Telerobotic Surgery: Feedback Time Delay Effects on Task Assignment

by

Mark Peter Ottensmeyer

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Master of Science in Mechanical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 1996

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Abstract

This thesis presents the development and results of experiments studying the interaction between a telesurgeon and an assistant local to a patient. In particular, a number of simulated laparoscopic surgical tasks were performed under various conditions of teleoperator time delay and tool assignment between the surgeon and assistant. The time delays ranged from no delay to 1.2 seconds. Tools used in the tests included a laparoscope, laparoscopic grippers, shears and clip appliers.

To provide a setting in which to perform the experiments, a telesurgery system was assembled. The central component is a three degree of freedom, bilateral force reflecting teleoperator with a two d.o.f. teleoperated surgical tool without force feedback. The surgical tool can actuate a laparoscope, laparoscopic grippers or shears. Other components include two surgical patient/task simulators, one-way video and two-way audio communications hardware and a delay generation device.

The experimental results obtained using this system suggest that under delay conditions, telesurgeons should act only by controlling the laparoscope and instructing, while delegating performance of the manual tasks to the assistant. Improvements to surgical teleoperators could allow surgeons to interact directly for low time delays, but, depending on the cost of increased completion time, delegation may always be necessary for higher delays to obtain the best performance.

Thesis Supervisor: Thomas B. Sheridan
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Acknowledgments

The author would like to thank Prof. Tom Sheridan for all of his assistance and guidance in pursuing this work, Jianjuen Hu for developing the teleoperator control software and Dr. James Thompson for advice regarding the medical aspects of the work and especially for acting as the telesurgeon in the experiments.

This work is supported by the U.S. Army Medical Research, Development, Acquisition and Logistics Command (Prov.) under Contract No. DAMD17-94-C-4125. The views, opinions and/or findings contained in theis report are those of the author and should not be construed as an official Department of the Army position, policy or decision unless so designated by other documentation.

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Chapter 1

Introduction

The last three decades have seen the advent of "tele-medicine", the provision of medical care over long distances through the use of telecommunications. Until recently, this involved transmitting audio and video signals and various forms of data (e.g., X-ray and MRI images). Now there are efforts underway to develop teleoperator systems that will allow doctors literally to extend their reach and perform examinations and surgery without needing to be personally present with a patient. There are many issues that need to be resolved before medical teleoperator systems are used clinically. The one that is addressed in this work is how to coordinate the interaction between a "telesurgeon" and a less skilled assistant physically present with the patient.

Early reported work in telemedicine is that done by Murphy, et al. [MBBB70, MBBY73, MB74]. A two-way microwave TV link was set up between Boston's Logan airport and Massachusetts General Hospital following an airplane crash in the mid-1960s in which traffic prevented ambulances from reaching the scene. With this system, a surgeon on call at MGH could visually examine patients and instruct the para-medical staff at the airport on how to treat them.

Recently, Kavoussi, et al. [KBM+94] have been using a telerobotic arm to remotely control an endoscopic camera in a form of telemedicine they call "telementoring". In their system, a robot arm holding a camera in a laparoscopic procedure is controlled by a surgeon facing a video screen in another room. This surgeon is an expert in the procedure being performed, and is guiding the local surgeon who is learning the procedure. While originally intended for use within a single facility, the telesurgeon could easily be located in another hospital in another city. The potential for this system as a training tool is clear, in that an expert in one facility can be "telepresent" in many others, eliminating the time and financial costs of travel.

Being able only to communicate over an audio-video channel prevents a doctor, and especially a surgeon, from using a significant portion of his or her skill set, notably the manual skills involved in palpation and performing surgical tasks. To extend telemedicine to include manual interaction with the remote environment, various groups are developing teleoperators specifically designed for surgical settings. One of the most advanced systems is being developed by a group at SRI International in California [GHJS95]. Their telesurgery system uses a two armed, five degree of freedom (each arm), bilateral force reflecting teleoperator system. The master manipulators are equipped with handles like surgical tools and the slave manipulators are equipped with interchangeable gripper and cutting tool tips. This system was demonstrated favorably in Washington, D.C. at the annual convention of the Association of the U.S. Army, in 1994. A teleoperator system with seven degrees of freedom for each arm is currently under development.

While the technology has been progressing, there has been little attention explicitly paid to the interactions between the telesurgeon and an assistant. Early applications for telesurgery systems are likely to be on the battle field, where rapid response to trauma is especially important [Sat94]. In this case, however, the assistant will not be a skilled surgeon simply learning a new procedure. More likely, he or she will be another soldier with limited medical training at best. In civilian telemedical trauma applications, the assistant might be a para-medic in an ambulance. In these cases, it is not clear how best to make use of the abilities of the assistant. Clearly, this person provides an extra pair of hands and eyes beyond what a telesurgeon has available, and can follow the surgeon's instructions. Further, the assistant is not encumbered by limitations of the technology, such as time delays involved in video image compression and transmission, limits to the field of vision imposed by the cameras and limited haptic feedback. There is a need for some sort of protocol to guide the surgeon in what aspects of the surgical task set can or should be delegated to the assistant, and which ones should remain under the direct control of the surgeon.

While there are many factors that would influence this decision, one of the more important is the effect of communication time delay in the system. The SRI and other current prototype systems use high bandwidth communications channels over very short distances, and as such, do not have to contend with non-trivial delays. However, currently available technology to do videoconferencing typically uses channels that result in delays in the video signals of at least a half second, round-trip (e.g. 600 ms for the Zydacron system [Zyd96]). If satellite communications are used, the delays become even longer. In a recent test between Tokyo, Japan and Washington, D.C., the round trip delay in the teleoperator system was 1.4 seconds [MWN$^+$95]. Thus, in addition to deciding what tasks to delegate under ideal conditions, guidelines must be developed when the system is compromised by time delays.

One of the few studies of cooperation mediated by a telecommunications system was performed by Weeks and Chapanis [WC76]. In their experiments, a problem solving exercise, mediated either by teletype, telephone or two-way closed circuit television, was performed and compared with direct interaction. They found no significant differences between any of the modes except teletype, which resulted in longer completion times. However, their work did not involve physical interaction between the participants, did not deal with time delays, and the participants were not expert-novice pairs, as they would be in a telesurgery environment.

A number of studies have been done on performance of manual tasks using teleoperators with time delays. Two of these [She92, Bla70] showed that as loop time delays increase beyond 0.1 seconds, operators begin to use a "move-and-wait" strategy to control the teleoperator. In move-and-wait, a user makes an open loop motion, then waits for the feedback to catch up before initiating another move. Because of this, when time delay increases, the time required to complete a task goes up. When higher precision is required in a task, the number of small, open loop moves increases, also increasing overall task completion time.

In studying telesurgeon/assistant cooperation, laparoscopic surgery was chosen as a context. In this form of surgery [KC93], a patient's abdomen is inflated with carbon dioxide gas, and sealed tubes called trochars are inserted through the abdominal wall. A laparoscope, a tube with fiber optic bundles and an attached TV camera, is inserted through one trochar, and surgical tools are inserted through the others. Often two or more tools and a camera must be manipulated simultaneously. Because of this, a surgeon cannot perform the operation alone, so the choice of laparoscopy provides a type of surgery that requires cooperation. Another characteristic of choosing laparoscopy is that the fulcrum created by the trochar in the abdominal wall constrains the motion of the tools, reducing the complexity required in a teleoperator controlling the tools.

In the course of this research, a teleoperated laparoscopic surgical tool was developed, as was a surgical simulator. A set of simulated tasks was performed by surgeon-assistant pairs under various time delay conditions. The details of the system components, the experiments and the results obtained are presented in the following chapters.

Chapter 2

Telesurgery Apparatus and Experiment Design

2.1 Experimental Apparatus

Figure 2-1 shows a diagram of all of the major system components in the Human-Machine Systems Laboratory telesurgery simulator system. The central components are the slave teleoperator with a teleoperated surgical tool, and surgeon's master control and tool handle. The other components include the surgical simulator, the audio/video communications equipment, including a delay generator, and the computer hardware used to control the tele-operator and perform image processing. These elements will be described in turn.

2.1.1 Teleoperator System:

The teleoperator used in these experiments consists of a pair of PHANToM haptic interface arms, one used as a master, the other as the slave (see Figure 2-2). The PHANToMs were designed to provide force feedback from virtual environments. Ours is the first known use of a pair of PHANToMs in a master-slave mode. The PHANToM arms are 3 degree of freedom robot arms (all revolute joints), providing force feedback to the user in x, y, and z directions. Our system is a bi-lateral, force reflecting teleoperator, so when a force is exerted by the slave on the remote environment, an equal and opposite force is displayed to the user at the master site. The potential to scale motions or forces or both between master and slave is available, but was not employed, as it was intended that the surgeon act as if using normal surgical tools without any special augmentation. Some groups (e.g. [HDLC93]) have done work on hand tremor attenuation, and force and geometric scaling, but this was outside the scope of the current research.

Because the arms are identical kinematically, control of the arms is less computationally intensive

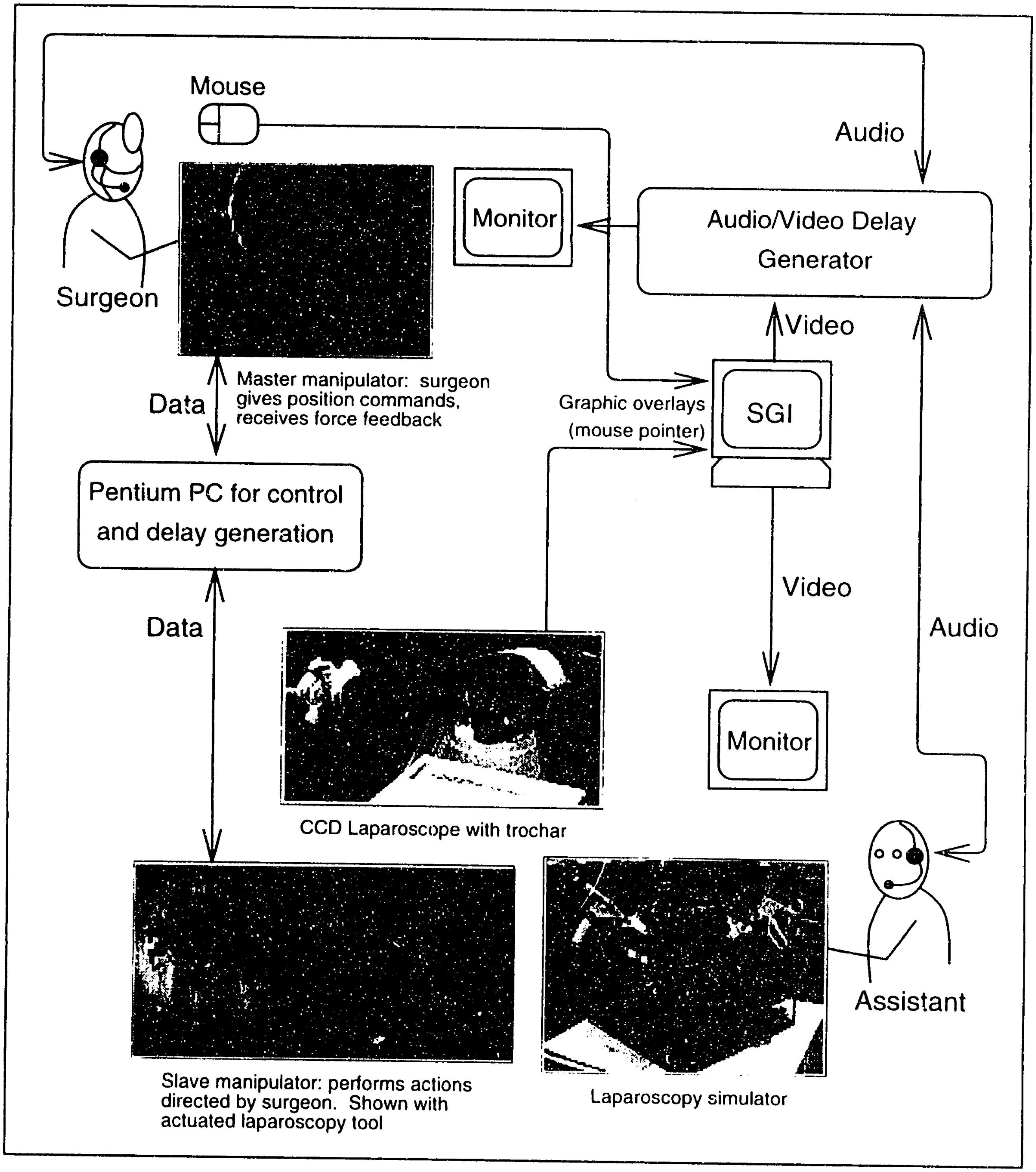


Figure 2-1: HMSL telesurgery simulator system components.

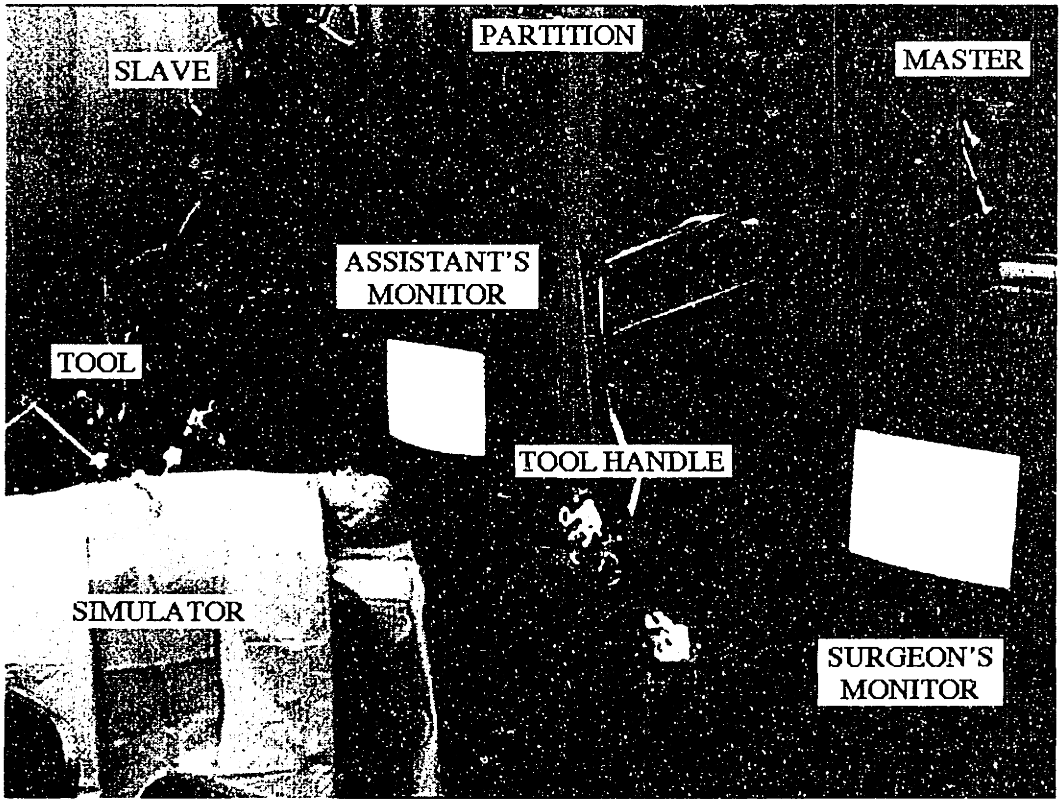


Figure 2-2: Telesurgery setting, with master and slave, simulator and video monitors. The apparatus on the right would be located remotely from the patient.

than would be the case if extensive forward and inverse kinematic calculations had to be performed. This is important because fewer calculations mean that the computer control loop can run more quickly, allowing a higher bandwidth of force information to be sensed and displayed to the user. The sensitivity to vibration in the skin of the hand is highest at approximately 200 Hz [SC86] and since the control loop runs at roughly 500 Hz, a significant range of the sensorium is available through the master-slave system. The control software for the arms was developed by Hu [HRTS96], and allows the arms to be used in a proportional-derivative control mode without time delays, and with a variety of other control modes which stabilize the system when time delays are present. The software was run on a 90MHz Pentium PC which also housed the interface cards for each arm. Time delays were generated in the control loop by buffering incoming commands for the desired amount of time. Though not used in these experiments, the system can also be run on two separate computers, one each for the master and slave, using an ethernet connection between the two.

The PHANToMs include a number of safety switches to prevent damage to the system or injury to the users. A "dead-man" foot switch near the slave arm is used by the assistant to cut off power to the motors when released. A hand-held dead-man switch for the surgeon is part of the tool handle, described below.

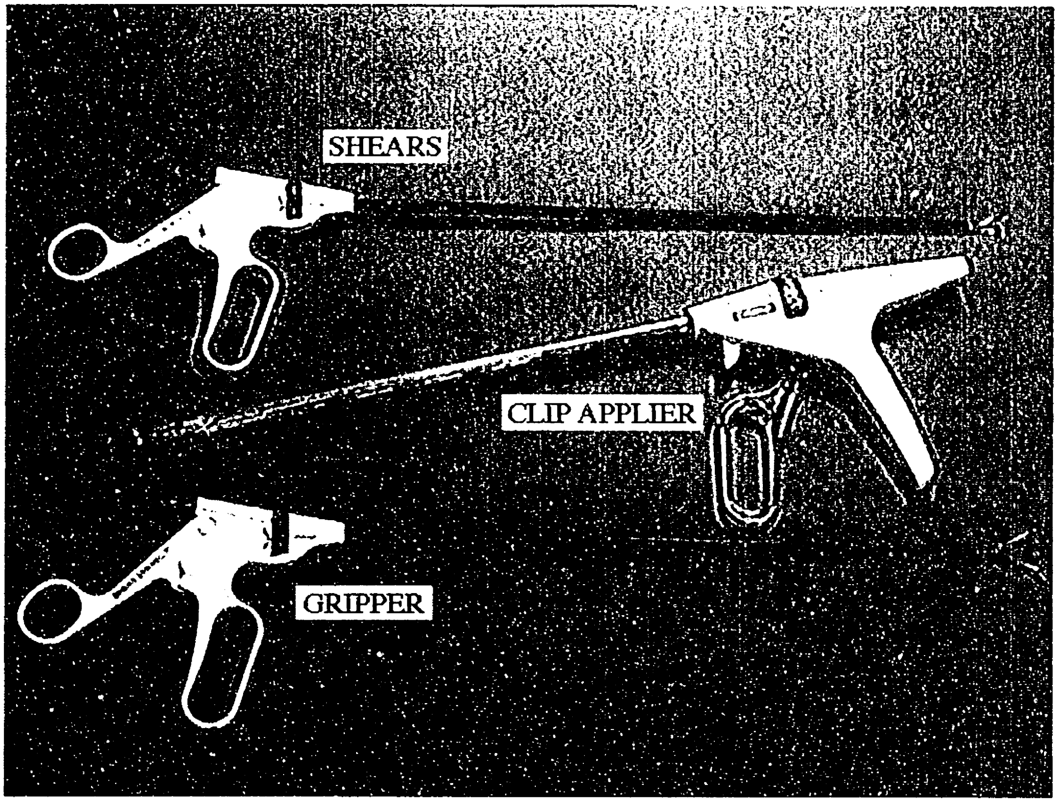


Figure 2-3: Laparoscopy tools: gripper, clip applier and shears. Finger wheel on handle controls roll motion, scissor grip actuates gripper/shear action.

2.1.2 Teleoperated Surgical Tool and Tool Tips:

To provide a surgeon with access to the remote environment, a special end effector and a control handle had to be built for the slave and master arms respectively. To provide the functionality of the laparoscope and tools such as laparoscopic grippers and shears (see Figure 2-3), the roll axis of a tool and the motion of the tool tip need to be controlled. Also, the end effector must support use of any of these tools. To meet these criteria, the tool and tool handle shown in Figures 2-4 and 2-5 were designed and built. (See also Appendix A for hardware and users' manual).

The tool is made up of a base unit, which includes the motors and encoders to drive and measure the position of the tools, and three interchangeable tool tips, one each for the gripper, shears and laparoscope (see Figures 2-6 and 2-7). The roll axis of each tool is driven by the small motor on the base unit through a simple pinion-gear mechanism. The gripper/shear motion is driven by a rod moving along the inside of the main shaft of the tool. The large motor drives this motion, using a lead screw to convert the motor's rotary motion to the linear motion of the rod. The base unit is attached to the slave PHANToM using the gimbal wrist supplied with the arm. Also supplied with the arms were three additional current amplifiers and encoder counters (beyond those for the first three axes), and two of these are used to drive the base unit motors and receive inputs from the encoders.

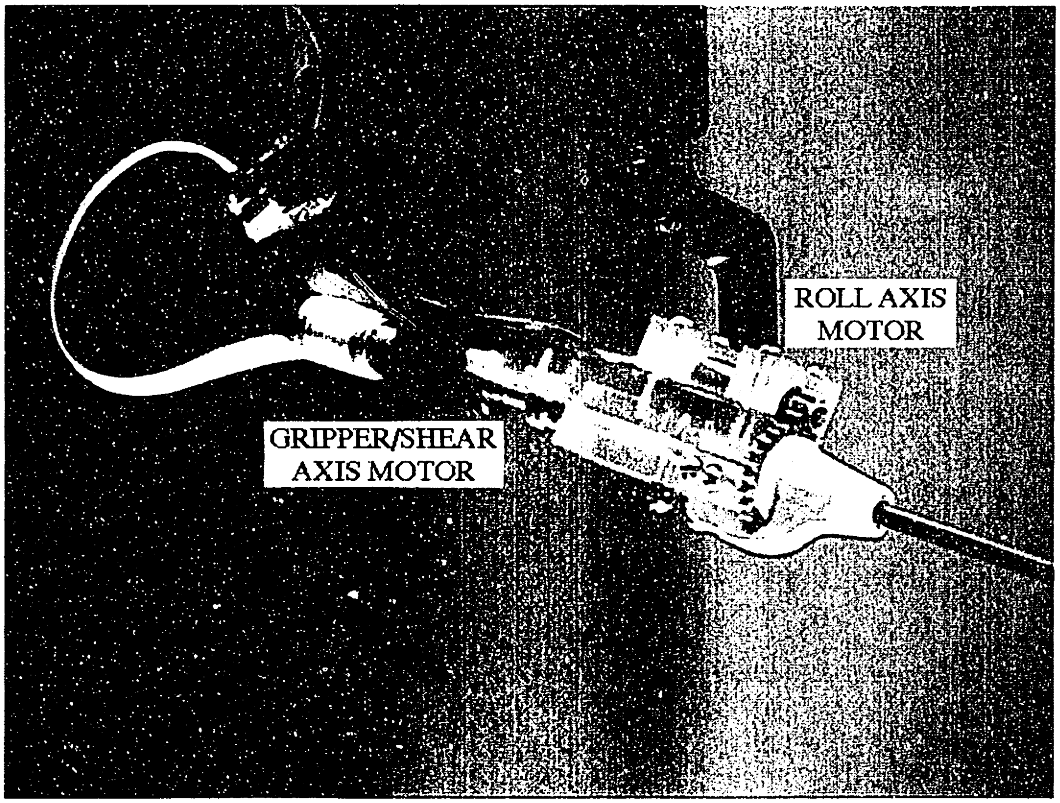


Figure 2-4: Teleoperated (slave) laparoscopy tool.

The gripper and shear tools were modified from tools like those in Figure 2-3, keeping the main shaft and part of the handle. To mount them to the base unit, lexan blocks were machined to accomodate the tool parts, the motion of the lead nut in the base and holes for thumb screws to hold the tip to the base. It was found during construction that the length of travel of the drive rod for the gripper/shear action was shorter for the gripper tip than for the shears tip. Because of this, a calibration scheme for the tools was developed, and different gains are used in the control program to match the tool position to the master handle position. The details of the calibration scheme and control functions are described further in Appendix A.

The laparoscope tip is a modified CCD desktop video camera mounted to a 3/8" acrylic plastic shaft. Real surgical laparoscopes use a CCD camera mounted to the "outside" end of a tube containing optics which bring light to the surgical site inside the abdomen and transmit an image back to the external camera. In these experiments, the camera never had to be removed from the surgical simulator, so it was not necessary to use expensive optics, and the camera was mounted to the "inside" end of the shaft (note the trochar in Figure 2-7). As described later, the simulator uses ambient room light to illuminate the surgical field, so it was not necessary to add a light source to the laparoscope tool tip. The camera is a fixed focus device, but has a small aperature, so it provided sufficient depth of field (approximately between 1.5" and 4" away from the objective lens) to complete the experiments.

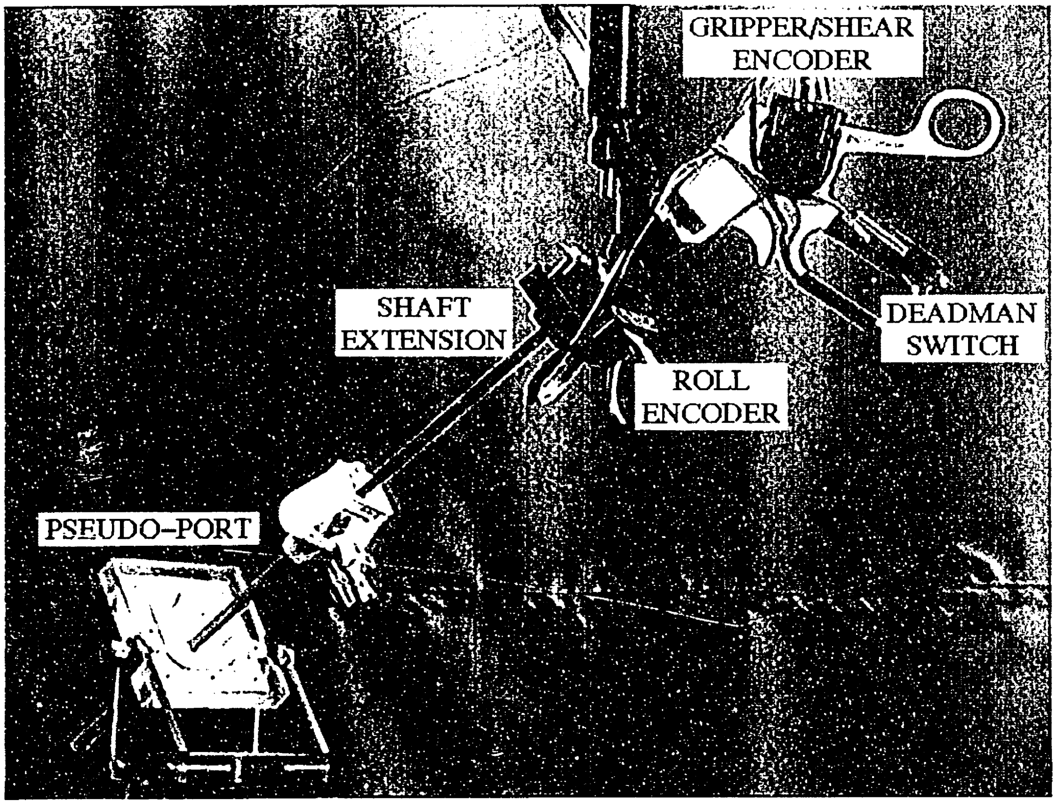


Figure 2-5: Surgeon's (master) tool handle.

2.1.3 Telesurgical Tool Handle:

The input device for the tool (see Figure 2-5) was also modified from a real laparoscopy tool. Optical encoders are used to measure the position of the roll axis and the scissor action of the handle. Because the roll axis encoder is attached to the tool shaft, turn of the finger wheel and turn of the handle as a whole are both measured. As a safety device, a "dead-man" switch is also attached to the handle, which, if released during operation, causes the entire system to shut down. The switch on the handle was used, rather than a foot switch or a switch in the surgeon's other hand, so that if the system became unstable, it would be very difficult to maintain a grip, and the surgeon would naturally release it.

The tool handle does not provide force feedback for either the gripper axis or the roll axis. As will be apparent later, the simulated surgical tasks for which it was used do not require fine control over gripper force or roll axis torque. Further, laparoscopic surgeons tend to use visual feedback as their primary source of feedback, and the force feedback provided by tools used in the operating room is poor at best. Improved manual tools and enhanced teleoperated tools are being designed [FPN95], but these are not currently in clinical use.

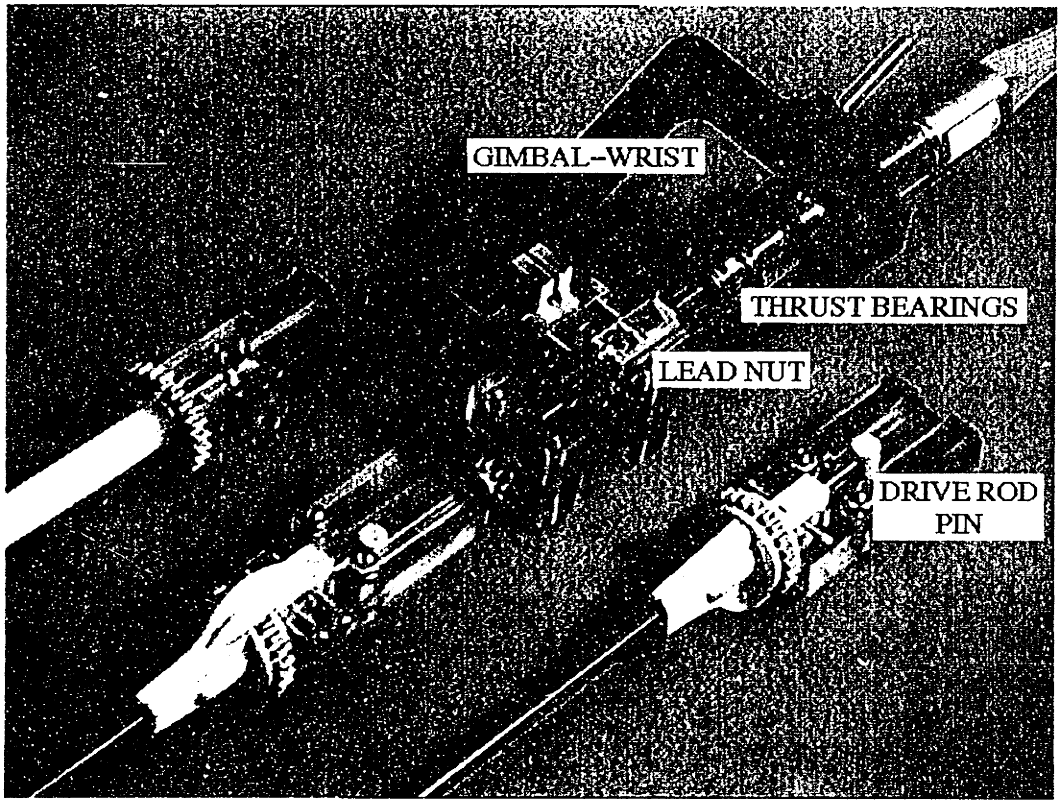


Figure 2-6: Tool components. Base unit houses drive motors (note thrust bearings for gripper action). Pinion meshes with gear on tool tip blocks, lead nut socket holds drive rod pin.

2.1.4 Kinematic Degrees of Freedom and Constraints:

The PHANToM arms provide control over only three position axes, and the tool handle controls one orientation axis. If the tool handle were moved in free space there would be two uncontrolled degrees of freedom. However at the slave end the fulcrum provided by the hole in the patient's abdominal wall constrains two degrees of freedom. To make the handle kinematics be the same and to constrain the last two orientation DOFs, a "pseudo port" (shown in Figure 2-5) was constructed to play the same role for the master. Figure 2-8 shows that this port is placed in the same place relative to the master's base as the real trochar is relative to the slave's base. In this way the tool handle always maintains the same position and orientation as the tool itself.

2.1.5 Patient (Abdomen) Simulators:

During the course of this research, two laparoscopic patient simulators were constructed. The first (Figure 2-9) is modelled after typical laparoscopy training devices [BIZ91, Mug92] and includes typical features: an opaque lid to prevent direct viewing of the simulated surgical task field and a number of ports through which trochars and tools are inserted. Two other features of this simulator include the shape of the lid which is intended to approximate that of the inflated abdomen of a

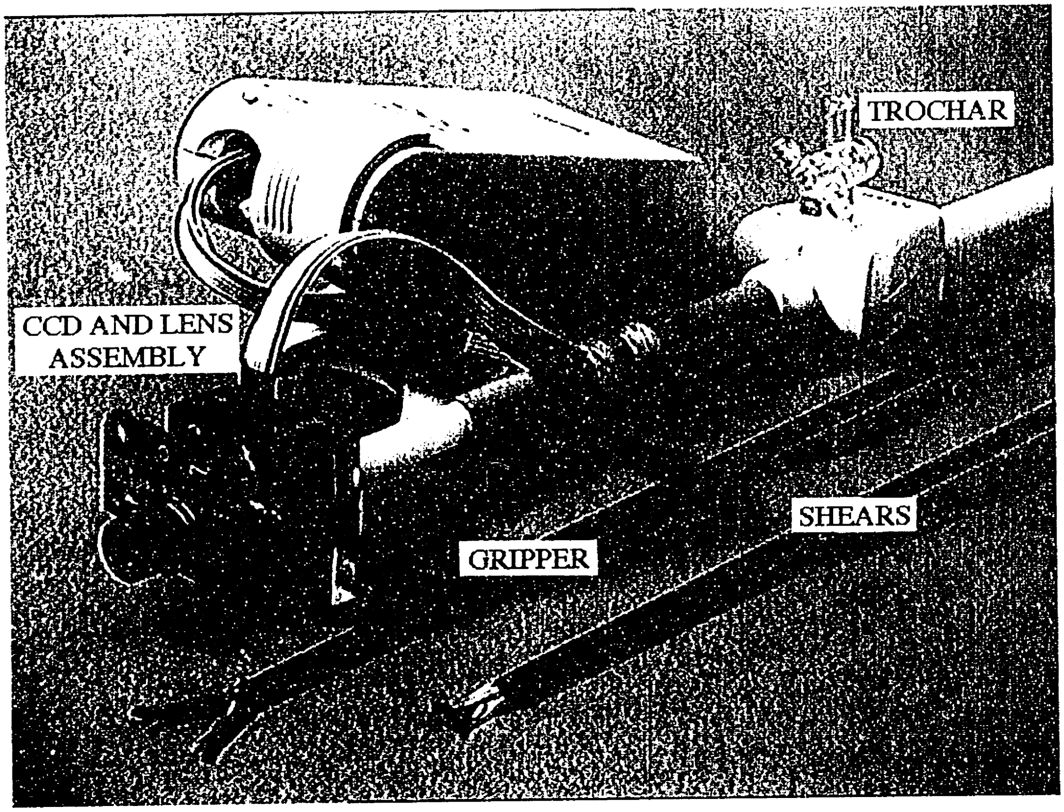


Figure 2-7: Tool tips. Laparoscope with CCD and supporting hardware, gripper and shears.

laparoscopy patient, and the transparent sides which permit an external view of the operation by observers or by an extra video camera.

A platform was constructed to be used in the simulator which supports the "task boards" (see section 2.2) with the individual elements of the test set-ups. A position sensing unit was attached to it which can measure the motions of a laparoscopic probe within the simulator. The platform can be seen inside the simulator in Figure 2-9.

The second simulator was built for demonstration purposes. It is a slightly modified CPR training mannikin (see Figure 2-10), which has space inside for part of the task board equipment, and holes located at the umbilicus and just below the "rib-cage" on the right and left sides for the trochars and tools. As the mannikin is opaque, light is provided by placing a lamp at the lower end, shining in through the large access hole. Surgical drapes are used to cover the mannikin to provide additional realism.

2.1.6 Audio/Video Equipment:

Beyond the CCD laparoscope, a number of components provided for verbal communication between the telesurgeon and assistant, displaying the video images from the camera, performing some basic image processing, and generating the audio and video time delays.

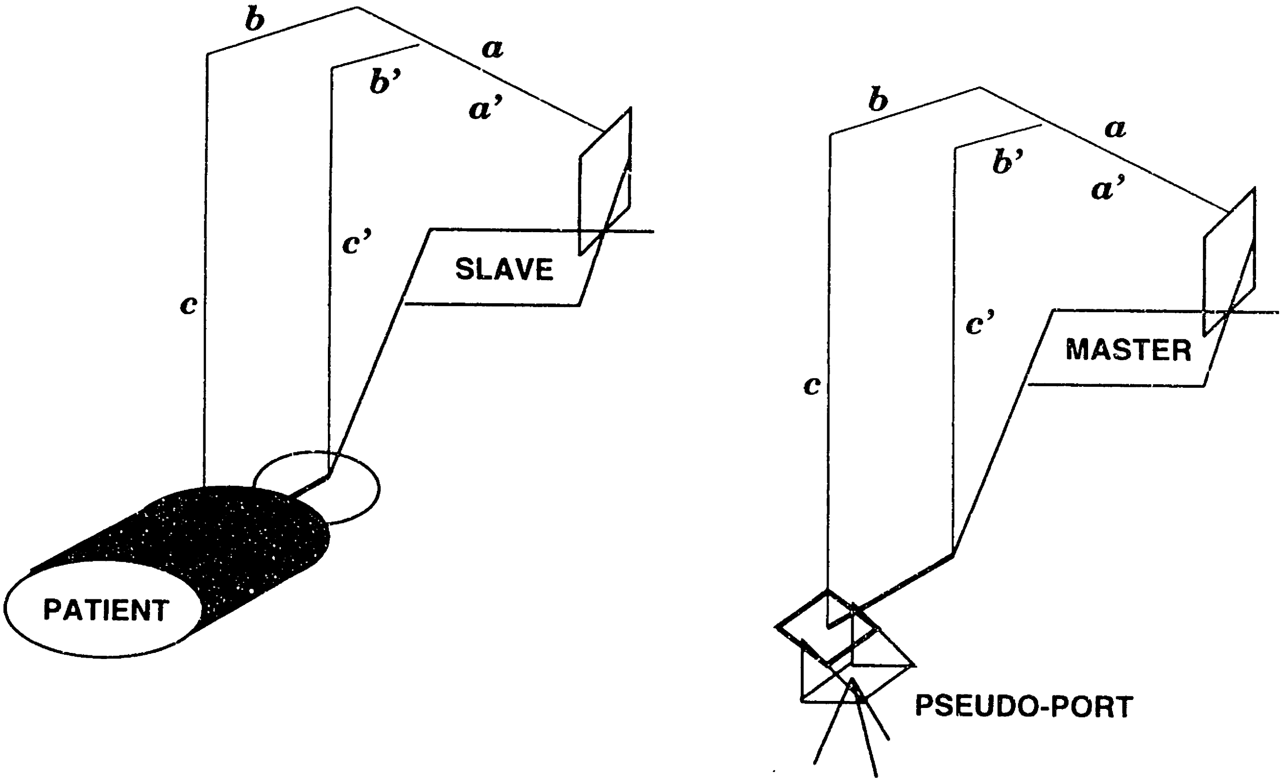


Figure 2-8: Geometric similarity in placement of slave/patient and master/pseudo-port.

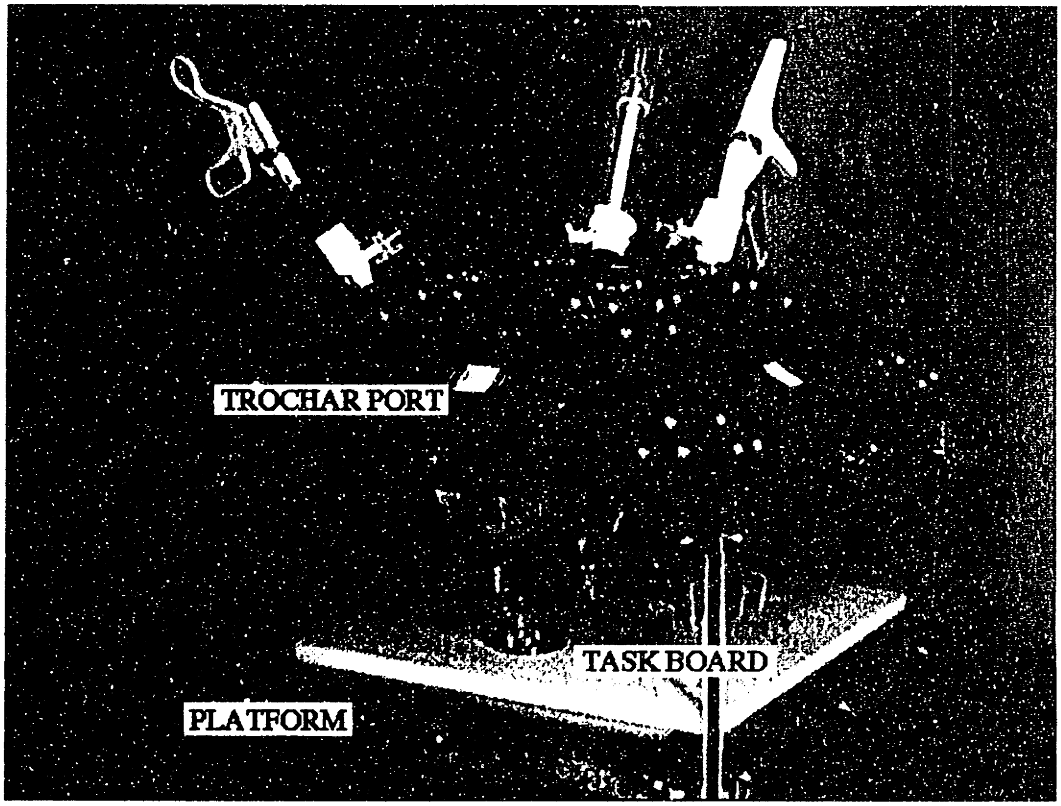


Figure 2-9: Laparoscopy simulator for experiments. Note opaque lid with trochar ports, transparent sides showing platform and task board.

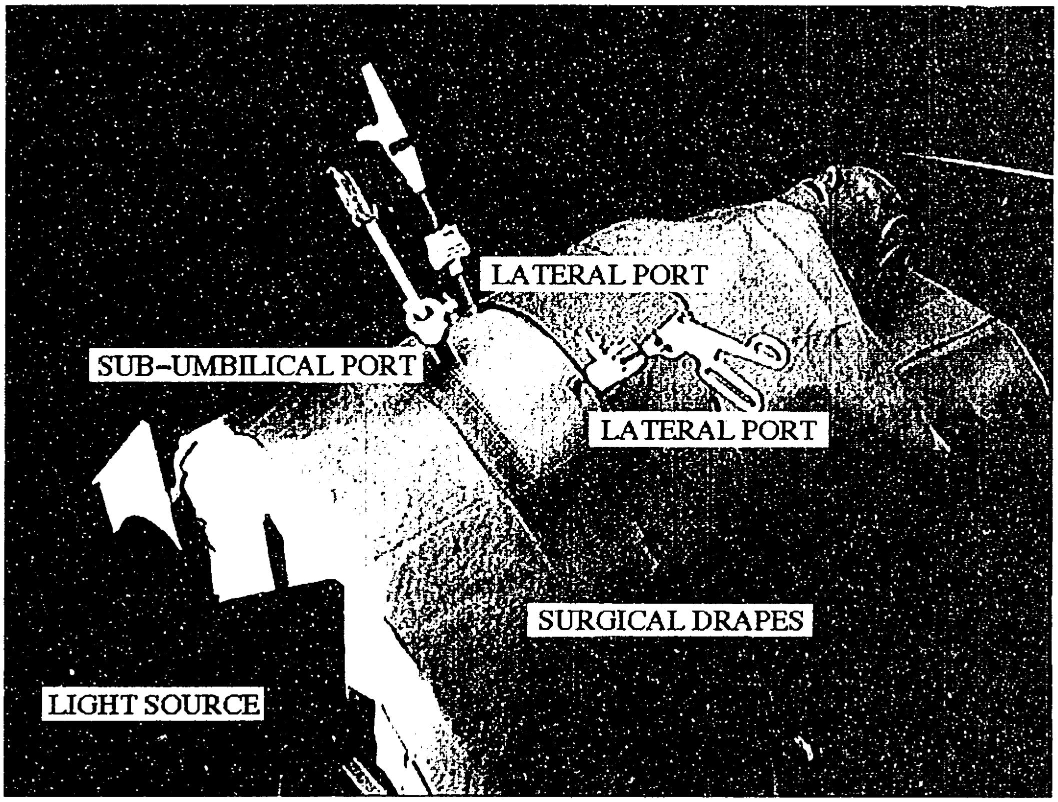


Figure 2-10: Demonstration simulator. Light source at lower left illuminates interior through access hole (hidden under drapes).

Audio communication was conducted by using two pairs of headphones with boom microphones. The microphone inputs were amplified using the left and right channels of a stereo home audio amplifier. Two 21 inch video monitors, one each for the surgeon and assistant, were used to present the camera images. An SGI Indigo2 Extreme workstation with a Galileo video card was used to overlay a mouse pointer on the video images seen by the participants. This pointer was controlled by the surgeon, who used it as an additional tool to direct the assistant.

Time delays in the audio and video communications were generated by using a device which buffers incoming signals for a period of up to two seconds. It is often used by television and radio broadcasters (who use units with higher capacity) to synchronize signals and to provide time to block inappropriate language from being transmitted. The delay buffer includes two audio channels and one video channel. Verbal communication used one channel in each direction (i.e. to or from the surgeon), and the video signal returning from the remote site was sent through the video channel. No video information was sent from the surgeon's site.

2.2 Experimental Tasks

Surgery is not an exercise that lends itself well to detailed quantitative analysis. Most forms of evaluation employ the times required to complete operations and rates of success or failure. One group [CSJG95] has attempted to break down the time requirements for different tasks within operations by video recording multiple views of activities in an operating room. They analyze them afterwards to determine the proportion of time spent on each aspect of the operation.

Since it was not intended that the research include animal or clinical trials, a set of simpler, related tasks had to be found. Requirements for the tasks included ease of measurement in quantitative terms and recognizable similarity to laparoscopic surgery to give face validity to the tests. [SHC94] have developed a set of basic training exercises for medical students learning the elements of laparoscopic tool manipulation. They do not specify how they evaluate the tasks, but by recording the view from the laparoscope on video tape, the elemental tasks can be evaluated for speed of completion and frequency of errors committed. As they are specifically for use in developing laparoscopic skills, the tasks also meet the validity requirement. A subset of the training tasks was chosen which covered a variety of the skills required and which could be performed with the available equipment. These are described in the following sections.

2.2.1 Grasp and Transfer (G&T):

This task provides experience in manipulation of gripper tools and control of the laparoscope. Two grippers are used, first to grasp an object from a cup with one gripper, transfer it to the second gripper, then to place the object in a second cup (Figure 2-11). In the version used in the experiments, six foam rubber ear plugs were transferred from the left hand cup (as viewed through the laparoscope) to the right, then the six were transferred back again. The cups were placed so that they could not both be seen completely at the same time, making it necessary to move the laparoscope to see either cup entirely.

The time between the surgeon's command to grasp a given plug and it's successful placement in the second cup was recorded for each transfer. When the surgeon was the first to pick up a plug, timing began when the surgeon started moving the tool towards the plug. Errors were judged to be any event which did not correspond with the task or the instructions given by the surgeon. Examples of these include dropping the plugs, knocking plugs out of either cup, picking up more than one plug at a time and picking up a plug other than the one indicated by the surgeon (assistant only). When a plug was dropped during a transfer, it had to be picked up with the tool that dropped it, or by the donor tool if the drop occurred in mid-transfer, and the task was then completed.

This task was modified from the original training task in that the ear plugs were used in place of short segments of dental swab. Both items are of similar size and weight, and both deform somewhat

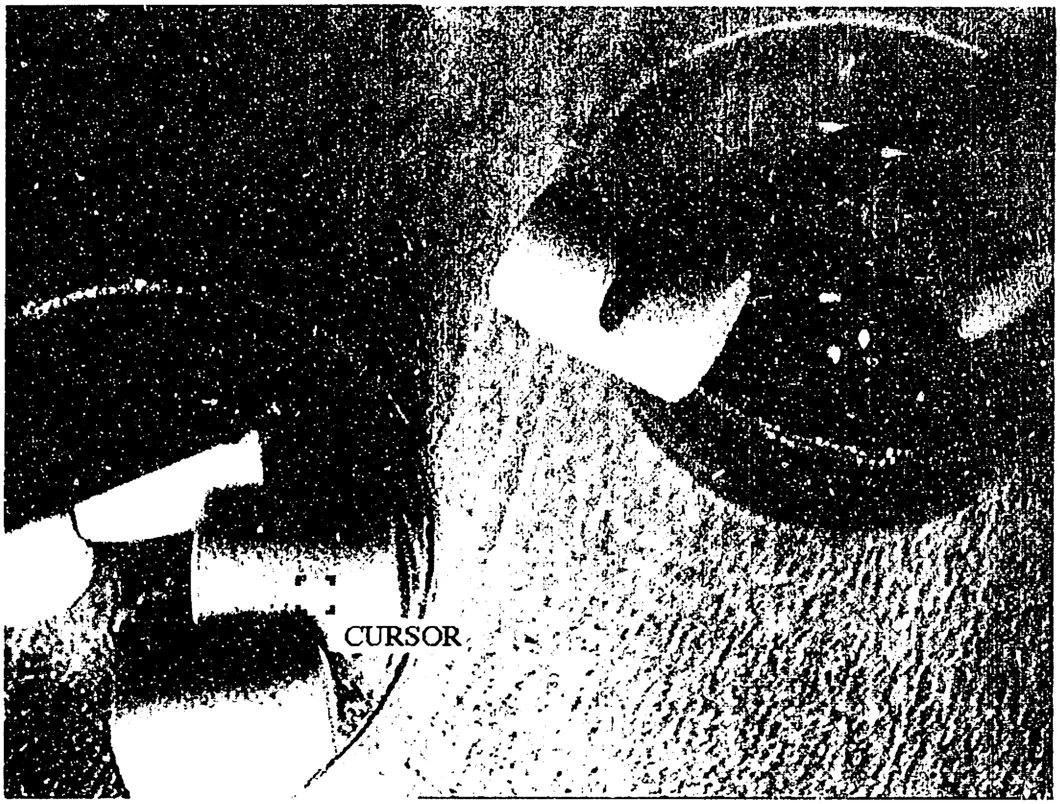


Figure 2-11: Grasp and Transfer apparatus.

under grasping force. Also, the original task did not specify the spacing between the cups.

2.2.2 Grasp and Transfer with Orientation (G&TwO):

A slightly more complex task than G&T, this task uses paper clips instead of ear plugs, but is otherwise very similar (Figure 2-12). Six paper clips were transferred from the left to the right cup and back again. Timing was judged as in G&T. However, the clips had to be grasped only at their ends rather than along the sides (where there were two parallel lengths of wire). The surgeon also specified one end or the other that had to be grasped by the assistant. In completing the transfer between the two grippers, the receiving gripper had to grasp the free end of the clip.

Errors include those listed for G&T, and also grasping a clip at the end not indicated by the surgeon, grasping the clip along the sides and receiving the clip by grasping the end already held by the other grasper. Recovery from dropping errors was carried out as in G&T.

2.2.3 Use of Clip Applier (CA):

The laparoscopic clip applier is a commonly used tool to control fluid flow (blood or other) in ducts or vessels that are to be severed. A small titanium clip is loaded into the jaws of the tool, and then squeezed around the desired structure. In a gall bladder removal for example [BIZ91], the cystic

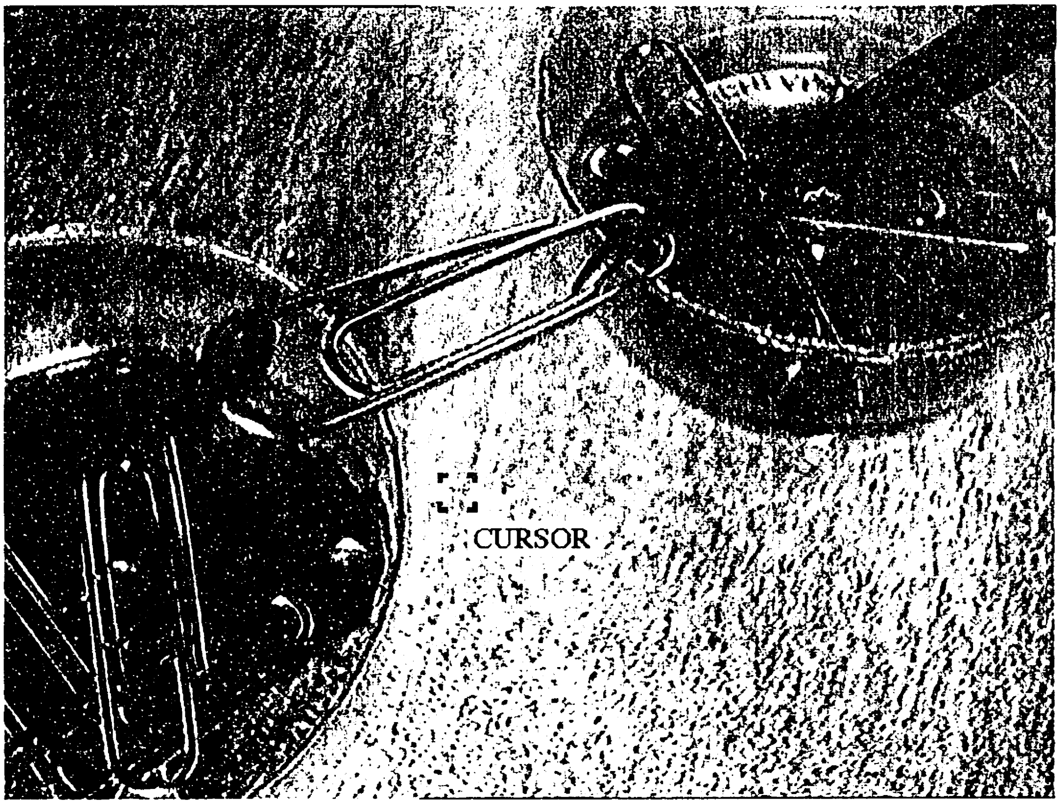


Figure 2-12: Grasp and Transfer with Orientation apparatus.

duct and a number of blood vessels leading away from the gall bladder are clipped on either side of the locations to be cut. This stops fluid flow, after which the vessels can be cut by various means including laparoscopic shears, electro-cautery or fiber optic laser. Blood vessels, nerves and other structures are often found together in "neurovascular bundles" [Gra59], so it is important that only the desired structure is clipped, excluding the other adjacent ones.

In this task, five sets of three adjacent rubber bands were placed around the cup (Figure 2-13). The bands were red, blue and light brown, roughly representing an artery, a vein and a duct. In this experiment, the "duct" was the structure to be clipped and cut. The clip applier jaws were placed around the "duct" at a surgeon-specified location along the band, then the clip was placed on the band. Another clip was placed at a second location and the shears were used to cut between the two clips. Timing began when the surgeon indicated the first location to be clipped or when the surgeon began to move the clip applier towards the band. It ended when the band had been cut. When the assistant controlled either the clip applier or the shears, the surgeon had to be satisfied with the placement of the tool and give a verbal confirmation before the assistant could complete the subtask.

Errors for this task included: placing a clip at a location other than the one specified; placing the clip before the verbal confirmation had been received; catching either the "vein" or "artery" in the clip; cutting at a location other than the one specified; cutting a structure other than the "duct";

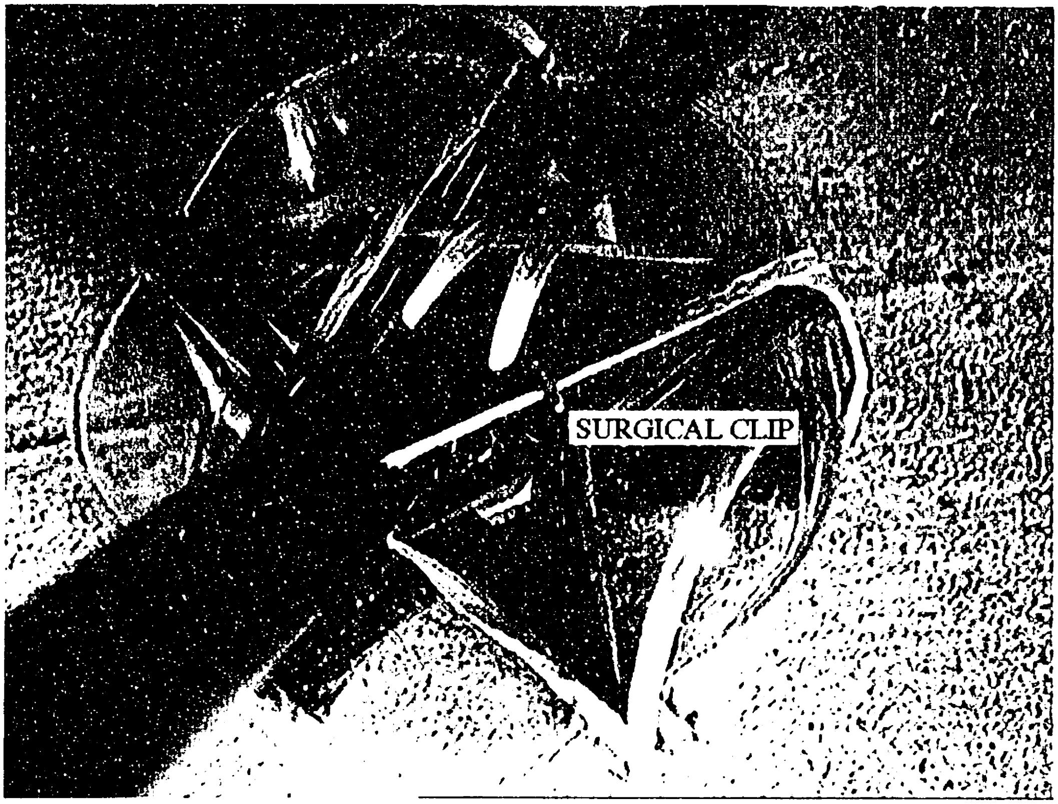


Figure 2-13: Use of Clip Applier apparatus. Note clip already placed on band.

and cutting before receiving confirmation.

The arrangement of the bands, beyond placing them around the cups, was not originally specified. Further, bundles of bands were used instead of the single bands of the [SHC94] training task. The change was made to more closely simulate real structures. The last change was that when the surgeon was using the teleoperator (for which there was no clip applier tip) the gripper tip was used in its place. Black marks were made on the "duct" in the locations where clips should be placed, and the surgeon's success in closing the gripper at the correct spot was determined from the video tape. In this mode, the assistant was instructed to make a cut between the two black marks.

2.2.4 Use of Scissors (UoS):

As with open surgery, sutures can be used laparoscopically to bring sections of tissue together. While sewing laparoscopically is a very difficult task, and beyond the ability of a surgeon working through a one-armed teleoperator and an unskilled assistant, removing excess suture material after knots have been tied is possible. In this task, a grasping tool was used to hold the end of a piece of suture material, and the shears (scissors) were used to cut at a specified location between the gripper and the point of attachment (Figure 2-14). The suture segments used in this task were alternately colored light and dark, in 1/4 inch sections, and cuts were made only in the light colored sections.

Figure 2-14: Use of Scissors apparatus. Note banding on suture material.

When the assistant used the shears, the surgeon had to give verbal confirmation that the shears were placed correctly before the cut was completed. Six pieces of suture material were available at the beginning of each set of tasks.

Timing for this task began when a given piece of suture was indicated or when the surgeon began moving towards a suture. It ended after the suture had been cut and the cut segment placed in the central cup. Errors recorded included grasping the wrong suture, grasping two sutures simultaneously, cutting in either the wrong light section or in a dark section, cutting two suture pieces at the same time, not waiting for confirmation before cutting, allowing the suture segment to slip out of the grasp of the grasper and dropping the cut segment somewhere outside of the cup. While in a real procedure, dropped segments of suture would have to be recovered, in these exercises timing for the dropped suture was stopped and the remainder of the exercise was completed.

The only modifications from the original training task were the banding of the suture segments and the mounting method. Banding made the decision of what constituted a position error in the cut easier and the mount made setting up for further repetitions more efficient.

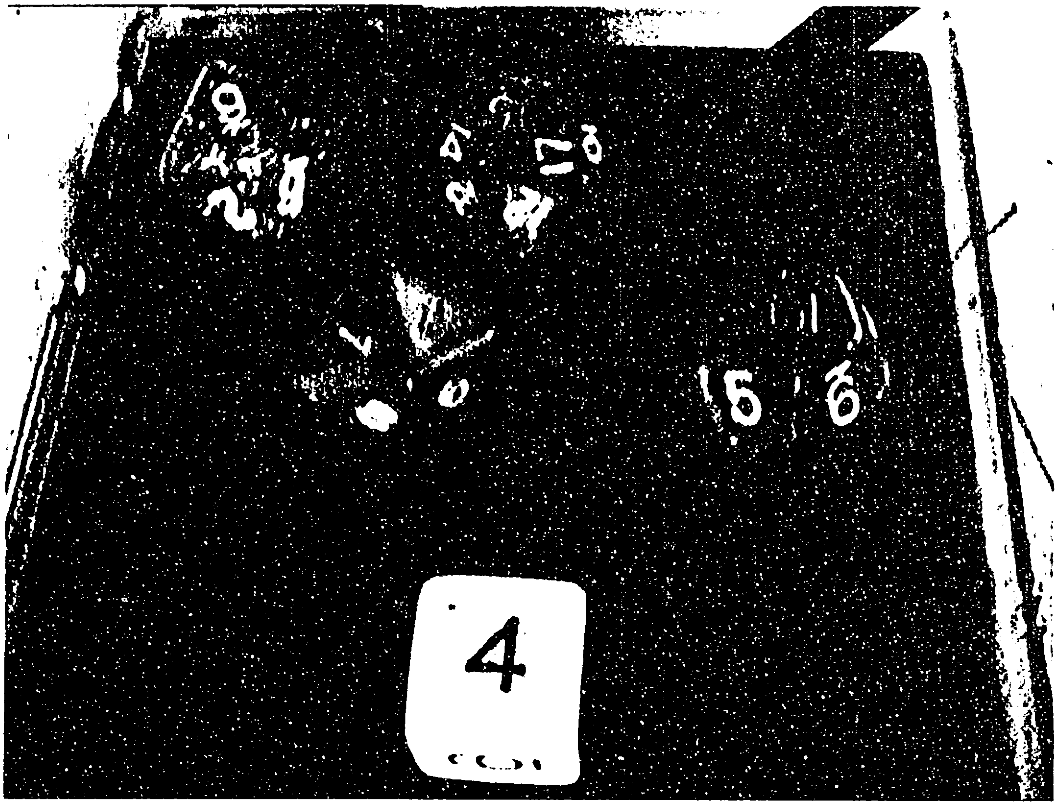


Figure 2-15: Observation task apparatus.

2.2.5 Observation (Obs):

One task that was not included in the set presented in [SHC94] concentrated on controlling a probe and the laparoscope to make observations/identifications. This task required the telesurgeon/assistant team to expose specific sides of various polyhedral dice. A probe tool (gripper with jaws closed) was used to roll the dice to expose a given side, then to expose the opposite side (Figure 2-15). The surgeon was aware of which numbers had to be shown but did not reveal this to the assistant, instead using the mouse pointer to indicate which face to push and in which direction. This simulated a surgeon examining specific locations on a structure that must be manipulated to show surfaces that may be hidden. This turned out to be more of a test of the ability to roll the dice correctly rather than an exercise in evaluating laparoscope control. The task required precise control over forces exerted through the tools to avoid rolling the dice in uncontrolled ways.

Completion time was the only variable recorded in this task, and is started when the first desired side was positioned face up and finished when the opposite side was shown face up. The results will be shown, but no extensive analysis was performed on them.

2.3 Experimental Procedure

In these experiments, a number of factors were held constant or were not variables that could be changed easily. Firstly, the same surgeon, Dr. James Thompson, M.D., served as telesurgeon for all of the subjects (assistants). Presumably there would be variations between surgeons based on innate ability and training. However, bringing other surgeons in would have increased the number of trials geometrically. Second, there was only one teleoperator system available for use. Use of a one-armed manipulator with only partial force feedback would very likely yield different results from a two-armed device with full force feedback.

The first independent variable in the study was the level of round-trip (closed loop) time delay in the teleoperator system. Three levels were considered: zero seconds, 0.6 seconds and 1.2 seconds. The zero second level of delay represented use of the teleoperator in cases where the master and slave are connected through the same control computer and there are no delays in the audio and video communications. Alternately, this case simulated the use of a very high bandwidth communications channel between the two locations (e.g. T-1 or T-3 phone lines at 1.5 and 45 Mbits/second respectively).

The 0.6 second delay level represented the delay inherent in the use of three ISDN telephone lines simultaneously (called fractional T-1, 364 kbits/second). A commercially available video conferencing system, acquired for use later in this project, employs an image compression chip set which adds a delay of 0.3 seconds between the master and slave, and another 0.3 seconds for the return trip [Zyd96]. In the experiments, the control program buffer in the Pentium and the audio/video delay generator were synchronized so that when the tele-surgeon made a motion, he would see, feel and hear the results all delayed by the same amount.

The 1.2 second delay was included to demonstrate the effects of further delay in the system, such as those that would be experienced if satellite communications were employed between the master and slave [MWN+95]. The delay was made up of a 0.6 sec. delay from the master to the slave, and another 0.6 sec. to receive feedback from the remote site.

One additional "delay" case was included as a "gold standard" for comparison purposes, namely that of direct interaction of the surgeon with the tools and simulator (i.e. unmediated by the teleoperator). This represented the case of a surgeon being physically present in the operating room with the patient rather than being "tele-present".

The second independent variable in these tests was the tool assigned to the surgeon. For the G&T and G&TwO tasks, the surgeon used either the laparoscope or the right gripper (as seen through the laparoscope) with his right hand. As mentioned earlier, the surgeon also controlled the mouse pointer, which was held with the left hand.

When the surgeon controlled the laparoscope, the assistant controlled both grippers; when the surgeon controlled the gripper, the assistant controlled the other gripper and the laparoscope. The assistants were instructed to hold their tools in the hands that felt most comfortable. Because the laparoscope was positioned to the right of the assistant's gripper, this meant that some subjects performed the task with their arms crossed in front of them. The effect of handedness and usage of the tools in this sense was treated as an uncontrolled, random variable.

For the CA and UoS tasks, the surgeon used either the laparoscope, the shears or the gripper (or clip applier for CA, direct interaction mode) and the assistant controlled the remaining tools. When controlling either the shears or the clip applier/gripper, the surgeon used the right hand trochar (laparoscope point of view) and the assistant's tool was inserted through the left trochar. The instructions for the assistant regarding which hand to use for which tool were the same as for the G&T tasks.

In the Obs task, either the surgeon or assistant controlled the laparoscope, and the other partner controlled a probe, in this case a gripper tool with closed jaws. When the surgeon controlled the probe, he used the right hand trochar, while the assistant used the left trochar when using the probe.

Each task was performed under all of the time delay and tool assignment modes described above. Thus, for the Obs, G&T and G&TwO tasks, there were eight combinations of time delay and tool assignment, and for CA and UoS, there were twelve. Pretesting and early subjects showed that the CA and UoS tasks were very difficult and fatiguing under time delay conditions, and that the Obs task was impossible to perform when the surgeon controlled the probe under time delay. Because of this, three bands (of five) in CA and four sutures (of six) in UoS were used when the surgeon controlled tools other than the laparoscope. Under time delay conditions in Obs, the surgeon only performed the laparoscope control case.

The subjects were six male students between the ages of 20 and 30. Each subject was tested over the course of two 3-1/2 hour sessions on different days. In the first session, an untrained test of each subject's ability was performed, followed by a training session. The subject then performed all of the tasks under direct interaction and teleoperation with no delay. In the second session, the two time delayed cases were performed.

The pre-training tests were of ability to perform the Obs and G&T tasks with the surgeon controlling the laparoscope with the undelayed teleoperator. The subject was shown the function of the gripper by the experimenter before beginning the tests, and the surgeon described what had to be accomplished once the test had begun. Upon completion of the pre-testing, the subject was shown a video tape of a real laparoscopic gall bladder removal. During the video, he was told how the tasks he would be performing related to the operation being shown. Afterwards, the assistant was taught how to perform each of the tasks correctly. He practiced all of the tasks under the observation of the experimenter to ensure that he could perform them properly.

During the post-training experiment sessions, the individual tasks were performed in the order Obs, G&T, G&TwO, CA and UoS. The order in which tools were assigned within the delay cases was varied between subjects to provide partial counterbalancing. Rest breaks of a few minutes were given between each tool assignment case to permit the experimenter to change tools and to prevent fatigue.

Chapter 3

Results

The measurements taken from the video recordings of the experiments were the individual task completion times and the number and types of errors committed by the telesurgeon/assistant pair. The time data will be presented first, followed by the error data, both by task. A more complete listing showing the statistical data can be found in Appendix B.

3.1 Completion Time Data

3.1.1 Grasp and Transfer:

This plot (Figure 3-1) shows the combined data for all subjects partitioned by the time delay case and by the tool assigned to the surgeon within each delay case. Plotted are the mean completion times, bars showing one standard deviation from the mean and the range of completion times. For direct interation (DI), no statistical difference was found between the case of the surgeon controlling the laparoscope and the surgeon controlling one of the grippers (t-test, p=3.1%). Assuming that the surgeon is already proficient at the task, this suggests that training was sufficient to bring the subjects to a fairly high level of proficiency.

In all three of the teleoperated cases, the task was performed more quickly when the surgeon controlled only the laparoscope (t-tests, p=3.5E-4, 2.5E-9, 6.0E-16 respectively). With the subject performing the task under direction, the completion time remained constant from no delay to 1.2 seconds delay (t-test, p=48%). This is encouraging because it indicates that there was little or no additional learning by the subject after the training session. Another interpretation is that the increased speed due to learning was offset by increasingly poor performance by the surgeon using the laparoscope. However, the placement of the laparoscope was not usually critical. Further, the surgeon often anticipated the completion of a task by moving the mouse pointer to the location of the next plug to be picked up in advance of actually giving the command. These two factors suggest

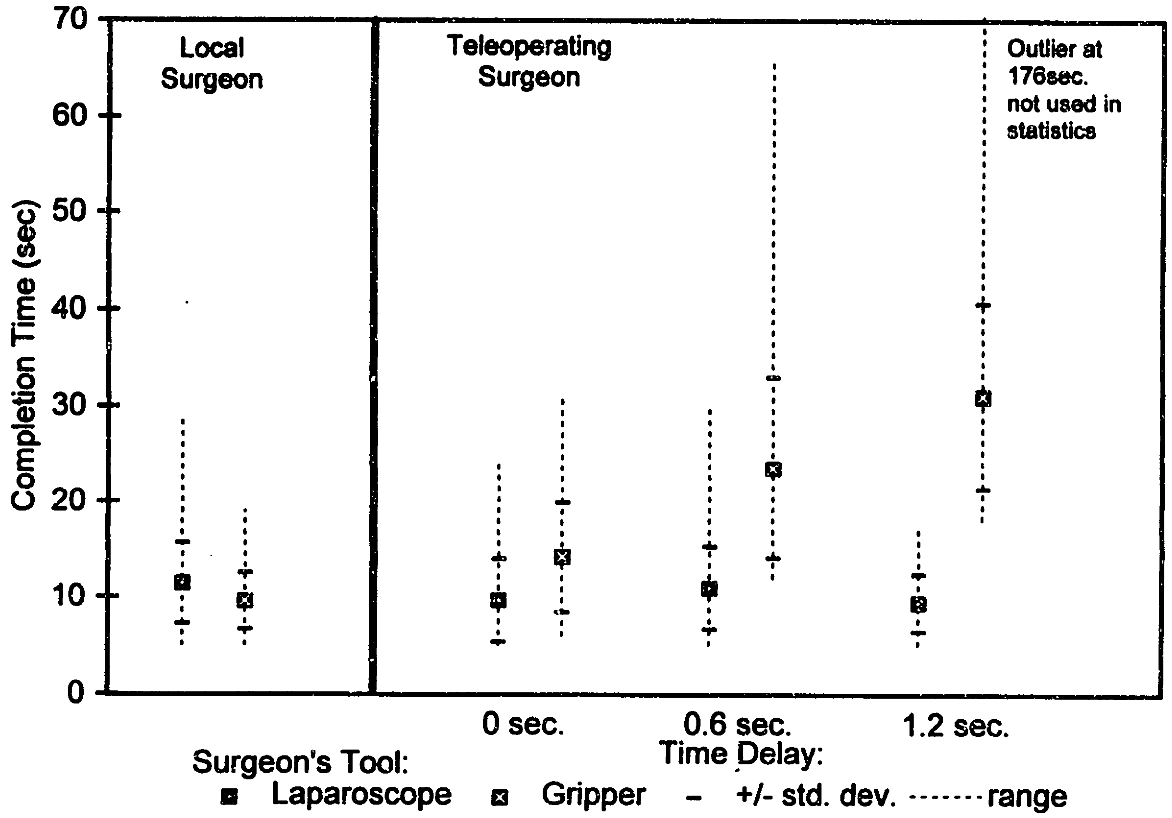


Figure 3-1: Aggregate (6 subjects) Grasp and Transfer task results by time delay mode and surgeon's tool assignment.

that the former interpretation is likely to have a larger effect than the latter.

When the surgeon participated by controlling a gripper, completion time increased with time delay. With only three data points, a detailed relationship between completion time and delay is difficult to determine. However, a very good least squares linear fit can be performed, with a slope of 14.0 seconds longer completion per second of time delay, an intercept at 0 sec. delay of 14.5 sec. completion time and an R square value of 0.996.

3.1.2 Grasp and Transfer with Orientation:

The format of this plot (Figure 3-2) is the same as that for G&T. Again, no difference was found under direct interaction between the surgeon using the laparoscope and the surgeon acting through the teleoperator (t-test, p=22%).

The results for G&TwO are similar to those for G&T. Performance when the surgeon controlled the laparoscope remained constant (p=59% between 0 sec. and 1.2 sec. delay), and performance became worse with increasing delay when the surgeon controlled the gripper. The slope and intercept for a least squares fit are 19.6 sec./sec. delay and 20.4 sec., respectively. Again, the fit is very good, with an R square of 0.995.

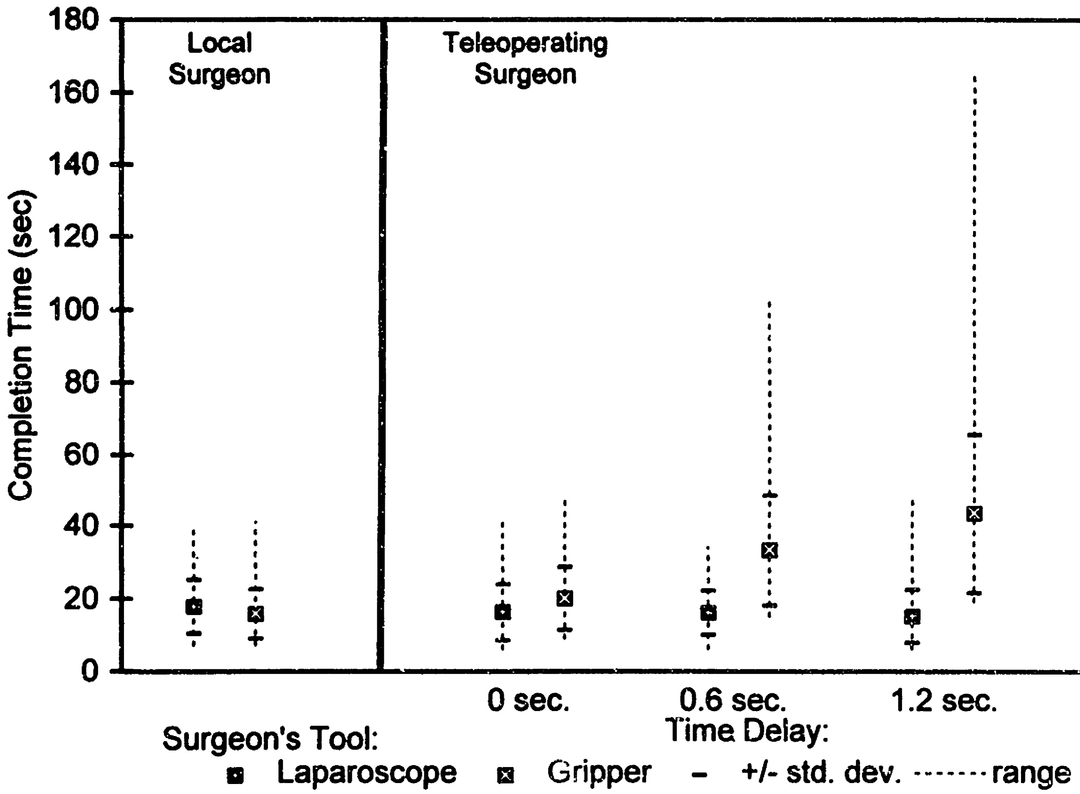


Figure 3-2: Aggregate Grasp and Transfer with Orientation task results by time delay mode and surgeon's tool assignment.

3.1.3 Use of Clip Applier:

With three experimental cases, the comparisons became more complex. Comparisons were made for all combinations of all three tool assignment cases using t-tests (Figure 3-3). In the case of direct interaction, there was no difference in performance between the surgeon controlling the laparoscope and the surgeon controlling the shears (p=19%). When the surgeon controlled the clip applier, the time was shorter than either laparoscope or shears (p=1.6E-5 and p=4.4E-4 respectively). As with the two previous tasks, completion time when the surgeon controlled the laparoscope remained constant across all delay modes. However, when the surgeon controlled the clip applier, performance degraded rapidly (slope = 157 sec. longer per sec. of time delay, intercept = 26 sec., R square = 0.979). A less severe increase occurred for the surgeon when using the shears (60.1 sec. longer/sec. delay, 38 sec. intercept, R square = 0.997).

Of particular note is how the task differed under the various tool assignments. When the surgeon controlled the clip applier/gripper, he had to place two clips with precision. When using the scissors, only one cut had to be made, and the positioning task was easier because any location between the clips was acceptable for cutting. Since the assistant's contribution was made very quickly in comparison with the time delayed surgeon, the main reason for the difference between performance with clip applier/gripper vs. shears is that twice as many more difficult positioning subtasks had to

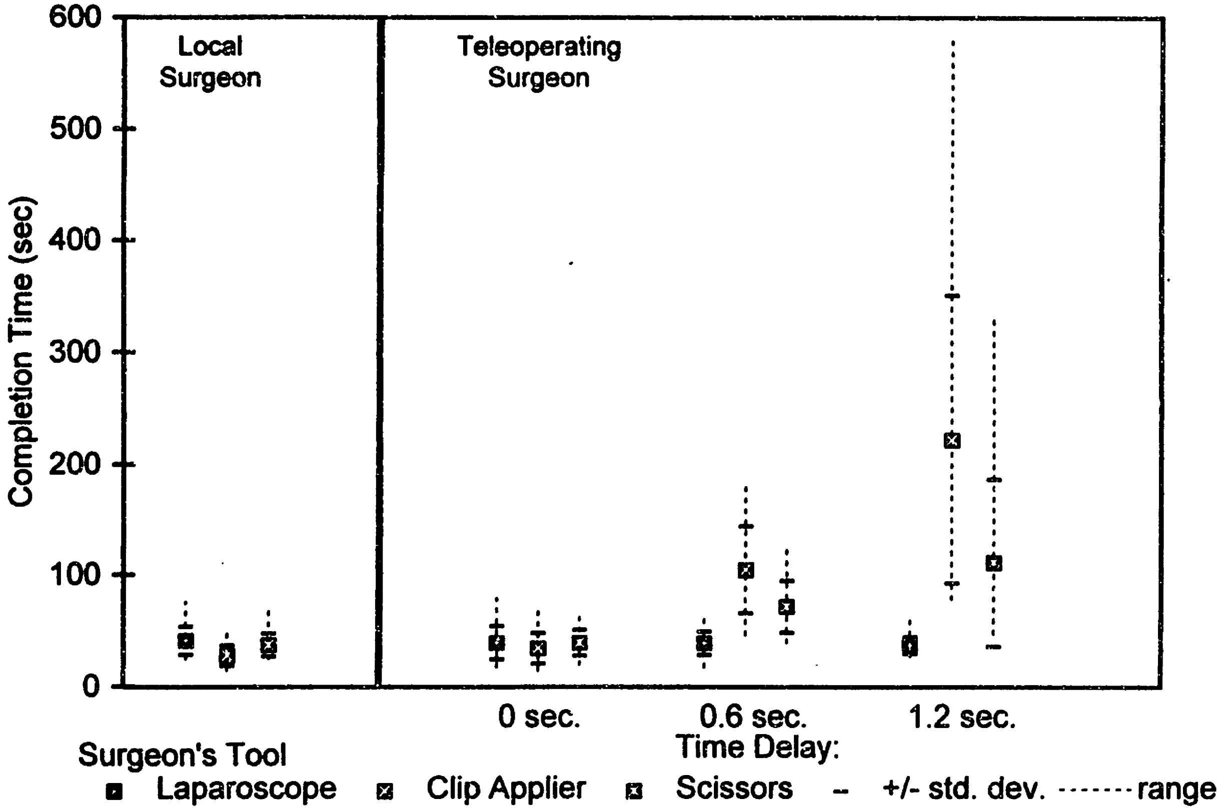


Figure 3-3: Aggregate Use of Clip Applier task results by time delay mode and surgeon's tool assignment.

be performed.

3.1.4 Use of Scissors:

The same comparisons were made for UoS (Figure 3-4) as they were for CA. For DI, performance was quickest when the surgeon controlled either the gripper or the shears; there was no statistical difference in performance between the two (p=22%). In fact, under all teleoperated modes, there was no difference between the cases where the surgeon controlled the gripper or the shears. In comparing this task with CA, one notices that the positioning task for both the gripper and the shears were of similar difficulty, and each tool was used only once, versus the clip applier being used twice in CA. Times were also lower because tool positioning was easier than in CA; suture segments were not in bundles, so no nearby structures needed to be avoided in most cases.

Completion time fell slightly when the surgeon controlled the laparoscope (p=0.12%), from 26 sec. to 21 sec. between teleoperation with no delay and 1.2 sec. delay. One possible explanation for this is that training on this task was insufficient, so a performance plateau was not reached before the experiments began.

The least squares fits of performance degradation versus time delay for surgeon using the gripper and shears are very similar: slope = 47.9 sec./sec. delay, intercept = 19.3 sec. R square = 1.000 for

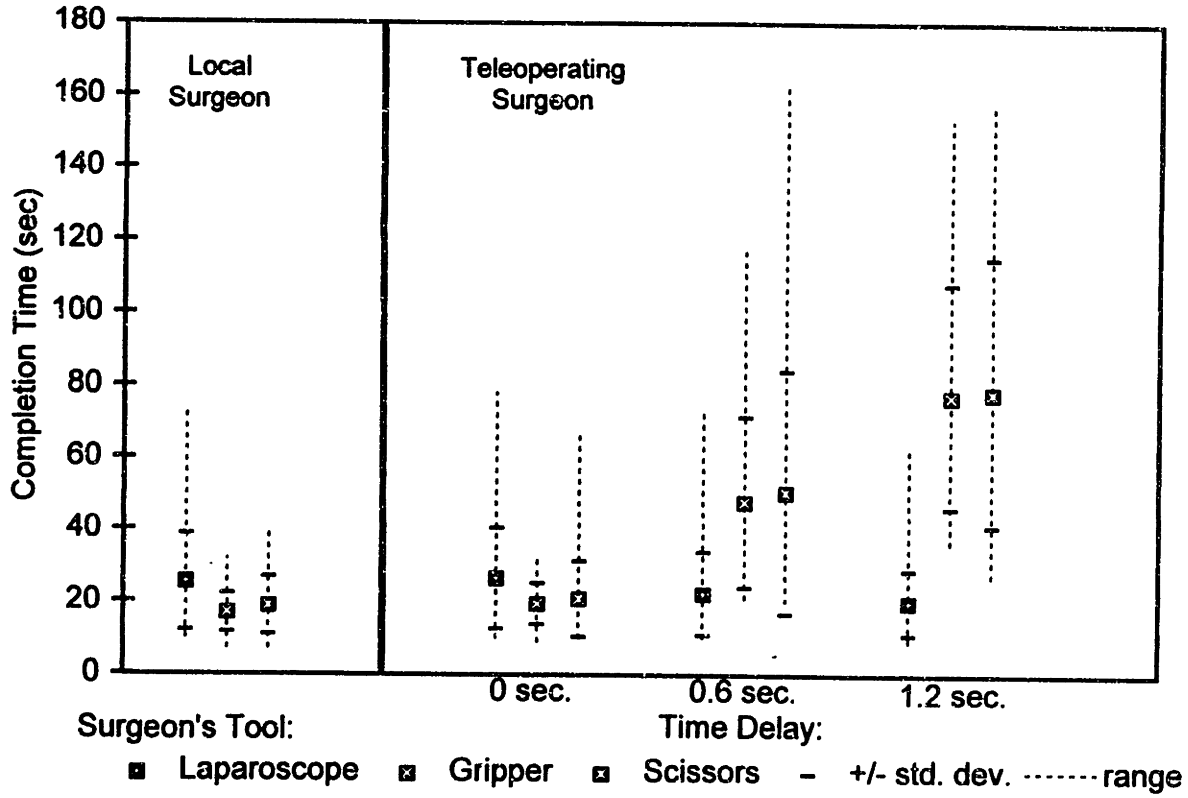


Figure 3-4: Aggregate Use of Scissors task results by time delay mode and surgeon's tool assignment.

gripper; slope = 47.7 sec./sec. delay, intercept = 21.1 sec. R square = 1.000 for shears.

3.1.5 Observation:

As mentioned earlier, the Observation task was not as successful as the other tasks. What can be shown from the data (Figure 3-5) is that in general, the task was completed more quickly when the surgeon controlled the probe. This is borne out in paired t-tests which compare times for each surgeon/assistant pair under the two tool assignment cases ($p < 5\%$). Two exceptions were T0s, 6-sided, in which there was no difference (p=19%) and T0s, 12-sided, where performance was actually better when the assistant controlled the probe (p=2.4%).

While the task does not provide any insight into laparoscope use, it does show that a task requiring fine force control requires more experience than was provided during the training session. Also, with time delays in the teleoperator system, the surgeon was unable to perform the task at all when controlling the probe. Because the surgeon's actions and their associated reactions were separated by a delay, and because the delay compensation scheme prevented most of the fine resolution force feedback, the surgeon was not able to reliably maintain control over the dice.

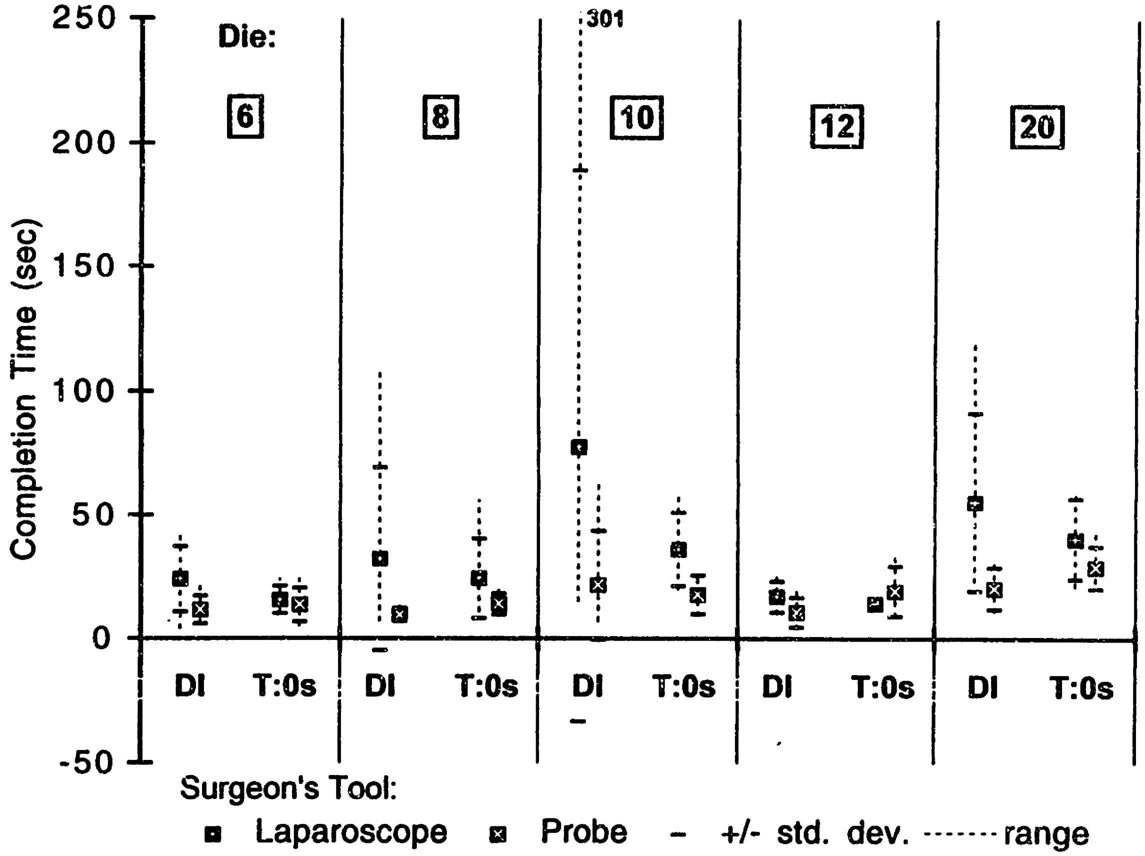


Figure 3-5: Aggregate Observation task results by polyhedral die, time delay mode and surgeon's tool assignment.

3.2 Error Data

Table 3.1 shows the distribution of errors by task, time delay mode, tool assignment and by who made them. These errors do not include errors in communication, such as the assistant placing a surgical clip or making a cut before receiving verbal confirmation from the surgeon. The numbers shown are the sums of errors for all six subjects. In the CA and UoS categories with time delay, where fewer repetitions of the tasks were performed, the real numbers of errors have been weighted (by 5/3 and 3/2 respectively) to make them comparable with the no-delay cases. In those cases, the real values are in parentheses.

A first comment is that in using only six surgeon/assistant pairs, there are not enough data points to develop a good estimate of probablilities of errors in these tasks. However, in examining the table, a number of trends are suggested. First the number of errors committed by the surgeon was not very much different from the number committed by the assistant. For G&T, they were equal, for G&TwO and UoS the surgeon made 18% and 22% fewer errors, and in CA, the surgeon made 22% more errors than the assistant. Next, for G&T, G&TwO and CA, fewer errors were made when the surgeon controlled the laparoscope than when controlling the gripper (or clip applier). However, in CA, the fewest errors were made when the surgeon controlled the shears, and in UoS, the fewest (though by a small margin) were made when the surgeon controlled the gripper.

Something to note in these results is that when controlling the laparoscope, the surgeon could not be charged with any errors as defined in the tasks. While this explains the zero entries for all of the laparoscope-surgeon blocks, it likely skews the data in the surgeon's favor.

		Interaction Mode											
	Error	Direct Int'n			Teleop. 0.0s			Teleop. 0.6s			Teleop. 1.2s		
Task	by	Sc	Gr		Sc	Gr		Sc	Gr		Sc	Gr	
G&T	Surg.	0	3		0	3		0	5		0	0	
	Ass't	0	0		3	3		2	0		3	0	
Totals:			Surg.	11		Sc.	8						
			Ass't	11		Gr.	14						
G&T	Surg.	0	9		0	11		0	9		0	12	
wO	Ass't	3	9		7	6		7	5		7	6	
Totals:			Surg.	41		Sc.	24						
			Ass't	50		Gr.	62						
CA		Sc	CA	Sh	Sc	CA	Sh	Sc	CA	Sh	Sc	CA	Sh
	Surg.	0	4	0	0	5	0	0	3.3(2)	0	0	11.7(7)	0
	Ass't	6	0	3	3	0	1	4	0	1.7(1)	1	0	0
Totals:			Surg.	24		Sc.	14		Sh.	5.67			
			Ass't	19.7		C.A.	24						
UoS		Sc	Gr	Sh	Sc	Gr	Sh	Sc	Gr	Sh	Sc	Gr	Sh
	Surg.	0	1	0	0	3	1	0	1.5(1)	4.5(3)	0	6	3
	Ass't	5	1	5	5	0	1	2	0	3(2)	2	0	1.5(1)
Totals:			Surg.	20		Sc.	14		Sh.	19			
			Ass't	25.5		Gr.	12.5						

Table 3.1: Summary of error results. Aggregate numbers of errors over 6 subjects. Values in parentheses are unweighted. Non-verbal errors only.

Chapter 4

Discussion and Conclusions

In a real surgical operation, both the length of the procedure and any errors made during the course of the procedure would have some sort of cost associated with them. Weighting of these measures probably depends heavily on factors such as the condition of the patient (e.g. critical or not) and potential for serious consequence due to error. In addition, the relative weighting of time and error could vary widely even within a given operation as conditions change. While developing a dynamic cost function is well outside the scope of this project, some tool assignment recommendations based on the data collected here can be made.

The completion time data clearly show that the best performance under teleoperator conditions is achieved when the surgeon controls the laparoscope and directs the assistant to perform the tasks. In nearly all cases, fewer errors were committed under the same conditions. Because of this result, any linear cost function with positive coefficients would indicate that the surgeon/laparoscope combination is the best.

The direct interaction case, however, shows the opposite result, at least in terms of completion time. The teleoperator system used was not ideally suited for performing surgical tasks, leading to the question of what changes might be expected from a better system. For example, the SRI system, which gives the surgeon control of two tools and provides force feedback in all degrees of freedom, elicited good reviews from surgeons who used it, to the effect that they felt as if they were directly performing the operation. It seems likely that with such a system, teleoperation without delay (at least) would show results more like those under direct interaction. If so, one can then ask what the time delay value is where a cross-over between direct telesurgeon participation and telementoring should occur. Based on the results obtained, it is likely that this cross-over delay will fall under 0.6 sec. Determining the cross-over with more precision would require experiments with an improved teleoperator, and more data on probabilities of errors and their relative costs. A related issue (to the cost of time and errors) is the responsibility for the outcome of an operation. Would a surgeon reserve most of the manual tasks for him or herself when coping with a delay, or have faith in the assistant to accomplish a task when time delay would make it more difficult/costly for the surgeon to perform it? Beyond a cost in quantitive terms including time and errors, whenever delegation of tasks to an assistant is considered, less tangible but no less important factors such as public acceptability, insurance, the Hypocratic oath and the surgeon's own morals must also be included.

In comparing the data presented with earlier work, it is encouraging to see that they are consistent with the results obtained by Ferrell [She92] and Black [Bla70] from our laboratory. Not only does completion time increase with increasing delay, but the tasks requiring more precision (e.g. CA) take much longer to perform than less precise ones (e.g. G&T). A quantitative value for precision required for each task would be difficult to obtain, but it is quite easy to determine qualitatively that difficulty increases in the order G&T, G&TwO, UoS and CA, which corresponds with increasing times required to complete the tasks.

Chapter 5

Recommendations for Future Work

Telesurgery is a very young field, and these experiments are among the first to examine the interaction between a telesurgeon and an assistant. They point to further work that will more closely approximate real surgery, and will examine in more detail some of the effects of time delay on the surgeon/assistant interaction. To get the most out of further experiments, improved evaluation methods and improved apparatus should also be developed.

In terms of increasing realism, tasks that include dynamic aspects such as the effect of a beating heart or breathing should be included. For example, in the SRI demonstration [GHJS95], a bleeding vessel was simulated through the use of a bulb of "blood" and a tube leading into the field of the operation. Breathing could be simulated by moving the apparatus in a periodic fashion. Even in the static case, a more comprehensive procedure should be simulated which would include the skills tested in each of the training exercises studied. One of the training tasks in [SHC94] that was not used involved the dissection of a section of porcine intestine with attached mesentary tissue. Such a test might go as far as including tool changes for the surgeon during the course of the operation, if, for example, the cross-over delay indicated that the surgeon should use the laparoscope for part of a procedure and some other tool for the rest.

When judging performance on more realistic simulations and real surgical procedures, it is desirable to have an accurate and reliable cost function or performance index. As mentioned, such an index would likely include time and errors, and might include factors such as fatigue of the surgeon or assistant. Variables that would alter the weighting within the cost function, such as patient condition and nature of the procedure, would also have to be considered.

Looking at the interaction itself, there are a number of modes of cooperation between surgeon and assistant that were not tested. One subject frequently suggested that he help the surgeon in grasping objects or in moving obstacles out of the way. He was restrained from doing so to make his results comparable with those of the other subjects, but modes such as this one could be more useful than the arbitrarily limited ones in these experiments. Another mode that might be especially useful under time delay conditions is for the assistant to guide the surgeon's tool close to a target. The surgeon would then make the final fine motions and the clip placement or cut. This mode suggests itself from the observation that a non-trivial amount of time was spent by the surgeon making gross motions towards the intended target.

Improvements to the teleoperator system are also important. Giving the surgeon full use of both hands is vital to further research, as a real telesurgery system would very likely do so. In addition, a two-handed system should have force feedback in all degrees of freedom, rather than the partial feedback system used in these experiments.

One possibility for improving performance is suggested by the nature of the telecommunications system being used to transmit the audio, video and data signals. In planned demonstrations, a commercial video-conferencing system will be used to carry signals between master and slave. This system performs image compression on the video signal, introducing a delay of 300 msec. each way. The audio and data streams require little or no compression, and therefore could be transmitted with little or no delay. While the experiments used synchronous A/V and data communication, this does not have to be the case. By giving up synchrony between the data and video signals, it may be possible to control the teleoperator system and provide force feedback with negligible round-trip delay, improving stability and the quality of the force feedback given to the surgeon. Whether the asynchronous feedback causes more or less difficulty than a consistent delay may be discovered in the demonstrations.

Ultimately, after simulated experiments have been performed to demonstrate the capabilities of telesurgery systems, the real test will be their function in animal trials and in clinical use with humans. While the time frame for such systems is still unclear, it seems very likely that they will eventually be a factor in saving lives that otherwise would have been lost.

Appendix A

Teleoperated tool hardware and users' manual

A.1 Introduction

In the course of developing a strategy to study cooperation in telesurgery, the model of laparoscopic surgery was chosen as a subset of surgery in general. To perform laparoscopy teleoperatively, a master and slave tool system had to be developed which would, at a minimum, provide the surgeon with the ability to give position commands to a teleoperated tool via a master input device. Ideally, force feedback would be provided to the surgeon through the master device, however it was not initially felt that this was necessary and was not included in this design.

Most common laparoscopy tools (e.g. graspers and shears) provide the surgeon with two axes to be controlled (beyond position in cartesian space). These are control of the tool roll axis and an additional "axis" to control the action of the gripper or shears. The tool that was built provides position control of both of these axes. When the tool is used to control the laparoscope, which uses only the roll axis, the gripper axis is disabled.

The tool is designed to be used with a pair of "shoulder-scale" PHANToM haptic interface arms (SensAble Devices, Inc.), controlled as a master-slave teleoperator pair. The tool and handle replace the standard gimbal mount at the ends of the arms. By using the auxilliary encoder and amplifier ports on the PHANToM amplifier boxes, interfacing the tool with the controlling PC is easy to do, and control functions take the same form as those used to control the regular PHANToM axes.

Control functions were written in Borland C++ (some functions are not included in ANSI C). The control method used for operation is P (proportional) control with additional logic to protect the motors from over-current situations. An automatic calibration routine is available which uses P+I (proportional plus integral) control, but it was found to be more convenient to calibrate the tool manually. The calibration methods will be discussed later.

Manufacturer's specifications on the motors and encoders used can be found in Appendix A.7.

A.2 Hardware

The teleoperated tool consists of an instrumented tool handle which serves as the master, and a slave tool actuated with DC motors. The master and slave were designed with a laparoscopy simulator built in-house in mind, so the simulator and related equipment will also be described.

A.2.1 Handle:

The tool handle is shown in Figure A-1. The connections for the encoders and dead-man switch are listed in Appendix A.5.

The handle is a modified EndoGrasp (Auto Suture Co.) laparoscopy tool instrumented with optical encoders taken from a PHANToM gimbal provided with the PHANToM arm. One encoder

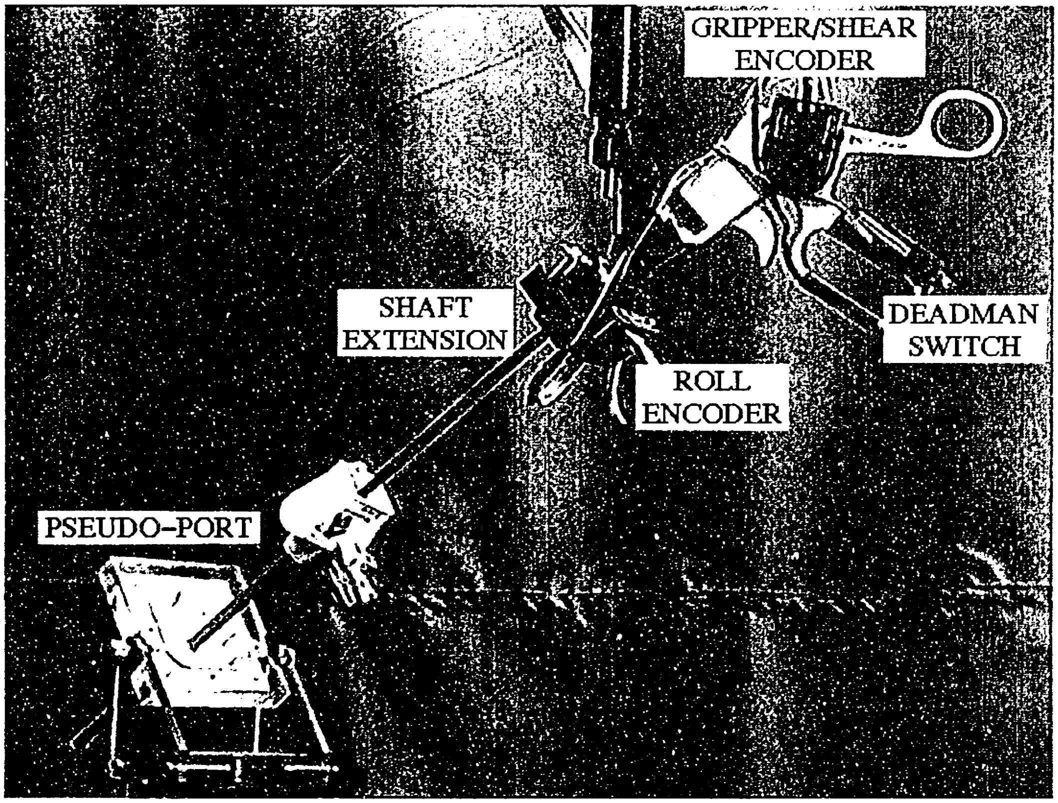


Figure A-1: Teleoperated tool handle (master).

measures the position of the scissor grip, while the other measures the angular position of the shaft of the tool. The shaft can be rotated either by rotating the tool, or by turning the thumb-wheel. Either motion is detected by the roll encoder.

In the interest of safety, a dead-man switch is provided on the handle. This switch must remain depressed at all times during operation. If it is released, the amplifiers are shut off and a digital signal is sent to the control code permitting the program to be shut down in a convenient manner.

In laparoscopy, the tools are inserted through ports (trochars) inserted through the patients abdominal wall. These ports constrain the motion of the tools in two degrees of freedom (D.O.F.), creating a fulcrum point. Since the PHANToM arms can control only three D.O.F., and the tool, as designed, controls only one spacial D.O.F. (the gripper axis does not contribute to tool position control), a method was required to provide two degrees of constraint for the master. The pseudo-port discussed in section A.2.3 provides the constraints when the shaft extension, attached to the roll encoder, passes through it. The shaft extension uses the portion of the original EndoGrasp shaft which was cut to permit mounting the handle to the roll encoder. It is detachable from the encoder if necessary.

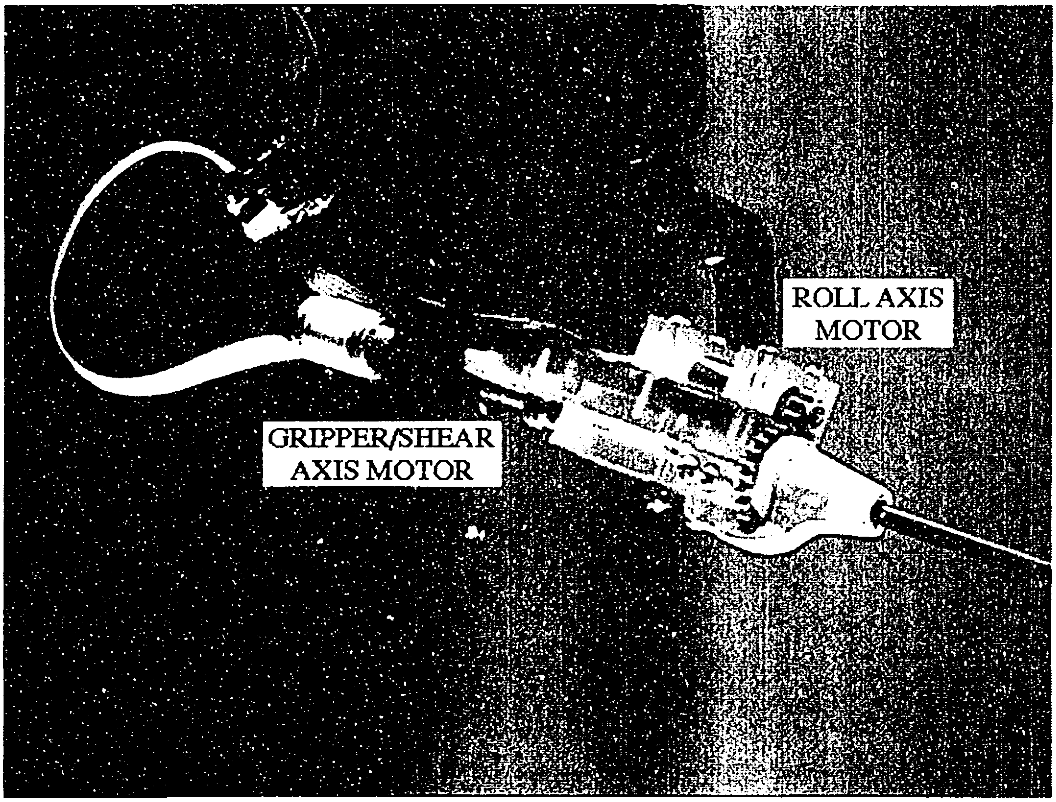


Figure A-2: Teleoperated laparoscopy tool (slave).

A.2.2 Tool:

The teleoperated laparoscopy tool (Figure A-2 consists of a base unit where the motors are mounted, and three interchangeable tool tips. They are an EndoDissect tip (slightly curved gripper tool), an EndoShears tip (scissors), and a tip which controls the CCD laparoscope.

Base unit:

The base unit is shown in Figure A-3. Technical drawings are shown in Appendix A.4, and connector data are listed in Appendix A.5.

The base unit was made from 0.5 inch clear Lexan sheet which was milled to the shape in the design. It holds two coreless DC motors (MicroMo Electronics Inc., see Appendix A.7 for full specifications) with reduction gearheads and optical encoders. The original design did not take into account certain out-of-spec dimensions; shims in various locations correct for this. These shims should not be removed.

The smaller motor (1016M012GK380 with 10/1 16:1 gearhead and HEM1016M10 encoder) controls the roll axis. In addition to the 16:1 reduction provided by the gearhead, a futher reduction of 3:1 is provided by the 8-tooth LEGO pinion mounted on the output shaft to a 24-tooth LEGO gear mounted to each of the tool tips. The encoder measures 10 counts per motor shaft revolution (40

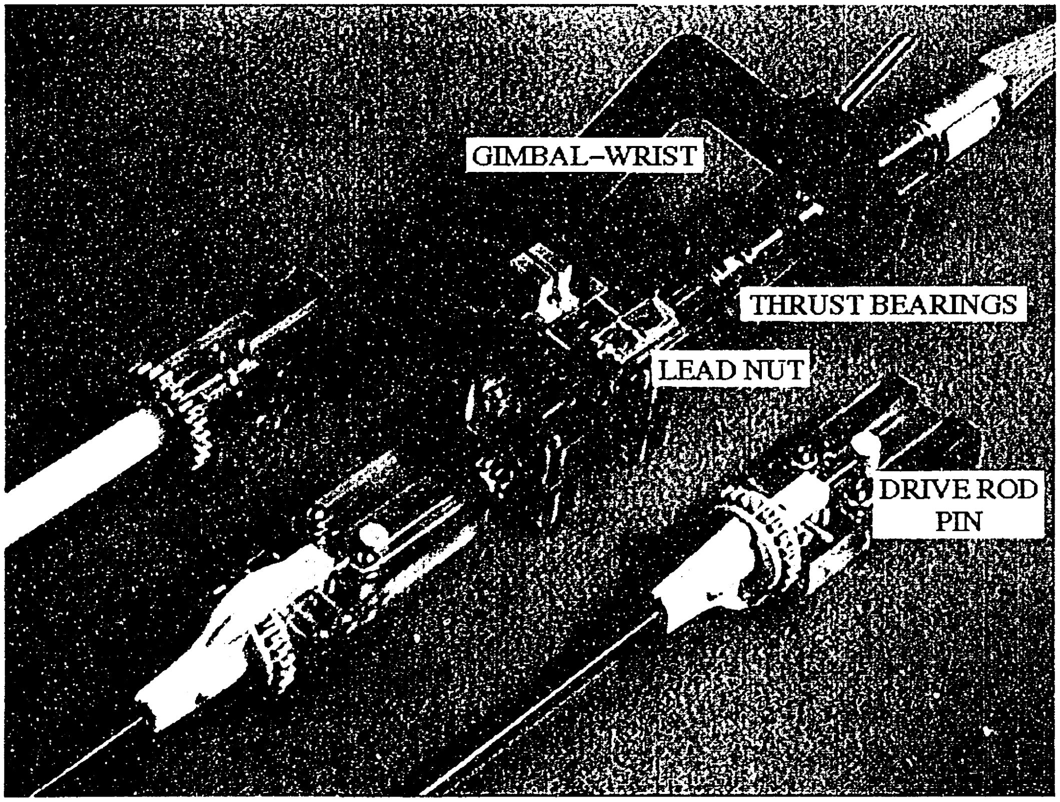


Figure A-3: Base unit and tool tip blocks.

edge-detections in the quadrature signals), so one full revolution of a tool yields 480 counts (1920 edges). There is some backlash between the pinion and gear, but the low precision required in actual operation means that this is not a significant problem.

Under most circumstances, the torque provided by this motor is sufficient to turn the roll axis. There are some exceptions to this, and suggestions as to how to compensate are discussed in section A.3.3.

Based on over-heating considerations, this motor should not ever be supplied with more than 115 mA of current (MicroMo technician recommendation). The coreless DC motor design results in a very short time constant for armature heating compared with regular DC motors. For this reason, a simple current limit is included in the control code, as opposed to the use of the thermal protection function provided with the PHANToM arms. The code is shown in section A.6.

The large motor (1331T012S123 with 14/1 14:1 gearhead and HEM1331T16 encoder) controls the gripper axis. The gearhead provides a 14:1 reduction at the output shaft. The rotary motion is converted to linear motion to actuate the gripper and shear tips through a lead screw mechanism. A coupling attaches a 6-32 threaded rod to the motor output shaft. A matching 6-32 "lead nut" has a socket which fits a short pin on the end of the drive rod in the tool shaft (either tool). This reduction yields a transmission ratio of 7168 counts (28672 edge detections) per inch of linear travel. The gearhead is only designed to tolerate an axial load of 5N, while the force required to actuate the shears is over 30N. To avoid damage, thrust bearings were placed between the gearhead and lead nut to carry the axial load. The set screw which holds the round coupling to the motor output shaft should be tight enough so that the coupling can slip along the shaft but not rotate around it. Tightening it further may cause the axial force to be borne by the gearhead rather than the thrust bearings.

Backlash is again present in the linear axis, but this is a shortcoming of the tool tip and will be discussed in section A.3.3.

Over-heating the larger motor is also a concern, as it was with the roll axis motor. The recommended current limit is 350 mA.

The base unit was originally designed so that the large motor was held in place rigidly in a two part Lexan housing. In this configuration, an automated calibration scheme had to be used (see section A.3.2). It is more convenient to perform calibration manually. In this case, the large motor is held in place with electrical tape and the second part of the housing is left off (housing not shown in Figure A-3).

CCD laparoscope tip:

In endoscopic surgery, the operation is observed through an endoscope, which is basically a tube containing fiber-optic bundles to carry light to the site and the image back to a CCD camera. In our application, it is not necessary to remove the laparoscope from the simulator, so a simpler, and less expensive solution was to place a desktop CCD camera inside the simulator, on the end of a shaft passing through a trochar (see Figure A-4).

The camera is a modified Toshiba IK-M28AT color CCD desktop camera. To function as a laparoscope, the CCD and lens set was separated from the main circuit board and housing, and an extension cable was fabricated to connect the two components. It was not possible to locate appropriate connectors through Toshiba, so surface mount components from a damaged camera of similar design were removed and modified for this purpose.

A light source was not included as part of the camera; ambient room light entering the simulator through the transparent sides was found to be sufficient. Lighting for the demonstration "dummy" is described in section A.2.3.

Two axis tool tips:

As mentioned, scissor and gripper tool tips are available for use with the tool base (see Figure A-3). Both tips are modified from the original surgical tools, retaining the tool shaft and part of the housing. The thumb-wheels were replaced with 24 tooth gears faced with Delrin disks to reduce friction between the gear and housing. The tools tips are held to the main body with a pair of finger-tightened screws.

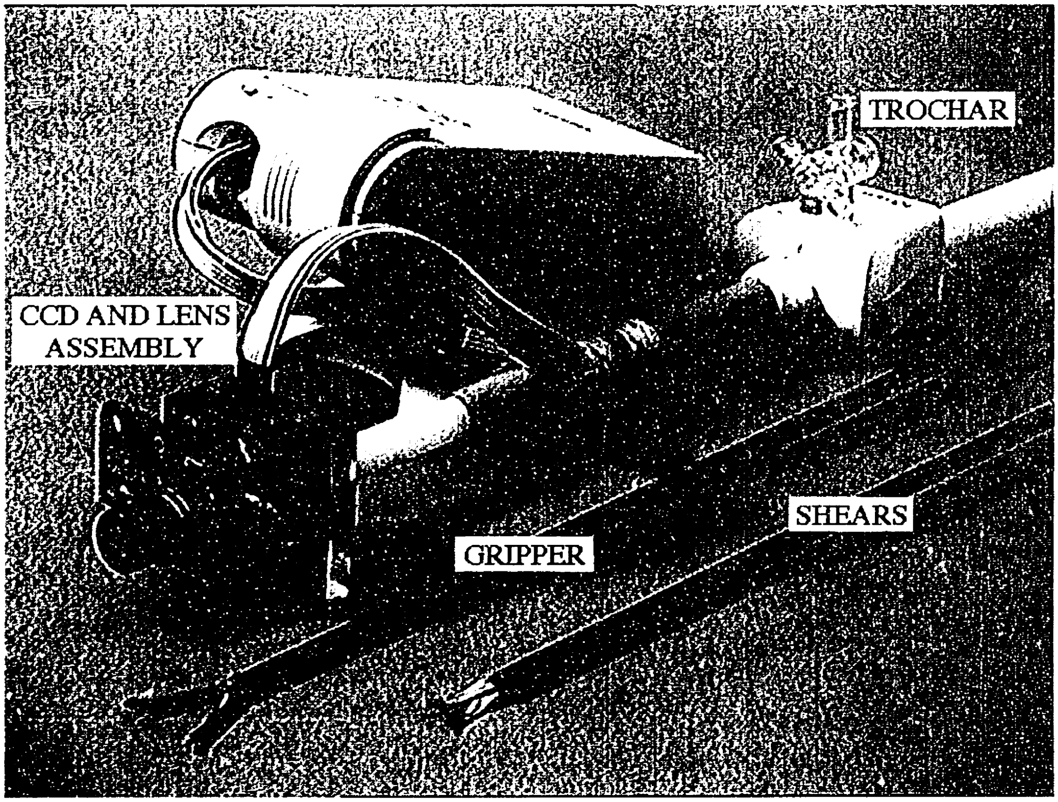


Figure A-4: Laparoscopy tool tips: CCD laparoscope, gripper and shears.

While similar in design, the original tools differ not only in the tip, but also the travel of the internal shaft which drives the tip. The shears tip shaft travel is nearly double that of the gripper tip. Figure A-5 shows the travel converted to encoder counts of both tools in relation to each other, and also to the master gripper axis encoder. Note that the absolute end points of travel for the shears and gripper are different. These data are taken into account in the calibration procedure, in that the tool and the handle are both set to a common neutral position before the system is used. The calibration procedure is described in section A.3.2.

A.2.3 Laparoscopy Simulators and Pseudo-port:

To provide a setting in which to perform the experiments, a surgical simulator was constructed based on commercially available products. The version used in the experiments is shown in Figure A-6. This simulator provides ports for trochars in many locations; an opaque cover to prevent direct viewing by the surgeon or assistant; transparent sides to permit external viewing/recording and lighting; a platform to support experimental task apparatus; and sealant along edges to prevent leaks if bleeders are to be simulated. In the 1996 telesurgery experiments, ambient room light was used to illuminate the experimental stage, though additional lighting could be used.

A second simulator for demonstration purposes was also built (see Figure A-7). It is a modified

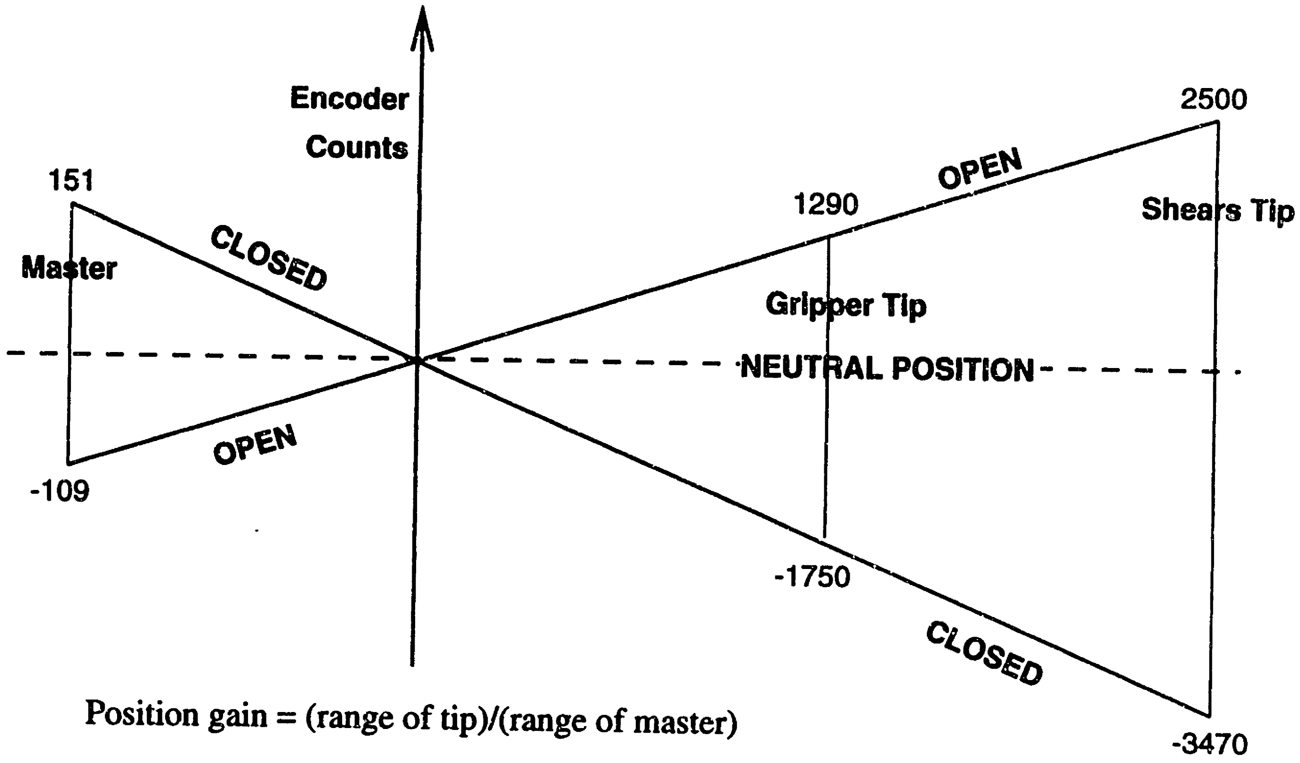


Figure A-5: Relationship between master encoder position and slave encoder in gripper and shears configurations

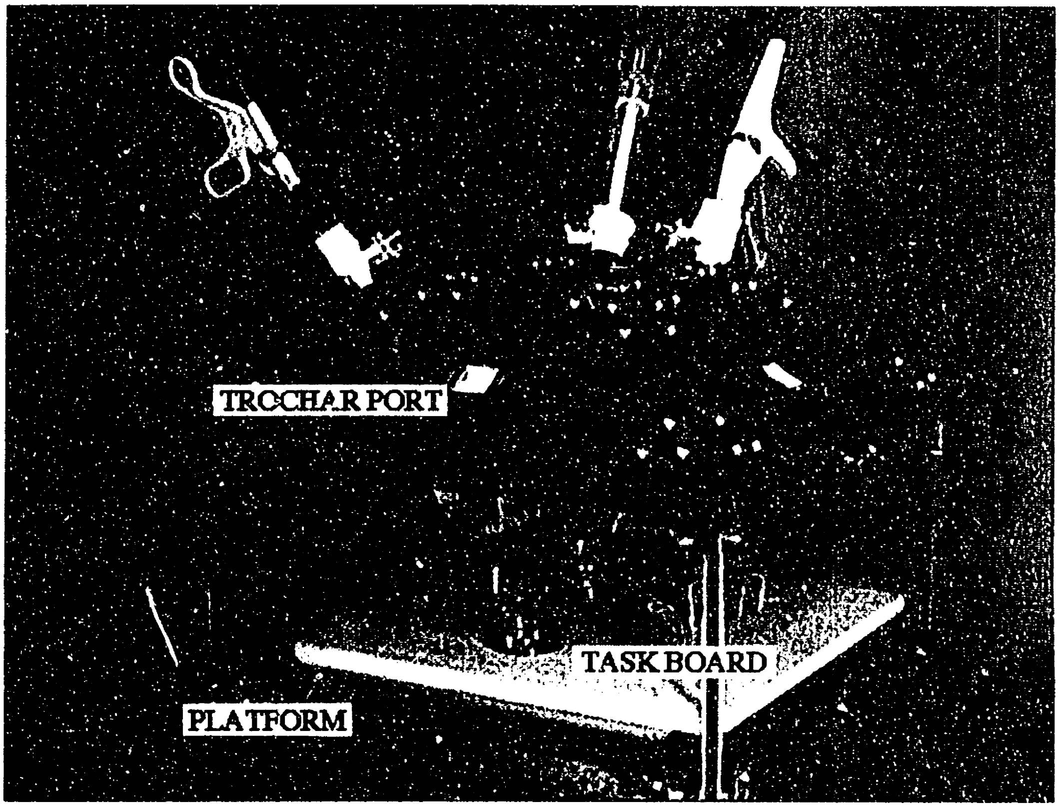


Figure A-6: Experimental simulator.

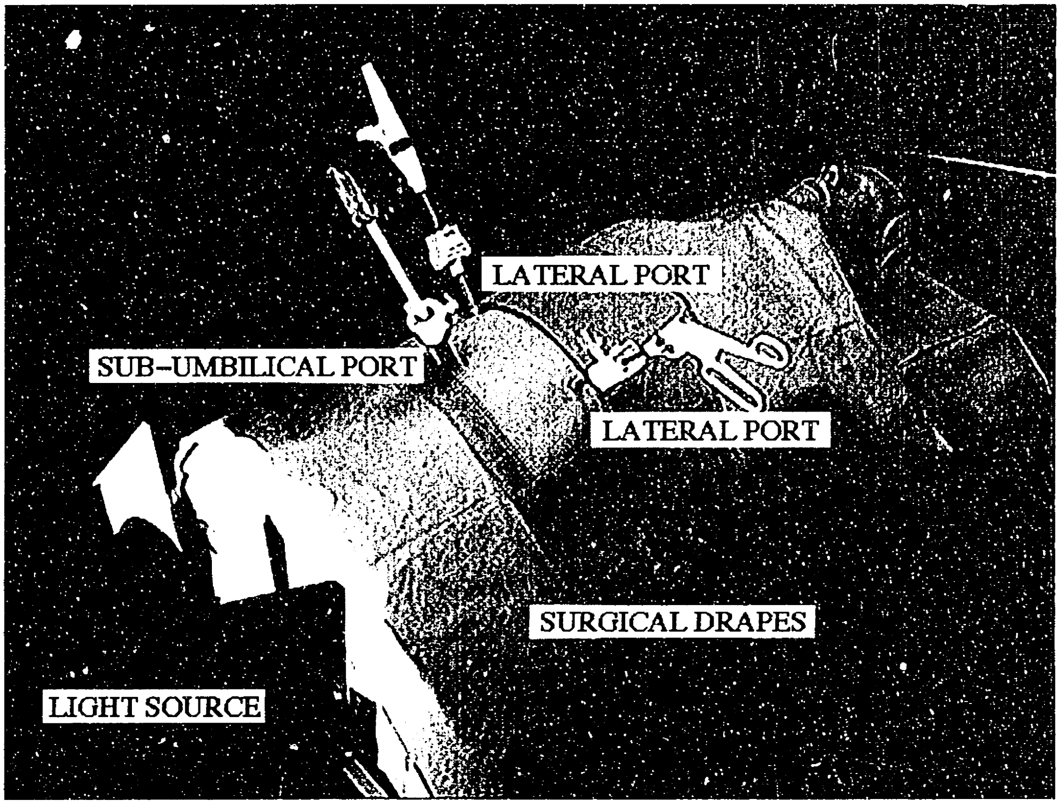


Figure A-7: Demonstration simulator.

CPR mannikin with a hole just below the umbilicus, and two holes below the lower margin of the "ribs", one each on the left and right sides. As the mannikins "skin" is opaque, and is also covered by surgical drapes, a light source beyond ambient is required. In Figure A-7, a 200W lamp with a directional hood is shown placed at the lower end of the mannikin, shining into the lower abdomen. This arrangement was found to be satisfactory for demonstration purposes.

The PHANToM haptic interface arms that were used as a master-slave pair in the experiments provide control over three degrees of freedom. Counting the axis (roll) controlled by the teleoperated tool, this leaves two uncontrolled degrees of freedom of the tool and tool handle. The tool, once placed through a trochar in the simulator, is constrained in these two DOF. The handle must be similarly constrained to prevent it from pointing in directions that do not correspond with the axis of the tool. A simple "pseudo-port" was built to provide these constraints (see Figure A-1).

When the pseudo-port is positioned relative to the master origin the same way as the real trochar is positioned relative to the slave (see Figure A-8), the position and orientation of the tool and tool handle will correspond correctly with each other. In this way, the surgeon using the tool will feel the correct force feedback from the remote site.

In a real tele-endoscopic system, using arms with six controlled degrees of freedom, the pseudo-port could be implemented as mathematical constraints to the master arm's motions. The location of the real trochar could be measured by the slave, and updated any time that the tool had to be

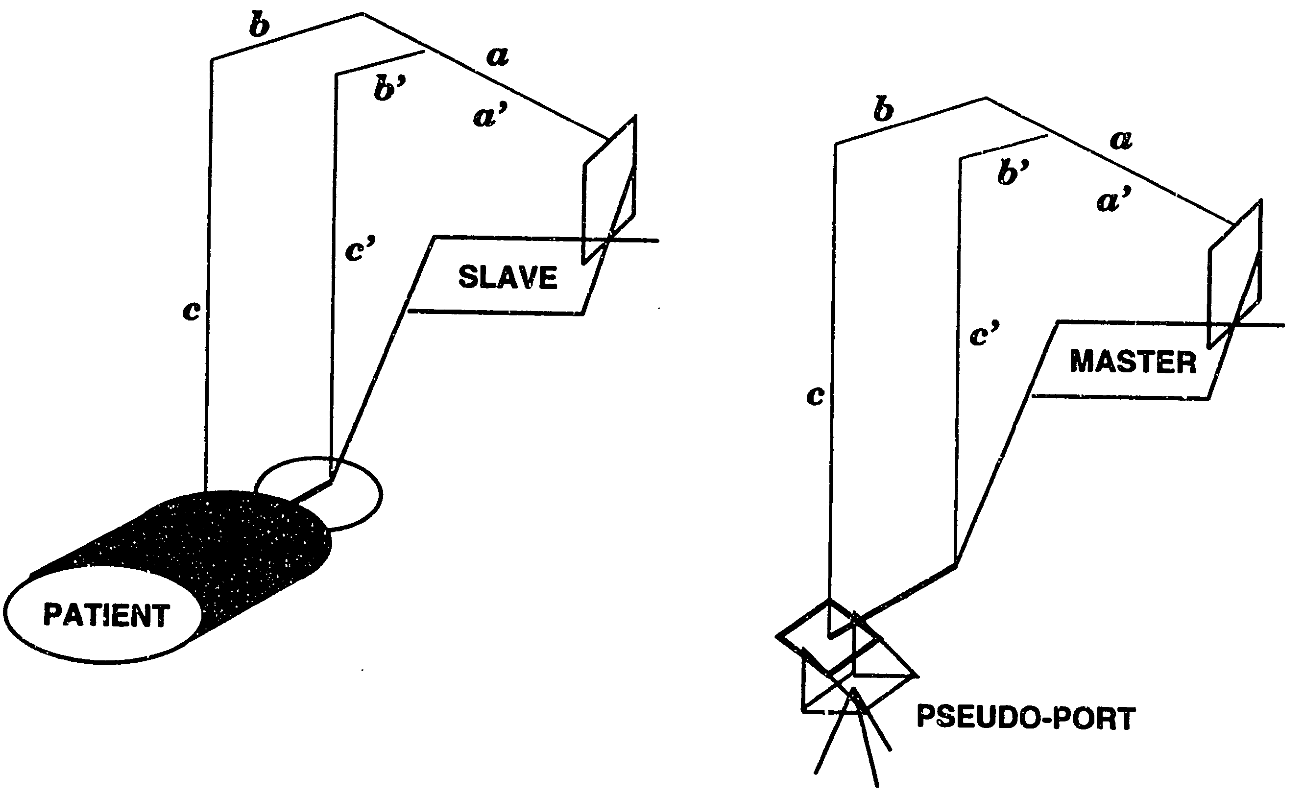


Figure A-8: Geometric similarity in placement of slave/patient and master/pseudo-port.

moved between one port and another. With the current system, the pseudo-port must be moved when switching between ports on the simulator.

A.3 Use of the Tool

A.3.1 Installation:

Both the tool and the tool handle incorporate original PHANToM gimbal-wrists, making installation and removal fairly simple.

For the tool handle, the 1/8" shaft is inserted into the socket at the end of the Phantom arm, then the set screw in the socket is tightened with the appropriate Allen wrench. The 9-pin male D-sub plug is attached to the corresponding socket located at the base of the Phantom. An extra counter-weight, a 4" C-clamp, is attached to the brass counter-weight on the master to balance the weight of the tool handle. The pseudo-port is positioned correctly as described in section A.2.3, then the shaft extension of the handle is inserted through the trochar in the pseudo-port.

Mounting the tool base (Figure A-2 and A-3) is the same as the tool handle, except that the power cable (8-pin DIN) must also be plugged in, and counter-weight C-clamps (two 4", one 2") are attached to the axis-2 motor of the Phantom. A piece of neoprene rubber is used to cushion the motor from the clamps. The clamps should NOT be tightened more than enough to hold the clamps in place. Over-tightenening will damage the motor.

Tool tips are attached using two screws attached to the tool tips (Figure A-3). For the laparoscope, the tip mounting block is placed so that the gear and pinion mesh, and the screws are finger-tightened. The gripper and shears require that the socket on the lead nut and the pin on the drive rod match, and that the lead nut is seated in the groove in the tip block. Again, the screws are finger-tightened.

A.3.2 Calibration:

When starting the control code, a calibration function is used to set all of the encoders to zero when the master and slave arms are in their respective (and identical) home positions. For the tool handle gripper axis, this home position is indicated by a detent near the middle of the range of the scissor action of the handle. The handle should be placed in this position and not moved until the control code is running. The roll axis does not need to be calibrated; zero is whatever position it starts in, then incremental motions are made from that point.

Two calibration schemes are available for the tool—automatic or manual. When the control program stops normally, the final position of the gripper axis is recorded to a file. The automatic scheme reads the file and moves the gripper motor far enough to return it to the zero position from the previous end position. A proportional plus integral control scheme was implemented to make the move automatically, but due primarily to friction in the tool, the phenomenon of "integral wind-up" was found to produce a limit cycling behavior in the calibration routine. Because of this, manual calibration was used during the experiments.

Manual calibration is performed by eye, based on what tool tip is being used. The instructions given by the computer in the manual calibration routine should be followed. When the program requests it, manual positioning is performed as follows. For the gripper, the round coupling is turned to open the tool fully, then turned in the opposite direction until the gripper tips are approximately 1/4 in. apart. The coupling can be used as a guide, as the setscrews in the coupling should be visible and face "down" with respect to the tool, as shown in Figure A-9. Calibration for the shears is similar, except that the tips of the shears should be between 1/4 and 1/8 in. apart, and the coupling setscrews should face into the base (i.e. are not visible). While this extra turn violates the mathematical relationship shown in Figure A-5 somewhat, it was found to work better in practice.

A.3.3 Use of the tool and tool handle

Once the control program is running, the tool can be moved, including the gripper/shears and roll axes. As the tool is a prototype, it possesses a number of idiosyncracies which, once the user is familiar with them, can be overcome easily.

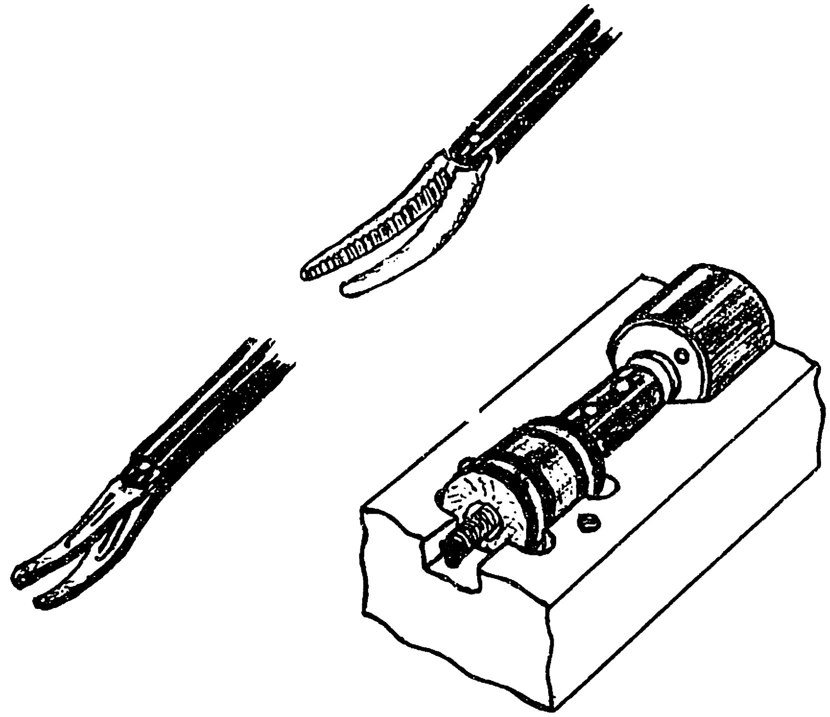
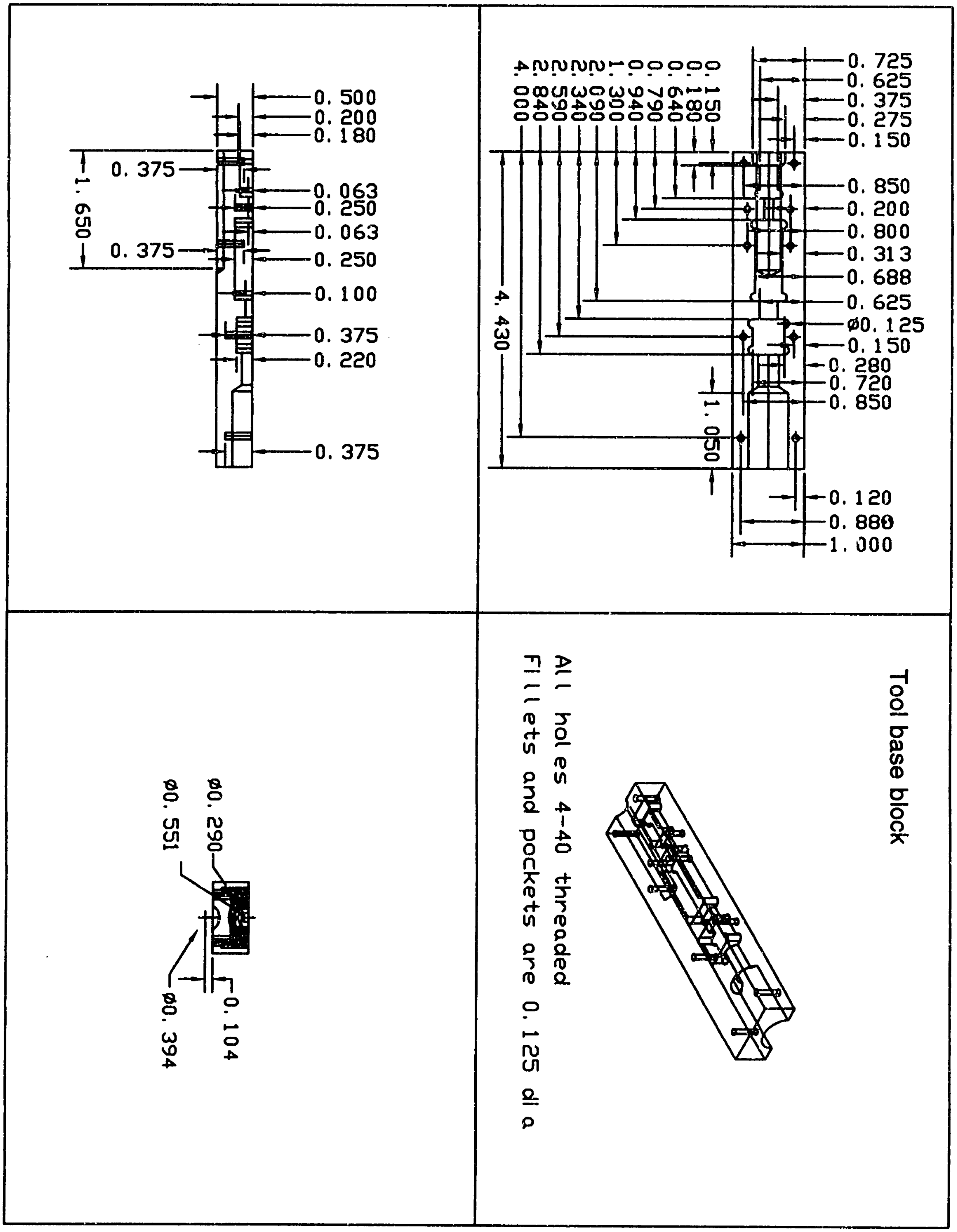


Figure A-9: Correct positioning for calibration of gripper and shear tool tips.

Firstly, if the gripper or shears are opened very quickly, the inertia of the larger motor is such that the lead nut will not stop at the desired position, but will overshoot, and can become jammed against the end of the pocket in which it travels. Jamming also occurs when the jaws of the gripper or shears close very tightly resulting in a large axial force along the drive rod. This extra load on the lead nut leads to torsional friction in the threads of the nut that is larger than the motor and gearhead can overcome. The best solution, using this tool, is to learn the limits of how fast the tool can be closed. If the tool does become jammed, it can usually be freed without having to shut down the system if someone near the slave manually turns the round coupling or thrust plate on the threaded rod. When doing this, the master handle should be in the detent position so that the gripper does not immediately overshoot to the other limit of the tool.

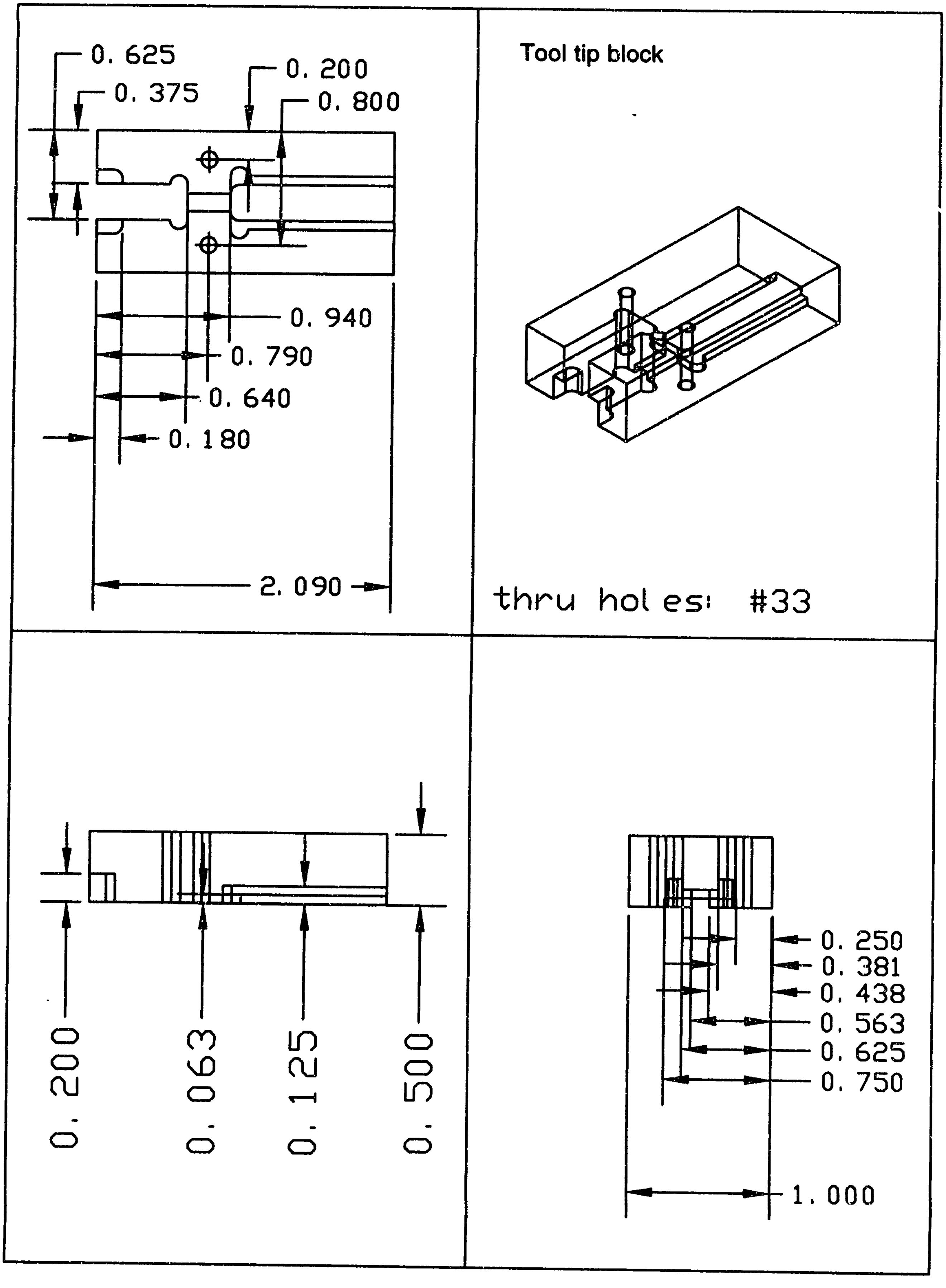
Secondly, the roll axis is slightly under-powered. The larger radius of the shaft results in larger torsional friction between the shaft and the seal in the trochar. To overcome static friction, the tool can be moved in or out slightly, so the dynamic friction regime will be entered. The stiction problem is also present, though to a smaller extent, for the gripper and shears tools, so small rotations are sometimes hard to achieve. The in-and-out motion of the tool can be used to minimize this effect as well.

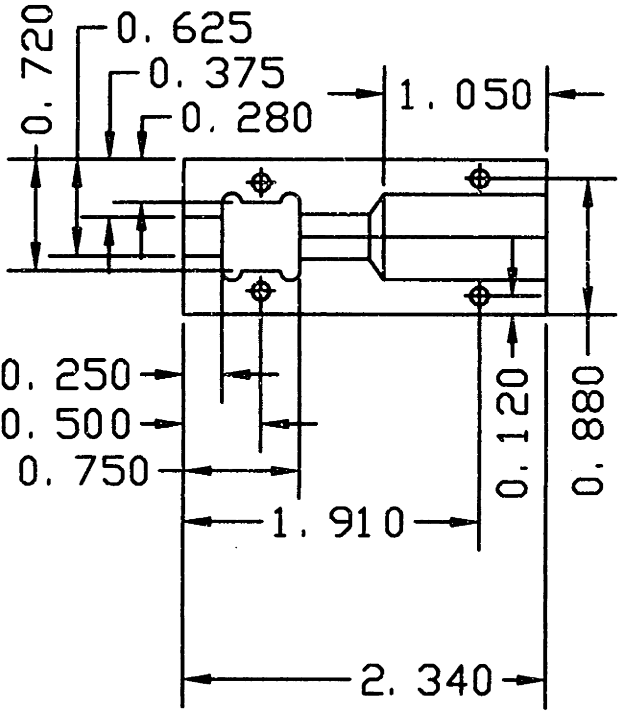
A.4 Technical Drawings



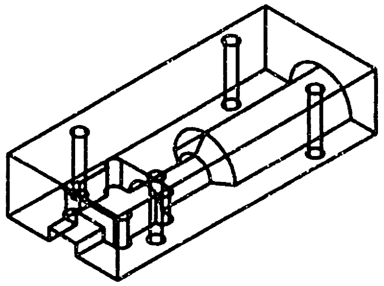
Tool base block

All holes 4-40 threaded
Fillets and pockets are 0.125 dia

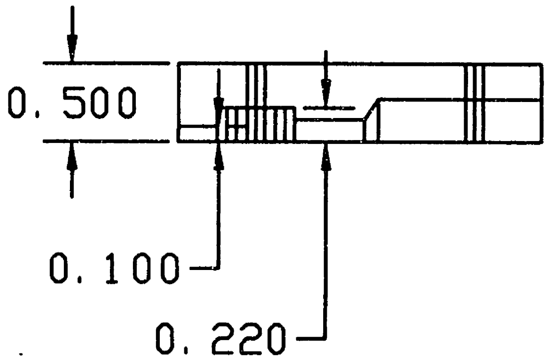

Tool tip block

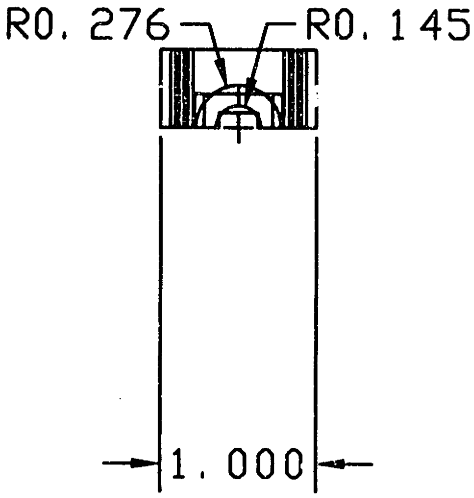


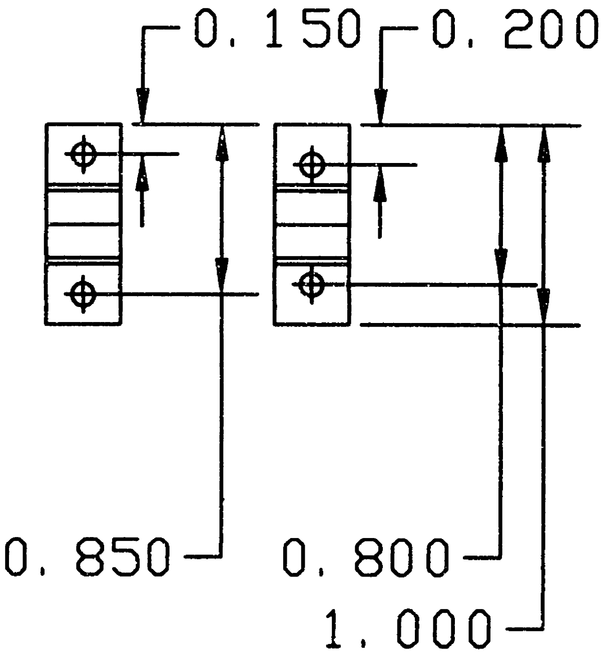
Tool bearing and gripper motor cover



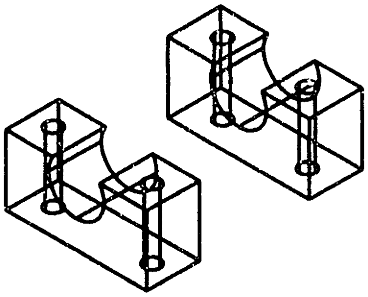
All thru holes #33



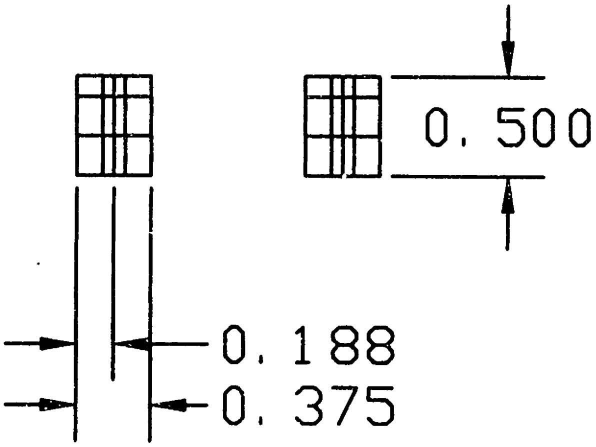


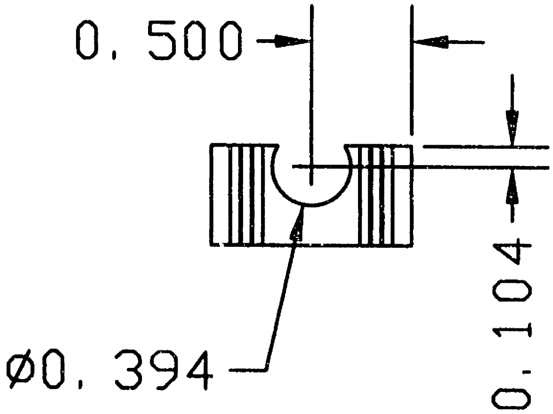


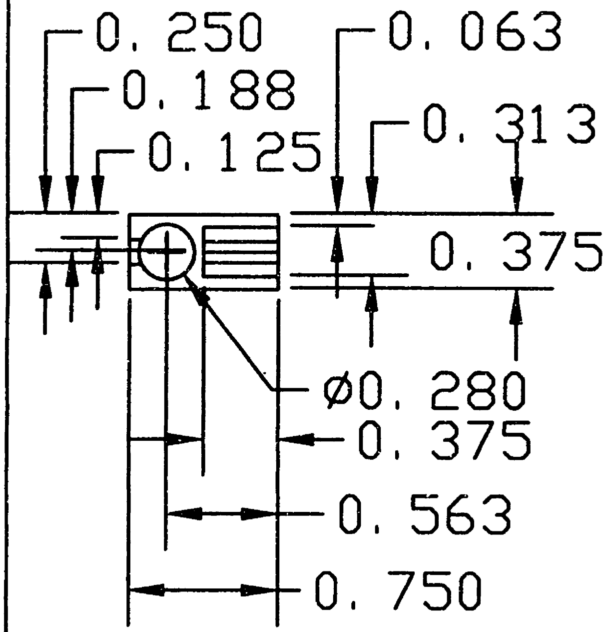
Tool roll motor brackets



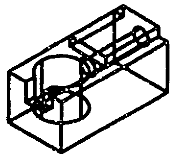
All thru holes: #33

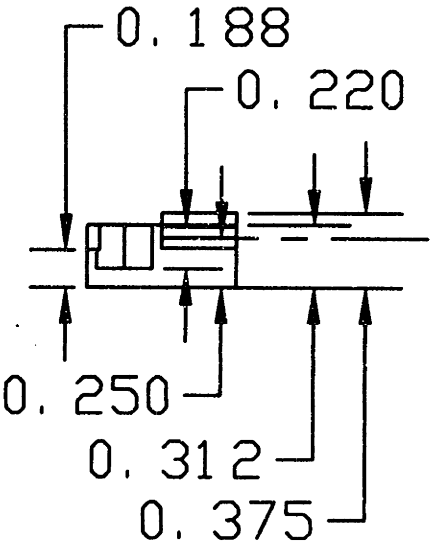


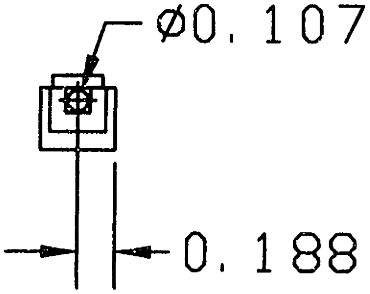




Tool lead nut







threaded hole: 6-32

A.5 Electronics and Interface Schematics

Table A.1: Signal cable pin-outs for handle (master) and tool (slave)

	d-sub connector/ribbon cable		amplifier box
pin/wire	description	pin	color
1	encoder 4 channel A (unused)	1	orange
2	+5 volts	4	red
3	encoder 5 channel A (gripper)	2	green
4	deadman signal (unused for tool)	5	white
5	encoder 6 channel B (roll)	11	grey
6	encoder 4 channel B (unused)	9	yellow
7	ground	12	black
8	encoder 5 channel B (gripper)	10	blue
9	encoder 6 channel A (roll)	3	purple
–	no connection	13	brown

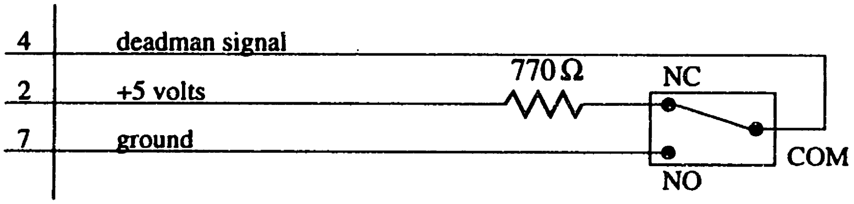


Figure A-10: Deadman switch wiring.

Table A.2: Power cable pin-outs for tool (slave)

	DIN connector	color
1	V+ (axis 4 unused)	
2	V+ gripper (axis 5)	white
3	V+ roll (axis 6)	red
4	V- (axis 4 unused)	
5	V- gripper (axis 5)	black
6	no connection	
7	V- roll (axis 6)	green
8	no connection	

A.6 C Functions and Annotation

```
allfxns.txt          Thu May  9 04:35:07 1996          1

HEADER FILE: toolaxis.h

/* This file contains the global variables for use with the
      ToolInit(), GripAxis() and RollAxis() functions.  When used in a
      control program, include the following code after the definition
      of the Phantom interface macros:
   #include "toolaxis.h"
   #include "toolinit.c"
   #include "rollaxis.c"
   #include "gripaxis.c"

*/
#define MASTER_ADDR  0x220
#define SLAVE_ADDR  0x240
#define AMP_ON 0
#define AMP_OFF 1
// Auxilliary Phantom axis numbers
#define D_IN 3
#define GRIP 4
#define ROLL 5
// values to be assigned to current_tool
#define SCOPE 0
#define GRASP -1
#define SHEAR 1
float grip_master=0.0, roll_master=0.0;
float grip_slave=0.0, roll_slave=0.0;
float grip_error=0.0, roll_error=0.0;
float grip_torque=0.0, roll_torque=0.0;
int   cal_master=0, cal_slave=0;
int   cal_error=0, cal_last=0;
float cal_errintgl=0.0;
float cal_looprate=80.;
float grip_gain, roll_gain=75.0;
int             current_tool;
float grip_resoln;
char  chr;
int   dummy;
// grip_gain and grip_resoln are set within the GripAxis() function
// current_tool is set in ToolInit() in version 1.0

FUNCTION FILE: toolinit.c

void ToolInit(void) {
/*  Teleoperated laparoscopy tool initialization function
      by: Mark Ottensmeyer, HMSL, MIT

   version 1.1: Jan. 1996
   version 1.2: 17 Jan. 1996--added manual calibration,
               removed extra reset of GRIP encoders
N.B.
   All variables are global, and are defined and/or initialized in the
      header file:
         TOOLAXIS.H
   This function should be run once as a control program begins, before
      entering any control loops.  It must occur before either
      GripAxis() or RollAxis() are called.
*/
// setting torques to zero
   torque(ROLL,SLAVE_ADDR,32768);
   torque(GRIP,SLAVE_ADDR,32768);
// check which tool will be used, set value of current_tool
   while(1) {
      clrscr();
      printf("\nAre you using the laparoscope? (y/n)");
      chr=getchar();
      if((chr=='n')||(chr=='y')) break;
   }
   current_tool=SCOPE;
   if(chr=='n') {
      while(1) {
         clrscr();
         printf("\nManual Calibration? (y/n)\n");
         chr=getchar();
         if((chr=='n')||(chr=='y')) break;
      }
// manual calibration section
      if(chr=='y') {
         printf("\nMove tool handle to detent position.  Then set gripper\n");
         printf("to neutral position manually.  Attach any tool-tip to be used.\n");
         printf("\nPress 'q' to quit or any other key to continue\n");
         if(getch()=='q') exit(0);
         reset_encoder(GRIP,SLAVE_ADDR);
         reset_encoder(GRIP,MASTER_ADDR);
         amp_enable(AMP_ON,SLAVE_ADDR); // turn on amps after reset
         amp_enable(AMP_ON,MASTER_ADDR); // turns them off
      }
// automatic calibration section
      else {
         printf("\n\tSurgical Tool Initialization Routine\n");
         printf("\nPlease remove any of the quick change tool tips from the\n");
         printf("teleoperated tool base.\n");
         printf("\n\tPress return when ready to continue.\n");
         getch();
// calling the calibration routine
         calibrate();
// zeroing the encoder used for digital inputs
         reset_encoder(D_IN,MASTER_ADDR);
         clrscr();
         printf("\n\tYou may now release the safety switches\n\n");
         printf("Please attach the desired quick change tool tip and\n");
         printf("insert the shaft through the desired trochar.  Then\n");
         printf("re-check that the handle grip is in the zero-detent\n");
         printf("position.  Try not to move either the roll or gripper\n");
         printf("axes on the handle until the control loop begins.\n");
         printf("\n\tPress return when ready to continue or q to quit.\n");
         if(getch()=='q') exit(0);
      }
      while(1) {
         clrscr();
         printf("\n\tPlease indicate which tool is being used:\n");
         printf("\nGrasper: 1\nShears: 2\n");
         chr=getchar();
         if(chr=='1') { current_tool=GRASP; break; }
         if(chr=='2') { current_tool=SHEAR; break; }
      }
   }
// zeroing the roll axis encoderr
   reset_encoder(ROLL,MASTER_ADDR);
   reset_encoder(ROLL,SLAVE_ADDR);
   amp_enable(AMP_ON,SLAVE_ADDR);
   printf("\nTool initialization complete.\n");
   printf("\nHold down safety switches and press return to continue.");
   getch();
}

FUNCTION FILE: grip-ax.c

/*  Teleoperated laparoscopy tool gripper axis control function
```

```
      by: Mark Ottensmeyer, HMSL, MIT
Notes:
   version 1.0: Dec. 14, 1995
   version 2.0: 16 Jan 1996 add time delay to function
   version 2.1: 18 Jan 1996 modify delay to match Mu's format,
                            add function GripAxisGetCmd()
   All variables are global, and are defined and initialized in the
      header file:
         TOOLAXIS.H
      except for those that contact the delay buffer (my_grip, my_gpdelay)
   The ToolInit() function must occur before any instance of GripAxis()
      in a control program.
2.0 notes:
   Delay buffer index is defined and modified from within main()
   This function will have to be modified when the master and
      slave are separately controlled.
2.1 notes.
   Delay buffer is modified from Mu's mecontrd() function.
Hardware notes:
   There is no temperature checking algorithm included because:
      a) the time constant on the coreless DC motor is very small, so...
      b) the maximum current has been set so that the motor never
         overheats (even when run continuously at maximum)
   From MicroMo: absolute maximum current = 350 mA due to thermal
                          considerations, so...
              Maximum current is set to 325 mA (=487 counts)
*/
void GripAxisGetCmd(void) {
// read master gripper encoder
   my_grip = encoder(GRIP,MASTER_ADDR);
   return;
}

void GripAxisDelay(void) {
// based on tool being used, choose correct gain and resolution
   switch (current_tool) {
      case SCOPE:
         grip_gain=0.0;
         grip_resoln=1.0;
         break;
      case GRASP:
         grip_gain=-15.0;
         grip_resoln=-13.0;
         break;
      case SHEAR:
         grip_gain=-15.0;
         grip_resoln=-25.23;
         break;
   }
// read slave gripper encoder
   grip_slave = ((float)(encoder(GRIP,SLAVE_ADDR)))/grip_resoln;
// compare with (possibly) delayed value from buffer
   grip_error = ((float)my_gpdelay)-grip_slave;
printf("\nslave=%d",encoder(GRIP,SLAVE_ADDR));
   grip_torque = grip_error*grip_gain;
   if(grip_torque>10000.) {printf("over-torque"); exit(0);}
   if(grip_torque<-10000.) {printf("over-torque"); exit(0);}
   if(grip_torque>487.) grip_torque=487.;
   if(grip_torque<-487.) grip_torque=-487.;
// send torque command to slave gripper axis
   torque(GRIP,SLAVE_ADDR,(long) (grip_torque+32768.)); /* 1500 counts/amp */
}

FUNCTION FILE: rollaxis.c
```

```
/*  Teleoperated laparoscopy tool roll axis control function
      by: Mark Ottensmeyer, HMSL, version 1: Dec. 1995
   version 2.0: 16 Jan 1996 modified from v1.0 by adding delay
   version 2.1: 18 Jan 1996 buffer modified to match format of Mu
                            added function RollAxisGetCmd()
   version 2.2: 20 Jan 1996 matching float/int agreement with Mu's
                            delay "black box"
N.B.
   All variables are global, and are defined and initialized in the
      header file:
         TOOLAXIS.H
      which should be included near the beginning of any control program.
      (a good idea might be to #include both the header and this function
         one right after the other)
      Also, the macros to access the Phantom interface card must be
         defined before this function.
2.0 notes:
      Delay buffer index is defined and modified from within main()
      This function will have to be modified when the master and
         slave are separately controlled.
2.1 notes:
      buffer is modified within Mu's mecntrd() function
2.2 notes:
      figured out what was wrong with float/int agreement
Hardware notes:
   There is no temperature checking algorithm included because:
      a) the time constant on the coreless DC motor is very small, so...
      b) the maximum current has been set so that the motor never
         overheats (even when run continuously at maximum)
From MicroMo: absolute maximum current = 115 mA due to thermal
                          considerations, so...
      Maximum current is set to 100 mA (=150 counts)
*/
void RollAxisGetCmd(void) {
   mx_roll = encoder(ROLL,MASTER_ADDR);
   return;
}

void RollAxisDelay(void) {
   roll_slave = ((float)(encoder(ROLL,SLAVE_ADDR)))*(2.0*M_PI)/1920.0;
   roll_error = ((float)mx_rldelay*(2.0*M_PI)/4096.0)-roll_slave;
   roll_torque = roll_error*roll_gain;
   if(roll_torque>10000.) {printf("over torque"); exit(0);}
   if(roll_torque<-10000.) {printf("over-torque"); exit(0);}
   if(roll_torque>150.) roll_torque=150.;
   if(roll_torque<-150.) roll_torque=-150.;
   torque(ROLL,SLAVE_ADDR,(long) -(roll_torque+32768.)); // 1500 counts/amp
   return;
}

FUNCTION FILE toolsave.c

void ToolSave(void) {
// when called, writes current gripper encoder position to file toolpos.dat
   FILE *Toolpos;
   if(current_tool!=0) {
      Toolpos=fopen("toolpos.dat","w");
      fprintf(Toolpos,"%d\n",(encoder(GRIP,SLAVE_ADDR)));
      fclose(Toolpos);
      printf("\nfinal gripper encoder position was %d\n",encoder(GRIP,
         SLAVE_ADDR));
   }
}
```

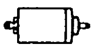
```
FUNCTION FILE: toolcal.c

void calibrate(void) {
/*  Teleoperated laparoscopy tool gripper axis calibration function
      by: Mark Ottensmeyer, HHSL, MIT
   version 1.0: Jan. 1996
N.B.
   All variables are global and are defined and/or initialized in the
      header file:
         TOOLAXIS.H
      except for the calibration file access variables and the position
         and integral gain variables.
   This function is called only from the TOOLINIT function, and must
      be #included before TOOLINIT.C
*/
#include <process.h>
#include <conio.h>
#include <stdio.h>
#include <time.h>
#include <math.h>
   time_t cal_start, cal_finish;
   long cal_counts=1;
   FILE *Toolpos;
   int start_pos;
   float Kp=-.05, Ki=-2;
   char chr;
   clrscr();
   printf("\n\tCalibration sequence beginning:\n");
   printf("\nPlease move the tool handle grip to thu detent position\n");
   printf("\nHold down safety switches and press return to continue\n");
   getch();
   printf("\n\tCalibrating...");
// get last known position of gripper axis
   Toolpos=fopen("toolpos.dat","r");
   fscanf(Toolpos,"%d",&start_pos);
   fclose(Toolpos);
// set torques to zero, set initial encoder position to zero
// and enable slave amps
   for(dummy=0;dummy<6;dummy++) {
      torque(dummy,MASTER_ADDR,32768);
      torque(dummy,SLAVE_ADDR,32768);
   }
   reset_encoder(GRIP,SLAVE_ADDR);
   amp_enable(AMP_ON,SLAVE_ADDR);
   printf("\nlast tool position was: %d. return to continue, q to quit\n",start_pos);
   if(getch()=='q') exit(0);
      time(&cal_start);
//continue is keyboard is not hit, deadman switch is not released
      while (!kbhit() && !STYLUS_SW(MASTER_ADDR)) {
         cal_counts++;
         cal_master = 0;
         cal_slave  = -(encoder(GRIP,SLAVE_ADDR)+start_pos);
         cal_error = cal_master - cal_slave;
printf(" error=%d ",cal_error);
// reset integrator at zero crossing
         if ((float)cal_error*(float)cal_last<=0.) cal_errintgl = 0.;
//check if done
         if ((abs(cal_error)<2)&&(abs(cal_error-cal_last)<1)) {
         reset_encoder(GRIP,SLAVE_ADDR);
         reset_encoder(GRIP,MASTER_ADDR);
         amp_enable(AMP_ON,SLAVE_ADDR); // turn on amps after reset
         amp_enable(AMP_ON,MASTER_ADDR); // turns them off
         printf("\n\tdone calibration...press return to continue...\n");
            getch();
            break;
         }
         cal_last=cal_error;
// update integral term
         cal_errintgl += ((float)cal_error)/cal_looprate;
printf("intgrl=%8.3f ",cal_errintgl);
// calculate command torque
         grip_torque = (float)cal_error * Kp + (float)cal_errintgl * Ki;
printf("cmd_trq=%7.2f ",grip_torque);
         if (grip_torque>10000.) {printf("over-torque"); break;}
         if (grip_torque<-10000.) {printf("over-torque"); break;}
         if(grip_torque>200.) grip_torque=200.; /* Current Limit=0.3A */
         if(grip_torque<-200.) grip_torque=-200.;
printf("Tm(ltd)=%7.2f\n",grip_torque);
/* make sure all torques are set to zero except grip axis */
         torque(0,SLAVE_ADDR,(long) 32768);
         torque(1,SLAVE_ADDR,(long) 32768);
         torque(2,SLAVE_ADDR,(long) 32768);
         torque(3,SLAVE_ADDR,(long) 32768);
         torque(ROLL,SLAVE_ADDR,(long) 32768);
// 1500 units/amp
         torque(GRIP,SLAVE_ADDR,(long) (grip_torque+32768.0));
   }
// error trap for release of deadman switch
   if(STYLUS_SW(MASTER_ADDR)) {
      printf("stylus switch released--quitting\n");
      exit(0);
   }
   time(&cal_finish);
   printf("\nelapsed time=%ld\n",cal_finish-cal_start);
   printf("cycle speed=%f\n",(float) (cal_finish-cal_start)/(float)cal_counts);
   printf("press return to continue\n");
   getch();
   return;
}
```

A.7 Component Technical Specifications

MicroMo• MOTORS

DC MicroMotors Series 1016

- Only 10mm (.394") in Diameter.
- Fits Our Planetary Gearhead Series 10/1 and Spur Gear Series 12/3.
- High Power to Size Ratio.
- Available with Integral Magnetic Encoder (10 PPR).



Actual Size

Continuous Duty Ratings:(1)

Speeds up to 13,000 RPM.
Torque up to .07 oz-in.
Power Output up to .3 Watts.

MAX CTS CURRENT = 115mA (THERMAL CONSIDERATION)

Electrical Specifications: @22°C (72°F)

For Motor Type 1016E	003G	006G	012G
Supply Voltage nom. (Volts)	3	6	12
Armature Resistance (Ohm) ±12%	8.7	20.1	103
Max. Power Output (Watts)(2)	0.25	0.46	0.37
Max. Efficiency (%)(2)	63	68	66
No Load Speed (RPM) ±12%(2)	14,200	17,600	16,000
No Load Current (mA) ±50%(3)	15	10	4
Friction Torque (@ No Load Speed)(oz-in)	0.004	0.004	0.004
Stall Torque (oz-in)(2)	0.10	0.15	0.13
Velocity Constant (RPM/Volt)	4,764	2,854	1,290
Back EMF Constant (mV/RPM)	0.210	0.350	0.775
Torque Constant (oz-in/Amp)	0.283	0.48	1.05
Armature Inductance (mH)	0.015	0.060	0.310

Mechanical Specifications:

Mechanical Time Constant (mS)(2)		9 All Types	
Armature Inertia ($x10^{-4}$ oz-in-Sec^2)	.57	.65	.71
Angular Acceleration ($x10^3$ Rad/Sec^2)(2)	160	193	175
Bearing Play (Measured at Bearing)			
Radial		Less Than 0.03mm (.0012 in)	
Axial		Less Than .2mm (.0079 in)	
Thermal Resistances (°C/W)			
Rotor to Case		10 All Types	
Case to Ambient		65 All Types	
Maximum Shaft Loading (oz)			
Radial (@ 3,000RPM) 3mm From Bearing		1.8 All Types	
Axial (Standing Still)		72 All Types	
Weight (oz)		.23 All Types	
Rotor Temperature Range		-30°C to 125°C (-22°F to 257°F)	

Direction of rotation is reversible and clockwise as seen from shaft end if red lead or solder tab marked + is connected to positive side of voltage supply.

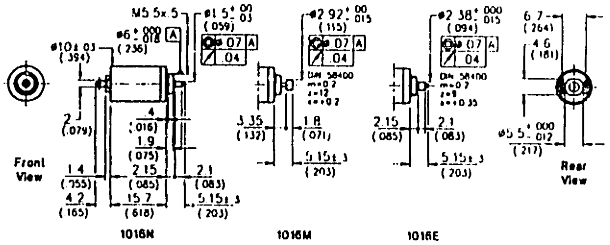
(1) Ratings are presented independent of each other
(2) Specified at nominal supply voltage
(3) Specified with shaft diameter = .8mm at no load speed

-Specifications Subject to Change-

MOTORS

DC MicroMotors Series 1016

Dimensional Outlines:



Dimensions are in mm (in.)

Dimensions with no tolerance indicated are as follows:

For Dimensions:	Tolerance
Less than or equal to 6mm	±.1mm (.0039 in)
Less than or equal to 30mm	±.2mm (.0079 in)
Less than or equal to 120mm	±.3mm (.0118 in)

Ordering Information:

Example: To order a 6 Volt, 1016 Motor intended to fit our 10/1 Gearhead, specify

Motor 10 16 M 006 G + 10/1 - 256:1

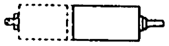
Motor Diameter
Motor Length
Output Shaft Configuration:
E = Pinion for 12/3 Gearheads (9 Teeth, Metric Module = .2mm, Modified Involute)
N = Ø1.5 mm x 2.1 mm Sleeve
M = Pinion for 10/1 Gearheads (12 Teeth, Metric Module = .2mm Modified Involute)
Nominal Voltage
Commutator Material
G = Gold
Special Order Numbers (where applicable)
Gearhead Type
Desired Gear Ratio

MicroMo Electronics, Inc.
FAULHABER GROUP
14881 Evergreen Avenue Clearwater, Florida 34622-3008 USA Phone (813) 572-0131 Fax (813) 573-5918

MicroMo• GEARHEADS

Gearhead Series 10/1

- Fits Motor Series 1016M, 1212M, and 1219M.
- Nickel Plated Brass Case.
- Sintered Bearings or Ball Bearings.



Actual Size

Maximum Ratings:

Type:	10/1	10/1K
Backlash at No Load:	≤ 3°	≤ 3°
Backlash at 20mNm (2.8 oz-in):	≤ 4°	≤ 4°
Bearings on Output Shaft:	Sintered Sleeve	Preloaded Ball
Maximum Shaft Load:		
Radial (4.5mm from Bearing):	≤ 1N (3.6 oz)	≤7N (25.2 oz)
Axial:	≤ 2N (7.2 oz)	≤ 5N (18 oz)
Maximum Shaft Press Fit Force:	≤ 10N (36 oz)	≤ 5N (18 oz)
Shaft Play:		
Radial:	.03mm (.0012 in)	.02mm (.0008 in)
Axial:	.10mm (.0039 in)	.0 mm
Temperature Range:	-30°C to 100°C (-22°F to 212°F)	

1	2		3		4					
Gear Ratio	Weight Without Motor		Length Without Motor		Length With Motor 1016M		Length With Motor 1212M		Length With Motor 1219M	
			L2		L1		L1		L1	
	g	oz	mm	in	mm	in	mm	in	mm	in
4:1	6	.21	8.7	[illegible]	25.4	[illegible]	[illegible]	[illegible]	28.4	[illegible]
16:1	7	.25	12.8	.504	[illegible]	1.128	25.0	0.984	31.6	[illegible]
64:1	8	.28	15.9	.626	31.6	1.244	28.1	1.106	34.6	1.362
256:1	10	.35	19.0	.748	34.7	1.363	31.2	1.228	37.7	1.484
1024:1	11	.39	22.1	.870	37.8	1.488	34.3	1.350	40.8	1.606
4096:1	13	.46	25.2	.992	40.9	1.610	37.4	1.472	43.9	1.728

1	5				6*	7
Gear Ratio	Maximum Output Torque				Rotation Direction	Efficiency
	Continuous Duty		Intermittent Duty		R=CW	
	mNm	oz-in	mNm	oz-in	L=CCW	%
4:1	5	0.7	200	28.3	R	90
16:1	15	2.1	200	28.3	R	80
64:1	54	7.6	200	28.3	R	70
256:1	100	14.2	200	28.3	R	60
1024:1	100	14.2	200	28.3	R	55
4096:1	100	14.2	200	28.3	R	48

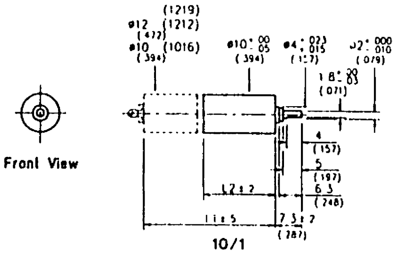
*R = Clockwise, L = Counterclockwise as viewed from shaft end with driving motor turning clockwise
All ratios are reversible

-Specifications Subject to Change-

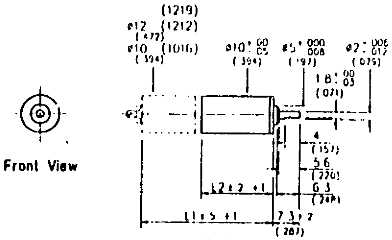
GEARHEADS

Gearhead Series 10/1

Dimensional Outlines:



10/1



10/1K

Dimensions are in mm (in.)

Dimensions with no tolerance indicated are as follows:

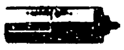
For Dimensions:	Tolerance
Less than or equal to 6mm	±.1mm (.0039 in)
Less than or equal to 30mm	±.2mm (.0079 in)
Less than or equal to 120mm	±.3mm (.0118 in)

MicroMo Electronics, Inc.
FAULHABER GROUP
14881 Evergreen Avenue Clearwater, Florida 34622-3008 USA Phone (813) 572-0131 Fax (813) 573-5918

MicroMo® MAGNETIC ENCODERS

Magnetic Micro Encoder Series HE

- Square Wave Output
- Logic Compatible
- 10 Pulse Per Revolution Standard
- Available as an Integral Package with 10 and 12 mm Motor Series
- 2 Channels, 90° Phase Shift

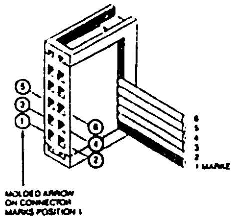


HEM 10 . . . Actual Size

HEM 12 . . . Actual Size

General Specifications:

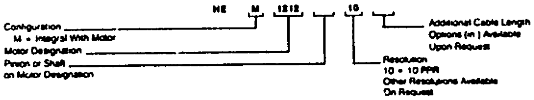
Nominal Power Requirement	5mA Nominal @ 5 VDC @ 22°C
Maximum Operating Voltage	15.0 VDC
Signal Phase Shift and Tolerance	90° ± 45° (2 phase signal)
Maximum Signal Frequency	7.2 K Hz
Operating Temperature Range	-20° C to 85° C
Storage Temperature Range	-40° C to 110° C
Connection	Standard 6 conductor 28 ga. ribbon cable with 10 pin ribbon cable connector
Maximum Asymmetry	10%
Signal Rise Time	Less than 5μS
PHASE RELATIONSHIP	Channel A leads Channel B when motor rotation is clockwise as seen from shaft end



HEM STANDARD CONNECTION 6 (SIX) CIRCUITS

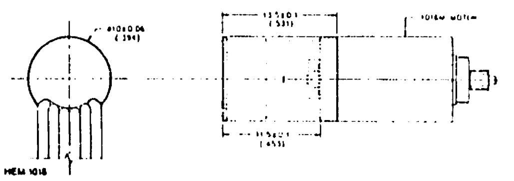
1 MARKED	MOTOR +
2	+ VDC 15.0 MAXIMUM (5mA @ 5 VDC)
3	CHANNEL A OUTPUT
4	CHANNEL B OUTPUT
5	-VDC GROUND
6	MOTOR -

Ordering Information

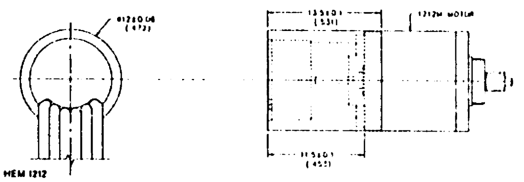


Magnetic Micro Encoder Series HE

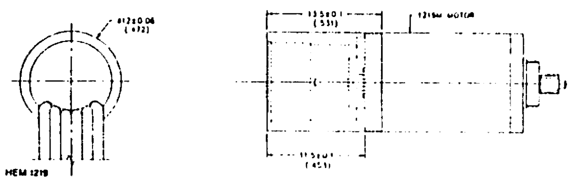
Dimensional Outlines:



HEM 1016



HEM 1212



HEM 1219

MicroMo Electronics, Inc.
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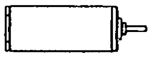
FOR MAX CURRENT [illegible] THERMAL CALCS THIS CONST IS REALLY LOW

MicroMo® MOTORS

DC MicroMotors Series 1331

- 1 oz-in Stall Torque.
- Samarium Cobalt Magnet and Reinforced Brushes Standard.
- Fits our Spur Gearhead 15/3 and 15/5 Series (Ratios 6.3:1 to 235,067:1)
- Fits our Plantetary Gearhead Series 14/1 (Ratios 3.71:1 to 5,647:1).
- Available with Integral Magnetic Encoder (15 or 16 PPR).



Actual Size

Continuous Duty Ratings:[1]

Speeds up to 12,000 RPM.
Torque up to .35 oz-in.
Output Power up to 2 Watts.

MAX CTS CURRENT: 350mA

Electrical Specifications:

For Motor Type 1331T @ 22°C (72°F)	4.5S	006S	012S	015S	024S
Supply Voltage nom. (Volts)	4.5	6	12	15	24
Armature Resistance (Ohm) ±12%	2.2	3.6	13.3	20.3	55
Maximum Power Output (Watts)[2]	2.3	2.5	2.7	2.8	2.6
Maximum Efficiency (%)[2]	75	77	78	74	75
No Load Speed (RPM) ±12%[2]	10,800	10,900	11,300	12,000	11,400
No Load Current (mA) ±50%[3]	35	25	16	14	8
Friction Torque (@ No Load Speed)(oz-in)	.020	.018	.021	.024	.023
Stall Torque (oz-in)[2]	1.11	1.20	1.25	1.20	1.20
Velocity Constant (RPM/Volt)	2,442	1,844	958	815	484
Back EMF Constant (mV/RPM)	.410	.542	1.04	1.226	2.067
Torque Constant (oz-in/Amp)	.55	.73	1.41	1.65	2.79
Armature Inductance (mH)	.04	.08	.3	.6	1.1

Mechanical Specifications:

Mechanical Time Constant (mS)[2]	9 All Types				
Armature Inertia ($\times 10^{-4}$ oz-in-Sec^2)	091	.096	.096	.094	.092
Radial Acceleration ($\times 10^3$ Rad/Sec^2)[2]	126	127	132	140	133
Bearing Play (Measured at Bearing)					
Radial	Less Than .03mm (.0012 in)				
Axial	Less Than .2mm (.0079 in)				
Thermal Resistances (°C/W)					
Rotor to Case	8 All Types				
Case to Ambient	40 All Types				
Maximum Shaft Loading (oz)					
Radial (@ 3,000 RPM) 3mm From Bearing	4.3 All Types				
Axial (Standing Still)	72 All Types				
Weight (oz)	.71 All Types				
Rotor Temperature Range	-30°C to 100°C (-22°F to 212°F)				

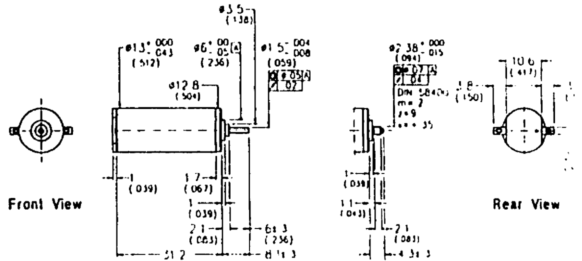
Direction of rotation is reversible and clockwise as seen from shaft end if red lead or solder tab marked + is connected to positive side of voltage supply.

---

[1] Ratings are presented independent of each other
[2] Specified at nominal supply voltage
[3] Specified with shaft diameter = 1.5mm at no load speed

DC MicroMotors Series 1331

Dimensional Outlines:



1331T

1331E

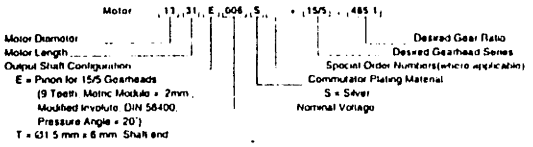
Dimensions are in mm (in)

Dimensions with no tolerance indicated are as follows:

For Dimensions	Tolerance
Less than or equal to 6mm	±.1mm (.0039 in)
Less than or equal to 50mm	±.2mm (.0078 in)
Less than or equal to 120mm	±.3mm (.0118 in)

Ordering Information:

Example: To order a 6 Volt Motor intended to fit our 15/5 Gearheads, Specify



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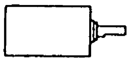
MicroMo• GEARHEADS

Gearhead Series 14/1

- Fits Motor Series 1319 and 1331.
- Planetary Gearing with Metal Case.
- Two Shielded, Preloaded Ball Bearings Standard.
- Permanently Lubricated for Long, Maintenance Free Operation.


Actual Size

Maximum Ratings:

Temperature Range:	-30°C to 100°C (-22°F to 212°F)
Load on Output Shaft:	
Radial at 6.5mm (.256 in) from Bearing:	20N (72 oz)
Axial:	5N (18 oz)
Maximum Press Fit Force: (Limited by Preload)	5N (18 oz)
Shaft Play:	
Radial	0.02mm (.0008 in)
Axial	0.0mm (.00 in)
Backlash, Unloaded:	≤ 1°
Continuous Output Torque:	42.5 oz-in (300 mNm)
Intermittent Output Torque:	63.8 oz-in (450 mNm)

1	2		3		4			
Gear (1) Ratio	Weight Without Motor		Length Without Motor		Length With Motor 1319		Length With Motor 1331	
			L2		L1		L1	
	g	oz	mm	in	mm	in	mm	in
3.71:1	17	0.600	20.9	0.822	33.8	1.330	45.9	1.807
14:1	20	0.706	25.0	0.984	38.0	1.496	50.0	1.969
43:1	24	0.847	29.2	1.150	42.2	1.661	54.2	2.134
66:1	24	0.847	29.2	1.150	42.2	1.661	54.2	2.134
134:1	27	0.952	33.3	1.311	46.3	1.823	58.3	2.295
159:1	27	0.952	33.3	1.311	46.3	1.823	58.3	2.295
246:1	27	0.952	33.3	1.311	46.3	1.823	58.3	2.295
415:1	30	1.06	37.4	1.472	50.4	1.984	62.4	2.457
592:1	30	1.06	37.4	1.472	50.4	1.984	62.4	2.457
989:1	30	1.06	37.4	1.472	50.4	1.984	62.4	2.457
1526:1	30	1.06	37.4	1.472	50.4	1.984	62.4	2.457
2608:1	34	1.20	41.5	1.634	54.5	2.146	66.5	2.618
4366:1	34	1.20	41.5	1.634	54.5	2.146	66.5	2.618
5647:1	34	1.20	41.5	1.634	54.5	2.146	66.5	2.618

1	5				6	7
Gear Ratio	Maximum Output Torque				Efficiency	Direction of Rotation
	Continuous Operation		Intermittent Operation			
	mNm	oz-in	mNm	oz-in		
3.71:1	200	28.3	300	42.5	80	All ratios
14:1	300	42.5	450	63.8	80	rotate
43:1	300	42.5	450	63.8	70	clockwise
66:1	300	42.5	450	63.8	70	as viewed
134:1	300	42.5	450	63.8	60	from
159:1	300	42.5	450	63.8	60	shaft end
246:1	300	42.5	450	63.8	60	with
415:1	300	42.5	450	63.8	55	driving
592:1	300	42.5	450	63.8	55	motor
989:1	300	42.5	450	63.8	55	turning
1526:1	300	42.5	450	63.8	55	clockwise
2608:1	300	42.5	450	63.8	50	
4366:1	300	42.5	450	63.8	50	
5647:1	300	42.5	450	63.8	50	

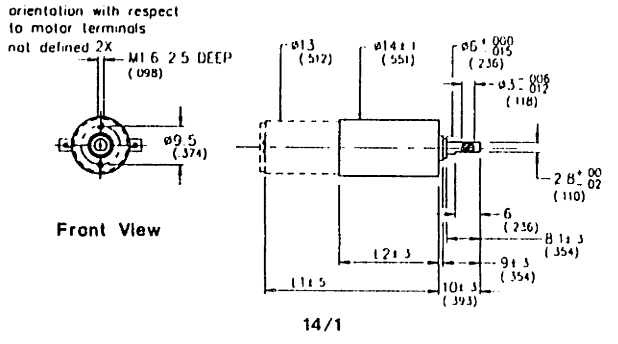
(1) Gear ratios are not exact

NOTE: Direction of rotation is identical to direction of motor rotation. All gearheads are reversible

-Specifications Subject To Change-

Gearhead Series 14/1

Dimensional Outlines:



14/1

Dimensions are in mm (in.).

Dimensions with no tolerance indicated are as follows

For Dimensions:	Tolerance
Less than or equal to 6mm	±.1mm (.0039 in)
Less than or equal to 30mm	±.2mm (.0078 in)
Less than or equal to 120mm	±.3mm (.0118 in)

MicroMo Electronics, Inc.
FAULHABER GROUP
14881 Evergreen Avenue Clearwater, Florida 34622-3008 USA Phone (813) 572-0131 Fax (813) 573-5918

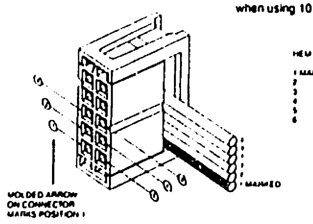
MicroMo® MAGNETIC ENCODERS

Magnetic Encoder Series HE

- Square Wave Output.
- TTL/CMOS Compatible.
- 10, 12, 15, or 16 PPR Standard (other Resolutions Available on Request).
- Available as an Integral Package with 13, 15, 16, 22, 23, 28, and 35mm Motor Series.
- 2 Channels, 90° Phase Shift.
- Also Available as a Free-Standing Unit with Precision Metal Housing.
- Weighs Less Than 1 oz.

General Specifications:

Nominal Power Requirement	5mA Nominal @5VDC @22°C
Maximum Operating Voltage	15.0 VDC
Signal Phase Shift and Tolerance:	90° ± 45° (2 Phase Signal)
Maximum Signal Frequency	7.2K Hz
Operating Temperature Range	-20°C to 85°C
Storage Temperature Range	-40°C to 110°C
Connection	Standard 6 Conductor 28 ga. Ribbon Cable With 10 Pin Ribbon Cable Connector
Maximum Asymmetry:	10%
Signal Rise Time	Less than 5μS
Phase Relationship	Channel A leads Channel B when using 15PPR Wheel (odd number) Channel B leads Channel A when using 10, 12, and 16PPR Wheel (even number)



HEM STANDARD CONNECTION 6 (SIX) CIRCUITS

1	MARKED MOTOR +
2	+VDC +15 MAXIMUM (5mA @ 5VDC)
3	CHANNEL A OUTPUT
4	CHANNEL B OUTPUT
5	VDC GROUND
6	MOTOR

Ordering Information:

HE M 1516 __ 15 __

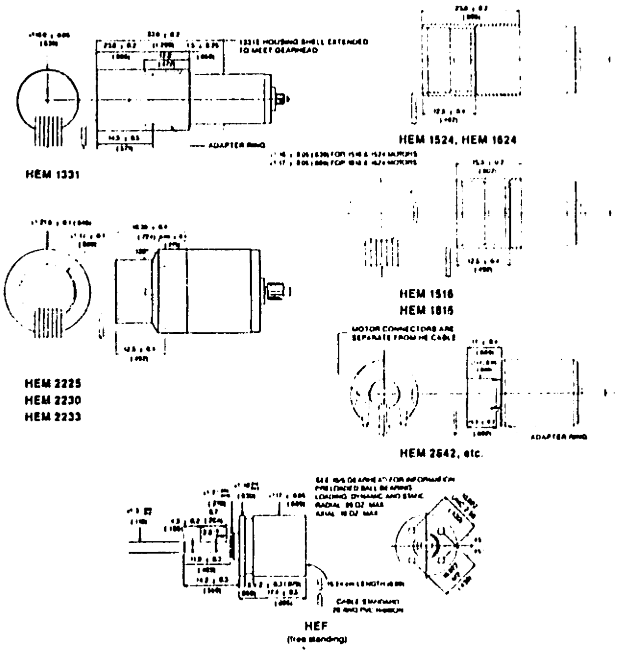
Configuration
  M = Integral With Motor
  F = Free Standing
Motor Designation
(Omit for F Configuration)
Pinion or Shaft
on Motor Designation

Resolution
10 = 10PPR
12 = 12PPR
15 = 15PPR
16 = 16PPR
Other Resolutions Available
On Request

Additional Cable Length
Options (in.) Available
Upon Request

Magnetic Encoder Series HE

Dimensional Outlines:



*Please contact our applications engineering department to discuss special designs or requirements not outlined above

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Appendix B

Summary of Statistical Results

Summary of Statistical Calculations

Grasp and Transfer Task

Aggregate statistics:		Direct Interaction	Teleop., 0s delay	Teleop., 0.6s delay	Teleop.,1.2s delay
Mean time	Surgeon uses 'scope	11.44444	9.694444	10.94444	9.402778
	Surgeon uses gripper	9.583333	14.16667	23.51389	31
Std. dev.	scope	4.188814	4.281105	4.265449	2.962963
	gripper	2.915476	5.73843	9.448143	9.649574
	t-statistic=	2.188022	-3.747971	-7.275133	-12.83737
	Smith-Satterthwaite γ =	105.9929	73.56822	49.70317	41.72812
	degrees of freedom=	105	73	49	41
	p-value=	0.030885	0.000354	2.49E-09	5.96E-16
	Significant at 1%?	No	Yes	Yes	Yes
	Surgeon should use:	No Diff.	Scope	Scope	Scope

Variation in completion time for surgeon using scope case		
Mean time	0s delay	9.694444
	1.2s delay	9.402778
Std. dev.	0s delay	4.281105
	1.2s delay	2.962963
	t-statistic	0.475349
	degrees of freedom	126
	p-value	0.635361

Linear regression on completion time				
delay	comp. time		*Regression Statistics*	
0	14.16667		Multiple R	0.997969
0.6	23.51389		R Square	0.995942
1.2	31			
			Intercept	14.47685
			Slope	14.02778

Table B.1: Grasp and Transfer Task Statistics Summary

Summary of Statistical Calculations

Grasp and Transfer with Orientation Task

Aggregate statistics:		Direct Interaction	Teleop., 0s delay	Teleop., 0.6s delay	Teleop.,1.2s delay
Mean time	Surgeon uses 'scope	17.80556	16.1831	16	15.08333
	Surgeon uses gripper	15.75	19.94444	33.22222	43.48611
Std. dev.	scope	7.433534	7.763118	6.08392	7.270914
	gripper	6.769338	8.703065	15.25116	21.99487
	t-statistic=	1.226718	-1.922996	-6.293191	-7.356484
	Smith-Satterthwaite γ =	99.19786	86.69625	46.44586	42.81542
	degrees of freedom=	99	86	46	42
	p-value=	0.222838	0.05779	1.05E-07	4.51E-09
	Significant at 1%?	No	No	Yes	Yes
	Surgeon should use:	No Diff.	No Diff.	Scope	Scope

Variation in completion time for surgeon using scope		
Mean time	0s delay	16.1831
	1.2s delay	15.08333
Std. dev.	0s delay	7.763118
	1.2s delay	7.270914
	t-statistic	0.589086
	degrees of freedom	141
	p-value	0.556746

Linear regression on completion time				
delay	comp. time		*Regression Statistics*	
0	19.94444		Multiple R	0.997279
0.6	33.22222		R Square	0.994566
1.2	43.48611			
			Intercept	20.44676
			Slope	19.61806

Table B.2: Grasp and Transfer with Orientation Task Statistics Summary

Summary of Statistical Calculations

Use of Clip Applier Task

Aggregate statistics:		Direct Interaction	Teleop., 0s delay	Teleop., 0.6s delay	Teleop.,1.2s delay	
Mean time	Surgeon uses 'scope	40.9	39.06667	38.48276	36.73333	
	Surgeon uses CA	27.46667	33.86667	104.25	221.7	
	Surgeon uses shears	36.93103	38.83333	71.40909	110.9	
Std. dev.	laparoscope	12.502	14.9388	10.63559	7.510606	
	clip applier	9.205446	13.75082	38.66982	129.231	
	shears	10.1978	11.62958	23.1777	75.11037	
t-statistics	'scope vs. CA	4.739141	1.402756	-7.414976	-6.393718	
	'scope vs. shears	1.338239	0.067506	-6.187348	-4.401302	
	CA vs. shears	-3.737993	-1.510534	3.767547	3.825773	
D.of F.	'scope vs. CA	53	57	20	19	
	'scope vs. shears	55	54	27	19	
	CA vs. shears	55	56	30	30	
p-values	'scope vs. CA	1.65E-05	0.166113	3.69E-07	3.93E-06	
	'scope vs. shears	0.186325	0.946428	1.29E-06	0.000307	
	CA vs. shears	0.000443	0.13653	0.00072	0.000615	
	Surgeon using:					Surgeon using
	'scope	worse than	not diff.	better than	better than	clip app'r
	'scope	not diff.	not diff.	better than	better than	shears
	clip app'r	better than	not diff.	worse than	worse than	shears

Variation in completion time for surgeon using scope case		
Mean time	0s delay	39.06667
	1.2s delay	36.73333
Std. dev.	0s delay	14.9388
	1.2s delay	7.510606
	t-statistic	0.76434
	degrees of freedom	42
	p-value	0.448938

Linear regressions on completion time			
	Surgeon using:	CA	Shears
delay	0	33.86667	38.83333
	0.6	104.25	71.40909
	1.2	221.7	110.9
	Multiple R	0.989697	0.998469
	R Square	0.979499	0.99694
	Intercept	26.02222	37.68081
	Slope	156.5278	60.05556

Table B.3: Use of Clip Applier Task Statistics Summary

Summary of Statistical Calculations

Use of Scissors Task

Aggregate statistics:		Direct Interaction	Teleop., 0s delay	Teleop., 0.6s delay	Teleop.,1.2s delay	
Mean time	Surgeon uses 'scope	25.41667	26.45714	22.27778	19.88889	
	Surgeon uses gripper	16.83333	19.44444	47.70833	76.88462	
	Surgeon uses shears	18.83333	20.77778	50.35714	77.96154	
Std. dev.	laparoscope	178.25	195.0202	129.6349	78.73016	
	gripper	28.94286	32.31111	563.9547	954.9062	
	shears	64.08571	109.3206	1126.979	1375.238	
t-statistics	'scope vs. gripper	3.577831	2.757075	-4.885157	-9.136687	
	'scope vs. shears	2.537397	1.93567	-4.240347	-7.824773	
	gripper vs. shears	-1.244151	-0.670037	-0.354232	-0.120843	
D.of F.	'scope vs. gripper	46	44	30	27	
	'scope vs. shears	57	62	31	27	
	gripper vs. shears	61	54	48	48	
p-values	'scope vs. gripper	0.000829	0.008459	3.22E-05	9.5E-10	
	'scope vs. shears	0.013928	0.057471	0.000187	2.06E-08	
	gripper vs. shears	0.218204	0.505689	0.724716	0.90432	
	Surgeon using:					Surgeon using
	'scope	worse than	worse than	better than	better than	gripper
	'scope	not diff.	not diff.	better than	better than	shears
	gripper	not diff.	not diff.	not diff.	not diff.	shears

Variation in completion time for surgeon using scope case		
Mean time	0s delay	26.45714
	1.2s delay	20.77778
Std. dev.	0s delay	4.459696
	1.2s delay	8.829583
	t-statistic	3.444845
	degrees of freedom	51
	p-value	0.001151

Linear regressions on completion time			
	Surgeon using:	Gripper	Shears
delay	0	19.44444	20.77778
	0.6	47.70833	50.35714
	1.2	76.88462	77.96154
	Multiple R	0.999958	0.999801
	R Square	0.999916	0.999603
	Intercept	19.29238	21.10694
	Slope	47.86681	47.65313

Table B.4: Use of Scissors Task Statistics Summary

Summary of Statistical Calculations

Observation Task

Aggregate statistics:	Polyhedron				
	6-sided	8-sided	10-sided	12-sided	20-sided
Direct Interaction					
Mean of (scope-gripper) times	12.5	22.66667	56.16667	6.333333	35
Std. dev. of (scope-gripper) times	9.934787	37.43617	114.19	7.339391	41.66053
t-statistic	7.549231	3.63285	2.95122	5.177541	5.040742
degrees of freedom	5	5	5	5	5
p-value	0.000646	0.015016	0.03184	0.003533	0.003964
Teleoperation, no delay					
Mean of (scope-gripper) times	2	10.5	18.5	-5	11.5
Std. dev. of (scope-gripper) times	7.899367	16.08415	18.4038	9.338094	11.74308
t-statistic	1.519109	3.916899	6.031362	-3.212647	5.875799
degrees of freedom	5	5	5	5	5
p-value	0.189201	0.011217	0.001804	0.023659	0.002027

Table B.5: Observation Task Statistics Summary

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