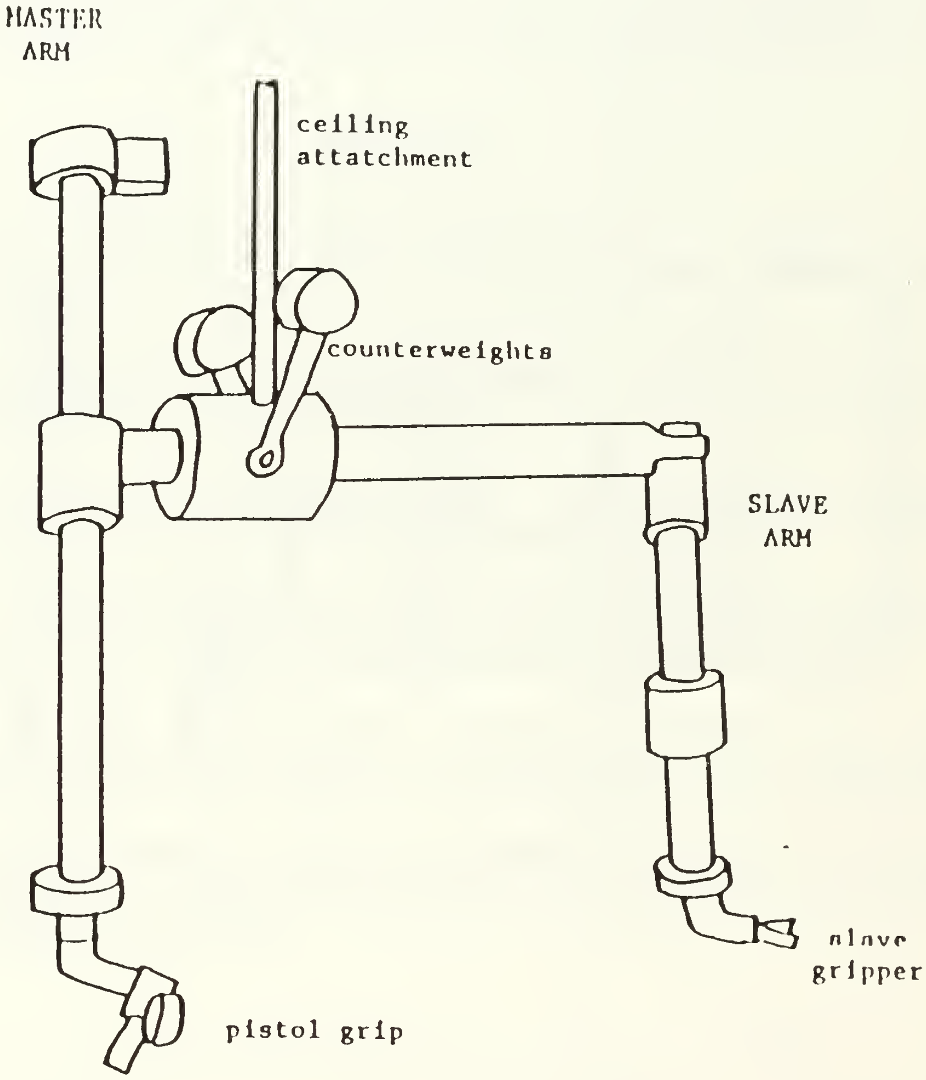


FIGURE 2 FORCE REFLECTING TELEMANIPULATOR

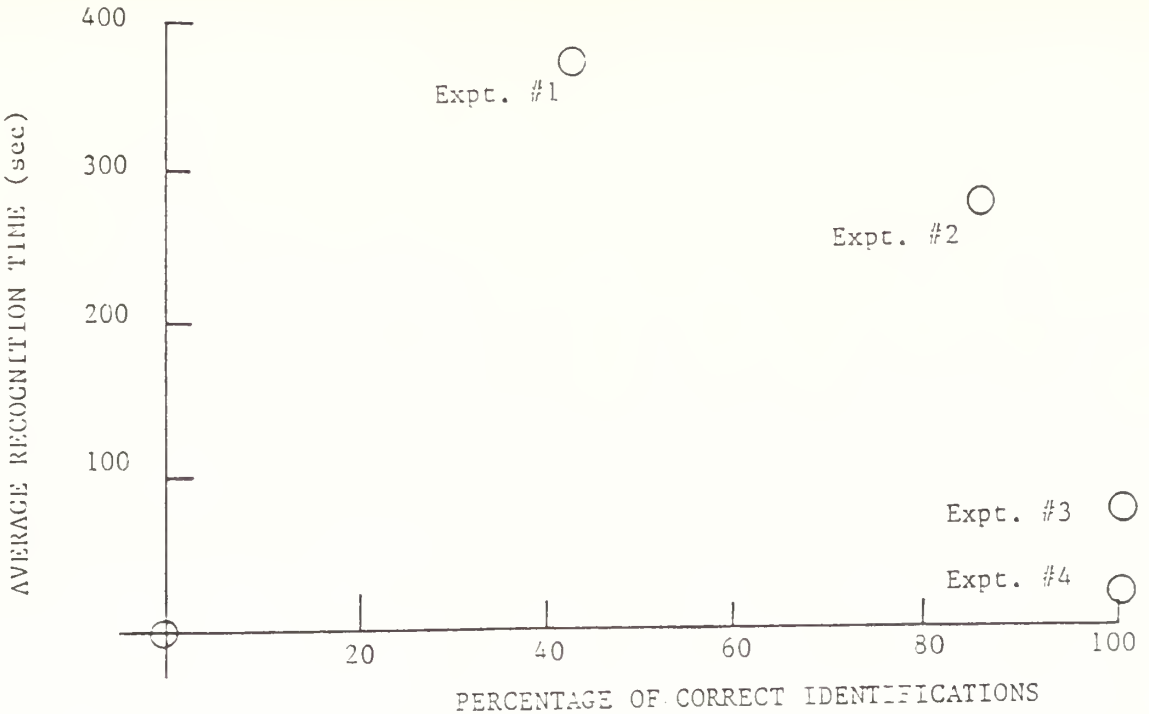


FIGURE 5 EXPERIMENTAL RESULTS

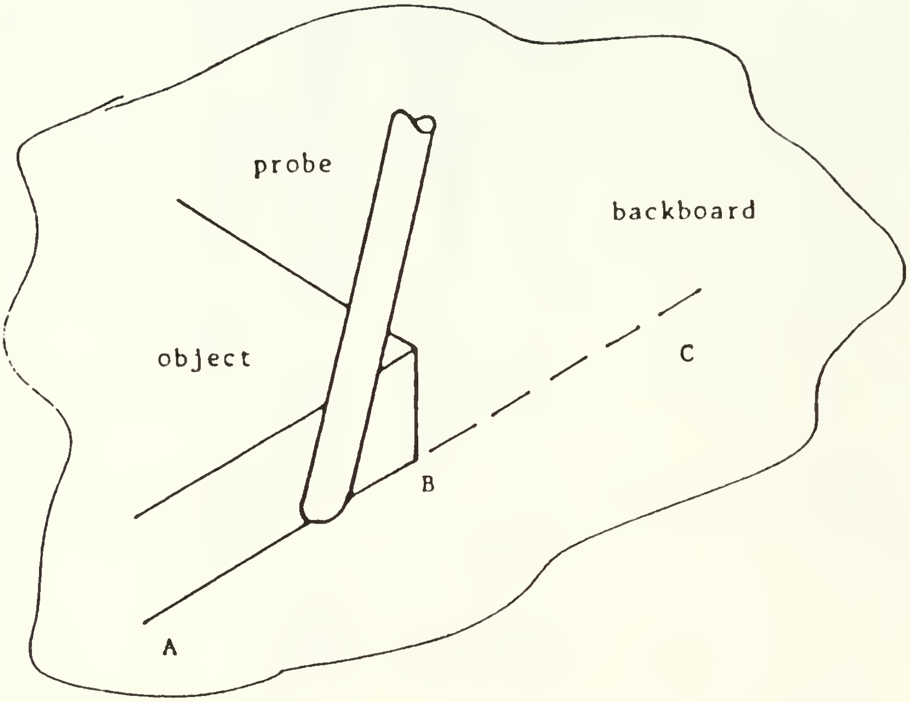
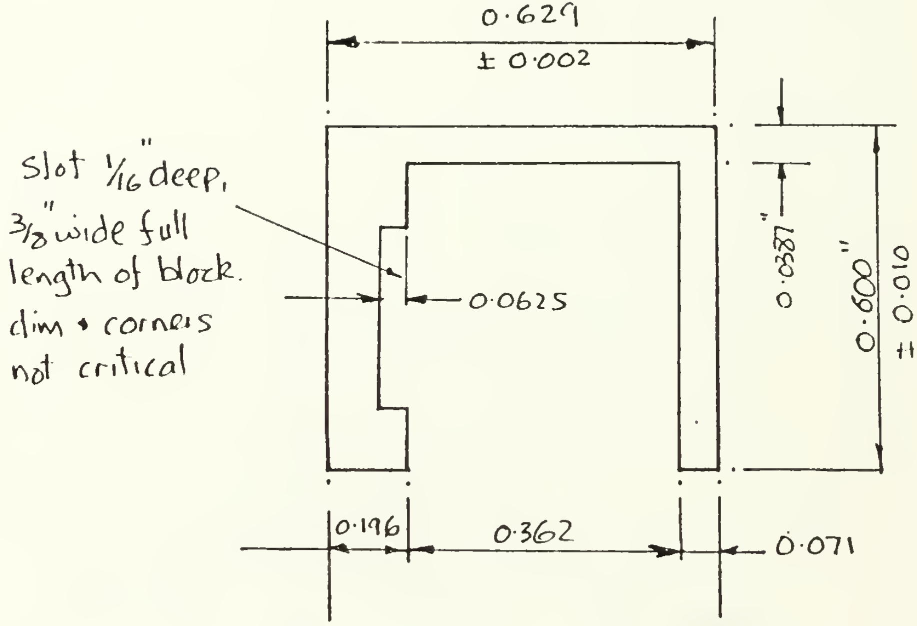
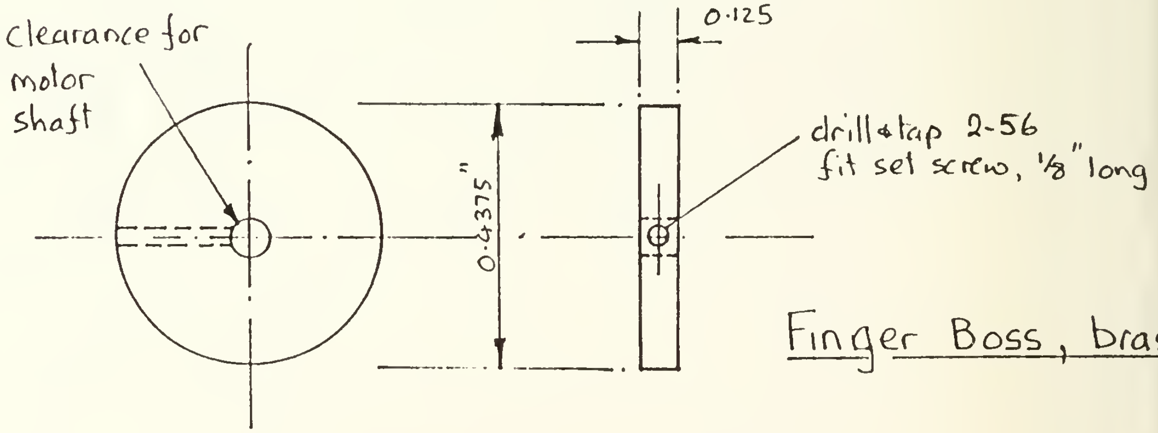


FIGURE 6 EFFECT OF FRICTION ON PROBE TRACKING

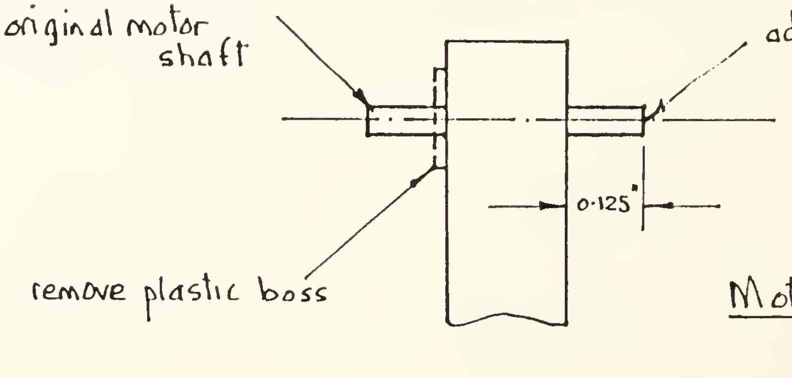
APPENDIX C



Aluminum motor block 1" long

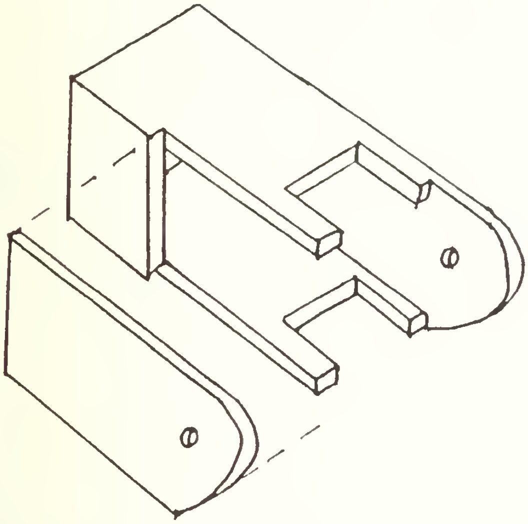


Finger Boss, bras



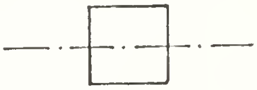
Motor modifications

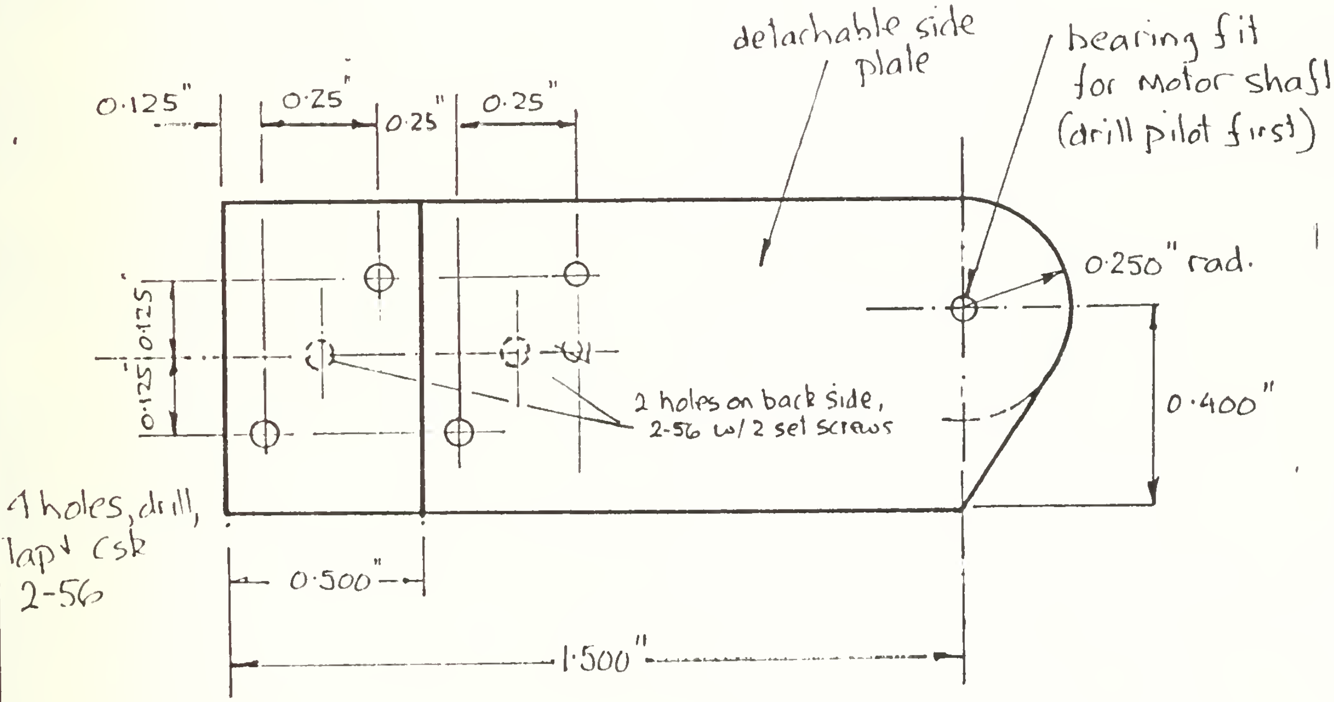
FINGER UNIT WITH DETACHABLE SIDE PLATE

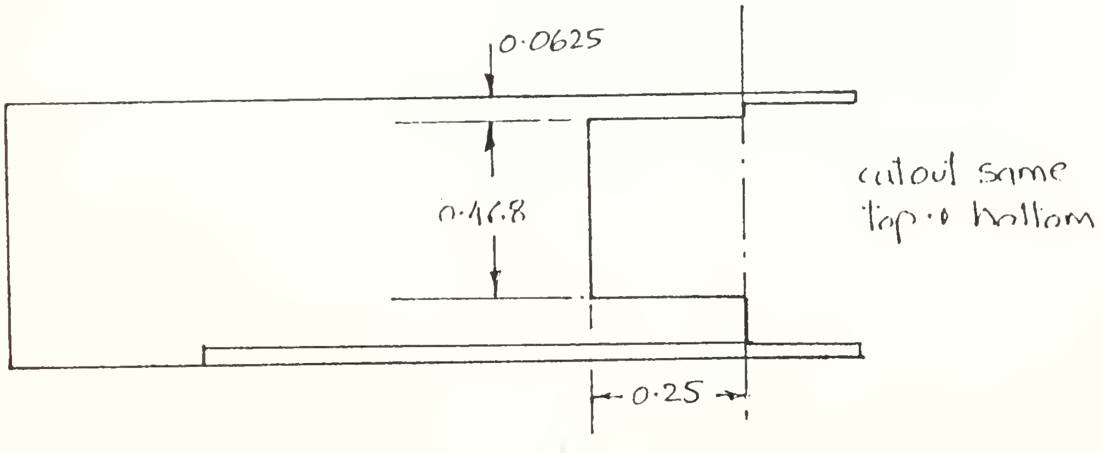


Notes:

1. Holes for motor shaft must be square to X-section

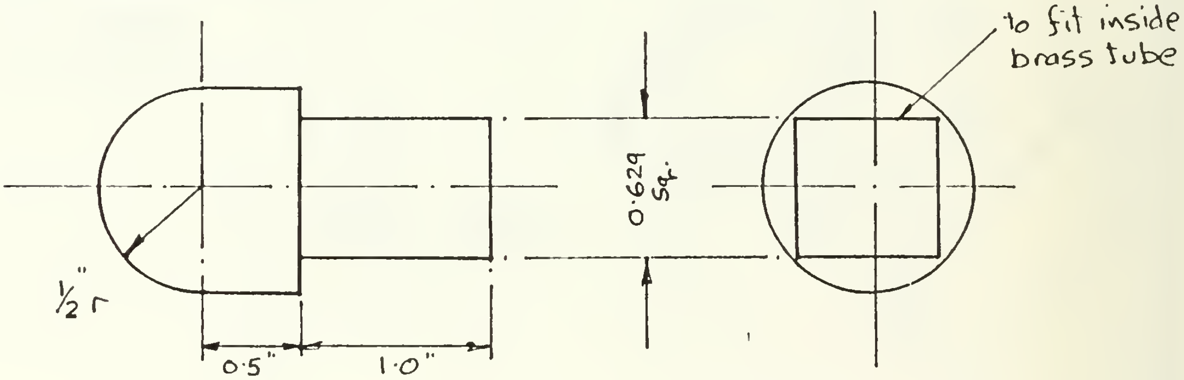






FINGER-TIP UNIT

1. Construct conventional finger unit with 1.5" dimension reduced to 1·25". Two 2-56 holes on back side not needed.
2. Use square section below instead of aluminum block to secure side plate.



FINGER TIP 1" DIA DELRIN

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