PORTABLE DEXTROUS FORCE FEEDBACK MASTER FOR ROBOT TELEMANIPULATION (P.D.M.F.F.)

Grigore C. Burdea
Electrical and Computer Engineering Dept.
Rutgers University
Piscataway, NJ 08855-0909

Thomas H. Speeter
A.T.&T. Bell Laboratories
Machine Perception Research Dept.
Holmdel, NJ 07733

Abstract

A major drawback of open loop masters is a lack of force feedback, limiting their ability to perform complex tasks such as assembly and repair. We present a simple dextrous force feedback master for computer assisted telemanipulation. The device is compact, portable and can be held in the operator hand, without the need for a special joystick or console. The system is capable of both position feed forward and force feedback, using electronic position sensors and a pneumatic micro actuator. The level of forces exercised by the pneumatic actuator is such that near rigidity may be attained. We present experimental results showing good system linearity and small time lag.

1. Introduction

Present telemanipulation techniques include mechanical masters, open loop servo masters, and to a lesser extent closed loop servo masters. Direct mechanical telemanipulation is often the simplest method, but cannot be used in applications where the slave is not in the immediate vicinity of the master, as may well be the case in space applications. Closed loop servo telemanipulation eliminates the proximity requirement, but when force feedback is provided by servo encoders on the slave arm, it is necessary to have two nearly identical devices to act as master and slave. This duplication of resources may be prohibitive in terms of cost and payload weight.

Current research efforts aim at eliminating the duplicate master by replacing it with force feedback joysticks or sensorized spheres[3]. These devices are less "natural" to use by an operator since direct similitude does not exist between human hand and robot finger motions.

Dextrous master control represents a recent addition to the field of telemanipulation. A dextrous master can replace the classical manipulator arm, joystick or keypad master with an operator's hand motions[6]. Use of the human hand is a natural form of control and is applicable to both nondextrous and dextrous slave devices. Because the human hand is used as master, duplication of hardware is not required, and weight, inertia and friction are reduced. This can bring significant improvements in the time necessary to complete a task. It is estimated [2] that an improvement on the order of 10 can be expected on the time efficiency quotient[7] when a dextrous master is used in place of keypad control.

While an open-loop dextrous master creates a natural control environment, it lacks the ability to bring force feedback to the operator hand, which in turn limits the utility of the slave device. This paper describes work towards the development of a dextrous master with force feedback. Such a device will allow the execution of complex tasks such as assembly and repair, using the human hand as master in closed loop teleoperation environment.

2. Conceptual design

The design of the Portable Dextrous Master with Force Feedback (PDMFF) was guided by the need to bring force feedback from a robot end effector to the human hand serving as master. The aim is to produce a compact, hand held device that fits inside the palm. It should function as position controller for the robot end effector (either conventional gripper or dextrous hand), and provide force feedback to the operator.

We have developed an initial master device to control and exert feedback in one degree of freedom. The position sensing device is an LVDT transducer and force feedback is provided by a small pneumatic piston in parallel with the LVDT (Fig. 1). The LVDT requires only two contact points to secure its ends, therefore two fingers are sufficient to hold it. Use of the thumb and middle fingers assures a good grip and sufficient distance to accommodate the LVDT and piston.

The first joint of the thumb has two degrees of freedom namely anteposition/retroposition and abduction (Fig. 2) [1]. Human factor studies[5] show that the most comfortable thumb postures are those with little anteposition. The need to minimize fatigue implies that such postures should be accommodated by the master. A sphere joint on the middle finger mount allows for 70 degrees rotation. This combined with the translation movement of the active element produces a conic work envelope as shown in Fig. 3 and allows the user to comfortably position the PDMFF between his fingers.

The volume of the master work envelope is given by:

$$\pi \sin^2\alpha \cos\alpha \, d \left(\frac{d^2}{3} + ld + l^2\right) \qquad (1)$$

where:

α is the sphere joint angle,
d is the linear travel,
l is the length of the mechanical mount.

Due to limitations on the thumb's range of motion, the useful volume used to control the slave gripper is about 25% of the work envelope.

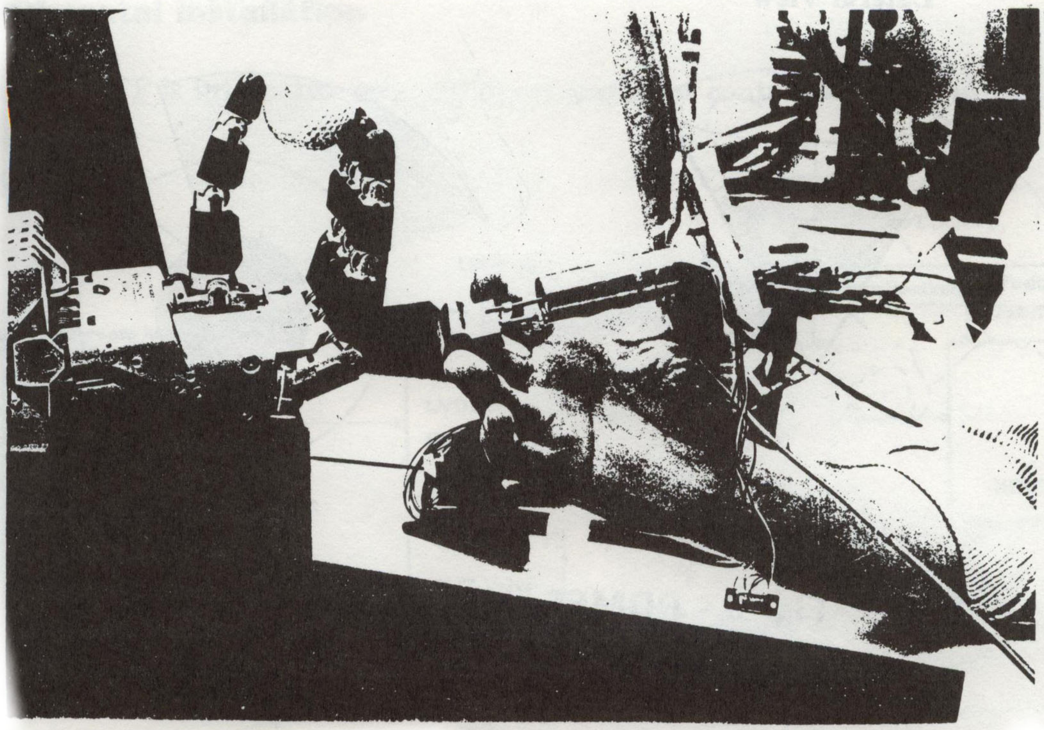

Fig. 1 - PDMFF prototype

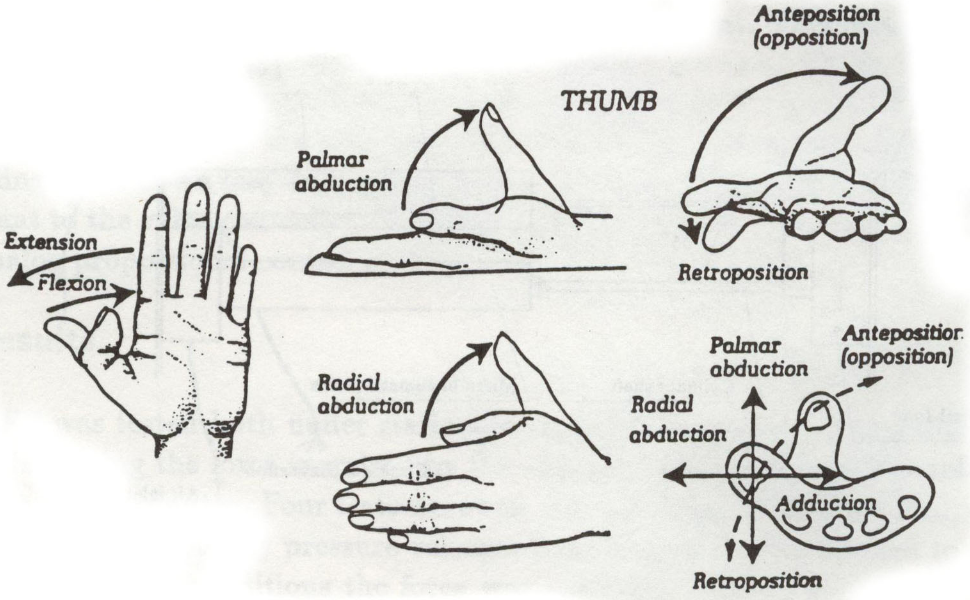

Fig. 2 - Terminology of thumb motion [1]

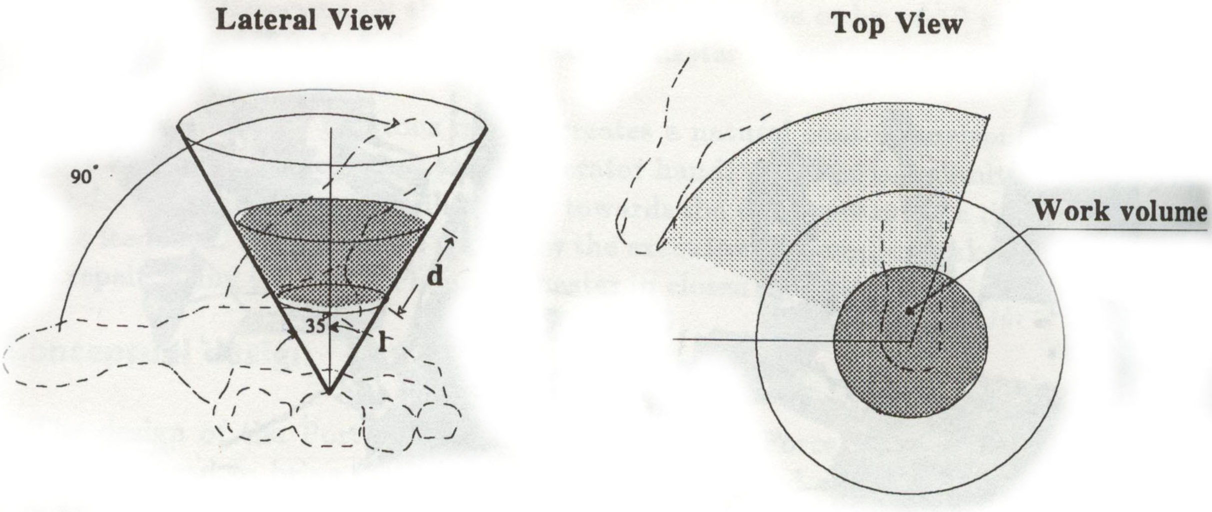

Fig. 3 - PDMFF work envelope

The desire for reduced dimensions and weight, while maintaining sufficient force capability led to the selection of a pneumatic micro cylinder as the active element. The cylinder spring is removed, allowing for free motion of the piston. The piston shaft is coupled with a second shaft attached to a magnetic core traveling inside the LVDT sensor. The resulting configuration is shown in Fig. 4.

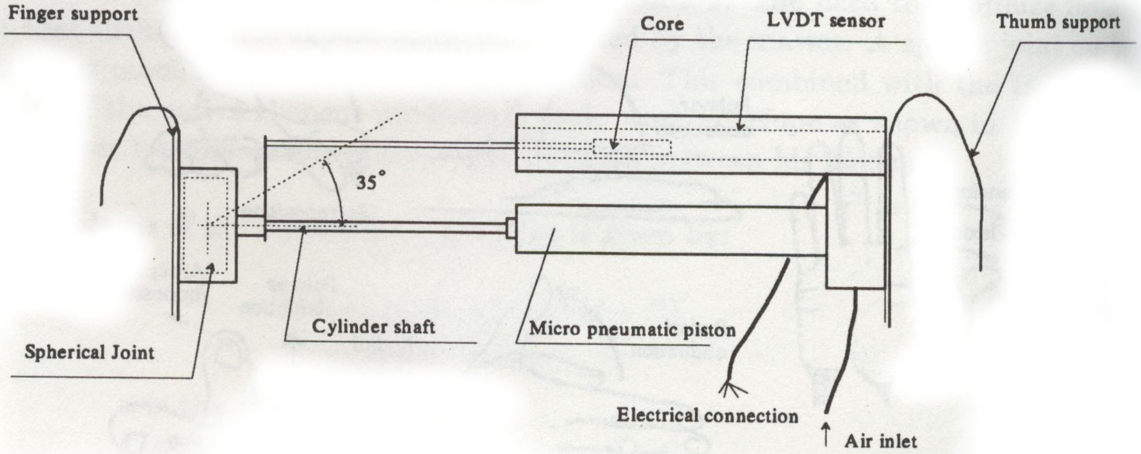

Fig. 4 - PDMFF design

3. Experimental installation

The PDMFF is integrated with a host computer for control as shown in Fig. 5.

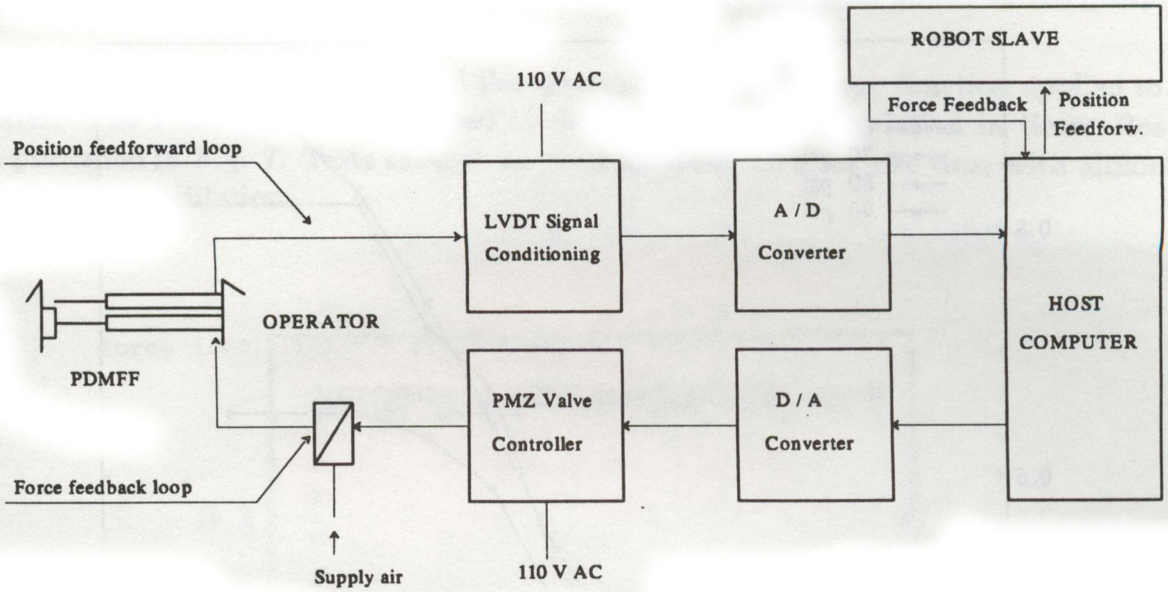

Fig. 5 - Experimental installation

Position signals from the LVDT are passed through a signal conditioning unit, giving an analog signal (voltage) proportional to the core's displacement. This voltage is digitized by an analog to digital converter and sampled by a host computer at 500Hz. The host uses this signal to position the slave robot, in this case the Utah-MIT hand[4]. Force feedback from the hand is sampled by the host and used to drive the pneumatic cylinder. At this point a scaling up or down may be implemented to adjust the gain in the feedback loop. A voltage is sent to the valve controller which raises or lowers the air pressure in the cylinder using an analog proportional control system.

4. Test results

PDMFF was tested both under static and dynamic conditions. The static test was aimed at determining the force exercised by the cylinder as a function of the voltage controlled by the host computer. Four tests were run with air supply pressures, P_{air}, of 60, 70, 80 and 90 psi. For each supply pressure voltages from 0 to 10 V were applied to the valve controller. Under these conditions the force was measured with a load cell. The results are presented in Fig. 6. The force feedback is given by:

$$F_{feedback} = P_{air}\ A - F_{friction} \tag{2}$$

where: A is the piston area,
P_{air} is the air pressure after the valve regulator,
$F_{friction}$ is the piston friction.

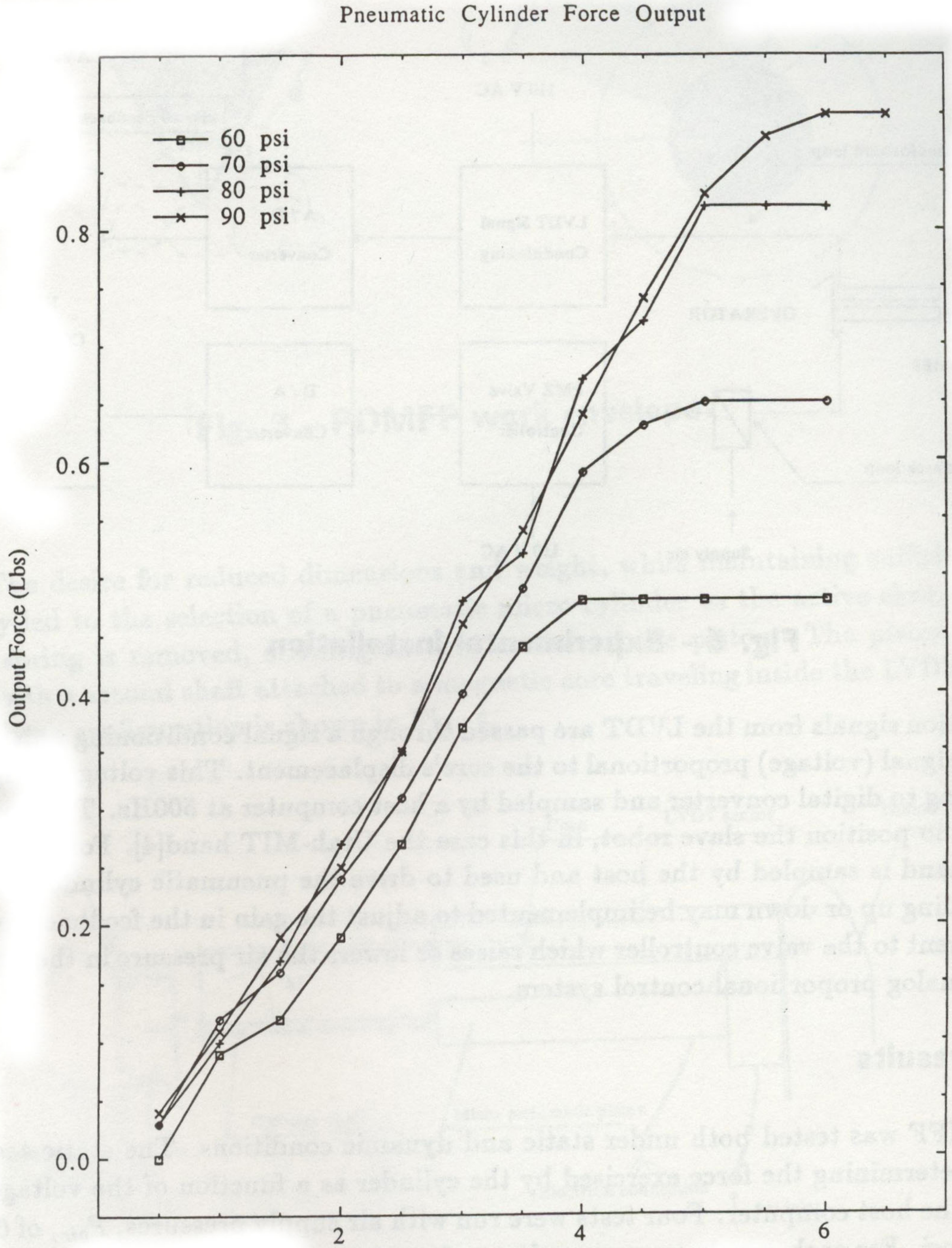

Fig. 6 - Micro cylinder force measurements

The linearity of equation (2) is reflected in the graph, with the exception of plateaus appearing at higher voltages. At these plateaus maximum air flow is applied on the piston, and force no longer varies with increased voltage. A supply pressure of 90 psi and a voltage of 6V results in almost a pound force. This is a large enough force to produce near rigidity in the master and is sufficient to simulate the sensation of a solid object in the grasp.

A second set of tests measured the system response to a step function applied to the master. The same load cell was used to determine the force variation in time. Results are presented in Fig. 7. Tests showed an approximately 50 msec rise time with almost no overshoot or oscillation.

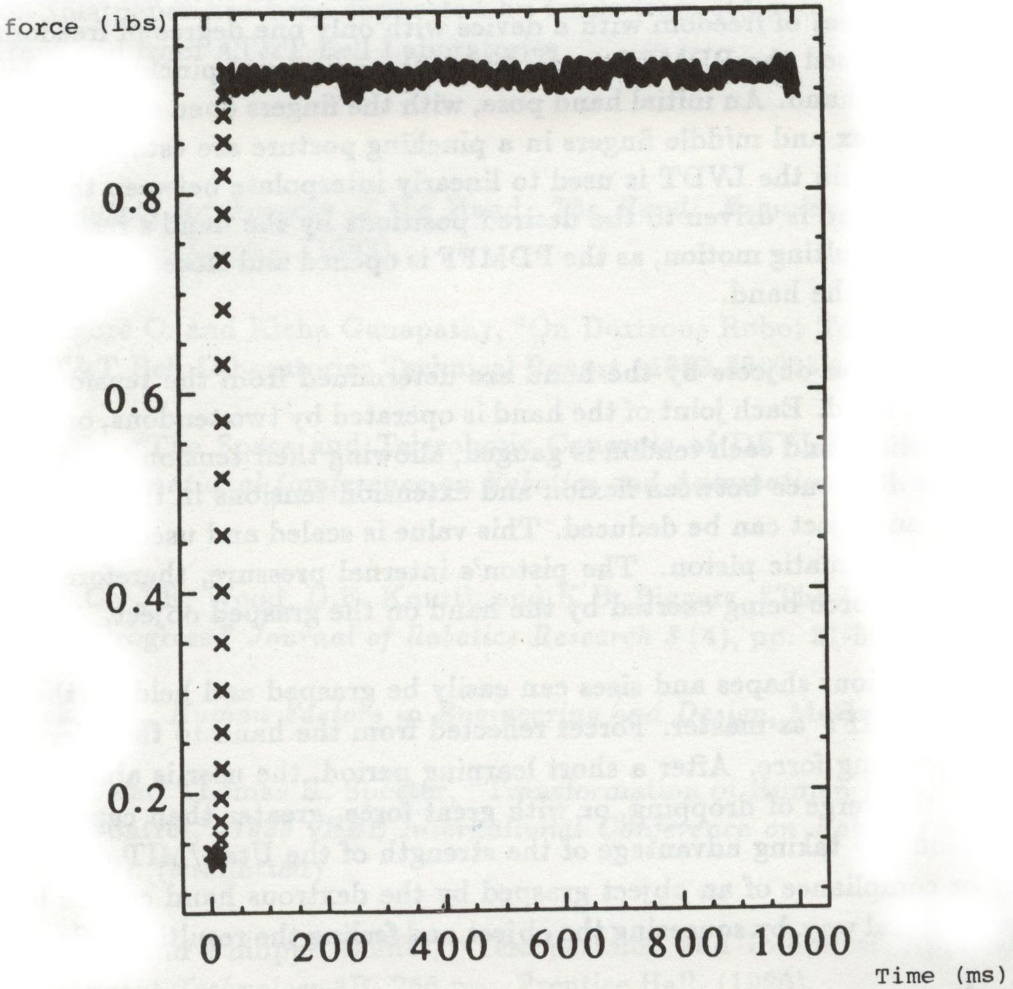

Fig. 7 - Dynamic response for step function input

5. Integration with robotic slaves

The design of the PDMFF makes it compatible with both dextrous and nondextrous end effectors. When coupled with a parallel finger gripper, the LVDT signal controls the gripper opening in a linear relationship. Since the piston travel is fixed for a given cylinder, the gripper opening is given by

$$L_{gripper} = LVDT_{signal}\frac{G}{d} \tag{3}$$

where

G is the gripper maximum opening,
d is the piston maximum extension.

When telemanipulating with a dextrous hand, we are faced with the problem of controlling multiple degrees of freedom with a device with only one degree of freedom. As an initial test we have used the PDMFF to control a three-fingered pinching motion of the Uhah/MIT dextrous hand. An initial hand pose, with the fingers open and a final position with the thumb, index and middle fingers in a pinching posture are established. The position of the core within the LVDT is used to linearly interpolate between the initial and final pose and the hand is driven to the desired positions by the hand's resident position servo system. The resulting motion, as the PDMFF is opened and closed is a natural pinch and release action of the hand.

Forces exerted on objects by the hand are determined from the tensions sensed in the tendons of the hand. Each joint of the hand is operated by two tendons, one for flexion and one for extension, and each tendon is gauged, allowing their tension to be monitored. By observing the difference between flexion and extension tensions in the thumb, the net force exerted on an object can be deduced. This value is scaled and used to directly drive the valve of the pneumatic piston. The piston's internal pressure, therefore, is directly proportional to the force being exerted by the hand on the grasped object.

Objects of various shapes and sizes can easily be grasped and held by the dextrous hand using the PDMFF as master. Forces reflected from the hand to the user allow deft control of the grasping force. After a short learning period, the user is able to grasp objects lightly, at the verge of dropping, or with great force, greater than capable with the human hand alone by taking advantage of the strength of the Utah/MIT dextrous hand. The rigidity or compliance of an object grasped by the dextrous hand can be felt by the user in a very natural way, by squeezing the object and feeling the resulting reflected forces.

6. Conclusion

The force reflecting master described here allows the user to control the motion of, and feel the force exerted on a slave robotic device. The PDMFF uses a simple parallel arrangement of an LVDT position sensor and micropneumatic piston to provide a closed loop telemanipulation system.

Interfaces to the PDMFF are simple, consisting of one voltage out, corresponding to the LVDT's position, and one voltage in, driving the pneumatic cylinder. Control of the slave will vary in complexity depending upon the device, however the simplicity of the PDMFF may allow the use of discrete components in the interface between master and slave rather than requiring the intervention of a processor. This can further reduce the complexity, cost and size of a master-slave system using the PDMFF, and may allow the development of compact, multidegree of freedom masters using several PDMFF-like mechanisms in parallel.

7. Acknowledgements

Work on this paper has been supported by funds from Rutgers University Research Council Grant and from AT&T Bell Laboratories.

References

1. American Society for Surgery of the Hand, *The Hand: Examination and Diagnosis*, Churchill Livingstone, London (1983).

2. Burdea, Grigore C. and Kicha Ganapathy, "On Dextrous Robot Telemanipulation and Learning," AT&T Bell Laboratories Technical Report 11352-881003-11TM.

3. Hirzinger, G., "The Space and Telerobotic Concepts of DFVLR Rotex," *1987 Proceedings IEEE International Conference on Robotics and Automation*, pp. 443-449, IEEE, (1987).

4. Jacobsen, S.C., J.E. Wood, D.F. Knutti, and K.B. Biggers, "The Utah-MIT Dextrous Hand: Work in Progress," *Journal of Robotics Research 3* (4), pp. 21-50 (1984).

5. McCormick, E.J., *Human Factors in Engineering and Design*, McGraw-Hill (1976).

6. Pao, Lucy Y. and Thomas H. Speeter, "Transformation of Human Hand Positions for Robotic Hand Control," *1989 IEEE International Conference on Robotics and Automation*, IEEE, (1989). (submitted)

7. Vertut, Jean and Philippe Coiffet, "Teleoperation and Robotics: Applications and Technology," *Robot Technology* 3B, 256 pp., Prentice Hall, (1986).