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Dextrous telerobotics with force feedback – an overview
Part 2: Control and implementation†

Grigore Burdea and Jiachen Zhuang

Rutgers – The State University of New Jersey, Department of Electrical and Computer Engineering, P.O. Box 909, Piscataway, NJ 08855-0909 (USA)

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SUMMARY
The control stategy for a dextrous masters is different from the general case of bilateral teleoperation since it models the human hand in much more detail. Such a model is discussed together with the selection of actuators used for force feedback control. Existing prototypes of dextrous masters with force feedback are then reviewed. These are the Servo Controlled Manipulator Device, the Portable Dextrous Force Feedback Master (P.D.M.F.F.), the Remote Handler, and the Advanced Multiple DOF Force Reflective Hand/Wrist Master.

KEYWORDS: Telerobotics; Force feedback; Control; Implementation; Dextrous masters.

3. DEXTROUS MASTER CONTROL

Part 1 of this paper (previous issue of Robotica) described the human factors which are involved in the design of dextrous masters. These factors are the hand geometry, the biological characteristics of force perception, as well as the man-machine impedance. In Part 2 of this paper we are emphasizing issues on control, and describe some practical implementations of dextrous masters with force feedback.

The control model presented in Section 2 ("Human Perception Environment") represents the general case of bilateral master/slave teleoperation. In the particular case of a dextrous master controller, the control strategy should model the human operator in more detail. According to S. Lee et al.,[23] the model of the human operator can be decomposed into the mental processing rules, neuro-muscular system model, dynamic coordination model, and visual system model. The relationship between these submodels and the model of dextrous master dynamics is presented in Figure 11. In this simulation study, the human operator reaction time, nonlinearities in the visual system and simplified hand controller gain were studied quantitatively using this hypothesized model. The combination of muscle and hand controller was represented by a first-order linear system, and the manipulator controller and load dynamics were modeled as a second order system. The visual systems and the coordination of visual and force/torque feedback signals were represented by simple nonlinearities followed by time delays.

In force reflective telemanipulation, dextrous masters are used to control multifingered robot hands. This control involves the determination of multivariable trajectories and simultaneous motion of a large number of joints. A feasible control strategy over the traditional point-to-point control is to set up either a joint-to-joint correspondence or a fingertip-to-fingertip correspondence between the hands. However, when there are different numbers of joints between master and slave hands, some functionally relevant information will be lost. Pao and Speeter[24] developed an algorithm that can translate human hand poses to corresponding robotic hand positions without loss of functional information and without the overhead of kinematic calculations. The first step is to define a set of poses that are common and functional, which span the useful range of human hand motions. After the poses are defined for both the human hand and robotic hand, an interpolation technique is developed to determine corresponding robotic hand positions given arbitrary human hand poses. For both the human and robot hands, a pose is defined by a row vector of joint angles. Let n_h and n_r be the numbers of joint angles for human and robot hands, respectively. Once the poses are defined, the relation of human and robot hands is:

$$HT = R \tag{18}$$

where H is an $n_p \times n_h$ matrix for human hand, n_p is the number of poses. Each row corresponds to a human hand pose and each column corresponds to a particular joint in the human hand. Similarly, R is the $n_p \times n_r$ matrix for robot hand. T is the $n_h \times n_r$ transformation matrix.

Since H and R are defined beforehand, the matrix T can be solved using the singluar value decomposition on H:

$$T = H^+R \tag{19}$$

$$T = V\Sigma^+U^TR \tag{20}$$

where $H = U\Sigma V^T$, and H^+ and Σ^+ are the pseudoinverses of H and Σ, respectively. U and V are orthogonal matrices, and Σ is a diagonal matrix of the singular values of H.

If $n_p > n_h$, the systems of equations are overdetermined. If $n_p < n_h$, they are under-determined. If $n_p = n_h$,

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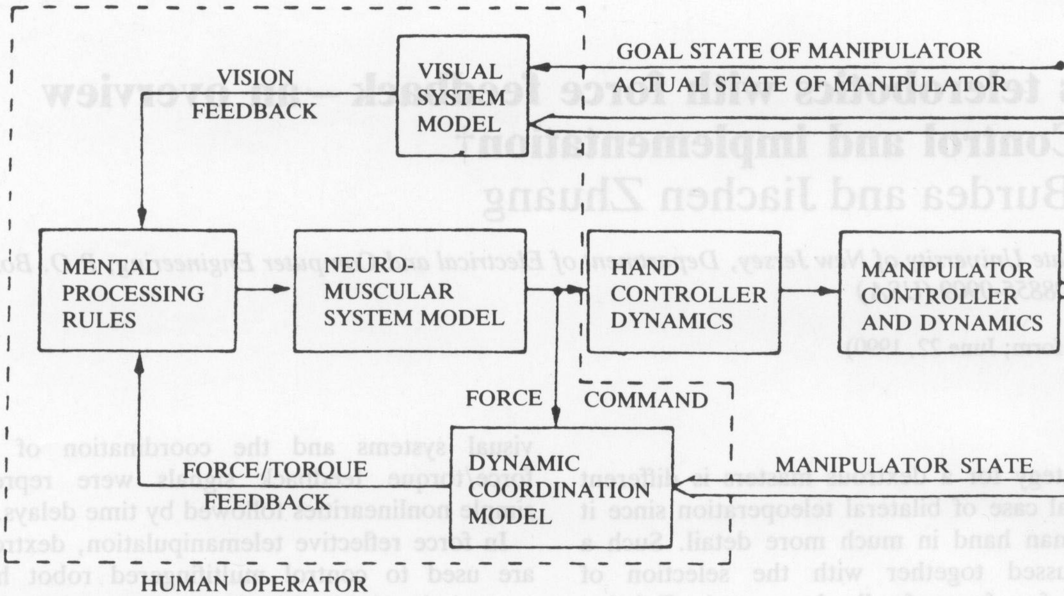

Fig. 11. Model of generalized bilateral manipulator control system.

then the transformation is exactly determined by $T = H^{-1}R$ (if H is nonsingular). If $n_h > n_r$, the human hand will have a wider variety of possible poses. If $n_k < n_r$, the robot hand will have a greater diversity of poses. However, as long as the poses of the robot hand span the range of useful poses of the human hand, corresponding poses can be defined for both hands and matrix T can be solved.

When providing force feedback the number of degrees of freedom is crucial. Theoretically this is the same as the number of DOF of the human hand joint angles, so that the human operator can feel the exertion on every DOF of every finger joint. But this proposition is either impractical or unnecessary. Since the most feasible method to drive fingers is to use two actuators antagonistically for each DOF, the number of actuators could double the number of DOF of force feedback. Then the space taken by these actuators as well as their weight become inevitable problems. Thus, the number of DOF of force feedback should be minimized while still providing adequate sensation for the task. Jacobsen,[25] shows that in order to execute all of the grasps with a reasonable amount of dexterity, a four DOF thumb and a minimum of two fingers, each with two one-DOF joints, are needed. The requirements for a wrist are abduction/adduction flexion/extension, and an axial rotation.

While the number of DOF is important in the master design, another important issue is actuator selection, as described in the next section.

4. ACTUATOR SELECTION AND CONTROL

In dextrous telemanipulation control, the quality of actuation system has long been regarded as one of the bottlenecks of progress. The actuators generally used include pneumatic actuators, electromagnetic actuators, and hydraulic actuators, each of them with its merits and limitations.

Pneumatic actuators have compact structure and low weight, but relatively low bandwidth, low actuation stiffness and low power output capability. Electromagnetic actuators have good stiffness and high bandwidth, but have large size and weight. Hydraulic actuators, standing between the above two, are usually considered as the appropriate choice for the development of dextrous force reflecting masters.

A newly developed actuator using shape memory alloys (SMA) has the potential for integration in dextrous masters. The basic SMA actuator configuration is illustrated in Figure 12. One pair of SMA wire-springs is arranged antagonistically because of the one-way characteristic of SMA. The principle is to utilize Joule effect to heat and cool the wire-springs, and causes a stroke motion. Shigeo Hirose et al.[26] made a detailed performance analysis comparing SMA with other conventional actuators. The experiments showed that SMA actuators have a performance equivalent to that of electric motors in terms of the output/weight ratio, with much smaller volume, no frictional parts, and no noise. The drawback is a relatively low response time due to the heat transmission property, which leads to low bandwidth. Attempts have been made to utilize this new

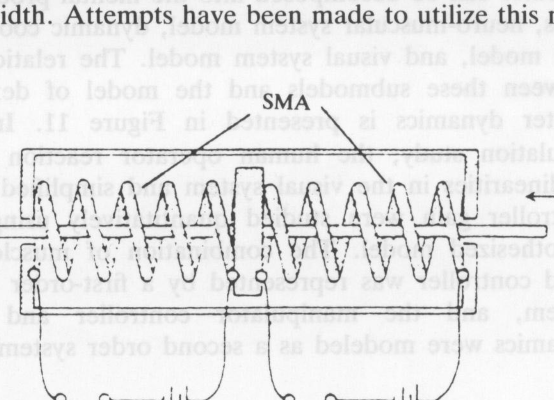

Fig. 12. Basic SMA actuator configuration.

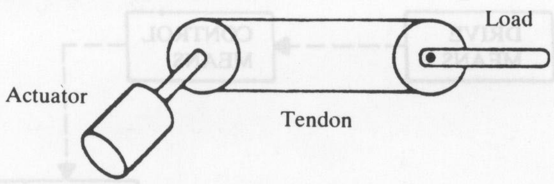

Fig. 13. Model of a single-joint driven by one rotary actuator.

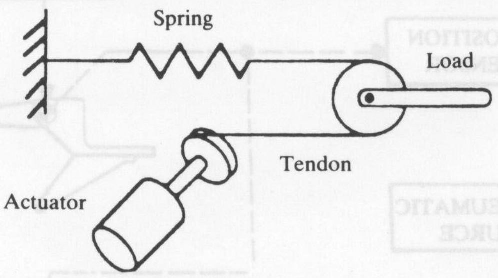

Fig. 14. Structure of a pulling actuator and relaxing spring for the single-joint.

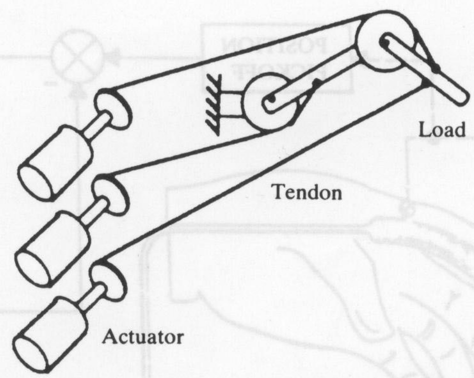

Fig. 15. An example of a two degree-of-freedom manipulator actuated by three actuators.

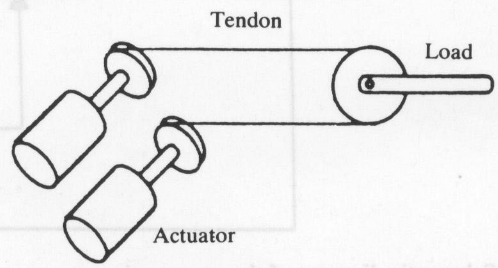

Fig. 16. Model of a single-joint driven by two actuators.

type of actuator in robotic technology. Because of the superior power/weight ratio, it is ideal for implementations where weight and space are at a premium. This is, in fact, the case for dextrous telemanipulation control.

Conventional actuators are too bulky to be placed directly on the fingers of the hand. Rather they are mounted on separate supports which are placed on the forearm or shoulder. The motion is then transmitted to the fingers using tendons or cables.[27] Tendons have the advantage of low inertia, backlash, friction, and minimal end effector volume. There are three main configurations for antagonistic tendon driven systems. These are the "N", "$N+1$", and "$2N$" configurations, where N represents the number of DOF.

The "N" configuration has basically two structures as presented in Figure 13. The first structure drives a single joint using one rotary actuator through a pair of opposed tendons. This approach requires pretensioning of the system to prevent slacking of the tendons when the joint moves at high velocities. The second structure uses one actuator to flex and a spring to extend, as shown in Figure 14. This approach prohibits low co-contractions when hard springs are used, which are necessary for high extension force and rapid response time.

The "$N+1$" configuration uses $N+1$ tendons and actuators to control N degrees of freedom with each joint to be flexed independently and extended by one common actuator (see Figure 15). This construction has the advantage of reducing the number of actuators per degree of freedom and therefore reduces the weight and volume of the actuator package.

For the "$2N$" configuration, two actuators are used to drive a single joint, each pulling an opposing tendon in agonist/antagonist fashion, as shown in Figure 16. This configuration provides low co-contraction forces, independently controlled joins, and equal strength actuators and tendons. Comparing these three tendon drive systems, the "$2N$" configuration requires twice as many actuators as the number of DOF controlled, but its precision and accuracy prevail over the other configurations. Therefore the "$2N$" configuration is commonly used for the dextrous master and slave designs.

5. DEXTROUS MASTER DESIGNS

We will present some of the prototypes of dextrous masters with force feedback. To our knowledge no commercially available products exist, although they should be available relatively soon.

5.1 Servo controlled manipulator device

One of the first servo controlled master manipulator devices was invented by Leon Jones and John L. Thousand.[28] Their system utilizes a glove which the human operator wears to control a remote robot gripper. The glove has position sensors for the finger joints. The corresponding position errors between the master and slave are used to drive the pneumatic actuator device to reposition the slave manipulator. The system is presented in Figure 17. The interesting design feature of this system is the pneumatic bladder for natural force sensation to the operator. The bladder is fixed in the glove to give the operator a kinesthetic sensation which closely simulates the force being placed on the manipulator. When two position signals from glove fingers and manipulator are compared with each other, the error signal derived from the summing device and the amplifier actuate the pneumatic control to inflate the bladder. Such inflation is proportional to the error signal and lets the operator feel the force being applied to the object by the manipulator. As the operator moves his fingers apart, the force applied by the bladder decreases with the error signal.

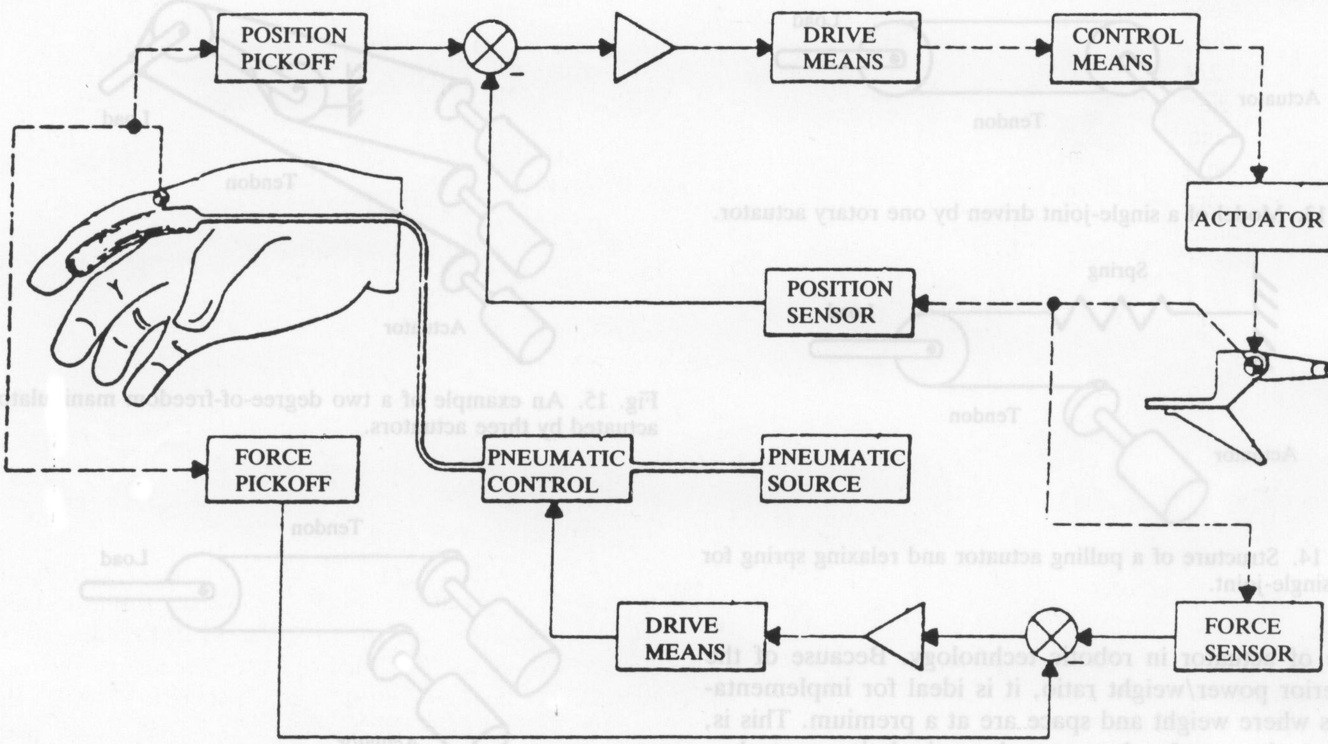

Fig. 17. Schematic diagram of the pneumatic actuator system.[28]

5.2 Portable dextrous force feedback master for robot telemanipulation

Burdea and Speeter[29] designed a portable dextrous force feedback master with one degree of freedom, capable of both position feedforward and force feedback. With the aid of electronic position sensors and a pneumatic micro actuator it can control the Utah/MIT Hand as shown in Figure 18. The characteristics of the human operator were taken into account to minimize human fatigue and improve operation comfort. Figure 19 presents the conceptual design configuration. It is a compact hand-held device which can fit inside the operator's palm. The pneumatic micro cylinder reduces the overall dimensions and weight but maintains sufficient force capability. When telemanipulating a dextrous slave, position signals, which are picked up from the core

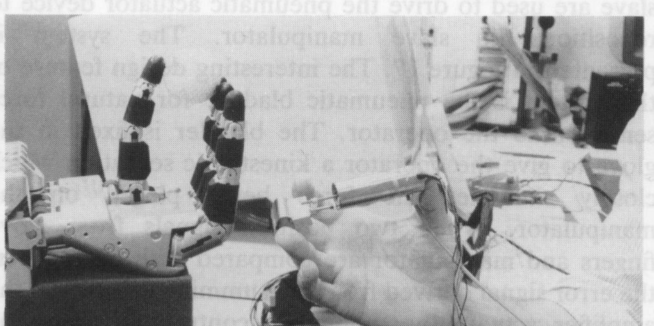

Fig. 18. PDMFF prototype.[29]

displacement in the LVDT sensor, are used to drive the robot slave using a host computer. Force feedback from the slave hand is sampled by the host computer, scaled up or down and used to drive a D/A converter. Using a proportional control law, this analog voltage is used to actuate the PMZ Valve Controller to adjust the air pressure in the cylinder.

Although this portable master has only one degree of freedom, it can control a dextrous robot hand of multiple degree of freedom, such as the Utah/MIT Hand. The control is in Cartesian space, where one can linearly interpolate the position of the core of the LVDT corresponding to the initial and final positions of the slave hand. The hand then is driven to the desired positions by a position servo system. Several manipulation macros are prestored in memory, and switched by voice or key commands. In this way the PDMFF can control not only pinching motions but also rotations or insertions.

Based on this design, a multi-degree of freedom master using several PDMFF-like mechanisms in parallel has been proposed by Burdea.[30] This proposed master with finger and wrist force feedback utilizes an existing open loop dextrous master, such as the Exos Hand Controller or the DataGlove, for position feed-forward control. Finger force feedback is accomplished by placing force actuators in the hand (see Figure 20). There are three micro pneumatic cylinders installed in the hand. Wrist position and force control may be provided by integrating the system with generalized NASA/JPL hand controller[31] with its parallel-finger gripper replaced by the three-finger master. The NASA/JPL universal force-reflecting hand controller has 6 degrees of freedom

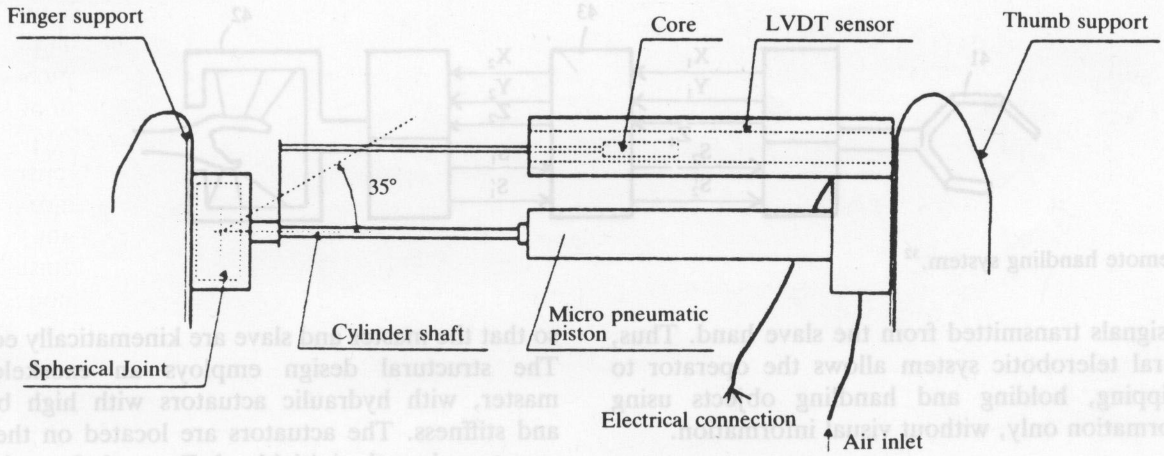

Fig. 19. PDMFF design.[29]

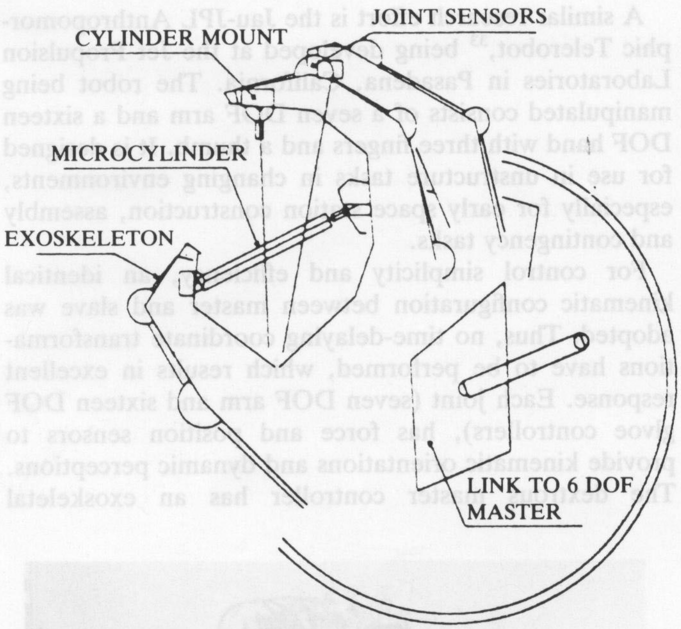

Fig. 20. Master with three finger force feedback.[30]

namely X, Y, Z translations as well as roll, pitch and yaw wrist motions. The schematic diagram of the proposed system is presented in Figure 21. Position data from both dextrous master and hand controller is sent to a host computer, while force data from the robot wrist is sent to the 6 DOF master interface. Force data from the robot fingers drives the individual pneumatic controllers.

5.3 Remote handling device

This remote teleoperation dextrous master system was invented by Alain Zarudiansky.[32] Its use was to improve the remote handling of an object using a slave hand which is teleoperated. The slave hand is provided with sensors for sensing contact forces. Those signals are applied to actuators associated with the master hand. The master is in the form of a glove in which the hand of a human operator is inserted. The actuators then provide force sensations to the hand of the operator. The overall system configuration is presented in Figure 22. The structure of the dextrous master is shown in Figure 23.

The human hand is connected to the rigid external shell 22 by a flexible shell 23 through rings 24, 25, 26 and collars 27, or more directly, through actuators and positioners 28, 29. The actuators used in the device can be any known mechanical or electromechanical devices. The displacement sensors in association with the actuators 29 and the angle sensors 33, 34, 35, 36 are used to sense the posed configuration of human hand to provide positioning commands to the slave hand. On the other hand, both the rings and collars, which comprise actuators 30, 31, 32 are capable of applying to the skin of the human hand local stimuli in response to the force

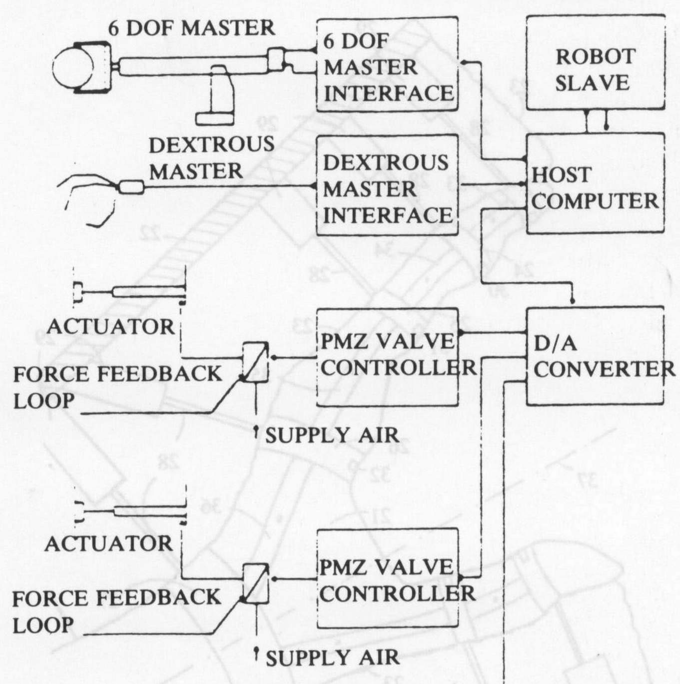

Fig. 21. Dextrous master with finger and wrist force feedback.[30]

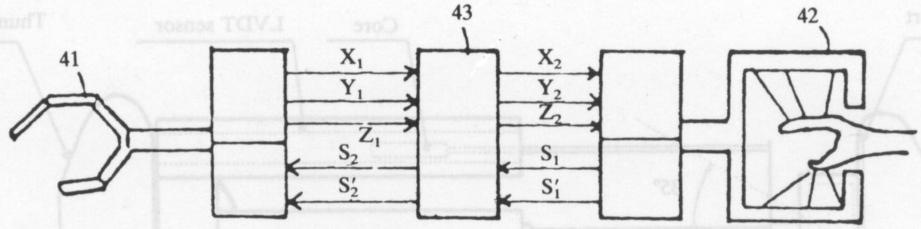

Fig. 22. Remote handling system.[32]

feedback signals transmitted from the slave hand. Thus, this bilateral telerobotic system allows the operator to adjust gripping, holding and handling objects using tactile information only, without visual information.

5.4 *Advanced multiple DOF force reflective hand/wrist masters*

An advanced multiple DOF hand master is under development at the Center for Engineering Design at the University of Utah.[25] It has nine actuated degrees of freedom with the configuration shown in Figure 24.

In order to achieve high performance every joint on the master was designed to be able to reflect the force encountered at the corresponding joint on the slave hand. High bandwidth, high resolution force reflection enhances the teleoperation "feel" of the master/slave system. The rotation axes of the master linkages were designed to coincide with those of human finger joints, so that the master and slave are kinematically equivalent. The structural design employs an exoskeletal type master, with hydraulic actuators with high bandwidth and stiffness. The actuators are located on the forearm area to reduce the initial load. For each finger joint there are two actuators operating antagonistically through tendons.

A similar research effort is the Jau-JPL Anthropomorphic Telerobot,[33] being developed at the Jet Propulsion Laboratories in Pasadena, California. The robot being manipulated consists of a seven DOF arm and a sixteen DOF hand with three fingers and a thumb. It is designed for use in unstructure tasks in changing environments, especially for early space station construction, assembly and contingency tasks.

For control simplicity and efficiency, an identical kinematic configuration between master and slave was adopted. Thus, no time-delaying coordinate transformations have to be performed, which results in excellent response. Each joint (seven DOF arm and sixteen DOF glvoe controllers), has force and position sensors to provide kinematic orientations and dynamic perceptions. The dextrous master controller has an exoskeletal

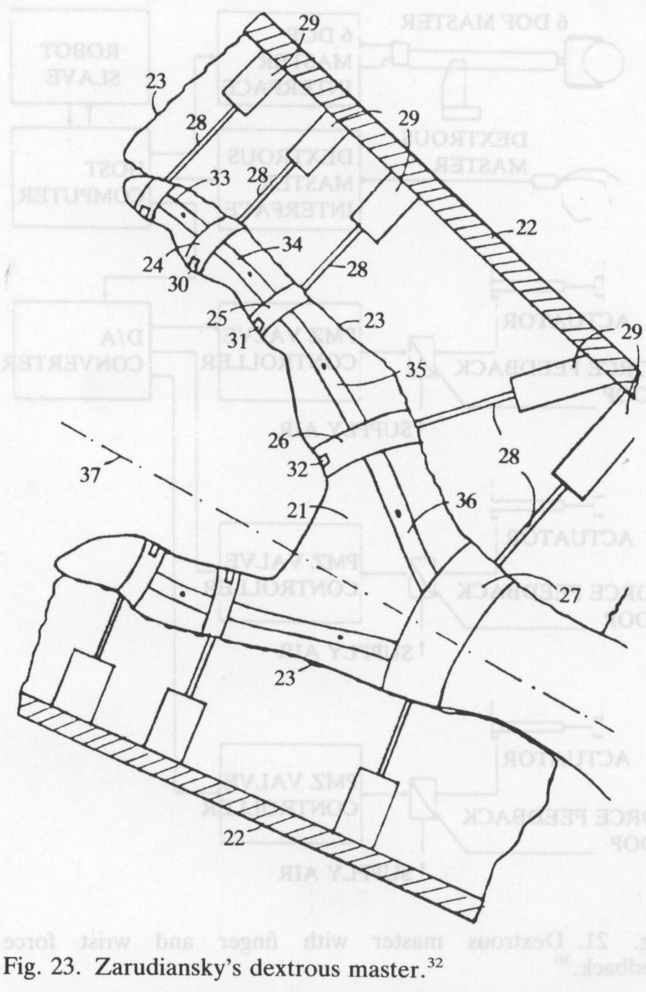

Fig. 23. Zarudiansky's dextrous master.[32]

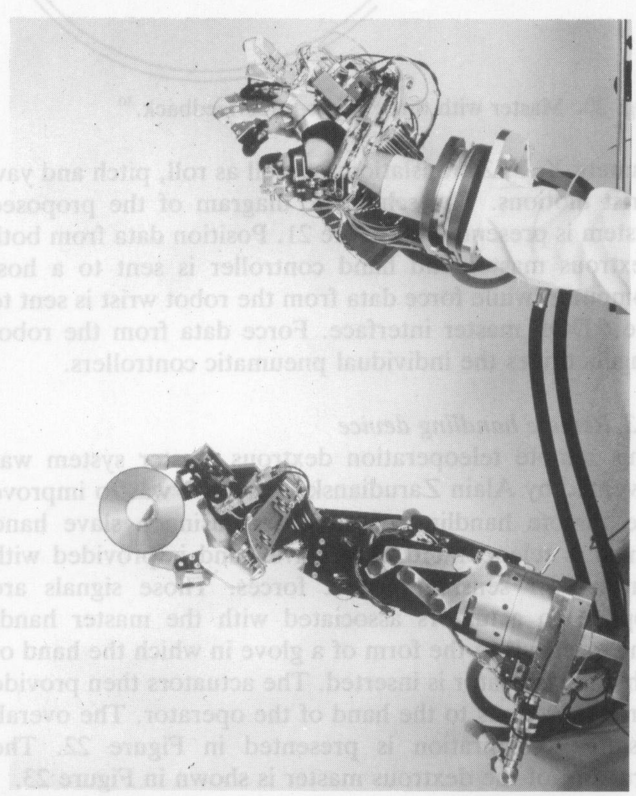

Fig. 24. Dextrous hand/wrist master and slave.

structure, which has three fingers and one thumb, each with four DOF. Above the human finger joints there are metal plates connected by linkages. These linkages have common pivot points with the finger joints. Each pivot point is the center for a pulley that rotates at equal angles at the finger joint. The pulleys can be back-driven in accordance with the slave's displacement to provide kinematic equivalency. Furthermore, the finger actuators are located in compact finger-drive packages at and above the elbow, and connected to the fingers by flex cables.

6. CONCLUSION

This paper is an overview of the state of the art in dextrous masters with force feedback. We have presented a number of aspects that have to be dealt with, from kinematics to human factors and actuator selection. We have then shown a number of prototypes.

The field is young, and under active research. This continuing effort will have to deal with numerous problems, some of which are outlined below.

(1) Due to the requirements of dextrous telemanipulation, the structures of both dextrous master and slave will be inevitably much more complicated than the conventional master/slave system. This structural complexity requires a much higher quality of control as well as better computer hardware and software.

(2) Dexterity implies the control of multiple degrees of freedom. Because of the kinematic and dynamic complexity of the human hand, coupling of exertions among fingers will be another difficult problem to deal with.

(3) All the adverse factors mentioned above will lead to physical fatigue of the human operator. A large number of actuators, and a complicatedly structure master controller will increase the weight and awkwardness of the system.

(4) To provide force feedback for multiple degree of freedom dextrous masters, a large number of actuators are needed, especially for the antagonistical drive type. Either the performance or the structure of the conventional actuators cannot satisfy such a demanding situation. There is a great need for new types of actuators, even using unconventional techniques such as electrical discharge to stimulate muscle contraction.

To solve these problems, some aspects of the design methodology have to be updated. Those design features include state-of-the-art master configuration, efficient and accurate control architecture, a powerful computation system, as well as high performance actuating components. If successful this effort will lead to more "natural" teleobotic systems, with improved productivity and better human interface. The results will then be applicable to other fields as well, such as virtual environments.

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