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Tim McLain
University of Utah Center for Engineering Design, mclain@byu.edu

S C. Jacobsen
University of Utah Center for Engineering Design

See next page for additional authors

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Authors
Tim McLain, S C. Jacobsen, E K. Iversen, C C. Davis, and D M. Potter

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DESIGN OF A MULTIPLE DEGREE OF FREEDOM, FORCE REFLECTIVE HAND MASTER/SLAVE WITH A HIGH MOBILITY WRIST

S.C. Jacobsen, E.K. Iversen, C.C. Davis, D.M. Potter, T.W. McLain

The Center for Engineering Design
The University of Utah
3176 Merrill Engineering Building
Salt Lake City, Utah 84112
(801)581-6499

ABSTRACT

The Center for Engineering Design (CED) at the University of Utah has developed a force reflective, teleoperated multiple degree of freedom hand and high mobility wrist. This hand/wrist teleoperation system is targeted to perform dexterous manipulation and assembly tasks in an effort to approach the capabilities of a human. A first-stage prototype of this hand/wrist master/slave system, which is scheduled for laboratory demonstration in February of 1989, has nine actuated degrees of freedom in both the hand master and hand slave. This paper discusses elements of the design of this hand/wrist master and slave with particular emphasis on servo system and actuator development. The progress and status of the development of the master/slave system is summarized. Issues relating to the design of the teleoperation system that were confronted during the initial stages of the design are addressed. Development of the piston actuators and servovalves is discussed in detail. A companion paper discusses aspects related to the mechanical design of the master and slave.

INTRODUCTION

In addressing the issues involved in performing manipulative tasks, robotic researchers have identified two different design approaches: task specific end effector design and multiple task dexterous end effector design [1,2,3]. Task specific end effector design involves designing the end effector and workspace according to the task to be performed. This is done through the use of specially designed jigs and tools which exclusively facilitate performance of the designated task. A combination of interchangeable jigs and fixtures can be implemented so that a single manipulator can proficiently perform a number of tasks. This approach is used in most robotic and teleoperation applications in industry today. The advantage of the task specific approach is that the end effector designs are usually less complex than their dexterous counterparts and in some cases more efficient in performing the task to which they are dedicated. The major disadvantage is that the ability to perform unanticipated tasks in an unstructured environment is limited. The multiple task dexterous end effector approach alleviates this problem by using one end effector to perform both the anticipated, routine tasks and the unanticipated, unstructured tasks. It should be noted that by designing a system which can use standard hand tools, a multiple task dexterous end effector can have some of the advantages of a task specific system. The disadvantage with this approach, of course, is the inherent complexity of a multiple degree of freedom dexterous manipulator. For this reason, a practical system must have as little complexity as possible while still being able to perform the desired dexterous tasks.

The CED is currently involved in the development of a force reflective bilateral teleoperation system. The primary goal of this teleoperation system is to extend the dexterous manipulation capabilities of a human to a slave manipulator operating in a hostile, unstructured environment. Achievement of such capabilities necessitated the development of a master/slave end effector system employing multiple degrees of freedom and high resolution, high bandwidth force reflection. The remainder of this paper addresses issues associated with the design and development of this hand/wrist master and slave. In the System Development Status section of the paper, the general progress of the hand/wrist master and slave development is discussed. Target tasks and grasps and the required degrees of freedom to perform them are discussed briefly in the Design Goals section. The Preliminary Design Issues section outlines the design trade offs that were examined in arriving at a preliminary design for the manipulator. The design and development of servovalves and actuators are discussed in the Actuation System Development section.

SYSTEM DEVELOPMENT STATUS

Development of the hand/wrist master and slave has been a multidisciplinary effort, involving not only mechanical design of the manipulators, but also the development of actuators, sensors, and servoelectronics specifically for this application. One of the initial steps in the design of the hand/wrist teleoperation system was to ascertain what features the design should incorporate to provide the high level of performance desired. The feasibility of such features was then determined through the construction of design mock-ups. Initially, the design mock-ups were simple. However, as the designs progressed, the mock-ups became increasingly sophisticated. Once the feasibility of the various design concepts was verified, the detailed design of master and slave systems began.

Work on the master and slave systems progressed in parallel. At the time of writing, the design, fabrication, and assembly of the hand/wrist master had been completed. Design of the slave had been completed and the fabrication had been started. In Figure 1 above, photographs of the first working model of the hand master are shown. Preliminary testing has shown that the hand master provides the degrees of freedom and ranges of motion necessary to accomplish more complex tasks. Gravity compensation will be used so that the operator won't have to support the weight of the hand master. It is also possible that dynamic compensation will be used to reduce the effects of the inertial forces that the operator feels. It is anticipated that this design will be trimmed down in future design iterations, reducing its weight and inertial load significantly.

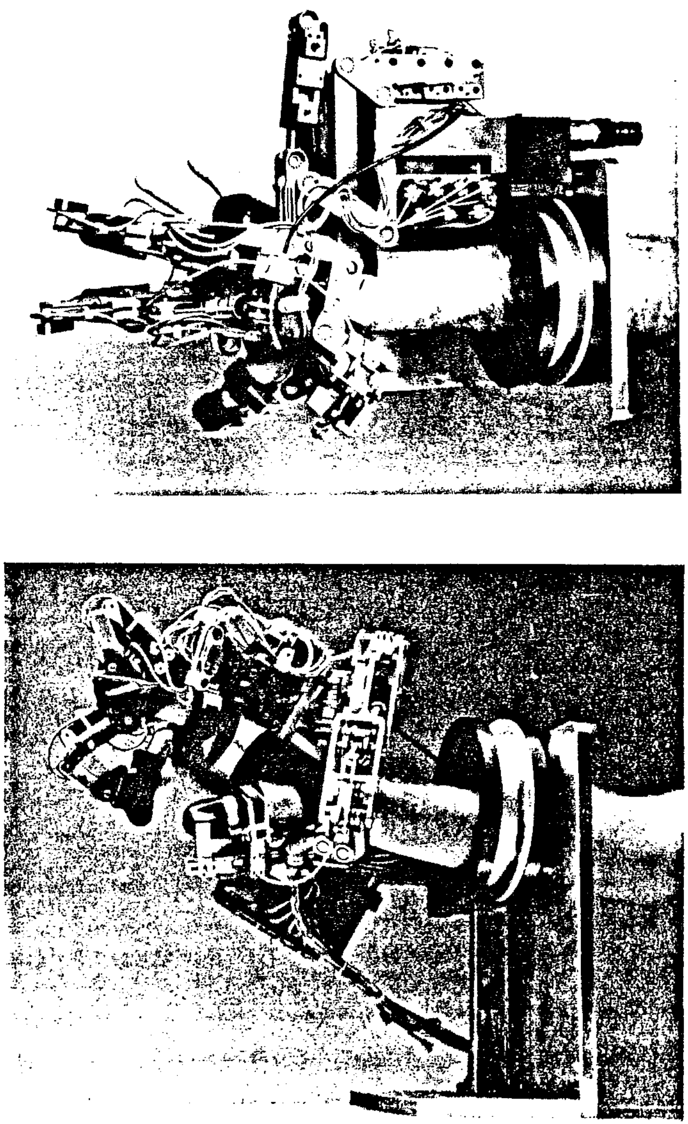

Figure 1. Hand/Wrist Master.

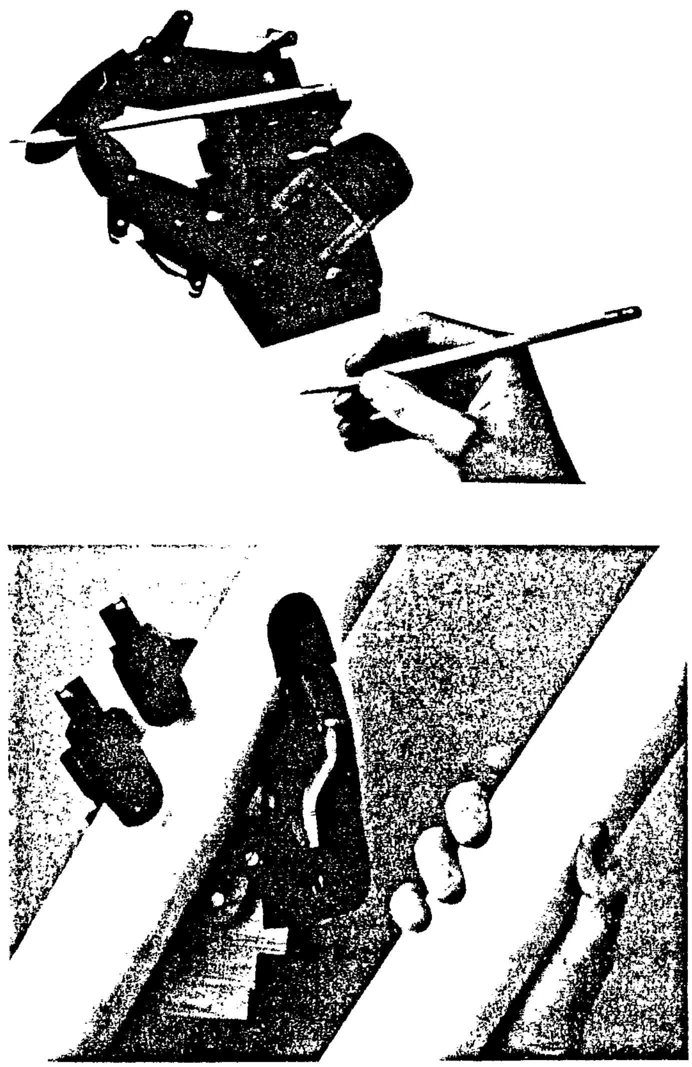

Figure 2. Hand/Wrist Slave Mock-Up.

Figure 2 shows the latest slave design mock-up. Fabrication and assembly of the first working slave model is scheduled to be completed by the end of the year (1988). Since the slave uses much of the same technology as the master, major problems in the initial operation of the master are not anticipated. It should be noted that these designs represent the first working model of the system, and that two complete design iterations will be performed before the first functional system is completed in November of 1990.

DESIGN GOALS

Desired Tasks and Grasps

The first step in the design of the master/slave system was to identify a representative set of tasks and grasps so that their successful completion by an operator using the manipulator would signify achievement of the high level of dexterity desired. The types of tasks targeted to be performed by the hand/wrist master/slave ranged from delicate manipulative tasks, such as threading nuts onto bolts, to tasks which require high strength, such as striking an object with a hammer. A number of grasps were also targeted to be performed. The ability to successfully execute these grasps would be indicative of possessing the dexterity required to perform a wide variety of unstructured, unanticipated tasks.

Required Degrees of Freedom

With the desired dexterous manipulations for the master/slave defined, the number and location of hand/wrist degrees of freedom (DOF) necessary to perform the manipulations were determined. In order to execute all of the grasps with a reasonable amount of dexterity, a four DOF thumb was needed; one DOF to bring the thumb from a position opposing the fingers into a lateral or salute position and one DOF in each of the three distal joints. A minimum of two fingers was required. A DOF corresponding to each of the first two joints was needed in each finger, along with a separate DOF for spreading the fingers. In total, the hand design required nine actuated degrees of freedom to fully perform the desired manipulations.

Proper execution of the target tasks and grasps also required a wrist with three degrees of freedom; an abduction/adduction DOF, a flexion/extension DOF, and an axial rotation (supination/pronation) DOF. Effective emulation of the human wrist required that these axes of rotation intersect at a point and be orthogonal to one another. A complete discussion of the required ranges of motion for each degree of freedom is beyond the scope of this paper, and therefore it is deferred to a companion paper [4].

PRELIMINARY DESIGN ISSUES

At the commencement of this project, an effort was made to identify the most important design issues in the development of the hand/wrist master and slave, and to enumerate all of the possible design alternatives for addressing these issues. These design issues and alternatives are addressed briefly in the following sections.

Force Reflection Capability

To achieve the desired level of dexterity, it was determined that all of the joints in the hand/wrist master should reflect the forces encountered at the slave to the joints of the operator. High bandwidth, high resolution force reflection to each joint of the master will greatly improve the teleoperation "feel" of the master/slave system.

Kinematic Equivalency

Kinematic dissimilarities between the master and slave would require that kinematic transformations be performed to have good correspondence between their positions and orientations. These kinematic transformations would add a significant amount of computational effort to the servo loops, thereby decreasing the bandwidth of the overall system and degrading the teleoperation performance. To ensure high quality teleoperation performance, the master and slave systems were designed to be kinematically identical. Kinematic equivalency between the master and slave not only reduces the computational effort required, but it also aids the operator by providing exact spatial correspondence between movements of the master and the slave.

Coincidental vs. Noncoincidental Axes

In order for the hand master to be natural and easy to use, the linkages of the master must rotate about the same axes as the finger joints of the operator. That is, the axes of rotation must be coincidental. Coincidental axes of rotation, along with kinematic equivalency between the master and slave, make good operator-to-slave mapping possible. Noncoincidental axes of rotation would make the master uncomfortable and awkward to use. For these reasons, the hand master was designed to have axes of rotation coincidental with the operator's hand.

Exoskeletal vs. Terminus Hand Master

The primary advantage of a terminus type hand master is its simplicity compared to an exoskeletal type master. However, since a terminus master would be connected only at the finger tip, force reflection to the individual finger joints would be impossible. Since a terminus master would be kinematically dissimilar to the slave, a large amount of kinematic computation would be required.

Because of these major disadvantages, it was decided that the more complicated exoskeletal master would be developed.

Anthropomorphic vs. Nonanthropomorphic Slave

A nonanthropomorphic slave design with a limited number of degrees of freedom, such as a parallel jaw gripper, would certainly be simpler to design and involve much less risk. An anthropomorphic design provides for a high level of correspondence between operator movement and the movement of the slave, enhancing the dexterous capabilities of the system. The multiple degrees of freedom that an anthropomorphic design requires also allows greater flexibility in performing a wide range of tasks.

Actuator Types

The operation of a force reflective, teleoperated manipulator places specific demands on the servo actuation systems used. Successful implementation required servo systems capable of demonstrating qualities such as high bandwidth, high stiffness, and high slew rate. The design of the actuators was constrained by size, weight, packagability, power output, efficiency, controllability, safety, cost, reliability, maintainability, and useful life. Three types of actuation systems were considered as potential actuator solutions for the hand/wrist master/slave manipulator: electromechanical (EM), electrohydraulic (EH), and electropneumatic (EP). These three types of actuation systems each have distinct performance characteristics that govern their applicability to a force reflective teleoperation system.

Preliminary tests performed at the CED gave results that concurred with performance characteristics described in the literature [5,6]. Pneumatic actuators, because of their relatively low bandwidth, low actuation stiffness, and low power output capability, did not meet the design criteria for good force reflective teleoperation performance. Electromagnetic actuators met many of the design requirements, but their relatively large size and high weight would have made packaging for a multiple degree of freedom end effector difficult, if not impossible. Furthermore, EM actuators have very poor static force capability in comparison with pneumatic and hydraulic systems. Hydraulic actuation systems possess qualities that make them the best choice for the development of a dexterous, force reflective, hand/wrist master/slave manipulator. High bandwidth, high actuation stiffness, and high power output can be attained with EH systems. Moreover, having the power conversion equipment located remotely to the point of actuation provides very high power density and the packaging capability necessary to actuate many degrees of freedom in a small space.

Location of Actuators

Locating the actuators was an issue of critical importance in the design of the hand/wrist manipulator. The large number of degrees of freedom and limited available space did not permit placing the finger actuators in the hand as might have been desired. Other possible locations for the finger actuators included the wrist, the forearm, the upper arm, and the torso area. Locating actuators in the torso or the upper arm would have been advantageous because it would have reduced the inertial load that the arm would have been required to control. Because of the difficulty in actuating a large number of joints remotely, as actuators in the torso or upper arm would have required, the hand wrist actuators were placed in the wrist and lower forearm area. Furthermore, remotely locating the actuators would have increased the damping and compliance in the tendon systems, reducing the quality of the teleoperation feel.

Drive Types

With the actuators for the master and slave located in the forearm area, the alternatives for linking the actuators to their joints were limited. A gear type transmission was unnecessary, and therefore, undesirable with a hydraulic actuator. A direct drive crank type mechanism wasn't a viable alternative for actuation of the fingers since they are located distal to the wrist. The most feasible method for actuating the fingers was to use two tendons antagonistically operating each joint. This method had been successfully implemented in the past in a similar application [7] where, due to space limitations, actuators were located remotely to the joints they actuated. The main disadvantage to this method is that it requires two actuators to operate each joint. Thus, for the nine degrees of freedom in the fingers, a total of eighteen actuators are required. In the master, the wrist rotation and flexion/extension DOFs are operated antagonistically, while the wrist abduction/adduction is actuated directly. The slave is similar except that wrist rotation is also actuated directly.

Actuator Configuration

Both rotary and linear actuator configurations were examined for use in the hand/wrist master and slave. With the exception of wrist rotation in the slave manipulator, linear actuators were chosen to actuate all of the degrees of freedom. Linear actuators were chosen because of their compatibility with tendon actuation, good packaging characteristics, and simplicity.

ACTUATION SYSTEM DEVELOPMENT

Central to the success of the hand/wrist master and slave was the development of an actuation system which would meet the high performance requirements while also satisfying the very tight constraints on size, weight, and packagability. Outlined in this section are detailed descriptions of the piston and valve design development for the hand master and slave.

Piston Design

Based upon initial designs of the hand, performance requirements for the linear piston actuators of the hand were formulated. In order to give the hand master and slave the desired amount of strength, it was determined that the piston actuators should be capable of pulling with a force of 100 pounds with a pressure differential of 1200 psi. To make the finger joints fast enough, the piston needed to have a maximum velocity of at least six in/sec. This placed a specific flow requirement on the servovalve to be used. The piston was required to have a 1-1/2 inch stroke. It was also desired to reduce the amount of stiction in the piston as much as possible and make the piston as small as possible.

In the design of the piston actuator, the rod diameter was chosen to be 3/16 inches. This was done to give sufficient thread area where the rod attaches to the piston to eliminate the possibility of failure due to excessively high stresses. To meet the force output requirement with a 3/16 inch shaft, the piston had to be .376 inches or greater. To allow the use of standard size seals, the piston diameter was decreased slightly to 3/8 inches resulting in a force output capability of 99.4 pounds. With a piston/rod configuration of this size, moving the piston at six inches per second required a valve flow of approximately .2 gpm. To improve the servo control of the actuation system, piston stiction was minimized through the use of radial spring-energized Teflon seals.

Valve Design

In recent years at the CED, a significant amount of effort has been directed toward the development of a small, relatively simple, and inexpensive servovalve. The primary result of this effort is a single stage, four way valve design that has been successfully implemented in commercial robotic applications requiring low supply pressures (500 psi) and low flow rates (< .4 gpm). The servovalve incorporates design characteristics of common jet pipe and swing plate valves (see Figure 3). Similar to a jet pipe valve, current commands to the torque motor of the valve modulate the position of the valve pipe tip, which correspondingly controls the areas of the supply and return orifices to each side of the actuator being servoed. Figure 2 shows a schematic of the valve pipe tip and receiver plate, which illustrates how orifice areas are changed as the valve pipe tip position is modulated. As a result of the success of this servovalve design, it was determined that subsequent valve development for the hand master and slave would be based upon this design.

Prior to commencing the valve design, a number of design goals and constraints were enumerated. It was determined that to make packaging of the actuation system feasible, that the valve would have to be less than 1/2 inches in diameter and no more than 2 inches long. In order to achieve the high force output and high bandwidth desired, supply pressures between 1200 and 1500 psi would be required. It was decided that for purposes of robustness, flexibility, and increased performance, that the valve should be capable of operating at pressures up to 2500 psi. Speed requirements of the piston actuator demanded that the maximum no load flow capability of the valve be a minimum of .2 gpm. It was also desired to keep leakage flow to a minimum to reduce unnecessary power consumption.

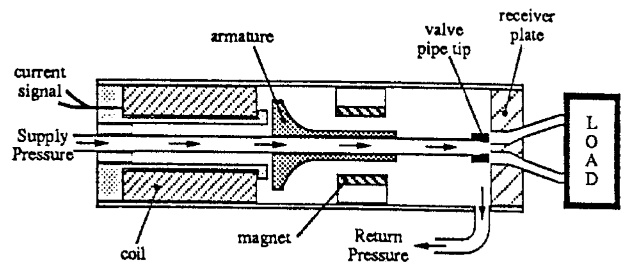

Figure 3. Single Stage Servovalve Schematic.

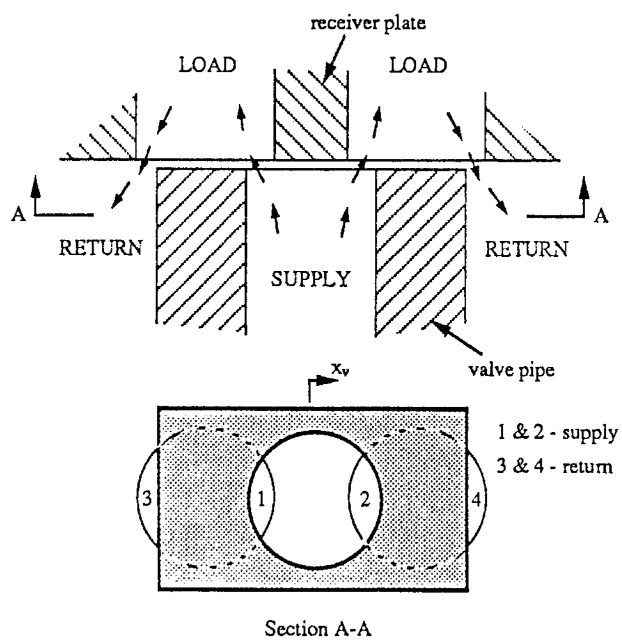

Figure 4. Valve Pipe Tip – Receiver Plate Schematic.

The first step taken in the valve design process was the scaling down of the existing valve design to within the desired size envelope. The initial design used a valve pipe tip/receiver plate configuration similar to that shown in Figure 4 with .040 inch diameter holes. The valve pipe had a .072 inch OD. This valve design was found to be both unstable and incapable of delivering the required rate of flow. From this point, additional improvements to the valve design were made by a sensitivity analysis. Deficiencies in valve performance were attributed to certain design parameters or configurations. Changes were then made to the appropriate parameters or configurations to amend these deficiencies. Design changes were then analyzed to determine their effectiveness. These steps were then repeated until satisfactory performance was attained. The following paragraphs briefly describe the progression of the valve development from the beginning to the present design.

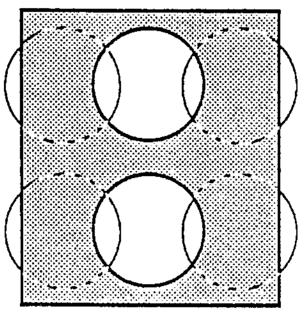

Figure 5. Aligned Orifice Configuration.

In order to improve the flow capacity of the valve, a second row of orifices was added to the tip and receiver plate (see Figure 5). This valve was also unstable above 1000 psi. The addition of a damper plate to the valve pipe tip helped damp out the valve pipe resonance, however, the valve was still only marginally stable. At this point, a clear acrylic housing and manifold was made for the valve so that instabilities could be visually observed. It was found that the valve pipe was oscillating in a direction perpendicular to its normal operating direction. A mechanism for positive feedback from flow forces on the valve pipe tip was postulated. Flow forces on the valve pipe tip tended to deflect the tip vertically moving the holes out of alignment with those in the receiver plate. The stiffness of the pipe opposed this deflection, forcing the pipe tip and receiver plate back into alignment. It was postulated that these two opposing forces were the cause of the vertical instability. A valve design with offset valve tip and receiver plate holes (see Figure 6) and a stiffer valve pipe was recommended to eliminate this vertical instability.

The next valve design incorporated a .095 OD valve pipe which was about three times stiffer than the previously used valve pipe. An offset orifice design was used with two holes in the valve pipe tip and six holes in

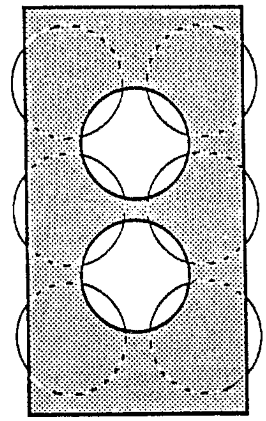

Figure 6. Offset Orifice Configuration.

the receiver plate. This valve was stable to over 2000 psi, but the maximum no load flow was only .15 gpm. Further testing of this valve showed the maximum valve tip deflection to be only .0035 inches, a small fraction of the .040 inch diameter holes available. In this case, flow forces opposing the horizontal motion of the valve, along with the increased valve pipe stiffness limited the torque motor's ability to open the orifices. At the same time, increasing the pipe stiffness resulted in a valve with a very high natural frequency – over 700 Hz. While this high natural frequency was not a measure of the open loop bandwidth of the valve, it was a reasonable indication of the closed loop bandwidth that could be attained. Further testing showed that the high natural frequency valve was extremely beneficial in terms of improving teleoperation feel.

It was decided that flow forces would possibly be lower if multiple rows of smaller holes were used rather than a two rows of the .040 inch diameter holes. In an effort to reduce flow forces, thereby increasing the flow capacity, two new valves were designed for testing. The first valve had .014 inch diameter holes – six in the valve tip and 14 in the receiver plate. The second valve had a slotted tip and two .006 inch wide slots in the receiver plate as shown in Figure 7. Both valves used .095 inch diameter tubing for the valve pipe and had maximum tip deflections of .004 inches. Both valves were stable up to 2500 psi. The flow rate for both valves was improved, but still marginal (< .20 gpm). To achieve greater tip deflection (i.e. higher flow rate), a more compliant .083 inch diameter tube was used for the valve pipe tip. The slotted valve was then unstable at pressures above 600 psi, but had a maximum flow rate of .30 gpm. By increasing the gap between the magnets and the torque motor armature, the .014 inch diameter hole valve could be made stable because widening the gap reduced the magnetic attraction on the valve pipe, thereby increasing the effective stiffness of the pipe. Increasing the gap also weakened the torque motor, resulting in smaller valve tip deflections. The net result was a valve that was marginally stable and had a maximum no load flow of only .2 gpm.

During the development of earlier valve designs, it was learned that in order to increase the valve gain dA/dx (change in orifice area/change in valve position), that valve pipe stiffness must be increased correspondingly to maintain stability. To increase the deflection of the valve pipe tip, it was decided to decrease the gap width between the magnets and the armature. To counteract the resulting decreased stiffness of the valve pipe, the valve pipe tip was

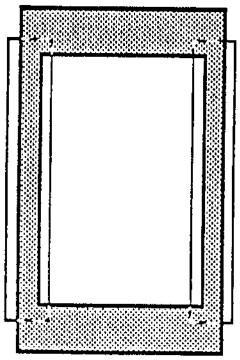

Figure 7. Slotted Orifice Configuration.

designed to have only four holes. This was done to reduce the valve gain in order to ensure stability. The receiver was left with 14 holes to prevent the flow to return from being limited which would have decreased the flow capacity of the valve. The valve pipe diameter was also left at .083 inches to allow large deflections of the tip. In this configuration, the valve was stable at 1500 psi with cool oil. However, as the oil temperature increased, the valve became slightly unstable because of changes in the properties of the hydraulic oil. This valve had a no load flow rate of .25 gpm.

At this point, a closer look was taken at the design of the torque motor. In experimentally evaluating the effects of changing many of the motor parameters, it was found that enlarging the area of the magnets, while decreasing their thickness, maximized the force producing capacity of the motor and simultaneously reduced the undesirable softening effect of the magnets on the spring constant of the valve pipe. A new motor was designed with thin, large-area magnets, a narrow magnet/armature gap, and a valve pipe sized to allow valve tip deflections up to .012 inches. These changes increased the force output capacity of the motor by a factor of two.

A valve was made using the improved motor with a four hole (.140 inch diameter) valve tip, a 14 hole receiver, and a .083 inch diameter valve pipe. In initial testing, the measured flow through the valve did not correspond to the deflections of the valve tip as the tip was deflected to its maximum because the new motor was deflecting the tip past the point where the tip holes and receiver holes were completely aligned. The net effect of this was that the supply orifice areas would increase as the valve was deflected initially ($dA/dx > 0$) and then begin to decrease as the tip passed the point of complete alignment ($dA/dx < 0$). To alleviate this problem, a valve was designed with three .020 inch diameter holes in the valve tip and eight .020 inch diameter holes in the receiver plate. This valve met the design requirements – it flowed at a rate of .35 gpm and showed no sign of instability up to 2500 psi. When tested on a finger joint test set up, the high natural frequency of the valve allowed high servo gains and therefore, a very free feeling force servo and a very stiff position servo.

A second valve was built for antagonist operation of the test finger joint. Although identical in design to the previous valve, this valve oscillated as the oil warmed. Since the designs were identical, this oscillation had to be due to the variability of the manufacturing and assembly. Two more valves were made with shorter (i.e. stiffer) valve pipes. These valves also were marginally stable when run on very hot oil at 1500 psi. A damping paddle was added to one of these valves to suppress the oscillation. However, the paddle, because of the additional mass it added to the valve pipe, had a detrimental effect on the bandwidth of the valve.

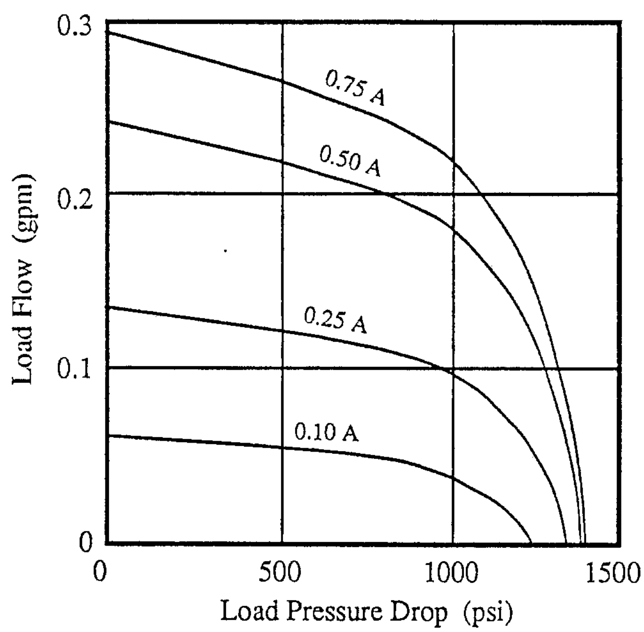

Figure 8. Prototype Servovalve Control Characteristic.

At this point in the design of the valve, it was necessary to make a production run of 25 valves to supply the hand/wrist master prototype system which was nearing completion. The decision was made to use the latest design without the damping paddles, but with a slightly stiffer jet pipe. Pressure and oil temperature could, if necessary, be easily controlled to prevent oscillation. A plot of the servovalve control characteristic is shown in Figure 8 above. Figure 9 shows a picture of the valve that was used in the prototype system. Meanwhile, investigations into the causes of these instabilities continued, as did the development of fixtures and techniques to ensure uniformity in the assembly of the valves. At the time of writing, detailed research into improving the orifice design of the valve was commencing.

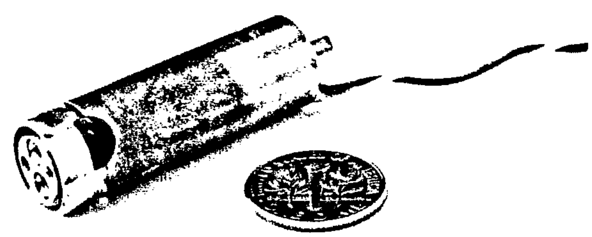

Figure 9. Prototype System Servovalve.

SUMMARY

A multiple degree of freedom hand/wrist teleoperation system has been designed. Fundamental design issues governing the development of the design were addressed and resolved in the initial stages of the design process. A miniature hydraulic servovalve has been developed to control the pistons which actuate the joints in the hand and wrist. Present valve performance is satisfactory, however, further modifications will be made to improve the robustness of the design. At the time of writing, the hand/wrist master system had been fabricated and assembled, and was undergoing initial testing. The hand/wrist slave system design has also been completed and fabrication has commenced. The complete hand/wrist teleoperation system is on schedule to be operational and ready for laboratory demonstration in February of 1989.

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