DIRECT-DRIVE FORCE FEEDBACK CONTROL FOR THE DATAGLOVE

Grigore Burdea, Jiachen Zhuang, Ed Roskos,
Deborah Silver, and Noshir Langrana.
College of Engineering
Rutgers - The State University of New Jersey
P.O.Box 909, Piscataway, NJ. 08855-0909, USA.

ABSTRACT

Dextrous masters control robots or artificial environments through hand gestures. Commercial products have open-loop control. There is a need for portable systems that have force feedback, and are sufficiently compact to be desk-top. A prototype providing force feedback for the Dataglove is discussed first. Then the master structure and its actuator characteristics are presented. A model for the control loop is discussed last.

1. Introduction

The teleoperation of multifinger robot hands [2,9] requires a dextrous master which is a multi-DOF controller worn on the operator's hand. Use of the human hand gestures is a natural form of control and can bring significant improvements in efficiency. Commercially available dextrous masters [7,12] control the position of a robot hand or of a simulated hand in open-loop, without force or touch feedback to the operator.

Studies done using non-dextrous masters [8] have shown that the completion time for difficult tasks was reduced by 50% when force sensation was present. This may indicate that force feedback can enhance the performance of dextrous systems as well.

The difficulty in the realization of dextrous masters with force feedback stems from a fundamental conflict between adequate control and human factors as they relate to hand geometry and human fatigue[4]. Force feedback provided for each joint of the hand as well as the wrist would necessitate a large number of actuators. Unfortunately, the geometry of the human hand reduces the volume which can accommodate these actuators. A number of prototypes with force feedback have been proposed[5,10,11] The feedback actuators used by these masters are either hydraulic[*10*] or electrical [11] with placement of the actuators remote from the hand. Thus motion/force is being transmitted through an exoskeleton structure with cables and pulleys. These complex masters are quite expensive and their usage limited.

Extending the usage to other areas than telerobotics, such as virtual environments,

S. G. Tzafestas (ed.), Engineering Systems with Intelligence, 453–460.

or video games, will require systems that are compact (desk-top), safe, quiet, and less expensive. Then user safety precludes the use of high pressure hydraulics, while compactness precludes cables, pulleys and electrical motors. If (a reduced number of) light actuators could be placed locally in the palm where force is required, then friction and backlash stop being a major concern. The resulting compact master should also have a reduced cost.

The present paper describes a portable dextrous master with force feedback that uses several pneumatic actuators placed in the hand. The resulting system is light, compact, desk-top and relatively inexpensive. This system addresses the needs of certain applications which now operate in open-loop and where the addition of feedback to some degrees of freedom is beneficial. Section 2 describes the system hardware configuration. Section 3 gives actuator characteristics and a model for the control loop. Concluding remarks and future work directions are given in Section 4.

2. System hardware configuration

Initial studies at Bell Laboratories [3] resulted in a one degree of freedom master used to control the Utah hand. This portable master with force feedback (PDMFF)[6] had one LVDT position sensor in parallel with a pneumatic actuator. The whole structure was compact enough to be held in the palm with only two fingers. While these experiments were qualitative in nature, they did show the utility of force information, even with only one feedback actuator. Considerable deprivation was felt by the users when the loop was opened, and no force information was fed back.

After the initial tests at Bell Laboratories, several PDMFF type actuators were integrated with the Dataglove master. The aim was to provide force feedback for multiple fingers. The glove position sensors on the back of each finger replaced the LVDT sensor. The resulting more compact structure has three actuators placed in the palm. This "direct-drive" system enjoys the same advantages as those used to drive robot arms, namely the absence of cables or pulleys and reduced friction. In order to allow the abduction-adduction of the fingers (thumb, middle and index), three sphere joints were installed on a small L-shaped platform attached to the exterior of the glove as shown in Figure 1. Three cylinders were mounted coaxially with the sphere joints, thus allowing for direct connection to air tubes passing through the sphere joints.

Each cylinder shaft is attached to the finger tips of the glove through cylindrical joints that allow movement in a plane normal to the fingertip. The attachment of the feedback structure to the glove is done with velcro™ strips mounted in the palm and on the fingertips. Each fingertip mounting block has three velcro strips that secure to the glove. This reduces the compliance of the user fingertip by creating a tight "two-ring" attachment which is beneficial to the overall system performance. These detachable connections also allow for adjustment to the hand characteristics of different users.

Since each actuator has its own controller, it is important to group the regulators in a modular hardware interface unit. This interface consists of three proportional pressure regulators, a pressure indicator for the main air input, power supply (24 V), and input port for for the cable from a D/A board installed in the host workstation. The design of

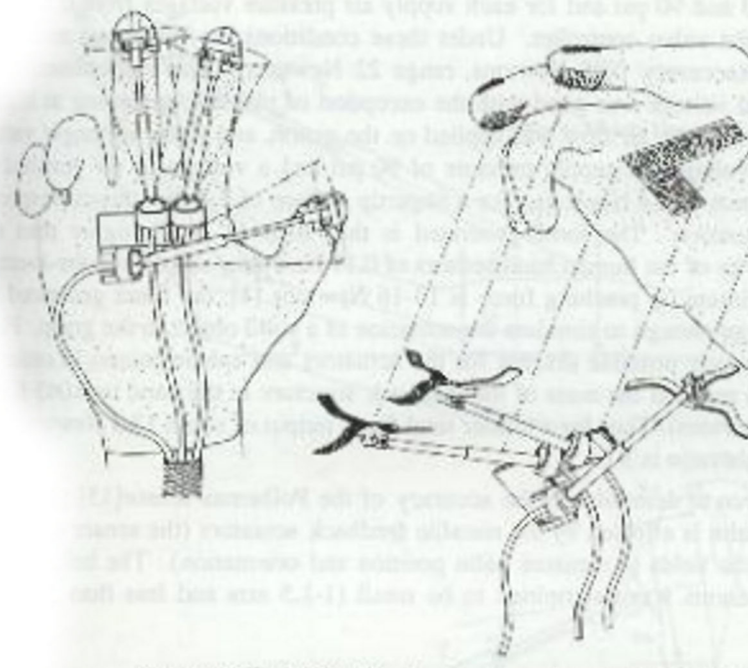

Figure 1. Force feedback structure for the Dataglove.

the interface is modular with the Dataglove electronic unit so the two modules can be "stacked-up" to save desk space.

3. Actuator characteristics

The cylinder springs were removed to allow free motion of the piston when no air pressure is applied. Since the most comfortable thumb postures are those with little anteposition[13], a sphere joint was integrated in the palm platform in order to accommodate these postures. The resulting work envelope $V_{work-envelope}$ for each actuator is a portion of a sphere sector as:

$$V_{work-envelope} = 2\pi\, d\,(1-\cos\alpha)\left[(l+s)^2 + d(l+s) + \frac{d^2}{3}\right] \qquad (1)$$

where: d=20mm is the piston stroke,
l=62mm is the cylinder length,
s=7mm is the length of the fingertip mounting block, and
α=30 degrees is the sphere joint half-angle.

The actuators were tested under both static and dynamic conditions. The static tests were aimed at determining the force exercised by the cylinder as a function of the voltage controlled by the host computer. These tests were run with air supply pressures,

P_{air}, of 60, 70, 80 and 90 psi and for each supply air pressure voltages from 0 to 10 V were applied to the valve controller. Under these conditions the force was measure with a load cell (accuracy 0.05 Newtons, range 22 Newtons). The proportionality of force with applied voltage was good with the exception of plateaus appearing at higher voltages. Here maximum air flow was applied on the piston, and force no longer varied with (increased) voltage. A supply pressure of 90 psi and a voltage of 6V resulted i almost a pound force or 4.4 Newtons. For a fingertip surface of 2-3 cm^2 this corresponds to 2.2-1.46 Newtons/cm^2. The force generated is thus 8 to 11 times higher than the minimum sensitivity of the human hand sensors of 0.19 Newtons/cm^2. While the average male/female maximum tip pinching force is 13-16 Newtons [1], the force generated by the PDMFF is large enough to simulate the sensation of a solid object in the grasp. Plastic was used wherever possible (except for the actuators and sphere joints) in order to save weight. This reduced the mass of the feedback structure in the hand to 0.045 Kg (a weight of 0.44 Newtons). Thus for a master total force output of about 13.3 Newtons, the force output/weight ratio is 30.

Tests were run to determine if the accuracy of the Polhemus sensor[15] placed on the back of the palm is affected by the metallic feedback actuators (the sensor uses low-frequency magnetic fields to measure palm position and orientation). The influence on position measurements was determined to be small (1-1.5 mm and less than 1 degree rotation).

4. Control model

For a given actuator pressure the feedback forces applied on the user fingers depend on several factors. One factor is the joint stiffness chosen by the subject, since a small stiffness will reduce these forces. Another factor is the user hand posture at the moment the actuators are pressurized. This factor is expressed by the angle γ between the normal direction to the fingertip and the actuator shaft, as shown in Figure 2. For a desired normal feedback force on the thumb F_N the air pressure P_{air} is

$$P_{air} = 1.1 \times \frac{F_N}{A_{cyl} \cos\gamma} \tag{2}$$

where

$$\gamma = 90^\circ - (\theta_1 + \theta_2 + \theta_3) + \tan^{-1} \frac{B_y - H_a}{B_x - L_a} \tag{3}$$

$$B_x = -[L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) + L_4 \cos(\theta_1 + \theta_2 + \theta_3) - H_b \sin(\theta_1 + \theta_2 + \theta_3)] \tag{4}$$

$$B_y = L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2) + L_4 \sin(\theta_1 + \theta_2 + \theta_3) + H_b \cos(\theta_1 + \theta_2 + \theta_3) \tag{5}$$

Here θ_1 is the thumb anteposition/retroposition angle and θ_2, θ_3 are joint flex angles. These angles are measured by the Dataglove. For the middle and index fingers the glove

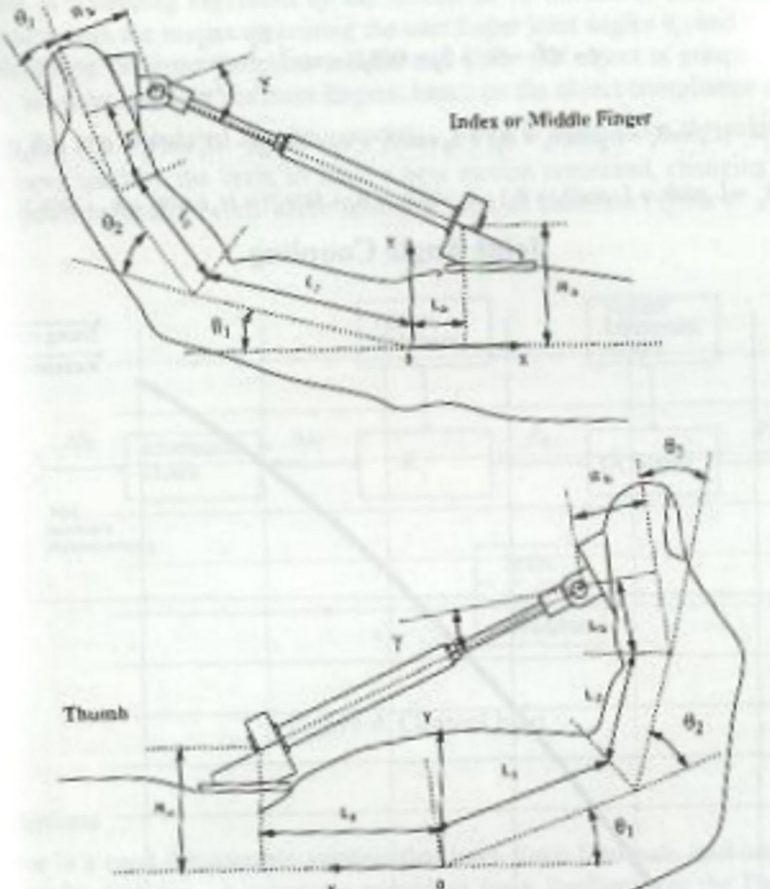

Figure 2. Finger parameters

cannot measure θ_3 directly. Another way of determining θ_3 is by taking into account the coupling $\theta_3 = \Theta(\theta_2)$ that exists over the range of motion of the master. As an example, the index finger θ_3 is determined experimentally to be:

$$\theta_3 = \Theta(\theta_2) = 2.319883 + 0.784963\theta_2 - 0.004902\theta_2^2 \qquad (6)$$

Data used to obtain equation (6) is presented in Figure 3. Equations (3) to (5) now become:

$$\gamma = 90^\circ - (\theta_1 + \theta_2 + \Theta(\theta_2)) + \tan^{-1}\frac{B_y - H_a}{B_x - L_e} \quad (7)$$

$$B_x = -[L_1\cos\theta_1 + L_2\cos(\theta_1 + \theta_2) + L_3\cos(\theta_1 + \theta_2 + \Theta(\theta_2)) - H_b\sin(\theta_1 + \theta_2 + \Theta(\theta_2))] \quad (8)$$

$$B_y = L_1\sin\theta_1 + L_2\sin(\theta_1 + \theta_2) + L_3\sin(\theta_1 + \theta_2 + \Theta(\theta_2)) + H_a\cos(\theta_1 + \theta_2 + \Theta(\theta_2)) \quad (9)$$

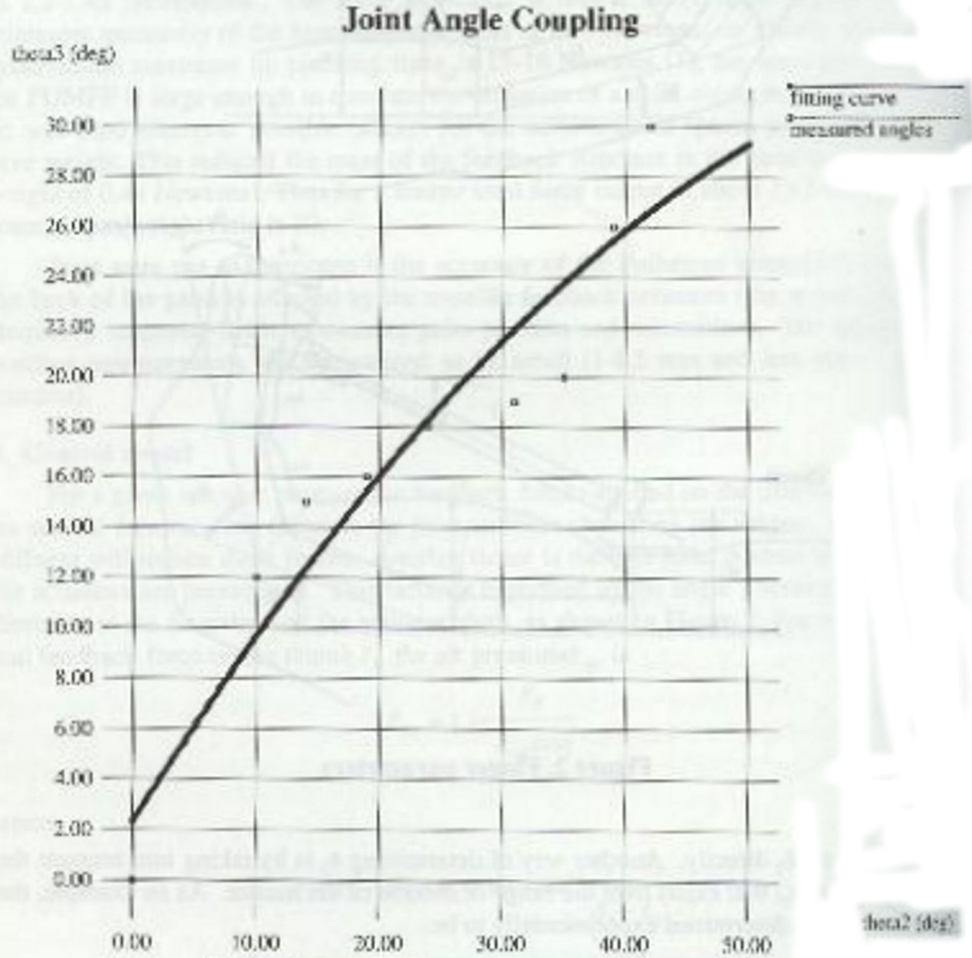

Figure 3. θ_2 and θ_3 **coupling for the index finger.**

In a virtual environment application F_N corresponds to contact forces appearing in the grasping of an object by the modeled hand. The actual value may depend on the stiffness of the simulated object K, its weight, as well as the hand grasping posture and the degree of squeezing expressed by the motion Δx of the model hand fingertips. The process starts with the master measuring the user finger joint angles θ_i, and the host computer calculating fingertip Cartesian motion ΔX_i. Once the object is grasped the normal forces F_{N_i} are calculated for the three fingers, based on the object compliance K. Then air pressures P_{air_i} are calculated for the γ_i and F_{N_i}. Force is applied on the subjects fingers and this input used by the brain to issue a new motion command, changing θ_i. This is basicly a position feedforeward- force feedback loop, as shown in Figure 4.

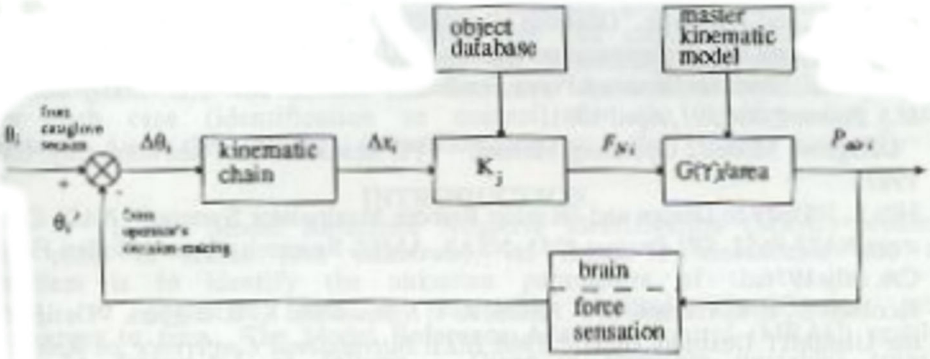

Figure 4. Control loop

5. Conclusions

There is a need for portable systems that have force feedback, and are sufficiently compact to be desk-top. A prototype providing force feedback for the Dataglove was discussed. The master structure and its actuator characteristics were presented. More experimental studies using a dedicated graphics workstation are underway. These studies will determine the performance improvement produced by the feedback system.

ACKNOWLEDGMENTS

The research reported here was supported by the CAIP Center, Rutgers University, with funds provided by the New Jersey Commission on Science and Technology and by CAIP's industrial members; by a Special Purpose Grant from the AT&T Foundation; and by National Science Foundation Grants MSS-89-09335 and CCR-89-09197.

REFERENCES

1. An K. , L. J. Askew and E. Y. Chao, "Biomechanics and Functional Assessment

of Upper Extremities,'' *Trends in Ergonomics/Human Factors III*, pp573-580 (Elsevier Science Publishers B.V., 1986).

2. Bekey B., R. Tomovic and I. Zalikovic, ''Control Architecture for the Belgrade-USC Hand,'' *1988 IEEE International Conference on Robotics and Automation*, IEEE press, 1988.
3. Burdea G. and T. Speeter, "Portable Dextrous Force Feedback Master for Robot Telemanipulation, *Proceedings 1989 NASA Conference on Space Telerobotics*, Vol. 2, pp153-161, Jan. 31 - Feb. 2, 1989, Pasadena, CA.
4. Burdea G. and J. Zhuang, "Dextrous telerobotics with force feedback - an overview. Part 1: Human factors", *Robotica*, UK, 1990 (in press).
5. Burdea G. and J. Zhuang, "Dextrous telerobotics with force feedback - an overview. Part 2: Control and implementation", *Robotica*, UK, 1990 (in press).
6. Burdea G., "Portable Dextrous Force Feedback Master for Robot Telemanipulation", *U.S. Patent 5,004,391*, April 1991.
7. ''Dataglove Model 2 Operating Manual,'' VPL Research, Inc., Redwood City, CA, 1987.
8. Hill J., ''Study to Design and Develop Remote Manipulator Systems,'' *NASA Contract NAS2-8652, SRI Project 4055*, NSAS, AMES Research Center, Moffett Field, CA, July 1976.
9. Jacobsen S., E. K. Iversen, D. F. Knutti, R. T. Johnson and K. B. Biggers, ''Design of the Utah/MIT Dextrous Hand,'' *1986 IEEE International Conference on Robotics and Automation*, IEEE, pp1520-1531, 1986.
10. Jacobsen, S., E. K. Iversen, C. C. Davis, D. M. Potter and T. W. McLain, ''Design of a Multiple Degree of Freedom, Force Reflective Hand Master/Slave with a High Mobility Wrist,'' *Third Topical Meeting on Robotics and Remote Systems*, March 1989.
11. Jau B., "The Jau-JPL Anthropomorphic Telerobot", *Proceedings NASA Conference on Space Telerobotics*, Pasadena, CA, pp75-80, Vol. IV, 1989.
12. Marcus B. and P. J. Churchill, "Sensing Human Hand Motions for Controlling Dextrous Robots", A. D. Little, 1988.
13. McCormick E., *Human Factors in Engineering and Design*, McGraw Hill, 1976.
14. Mokshagundam A., "Sensor Application to Peripheral Neuropathy of the Hand", in *Tactile Sensors for Robotics and Medicine*, J. Webster editor, John Wiley & Sons, pp299-307, 1988.
15. Polhemus Navigation Sciences Division, *Space Isotrak User's Manual*, Colchester, VT., 1987.