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Dextrous telerobotics with force feedback – an overview. Part 1: Human factors†

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SUMMARY

Complex tasks that need to be performed through teleoperation led to the development of multifinger robot hands. A dextrous master is a multi-DOF controller which is worn by the operator in order to teleoperate these anthropomorphic hands. Force feedback is very useful when there is interaction with the environment. Providing force feedback to dextrous masters is an area of active research. We outline some of the human factors that influence the design of such masters. Of obvious importance is the hand geometry and the desired number of degrees of freedom. Additional criteria relate to the force perception of the hand. Finally, the man-machine impedance is of importance, since at the man/machine interface there are two impedances acting in series. One is the effective impedance of the human operator holding the master controller, the second is the impedance of the master controller being manipulated.

KEYWORDS: Telerobotics; Force feedback; Human factors; Impedance; Dextrous master.

1. INTRODUCTION

The present emphasis on telerobotic research has two causes. The first is utility, since teleoperation protects humans from adverse environments such as space, undersea, or nuclear radiation. The second cause is the (recently understood) limit of robot machine intelligence. Due to this limit the operator needs to be kept in the control loop, in order to supervise, teach or rescue the robot slaves.

The requirements to perform increasingly complex tasks through teleoperation led to the development of a number of robot end-effectors.[1] Earlier robot grippers which had only two fingers will be replaced with multi-finger hands. Figure 1 shows the Stanford/JPL, the Utah/MIT and the Belgrade/USC hands which are examples of these state-of-the-art devices. They have been designed to take advantage of human dexterity and have the ability to perform versatile tasks. The disadvantage, of course, is the inherent control complexity of a multiple degree of freedom dextrous manipulator. The Stanford/JPL Hand,[2] for example, has three fingers, each with three rotary joints actuated by four DC motors through steel tendons. The Utah/MIT Hand[3] has four fingers each with four joints, while the Belgrade/USC Hand[4] has five fingers controlled by three motors.

Earlier non-dextrous slaves were easier to telemanipulate using such masters as joysticks, sensorized spheres or teach pendants. These masters, however, are not suited for dextrous teleoperation, since they do not have sufficient degrees of freedom. The control of multifinger robot hands requires a new type of master, namely a dextrous master. A dextrous master is a multi-DOF robot controller which, worn on human operator's hand, is used to teleoperate anthropomorphic robot hands with the aid of a host computer. Commercially available models are the VPL DataGlove[5] and the Exos Inc. Dextrous Hand Master.[6] Both allow position control of the robot hand, without force feedback to the operator.

The DataGlove[5] (Figure 2) is a sensorized glove which can be used to track human finger and wrist movements. The system can measure up to 16 human finger joint angles over their full range. When controlling a remote dextrous robot, the glove polhemus sensor sends position information for the robot wrist, while the optical sensors on the fingers control the robot hand joints.[7]

Another commercially available master is the Dextrous Hand Master[6] which replaces the glove by a sensorized metal structure worn on the operator hand (see Figure 3). This low-weight master has a resolution and accuracy that is reported to be superior to that of the DataGlove, and can measure 16 finger joint angles. Using hall effect sensors with built-in amplification and excellent temperature stability, it can accurately and comfortably track the complex motion of the human finger joints, but, in its present version, cannot control robot wrist motions.

The open loop dextrous masters described above are efficient and natural to control, since they emulate operator hand motions. However, they lack force feedback to enhance the task performance. Interaction between the robot and its environment requires that the human operator have a direct perceptual feeling of the remote operation process. This includes force and torque feedback from contact between the remote robot manipulator and its working environment. The utility of force information is the execution of various tasks has

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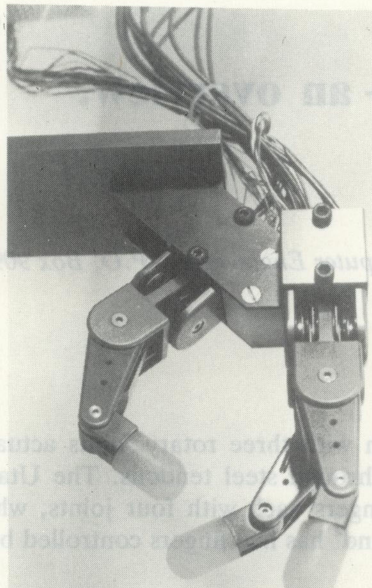

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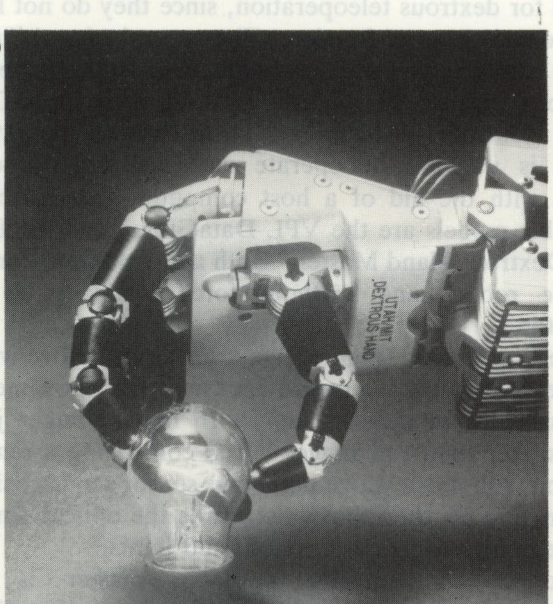

Fig. 1. Multifinger Robot Hands. a) Stanford/JPL Hand. b) Utah/MIT Hand. c) Belgrade/USC Hand.

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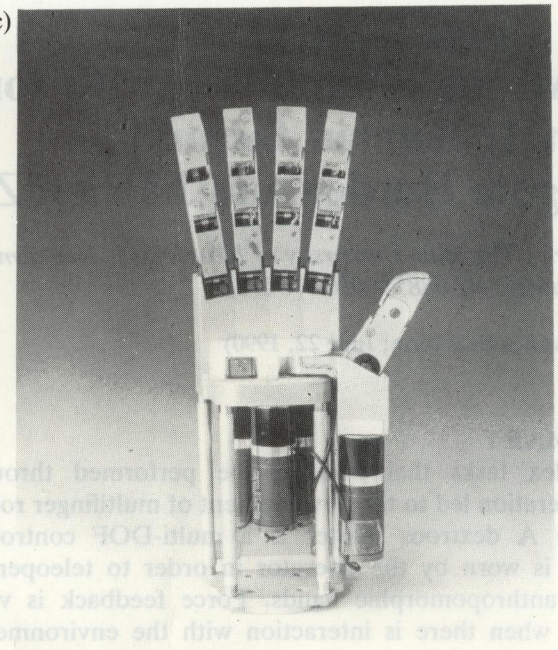


Fig. 1 (*continued*)

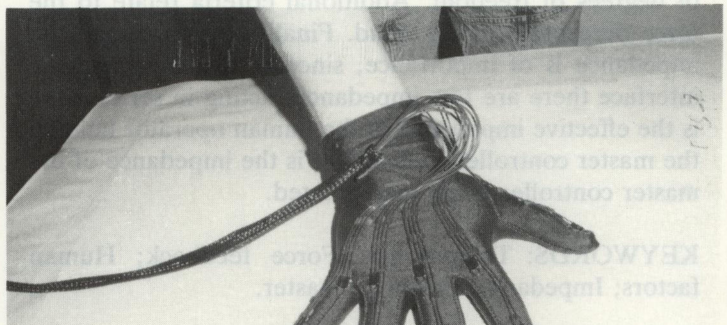


Fig. 2. VPL DataGlove.

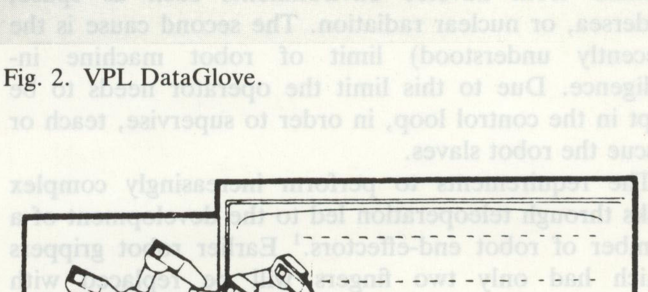


Fig. 3. Dextrous Hand Master (DHM) System.

been proven through several studies.[8] These studies done on non-dextrous systems show that task completion times were often reduced by 40% when the operator was given force information. The completion times for the most difficult tasks were reduced by 50%. Thus force feedback should be included in the control loop of dextrous systems as well, in order to enhance their performance.

Force feedback needs to be distinguished from tactile feedback which has been proposed for the DataGlove. Tactile feedback produces a perception of touch/no-touch and a discretization of the contact surface. However, it does not give an adequate perception of the magnitude of contact forces, or the compliance of the manipulated objects. More importantly, it is not capable of producing total rigidity of motion for large contact forces. Force feedback, on the other hand, uses actuators to control the magnitude of forces on the operator hand and wrist. Therefore it is capable of capturing the effect of object compliance and may produce rigidity of motion. This capability then actively prevents the operator from crashing the manipulated objects or the robot arm.

While bilateral coupling between a non-dextrous master and its slave has existed for some time, the development of dextrous masters with force feedback is presently an area of active research. The difficulty in the realization of these devices stems from a fundamental conflict between adequate robotic control, and human factors as they relate to the hand geometry and human fatigue. Adequate force feedback control requires that each joint of the hand as well as the wrist be provided with force feedback. This, in turn, necessitates a very large number of actuators, especially when feedback is desired for both the closing and opening of the hand. However, the geometrical characteristic of the human hand reduces the volume which can accommodate these actuators. Complicated structures may then arise, which become cumbersome for the operator.

Section 2 of this paper presents the important man-machine interface aspects which should be taken into account in the design of dextrous masters with force feedback. Section 3 gives some control strategies, while Section 4 gives a selection of actuators that are presently available to provide force feedback for dextrous masters. Section 5 presents some prototypes of dextrous masters with force feedback and compares their characteristics. Finally, we give our thoughts on future developments in this area. Sections 3, 4 and 5 were included in Part 2 "Control and Implementation" of this paper, which will appear in the next issue of the Journal.

2. HUMAN PERCEPTION ENVIRONMENT

Before the design and implementation of a dextrous master controller is attempted, many aspects of the human perception environment should be taken into account. Those factors, which directly affect master manipulation, include human hand kinematics, biological sensor structure, and human impedance.

2.1 Hand geometrical characteristics

From a mechanical point of view,[9] the thumb has three joints. The first joint is the proximal joint or carpometacarpal joint, which has two degrees of freedom (DOF), i.e. adduction-abduction and flexion-extension, each with a range of approximately 90 degrees. The second joint is the metacarpal-phalangeal joint, which has one DOF of flexion-extension towards the palm, over a range of about 60 degrees. The third joint is the distal joint or interphalangeal joint, which has one DOF over a range of about 90 degrees. The other four fingers have three joints each, namely, one metacarpal-phalangeal joint and two interphalangeal joints. The former has two degrees of freedom, 30 degree adduction-abduction and 120 degree flexion-extension. The latter are hinge joints which have one degree of freedom of approximately 90 degrees. Thus the hand (without the wrist) has a total of 20 DOF.

Biomechanically, the human hand can be regarded as a linkage system of intercalated bony segments. Between each phalanx, there are ligaments, tendons and muscles that span over the joints. With the constraint of the interposing soft tissues and bony articulations, the muscles can pull the joint and move it in a specific manner. In order to establish a mathematical model to determine the three-dimensional forces involved, six Cartesian coordinate systems have been established to define joint configuration, forces and torques.[10] Referring to Figure 4, there are two coordinate systems for both the middle and proximal phalanges and only one system for both the distal phalanx and metacarpal. The origins of primary systems 2, 4 and 6 are located at the center of rotation of the phalangeal and metacarpal heads, while those of the secondary systems 1, 3 and 5 are a translation of the proximal systems to the centers of the concave articulation surface. The orientation of the coordinate systems is determined as follows: The x-axis is projected along the phalangeal or the metacarpal shaft, passing from the center of rotation to the center of the concave articular surface at the proximal end. The y-axis is projected dorsally and the z-axis is projected radially for the right hand and ulnarly for the left hand. The translations between two coordinate systems for each finger joints, represented by mean and standard deviations for 10 specimen are presented in Figure 5.

To study the forces and torques exerted on each joint, two parameters are used to describe the orientation and location of each tendon, i.e. force potential and moment potential. The force potential provides the contribution of a particular tendon in generating joint constraint forces and the moment potential specifies the functional moment of each tendon in rotating the joint at three mutually perpendicular directions. Those mean values of the parameters have been obtained experimentally for constructing the normative model of a human hand. Thus, the force and moment equilibrium equations can be derived about the center of rotation of the joint as:

Force equations

$$\sum \alpha_i F_i + C_x + R_x = 0 \quad (1)$$

$$\sum \beta_i F_i + C_y + R_y = 0 \quad (2)$$

$$\sum \gamma_i F_i + C_z + R_z = 0 \quad (3)$$

Moment equations

$$\sum a_i F_i + M_x + T_x = 0 \quad (4)$$

$$\sum b_i F_i + M_y + T_y = 0 \quad (5)$$

$$\sum c_i F_i + M_z + T_z = 0 \quad (6)$$

where α_i, β_i, γ_i = force potential parameters, a_i, b_i, c_i =

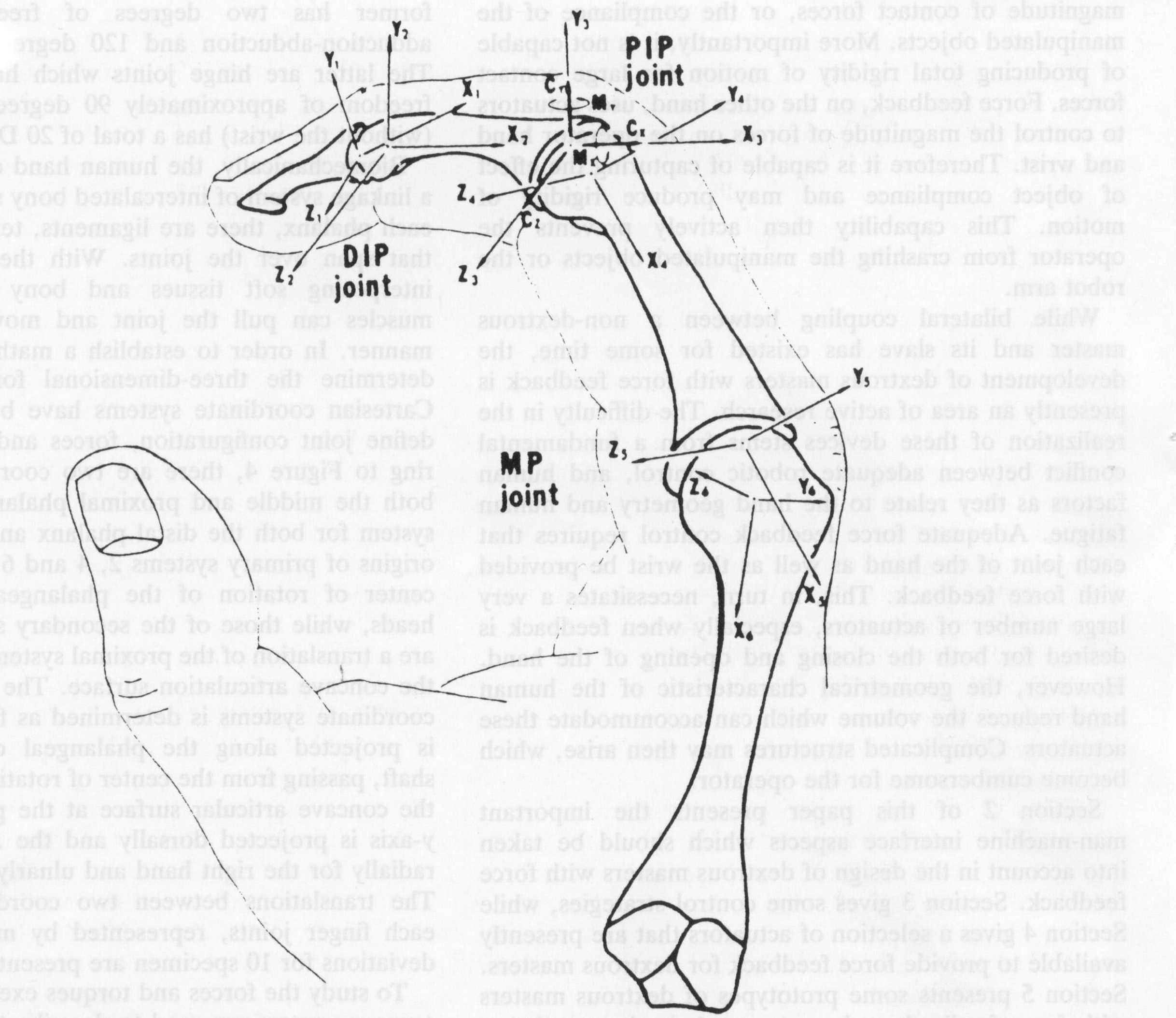
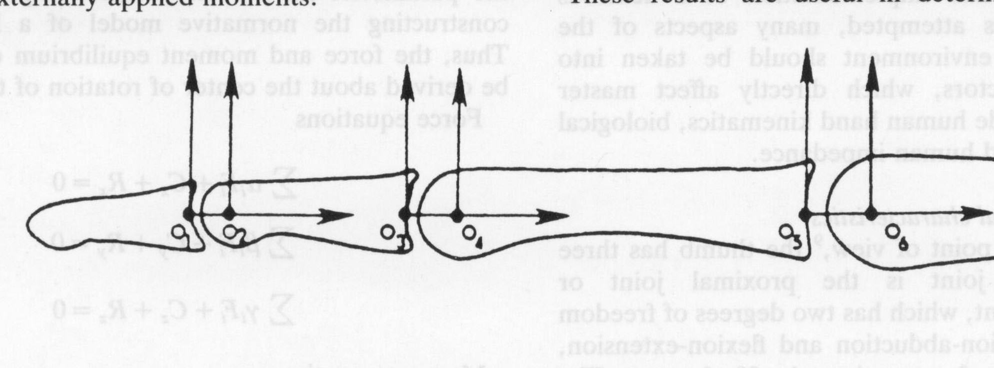


Fig. 4. Two coordinate systems established at each joint.[10]

moment potential parameters, C_x, C_y, C_z = unknown joint constraint forces, M_x, M_y, M_z = unknown joint constraint moments, F_i = unknown tendon or muscle forces, R_x, R_y, R_z = externally applied forces, and T_x, T_y, T_z = externally applied moments.

With the force and moment potential parameters,[10] the unknown tendon forces and joint constraint forces and moments can be determined through the above equilibrium equations using quasi-static force analysis. These results are useful in determining the extent of



	O_1O_2	O_2O_3	O_3O_4	O_4O_5	O_5O_6
Index	0.22 ± .04	1.0 ± .0	0.29 ± .04	1.94 ± .28	0.45 ± .05
Long	0.17 ± .03	1.0 ± .0	0.22 ± .04	1.62 ± .08	0.37 ± .05
Ring	0.15 ± .02	1.0 ± .0	0.21 ± .04	1.56 ± .07	0.34 ± .03
Little	0.21 ± .03	1.0 ± .0	0.29 ± .04	1.78 ± .14	0.49 ± .09

Fig. 5. Translations between two coordinate systems.[10]

external force and torque feedback required for the dextrous master.

When a finger is in the functional configuration other than its neutral position, the relationship of proximal and distal coordinate systems for each finger joint can be represented by a simple rotational and translational transformation between two coordinate systems.

$$\begin{bmatrix} X_D \\ Y_D \\ Z_D \end{bmatrix} = \begin{bmatrix} c\theta c\phi & c\theta s\phi & -s\theta \\ -c\psi s\phi + s\psi s\theta c\phi & c\psi c\phi + s\psi s\theta s\phi & s\psi c\theta \\ s\phi s\psi + c\psi s\phi s\theta & -s\psi c\phi + c\psi s\theta s\phi & c\psi c\theta \end{bmatrix} \times \begin{bmatrix} X_P \\ Y_P \\ Z_P \end{bmatrix} + \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}, \quad (7)$$

in which X_D, Y_D, Z_D = coordinates of a tendon point or components of a vector measured with respect to the distal system, X_P, Y_P, Z_P = coordinates of a tendon point or components of a vector measured with respect to the proximal system, X_0, Y_0, Z_0 = coordinates of the origin of the proximal system expressed in the distal system, s = sine, c = cosine.

Using the above linear transformation, the joint force and moment can be transformed into either coordinate system, and the finger joint angles are precisely depicted by the three Euler angles in the rotational transformation matrix, as shown in Figure 6.

The need to minimize operator fatigue requires that the hand postures be easily accommodated by the master. Therefore, the study of human hand grasps is beneficial in designing the geometry of the master controller. The human hand has various basic grasps for different tasks. According to Taylor and Schwartz[11] there are six basic human hand grasps. These are the cylindrical grasp, the tip grasp, the hook grasp, the palmar grasp, the spherical grasp and the lateral grasp. This classification relates grasps with part shape. However, in practice, people don't commonly use the above six basic grasps individually, but in combination. The fact that the choice of a particular grasp is dictated less by the size and shape of objects than by the tasks people want to accomplish suggests that grasps should be categorized according to function instead of appearance. Cutkosky[12] developed a hierarchical tree of grasps based on the two basic categories suggested by Napier, namely, power grasps and precision grasps. The comprehensive hierarchical tree of grasps is presented in Figure 7. Power grasps are chosen for the considerations of stability and security, while precision grasps are chosen for sensitivity and dexterity.

Once the basic choice between a power grasp and a precision grasp has been made, moving down the tree, a combination of task-related and geometric considerations comes into play and both considerations become equally important. Moving to the left, the grasps become more compatible with increasing object size and power, while moving to the right, the grasps are more suitable for the requirements of decreasing object size and increasing dexterity.

The hand configurations during grasping may have topological, functional, structural or graphic representations, which are detailed in Nguyen et al.[13]

2.2 Biological Characteristics

In order to provide force feedback for the master controller, we need to know the performance of the human biological sensors. The sensor "sensitivity" will then give the minimum level of force that has to be provided, in order to be perceived. The human biological sensors[9] can be categorized as internal receptors, epidermal receptors and dermal receptors. Internal receptors are sensitive to the relative position of the parts of the body, which is termed "proprioception". Epidermal receptors react to external stimuli, while dermal receptors sense light touch and accelerating mechanical displacements. These hand and arm sensors have a frequency response of 0 to 400 Hz, a response range of 0 to 100 g/mm^2, a sensitivity of approximately 0.2 gms/mm^2, and a spatial resolution of 1.8 mm (about 1.35/mm^2). These characteristics are of obvious interest to the master designer since the force applied should be within the range of the receptors.

Another important factor that needs to be known is the average force exertion capability of a person. This represents the upper limit to the force feedback signal. Larger force may harm the operator. Clinical studies[14] performed in order to determine the average pinch and grasp strengths of normal subjects showed that males have a maximum force of 400 N during grasping. In general, female hand strength ranges from 60% to 80%

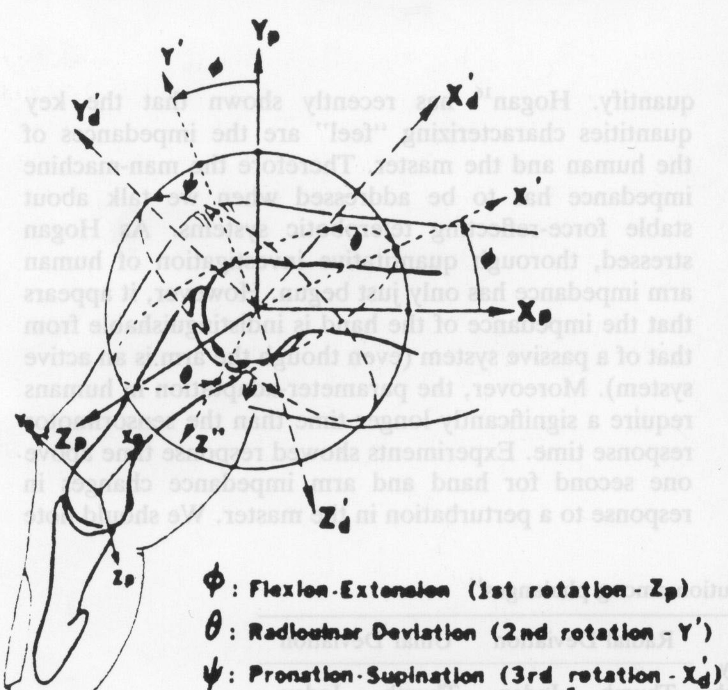


Fig. 6. Euler angles used to define the orientation of the finger.[10]

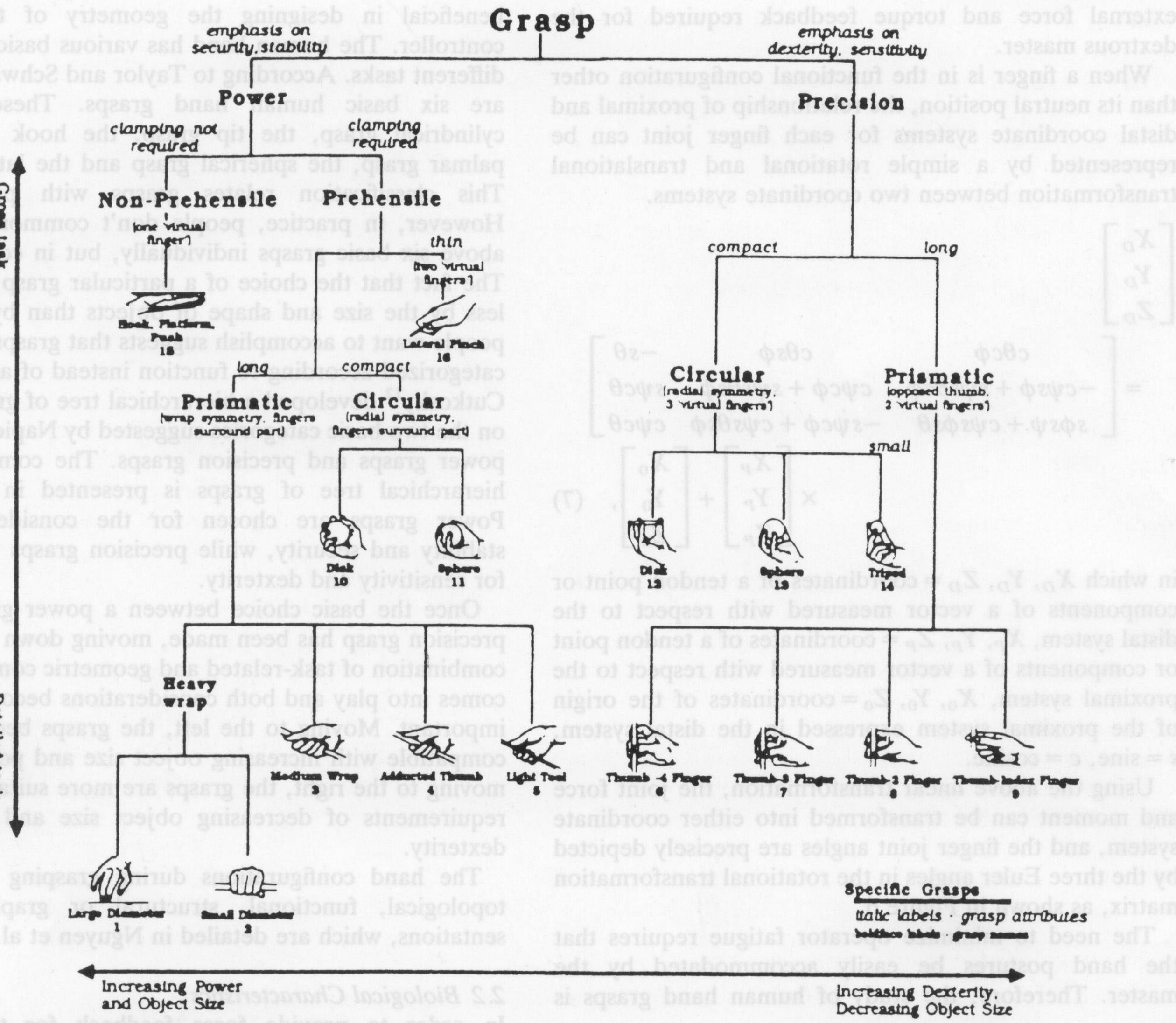


Fig. 7. A partial taxonomy of manufacturing grasps.[12]

of that of males, as shown in Table I (forces are in Newtons).[14] These figures can be utilized to give an upper limit to the force feedback signal generated by the master.

2.3 Man-machine impedance

At the man/machine interface there are two impedances acting in series, one is the effective impedance of the human operator holding the master controller, the second is the impedance of the master controller being manipulated.[15]

In the introductory section we stressed the importance of force perception or "feel" on the part of the operator in a telerobotic system. "Feel", however, is difficult to quantify. Hogan[16] has recently shown that the key quantities characterizing "feel" are the impedances of the human and the master. Therefore the man-machine impedance has to be addressed when we talk about stable force-reflecting telerobotic systems. As Hogan stressed, thorough quantitative investigation of human arm impedance has only just begun. However, it appears that the impedance of the hand is indistinguishable from that of a passive system (even though the arm is an active system). Moreover, the parameter-adaptation in humans require a significantly longer time than the sensorimotor response time. Experiments showed response time above one second for hand and arm impedance changes in response to a perturbation in the master. We should note

Table I Force distribution among phalanges[14]

	Power Grasp	Tip Pinch	Pulp Pinch	Key Pinch	Radial Deviation Thumb	Radial Deviation Index	Ulnar Deviation Thumb	Ulnar Deviation Index
Male	400	65	61	109	43	43	75	42
Female	228	45	43	76	25	31	43	28

however that this data was obtained using nondextrous masters (2 DOF) and should be only qualitatively extended to dextrous masters with multiple DOF.

While viewing the telerobot system as a multiport impedance, it is interesting to determine the impedance which the operator presents to the master port. By linearizing the curves of isometric and isotonic muscle contractions, Raju[15] has shown that the operator arm, when viewed from the master end, appears as an impedance $Z_h(s)$ and an effort source such that

$$T_{hf}(s) = \Omega_h(s) Z_h(s) \tag{8}$$

where $T_{hf}(s)$ = human net input applied to the master, $\Omega_h(s)$ = arm velocity, $Z_h(s)$ = arm impedance and f = frequency of muscle firing which determines muscle force and stiffness.

Raju approximates the arm as a mass-dashpot-spring model and determines

$$Z_h(s) = J_h s + B(f) + \frac{K(f)}{s} \tag{9}$$

where J_h = arm inertia, $B(f)$ = damping coefficient and $K(f)$ = stiffness parameter.

Experiments have been done by Abul-Haj[17] to get the impedance parameters for the human model $Z_h([J_h, B_h, K_h])$. The results show that for an average adult male the inertia of the forearm about the elbow is approximately $0.06N\text{-m-sec}^2$. The damping ratio ζ_h falls in the range $0.15 < \zeta_h < 1.5$, and the stiffness K_h is within the range $1.0 < K_h < 200N\text{-m/rad}$.

$$B_h = J_h(2\zeta_h \sqrt{K_h/J_h}) \tag{10}$$

It should be noted that both damping $B(f)$ and stiffness $K(f)$ depend on muscle firing frequency, which in turn is under the control of the brain. With the above simplifications, the telerobotic system may be represented as the model shown in Figure 8, where Z_t is the impedance of the remote task, Ω_s, is slave velocity, and T_s is the force produced by the slave.

Goldenberg[18,19] has shown that the interaction between a robot and its environment may be modeled by a spring-dashpot-mass system so that

$$Z_t = J_t s + B_t + \frac{K_t}{s} \tag{11}$$

where J_t, B_t, K_t are task inertia, damping and stiffness.

For a master-slave system with feedback,

$$\begin{bmatrix} T_m(s) \\ \Omega_s(s) \end{bmatrix} = \begin{bmatrix} H_{11}(s) & H_{12}(s) \\ H_{21}(s) & H_{22}(s) \end{bmatrix} \begin{bmatrix} \Omega_m(s) \\ T_s(s) \end{bmatrix} \tag{12}$$

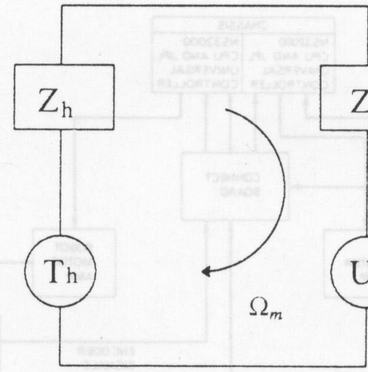


Fig. 9. Master port impedance with task at the slave port.

or the force in the master loop depends on that in the slave since:

$$T_m(s) = H_{11}(s)\Omega_m(s) + H_{12}(s)T_s(s) \tag{13}$$

To capture the effects of the feedback present when interaction exists in the slave loop, T_m may be written as

$$T_m = Z_m(s)\Omega_m(s) - U_h(s) \tag{14}$$

where $Z_m(s)$ is the master arm impedance. With this notation the master loop may be modeled as shown in Figure 9.

Here

$$T_h = Z_h \Omega_m + Z_{ma}\Omega_m - U_m \tag{15}$$

To capture the effect of the task impedance $Z_t(s)$, the master-slave-task system may be replaced by an impedance Z_m, which according to Hogan[16] is

$$Z_m(s) = Z_{ma}(s) + f_{11}(s) - \frac{f_{12}(s) + f_{21}(s)}{Z_{sa}(s) + f_{22}(s) + Z_t(s)} \tag{16}$$

where $Z_{sa}(s)$ is the impedance of the slave arm, $f_{11}(s)$, $f_{12}(s)$, $f_{21}(s)$, $f_{22}(s)$ are functions of the control law:

$$\begin{bmatrix} U_m(s) \\ U_s(s) \end{bmatrix} = \begin{bmatrix} -f_{11}(s) & f_{12}(s) \\ f_{21}(s) & -f_{22}(s) \end{bmatrix} \begin{bmatrix} \Omega_m(s) \\ \Omega_s(s) \end{bmatrix} \tag{17}$$

This leads to the conclusion that the level of force-feedback that the operator feels is determined by the specification of the master port impedance. In addition, for the slave port, adjusting the impedance of master/slave manipulator is advantageous in executing tasks of different characteristics.

An initial approach has been made by Hannaford and Anderson,[20,21] in which experiments and simulations had been done using SPICE,[22] a general purpose circuit simulator, in order to analyze not only the behavior of

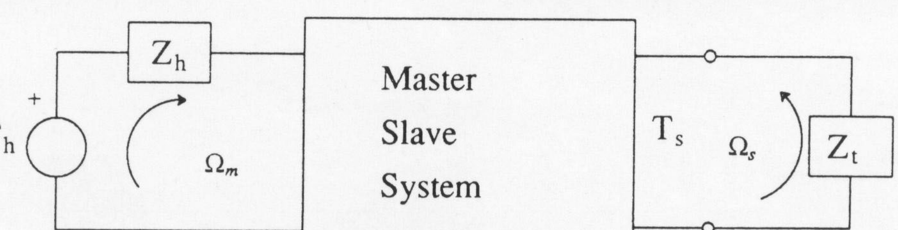


Fig. 8. Master-Slave System.

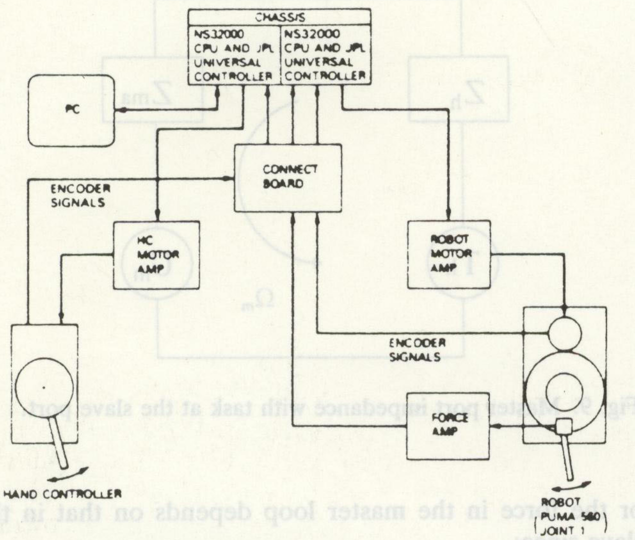


Fig. 10. Block diagram of the system.[20]

the real system, but also the effects of human operator biomechanics. In the experiment performed by Hannaford and Anderson, the human operator used various grasps on the hand controller when driving a single joint of a PUMA 560 robot in order to explore the effects on system performance due to changes in the human operator impedance. Figure 10 shows the experimental system used consisting of the robot, electronics, hand controller, human operator, and the environment. The hand controller has a wheel with a bar attached which served as a joystick. After the system was modeled as an electrical circuit using SPICE, the results showed that placing a harder grasp on the handle was equivalent to increasing the hand controller velocity damping in terms of the system stability. On the other hand, if the local damping feedback was added to the hand controller, it would change the subjective perception from sensitive to sluggish. So, the system with velocity damping would make the operator feel "stiff" or "unresponsive". According to this study, the human operator impedance in teleoperation should always be taken into account to minimize the necessary amount of damping supplied by the system for stability purposes. Then the system can reach optimum performance without sacrificing to ensure safe and stable operation. One feasible implementation for the control system is to adjust in real time the system damping appropriately according to the estimation of human operator impedance from force/torque and displacement readings.

In Part 1 of this paper we have described the human factors which are involved in the design of dextrous masters. These factors are the hand geometry, the biological characteristics of hand force perception, as well as the man-machine impedance. In Part 2 of this paper we will emphasize issues on control and present some practical implementations of dextrous masters with force feedback. The full list of references will be given at the end of part 2 (next issue of the journal).