Analysis of force-reflecting telerobotic systems for rehabilitation applications

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ABSTRACT

There is interest in a class of assistive technology devices for people with physical disabilities where a person's existing strength and movement has a direct relation to the force and position of the tool used to manipulate an environment. In this paper we explore the design of a head controlled force-reflecting master-slave telemanipulators for rehabilitation applications. A suitable interface philosophy is to allow the system to function in a way that is conceptually similar to a head-stick or mouth-stick. The result is an intuitive method to operate a rehabilitation robot that is readily learned, and has the ability to provide the person with added strength, range of movement and degrees of freedom. This approach is further expanded for a similar class of assistive devices, power assisted orthoses, that support and move the person's arm in a programmed way. The techniques developed for powered orthoses and telemanipulators can also be apply to haptic displays that allow an individual to feel a virtual environment. The so called two-port model is used to predict the behaviour of telemanipulators, powered orthoses. and haptic interfaces and issues relating to stability are discussed.

Keywords: Haptic, Telerobot, Telemanipulator, Spinal cord injury, Proprioception

1. INTRODUCTION

Two classes of assistive device that require intimate human involvement are telerobotic devices and power assisted orthoses. Telerobotic device are an appropriate technology for individuals with spinal cord injuries where the traumatic spinal damage affects both fine motor skills and sensory channels. When a spinal cord injury level is between C2 and C5 there may be some limited hand function, although typically the individual retains a near to normal range of head movement (Stanger 1994), thus head movements are an obvious candidate for telerobot operation. Individuals with higher-level spinal cord injuries often use head-sticks and mouth-sticks to manipulate their environment, and such devices can be considered as a very simple example of a telemanipulator. Telerobots may also be an appropriate technology for individuals with arthrogryposis where there is a need to map a limited range of input motion to a full range of motion at a remote site. Head-sticks mouth-sticks and telerobots form a class of assistive technology that utilise extended physiological proprioception (EPP) - a concept derived by Simpson (1977). Devices of this nature, which also include prosthetic limbs, allow the user to extend existing proprioceptive skills to the tip of the device and so readily conceptualise the movement of the tip in freespace. In addition the forces that are experienced at the end of the device are relayed back directly to the user. Head-sticks and mouth-sticks have an added advantage of being lightweight and highly rigid, and can therefore convey tactile and kinesthetic information from the environment with high bandwidth. Two limitations of head-sticks and mouth-sticks are that they have a limited workspace, both in positional and orientational degrees-of-freedom, and there is no possibility of increasing the mechanical power a user can transfer from the interface to the environment.

Individuals with muscular dystrophy maintain proprioceptive skills but lose muscle strength throughout the progression of the disease. One possible rehabilitation device that can be prescribed during the stage when an individual has insufficient strength to support his or her arms against gravity, is the balanced forearm orthosis, also known as the ball bearing feeder or the mobile arm support. Because the individual's proprioceptive skills are retained, the balanced forearm orthosis is highly successful as a rehabilitation device. A natural consideration for this class of rehabilitation device is whether the person's strength can be enhanced, or whether greater vertical movement might be possible, or whether an advantage is gained by allowing other mechanisms such as voice commands to assist in the movement of the person's arm. All three cases allow the person's proprioceptive abilities to be exploited to the full (Stroud, 1995; Rahman, 1995).

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A third instance where proprioception plays an important role in a human machine interface is the haptic displays that are emerging to enhance an operator's interactions in virtual environments. Many immersive virtual reality environments utilise instrumented gloves to allow the individual to interact with virtual objects. Such an interface relies totally on visual feedback to indicate when an object has been grasped, whereas in real environments an individual also uses proprioceptive and tactile cues to determine the location and physical characteristics of an object. A haptic display can be used either in virtual environments or as a telerobotic master where force information is relayed back to the operator.

2. IMPLEMENTATION OF A HEAD OPERATED TELEROBOT

A test-bed head operated telerobotic system has been built at the Applied Science and Engineering Laboratories. It consists of two 6 degree of freedom master and slave robots, each controlled by separate IBM-PC 486DX/66 compatibles and linked with a high-speed parallel data link (figure 1). The master is the PerForce hand-controller (manufactured by Cybernet Systems of Ann Arbor, MI). The PerForce has been mechanically modified so that it is controlled by the user's head movements. PID position controllers are implemented digitally and these can be used under appropriate conditions to apply forces at the user's head. The manipulation tasks in the environment are performed by the Zebra-ZERO (manufactured by IMI, Berkeley, CA) which has a force sensor at its wrist. Figure 2 shows the master and slave of the telerobotic test-bed.

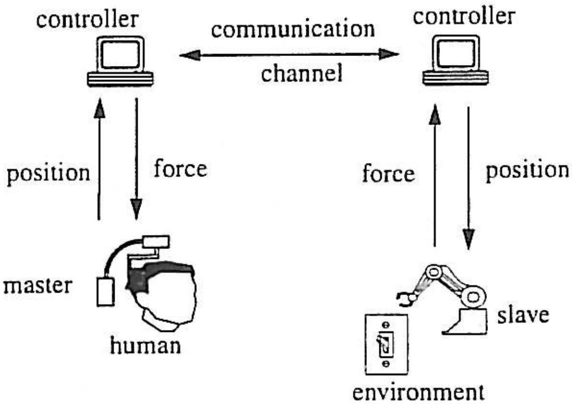

Figure 1. *Configuration of telerobotic system*

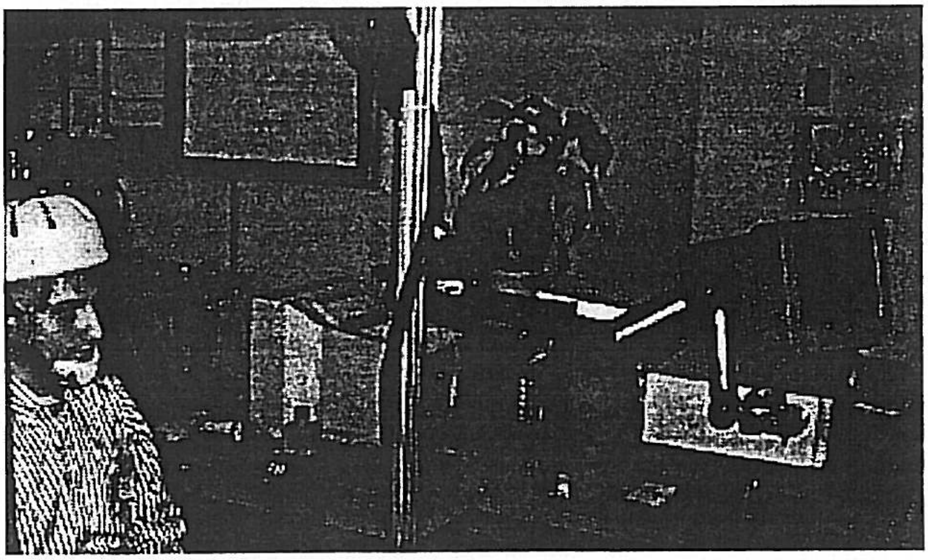

Figure 2. *Master slave telemanipulator setup*

Since an electronic link exists between the two robots, and the force and position data that are collected are available for manipulation by the software, it is possible to evaluate a variety of different control schemes. Additionally, the system is modular allowing for the possibility of different input and output devices, since the kinematics of the master and slave need not be the same.

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2.1 Head-Stick Control

One natural method of operating the telerobot is to simulate the characteristics of a head-stick or mouth-stick using the telerobot test-bed. An appropriate choice of parameters also allows us to enhance the user's strength and to re-orientate the gripper to the needs of the task.

Figure 3 shows the assignment of coordinate frames on the master and slave robots. The virtual head-stick method of operation involves adding a rigid imaginary link of length l at the origin of the final coordinate frame on the master robot (the centre of the helmet). Using the master robots forward kinematic transform **A** and a transform relating to the positioning of the virtual head-stick **HD** it is possible to determine the target position of the slave robot. This can then be implemented using the slave forward kinematic transform **G**. That is

$$G = CAHD \tag{EQ 1}$$

When the slave is not in contact with the environment equation 1 determines the trajectory of the slave and the matrix **G** is used to calculate the joint angles of the slave. When the slave is in contact with the environment forces are measured at the wrist sensor and these must be relayed back to the user in an appropriate fashion.

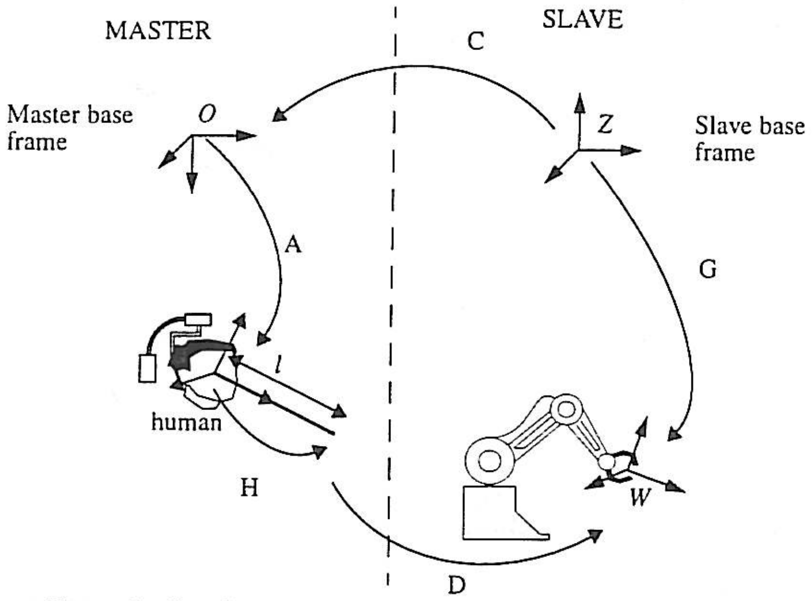


Figure 3. *Coordinate frames used to implement a virtual head-stick*

The sensed forces are measured with respect to the wrist frame and this is first transformed through **G** to estimate forces with respect to the slave base frame and then via the forward master kinematics to determine the orientation of the forces with respect to the tip of the virtual head-stick. A geometrical relationship is then used to determine the torques that must be applied to the master to allow the operator to experience a scaled value of these forces (Salganicoff 1995).

3. IMPLEMENTATION OF A POWER ASSISTED ARM ORTHOSIS

A test-bed power assisted orthosis has also been built at the Applied Science and Engineering Laboratories. It consists of a 6 degree of freedom master (RT200 from Oxford Intelligent Machines Limited) with the end effector replaced by a 6 axis force/torque sensor (Mini from Assurance Technologies Incorporated). A splint assembly is mounted on the force torque sensor and this in turn supports the person's arm (figure 4).

The base level control system first subtracts the weight of the individual's arm from that measured by the sensor, and uses the torque measurements to servo the RT200 robot so that no net torque is experienced by the individual over the combined range of movement of the individual and the robot. Once these servo mechanisms are established additional control algorithms can be instantiated to relate the resultant force that the individual exerts on the force torque sensor to the movement of the robot. Algorithms relating the estimate of the user's residual force to robot position, velocity and acceleration have all been demonstrated (Stroud 1995).

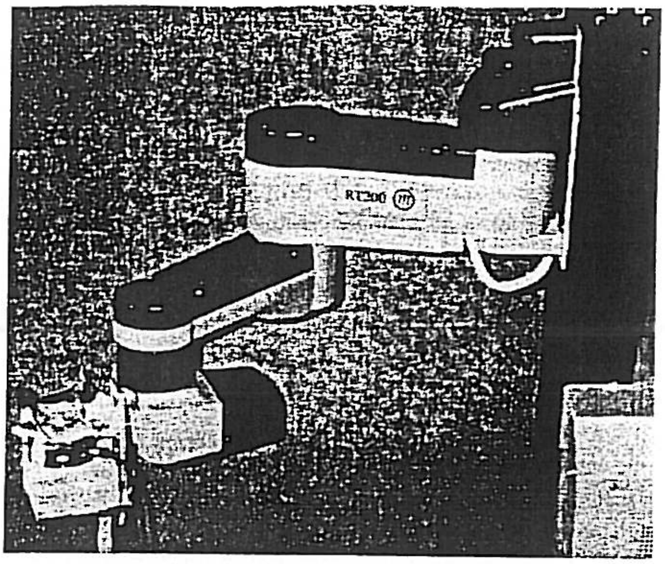


Figure 4. *Power assisted orthosis setup*

4. IMPEDANCE MODELS OF PROPRIOCEPTIVE INTERACTION DEVICES

Hogan (1985) postulated a mechanism for human movement that is now widely accepted, the philosophy of impedance control. In his seminal papers he suggested that human movement is achieved by the central nervous system establishing an end point for the trajectory and an associated movement stiffness, both of which remain constant for an uninterrupted movement and which alone determine the movement trajectory. This concept has gained acceptance in telemanipulator research with Hannaford (1989), Lawrence (1992) and others using it as a criteria for telemanipulator designs. The methods used can give an insight to the operation of telerobots, power assisted orthoses, and haptic interfaces and these methods are developed in the following.

4.1 Two Port telemanipulator model

The Applied Science and Engineering telerobotic test-bed has been designed to study two control architectures, position forward/force reflection, and force forward/position reflection (Rahman 1994). The position forward force reflection is readily implemented on the test-bed since the master contains position encoders and the slave incorporates a 6 axis force sensor. The master has been fitted with a force sensor and work is ongoing to implement the force forward/ position reflection method.

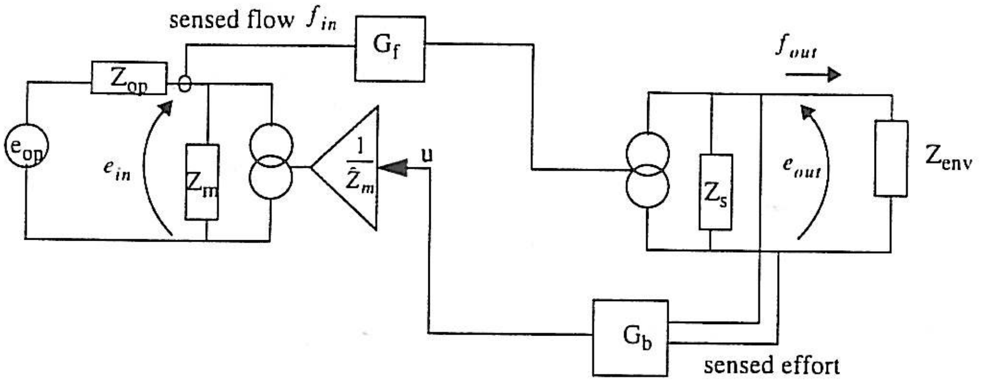


Figure 5. *Two port telemanipulator model*

The Cartesian position forward/force reflection architecture can be modelled in a one-dimensional case using an equivalent network (figure 5) where *e* is used to represent effort (force or voltage), and *f* is used to represent flow (velocity or current). For the following discussion force will be used interchangeably with effort, and flow with velocity. Both master and slave use position controllers at the lowest level. Since position relates directly to flow it is appropriate to model the actuators as a dependent flow source. The hybrid parameter matrix (H-matrix) can be used to gain insight into properties of the system and equation 2 shows how effort is related to flow.

$$\begin{bmatrix} e_{in} \\ f_{out} \end{bmatrix} = H \begin{bmatrix} f_{in} \\ e_{out} \end{bmatrix} \qquad \text{(EQ 2)}$$

An ideal telemanipulator system would appear transparent to the operator, although it may magnify the operator's strength and scale the operator's movements. The ideal H-matrix is as follows

$$H_{ideal} = \begin{bmatrix} 0 & \frac{1}{Q} \\ -P & 0 \end{bmatrix} \qquad \text{(EQ 3)}$$

where Q is the level of force scaling, and P is the level of amplitude scaling. Using the configuration shown in figure 5 it is possible to derive the H-matrix for the telerobot as shown in equation 4.

$$H = \begin{bmatrix} Z_m & G_b(q) \\ -G_f(p) & \frac{1}{Z_s} \end{bmatrix} \qquad \text{(EQ 4)}$$

The master and slave impedances can be represented as the lumped parameters model $Z=ms+b+k/s$, where m, b and k are the equivalent mass, damping and stiffness of the robot. Using the H parameterisation we can determine the apparent input stiffness of the telerobot as

$$Z_{in} = Z_m + G_f G_b \left(\frac{Z_s Z_{env}}{Z_s + Z_{env}} \right) \qquad \text{(EQ 5)}$$

Equation 5 can be used to examine the free space and hard contact impedance of the telemanipulator as the task impedance varies from 0 to ∞. For the free space condition the environment we have:

$$\lim_{Z_{env} \to \infty} Z_{in} = Z_m$$

Thus only the impedance of the slave Z_s is felt by the operator in free-space motion, as we would expect, since the force sensor returns no signal. A simple extension to this model would allow scaled values for slave flow to be added to the sensed force thus allowing the operator to experience more of the dynamic character of the slave in free-space movement in terms of a perceived impedance. Although the test-bed architecture allows for this to be implemented the dynamic characteristics of the slave exceed that of the master and human so have little effect on the operator's perception in this instance.

For the hard contact condition,

$$\lim_{Z_{env} \to \infty} Z_{in} = Z_m + G_f G_b Z_s \qquad \text{(EQ 6)}$$

thus for hard contact the stiffness of the master and slave are additive. In order to feel the environmental impedance, the slave mechanical impedance Z_s must be very high, since it is effectively shunted across the environmental impedance Z_{env}. Secondly, as equation 6 shows, in order for the feel of the task impedance to remain the same, the product $G_f G_b$ must be constant, otherwise impedances presented to the operator will vary. If we increase the forward flow scaling value, we must decrease the reverse force gain proportionally. Obviously, we cannot do this arbitrarily, as the system stability will also be affected by the magnitudes of G_f and G_b.

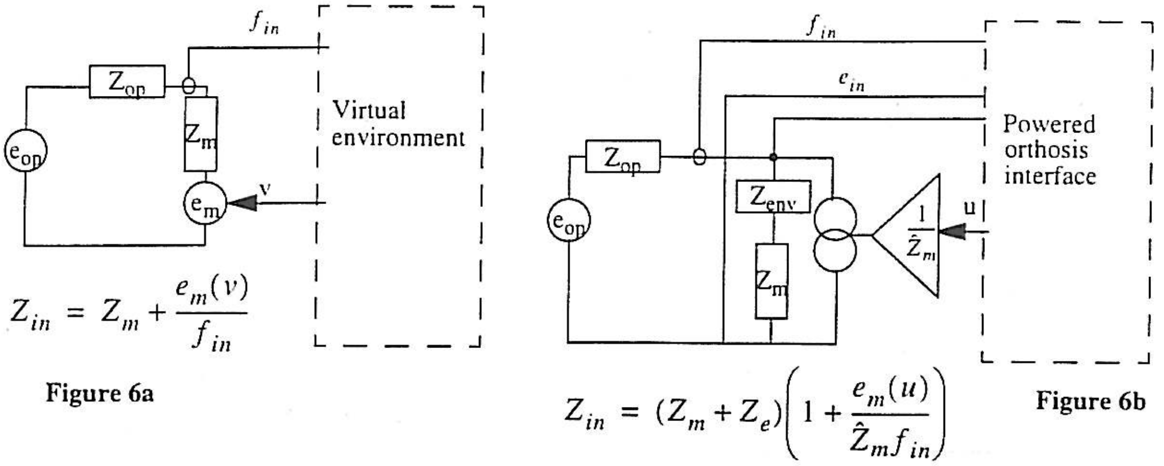
Based on the expected task impedances, we can select the forward position gain G_f and force feedback gain G_b to match comfortable force and displacement levels as measured for the target user population (stanger94). Additionally, closed loop system properties that have user-interface and safety impact, such as bandwidth and stability can be analysed by using the **H** matrix parameters (Hannaford 1989).

4.2 One Port models

The two port model adapts readily to consideration in the design of power assisted orthoses and haptic display designs. A haptic display is equivalent to a situation where the slave and environment are determined solely by the virtual environment. It is easy to simulate infinite stiffness and equation 5 becomes

$$Z_{in} = Z_m + G_f G_b Z_{env}$$

where G_f and G_b can be now be chosen to simulate different arbitrary environmental impedances while maintaining system stability. A one port haptic display model is shown in figure 6a. One common lightweight haptic interface is the PHANToM from SensAble Devices. This interface is based on controlling joint torques via motor current hence the effort controlled model is appropriate.



$$Z_{in} = Z_m + \frac{e_m(v)}{f_{in}}$$

Figure 6a

$$Z_{in} = (Z_m + Z_e)\left(1 + \frac{e_m(u)}{\hat{Z}_m f_{in}}\right)$$

Figure 6b

Figure 6. *Controlling impedance from a virtual environment or a powered orthosis*

For the case of the one port model of a power assisted orthosis an additional complication exists in that user may wish to interact with his or her environment through the same port as the arm interface. This can be accomplished by adding the environmental impedance in series with the user impedance and considering the two cases when this tends to zero (no contact) and infinity (contact). This is shown in figure 6b.

5. RESULTS

Good characterisation of the master is essential to the control of the telerobotic system. A system identification of the master robot was carried out to determine the effects of closed loop controller parameters on the impedances along different axes. A PID controller is available on each axis of the robot however only the proportional and derivative terms were used. The individual axes of the master were modelled as a classic closed loop controller and plant. The system identification process then allows the determination of the combined master and controller dynamics and then allows these to be used to establish appropriate values of master impedance.

Step responses were used to command master movement. The resulting movement was measured for different settings of k_p and k_d. The smoothed out data sets were fitted into second-order discrete-time models using MATLAB's system identification package.

The discrete time model was then converted into continuous time format and a closed loop transfer function was generated for each setting of k_p and k_d. Master stiffness was determined in the quasi static case when different vales for k_p were established in the controller and weights used to displace the master from a neutral position. The displacement was measured using the master position encoders.

Results for all axes were determined and it is helpful to consider the characterisation of the linear x axis of the master. Jayachandran (1995) showed that this could be expressed as

$$M = 10^4(0.033k_p - 0.1507k_d + 0.0011)\text{Kg}$$
$$B = 10^4(-1.07k_p - 162.11k_d)\text{ Ns/m}$$
$$K = 10^4(-166.07k_p)\text{ N/m}$$

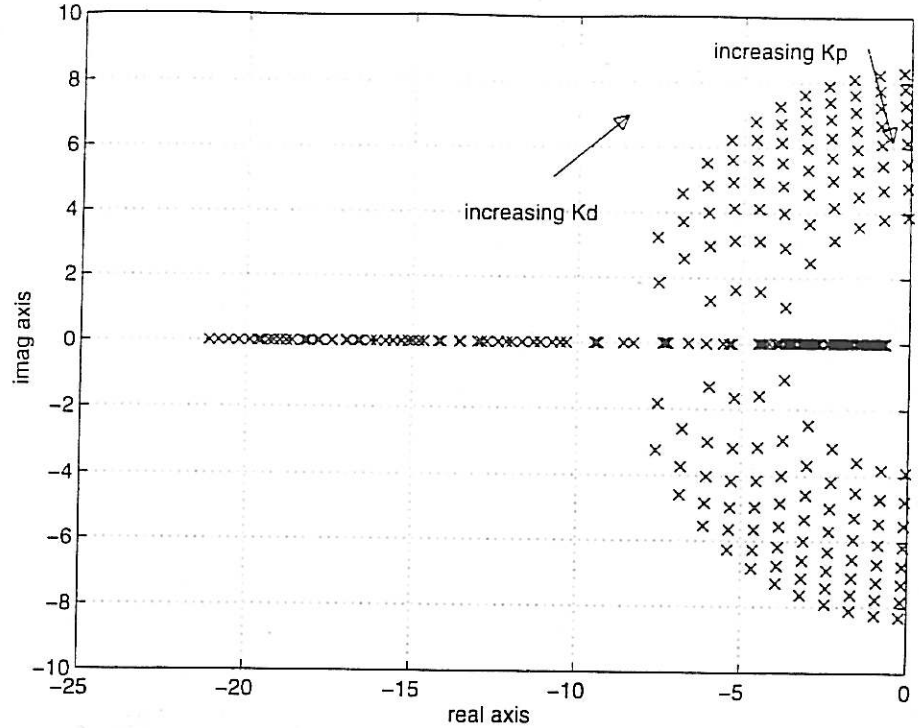


Figure 7. *Stability region for the telerobot test-bed master*

From this it is possible to determine a region of stability for the master in operation and select values for k_p and k_d so as to establish a desired dynamic characteristic for the region of operation. The stability of this mechatronic system can be determined from the defining equations and the movement of the poles in response to settings of k_p and k_d is shown in figure 7.

6. DISCUSSION

It is often not easy to make a direct estimation of the dynamics of a robot, whereas a good model of system dynamics is important in understanding the interaction between the robot and the environment or user. Reasons include the complexity of the mathematics involved, difficulty in determining the position of the necessary mechanical characteristics such as link inertia and actuator characteristics. Also in the test-bed system described, the manufacturers claimed that each axis was controlled via a PID controller, however additional terms were added to improve performance and this was poorly documented. Further it was not possible to access the controller software as the implementation was proprietary. For regions around the operating point it is reasonable to use system identification methods to determine baseline impedance measurements for the purpose of designing the controllers for the master-slave telerobot. This approach also allows us to change the impedance characteristics for the master in a limited fashion by changing the controller parameters.

The results for the PerForce master used in the telerobot test-bed show the range of results for which the master will remain stable and the behaviour of the master in this region (figure 7). Although this guarantees the stability of the master in a particular region of k_p k_d it ignores the effect of the operator modulating his or her impedance and forces (Z_{op} and e_{op} in figures 5 and 6). Experience has shown that this is most likely to occur in the non linear region of the boundary where the environmental stiffness changes radically over a short distance. This is an area of active research in telerobotics, power assisted orthoses and haptic interfaces.

7. CONCLUSION

The telerobotic research test-bed has demonstrated the concept of a virtual head-stick to allow individuals with spinal cord injury to successfully manipulate their environment. The advantages of a telerobotic system of this nature will have over head-sticks and mouth-sticks is the ability to increase the available workspace and degrees of freedom of the individual, as well as increasing power and range-of-movement abilities.

The user's perception of the environment has been shown to be highly dependent on the master and slave impedance characteristics. Ideally, we would like Z_m, the master inertia, to be small, and the stiffness of the slave, Z_s, which is in parallel with Z_{env}, to be as high as possible so that $Z_{in}=Z_{env}$. However making the slave impedance high can lead to high interaction forces. Using the controller it may be possible to change impedance characteristics as a function of the activity thus for free space movement the slave impedance would be reduced so that accidental collisions minimised the forces that resulted. When the operator intends to apply high levels of force to the environment the slave stiffness could be increased to reduce the artifact introduced by the telemanipulator.

It is possible to design telerobotic systems where a mechanical link couples the master and slave robots. This approach will lose the flexibility with regards varying master and slave impedances, however because it is possible to reduce the system complexity this may result in a more effective rehabilitation device.

The discussion of the two port telemanipulator model can be applied readily to the design of power assisted orthosis and haptic display devices in virtual reality. In this instance the operations of the slave are determined by a computer that can either create a virtual environment for the slave or have the environment determined through other commands by the user. For example the user might slide his or her arm along a virtual surface before immobilising it in a convenient region while a particular task is completed.

The two port telemanipulator model allows the operation of a telerobotic system to be modelled easily, and conclusions drawn about the behaviour of a telerobot. Although it is possible to determine the regions of stable operation using this model, it is not sufficiently general to study the conditions where the effort of the operator e_{op} is a function of the overall telerobot dynamics, a situation that may occur both in telemanipulator and virtual environments.

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