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A Virtual Headstick for People with Spinal Cord Injuries

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SUMMARY

This paper presents a virtual headstick system as an alternative to the conventional passive headstick for persons with limited upper extremity function. The system is composed of a pair of kinematically dissimilar master-slave robots with the master robot being operated by the user's head. At the remote site, the end-effector of the slave robot moves as if it were at the tip of an imaginary headstick attached to the user's head. A unique feature of this system is that through force-reflection, the virtual headstick provides the user with proprioceptive information as in a conventional headstick, but with an augmentation of workspace volume and additional mechanical power. This paper describes the test-bed development, system identification, bilateral control implementation, and system performance evaluation.

KEYWORDS: Assistive robotics; Head-control; Proprioception; Tele-manipulators; Force-reflection; Master-slave manipulation systems; Man-machine systems; Force-feedback control; System identification; Fitts' law.

1. INTRODUCTION

People with higher-level spinal cord injuries often use headsticks and mouthsticks to perform manipulations. Headsticks provide extended physiological proprioception (EPP)[1] which allows users to directly feel forces and other perceptual cues present at the tip of the headstick. The conventional head-stick is effective for two reasons: it is in close contact with the human head which extends its proprioception to the tip of the head-stick, and it is lightweight and very stiff, and therefore conveys tactile and kinesthetic information from the environment with high bandwidth. Traditional head-sticks, however, are limited in workspace and in the mechanical power that they transfer because of user mobility and strength limitations.

Since the mid 80s, substantial efforts have been made in developing as well as improving rehabilitation robotics systems[2–7] for persons with physical disabilities. Recent rehabilitation robotics projects addressing the needs of individuals with quadriplegia due to spinal cord injury have primarily focused on the user input[7–11] and, to a much lesser extent, on the feedback to the user. Because of the severe physical limitations that a disability places on the individual and the loss of sensation below the spinal lesion, inputs such as voice recognition, joysticks, and switches have been common. Feedback has been primarily visual.

In the robotics area, the study of force feedback control has been a topic of interest for many years. Goertz[12] implemented force reflection using electric servo manipulators to provide the operator with the contact force experienced by the slave robot via force reflection of the joints of an exoskeleton. In reference 13, Hogan formulated the position/force controller problem within the context of a mechanical impedance control. Khatib[14] showed the effective control of both force and position using end-effector dynamics and force/position specification matrices. Telemanipulation systems which provide force feedback have also demonstrated greater success.[15–17] Given the successful precedent set in related fields charged with augmenting human manipulation ability, considerable possibilities exist for the use of robots as augmenters of the manipulation ability of individuals with severe spinal cord injuries. Many of the problems involved in designing a robot system for persons with disabilities are similar to those that have been addressed in telerobotic research efforts. However, user motion ability, motion range, sensory ability, and safety pose different requirements than those evident in industrial telerobotic systems.

This paper describes a head-operated telerobot system (virtual headstick) suitable for individuals with high level spinal cord injuries. Utilizing industrial teleoperation principles, this virtual headstick system emulates the proprioceptive quality of a traditional head-stick while also allowing for augmented end-effector ranges of force and motion. The approach taken in this virtual headstick project is to construct a master-slave robot system with the master robot attached to a helmet that an individual with spinal cord injury wears. The master robot is electronically linked to the slave robot and the system allows the person to manipulate the slave robot with the movements of the head. Environmental contact forces sensed by the slave robot are reflected back to the master side, that is, to the user. The system is designed and constructed such that the end-effector of the slave robot moves as if it were at the tip of an imaginary headstick attached to the user's head. Through the force-reflection, the system provides the user with extended propriocetion as in a conventional headstick but with augmentation of workspace volume and mechanical power.

The article is organized as follows. Section 2 gives the details of the design and implementation of the system including master robot impedance parameter adjustment, slave robot frequency response, bilateral control strategies,

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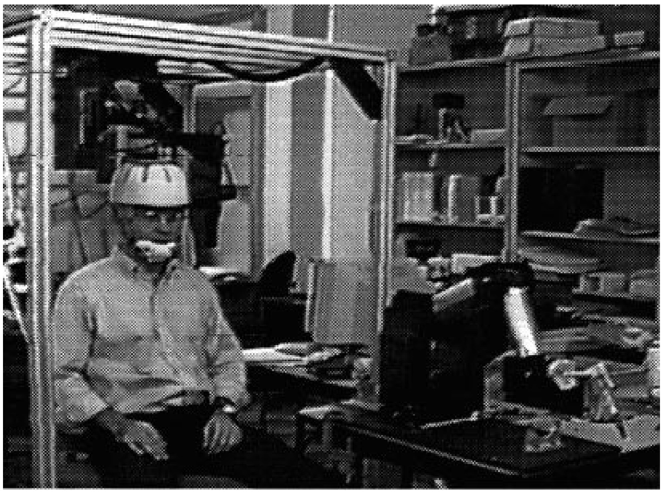

Fig. 1. A head–controlled master–slave telerobot system

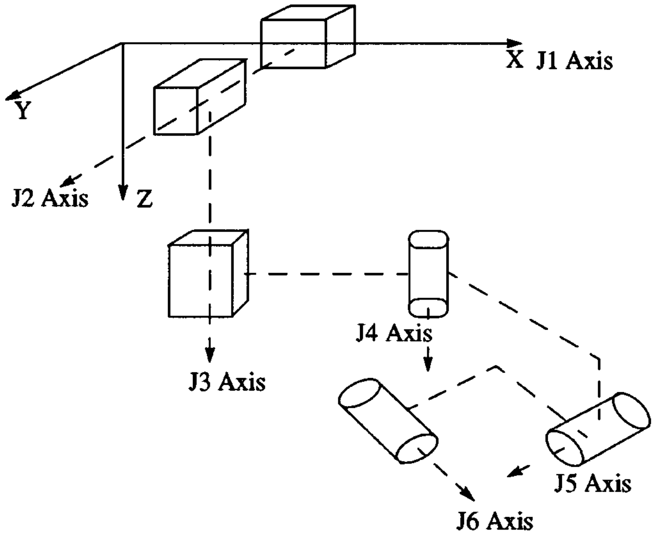

Fig. 2. PerForce robot kinematics

and safety measures. Section 3 describes the design of the performance evaluation experiments using Fitts' motion, and Section 4 presents the statistical analysis based on the experimental data. Finally, conclusions are discussed in Section 5.

2. VIRTUAL HEADSTICK SYSTEM

The virtual headstick system developed in the Center for Applied Science and Engineering at the University of Delaware contains a pair of kinematically dissimilar master-slave robots. The master robot is operated by the user through his/her head motion, and the slave robot moves accordingly at the remote site (see Figure 1). The force-motion information exchange between the master and the slave is carried through a parallel communication link. The force and motion vectors are defined with respect to the master robot base coordinate frame. The current system is capable of performing position and rate control. In this study, position control is used.

2.1 Master robot

The master robot is the PerForce™ six degree of freedom hand-controller device manufactured by the Cybernet Systems Corporation; Figure 2 shows its kinematics. This device has been modified to facilitate head control via a helmet. All six axes, three translational axes and three rotational axes, are decoupled. The helmet is attached to the last link in such a way that the center of the user's head lies approximately at the intersection of the three rotational joints. This helps to make the input mechanism easier and more intuitive to use. Each joint of the master robot is equipped with a brushless DC motor. The master robot is designed to be easily manoeuvered in either passive or active mode. In the passive mode, the master robot is simply a position measuring device. In the active mode, the motors are powered and can be driven in a direction opposing operator movement. This functionality is used to generate force-reflection sensation in a master-slave configuration.

The master robot receives force signals when the slave robot encounters an obstacle. The force information is input as a reference to a software PID controller. The PID controller generates a command signal to drive the motor in a way such as to recreate the dynamic interaction between the slave and environment. This is accomplished by setting the appropriate PID parameters that produce the desired impedance. The process of setting the PID parameters starts by considering the dynamic model of the master robot's end effector described by:

$$F(t) = M\frac{d^2}{dt^2}X(t) + B\frac{d}{dt}X(t) + K(X(t) - X_0(t)) \qquad (1)$$

where F is a vector that specifies the applied external force and consists of three cartesian force components and three moments, X is the current position vector consisting of three cartesian position components and three angular orientations, X_0 is the position vector that the robot's controller tries to enforce, and M, B, and K are the apparent inertia, apparent damping, and apparent stiffness tensors, respectively.

In general, finding the coefficients in Eq (1) is difficult because of non-zero off-diagonal terms in the impedance tensor. Salisbury *et al.*[18] realized the off-diagonal terms in the impedance tensor through a combination of impedances

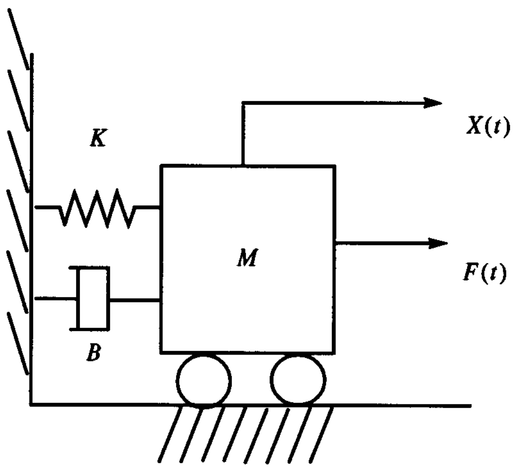

Fig. 3. One DOF system

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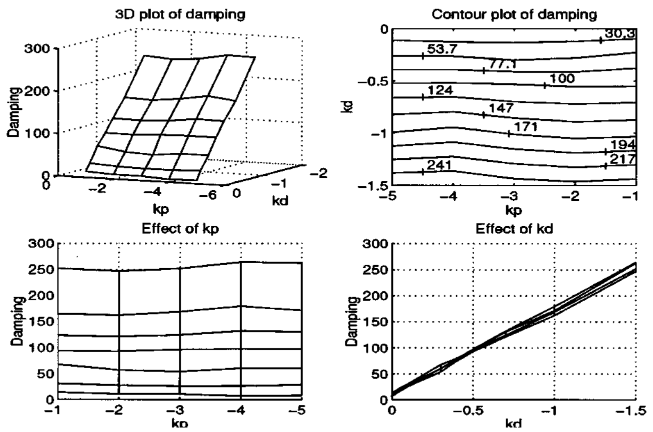

Fig. 4. X–axis damping coefficient

along different axes. This method was employed in this study. It was ensured that while a specific axis was being tested, all the other axes of the robot were tightly bound and not allowed to move. Each of the master robot axes was modeled as a one degree of freedom second order system represented in Figure 3.

It is conventionally shown that in the absence of external forces along a specific axis, the transfer function for a one DOF system is modeled as:

$$\frac{x(s)}{x_0(s)}=\frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2} \tag{2}$$

where x is the position output, x_0 is the command position, ζ is the damping coefficient, and ω_n is the natural frequency of the closed loop position control system. Then based on Equations (1) and (2), the inertia M, damping B, and stiffness K of a second order system may be related to the close loop damping coefficient ζ, and natural frequency $\omega_n$with $\omega_n^2=K/M$ and $\zeta\omega_n=B/(2M)$.

The parameters ζ and ω_n can be experimentally determined through system identification[19] by using either step function or random signals. It is understood that by varying PID controller parameters k_p, k_d and k_i, the close loop system frequency response changes accordingly. That is, the PID parameters affect the values of ζ and ω_n, therefore, the values of M, B, and K. Least square fitted solutions were found for expressing the inertia, damping and stiffness in terms of the PID controller gains. The least square fitted planes that describe the dependent variables for the X-axis are:

$$M=0.033\,k_p-1.5072\,k_d+11 \tag{3}$$

$$B=-1.07\,k_p-1.62.11\,k_d \tag{4}$$

$$K=-166.07\,k_p \tag{5}$$

in the range $-1\leq k_p\leq -5$, $0\leq k_d\leq -1.5$, and $k_i=0$. The plot of the damping coefficient ζ for the X axis is shown in Figure 4.

Through Equations (3), (4) and (5), the desired impedance of the master robot can be achieved by adjusting the PID parameters. It is noted that the quantification of impedances was obtained experimentally so that the impedance equation is accurate only for the robot that was tested, assuming stationary plant dynamics. A verification test was performed in which the forces being sent by the slave were compared with the forces being actually applied by the master on the user's head (the actual forces were measured using a force sensor mounted between the helmet and the master's end effector). The test results for the master's X-axis plotted in Figure 5 shows a good match between the commanded and applied forces.

2.2 Slave robot

The slave robot is the Zebra ZERO™ six degree of freedom articulated manipulator manufactured by Integrated

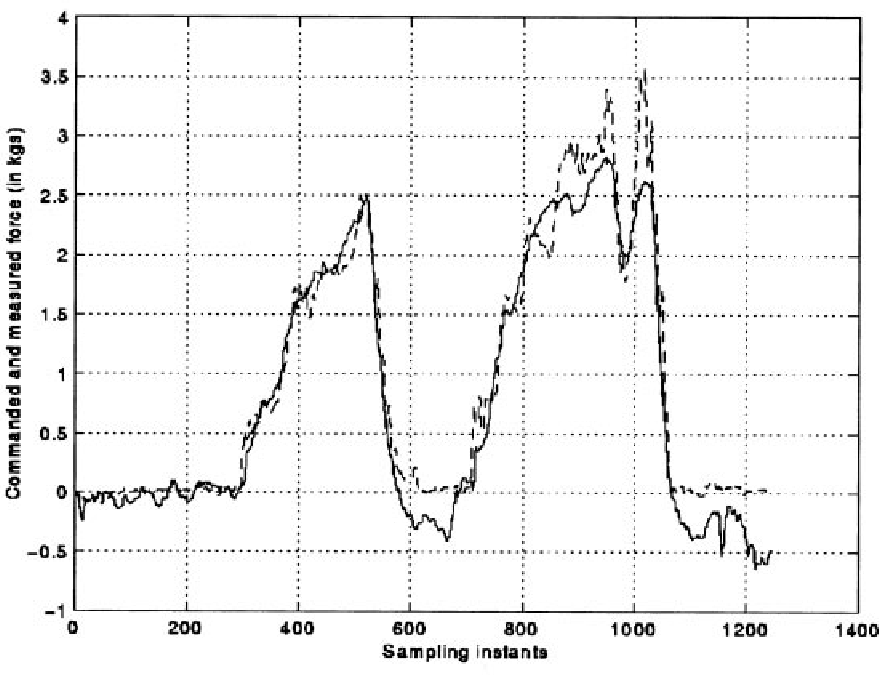

Fig. 5. The command and applied forces

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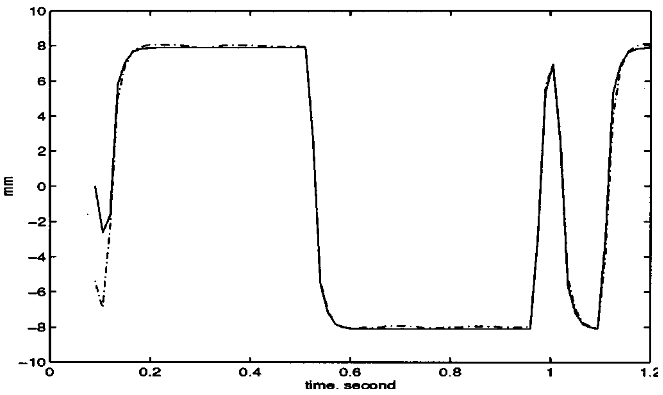

Fig. 6. Dot line: arm real motion position; solid line: model output

Motions, Inc. This robot has a six degree of freedom force sensor mounted at the wrist of the arm. As forces and moments are applied to the end-effector, the strain gauges in the force sensor produce a 6×1 calibrated force/moment measurement vector to be used locally or sent to the master side.

To facilitate the master-slave teleoperation, a study on the slave system frequency response is desirable. Experimentally identifying the dynamic model of the slave robot (the Zebra ZERO™) has been conducted[20]. The robot arm is treated as an unknown device that receives an excitation and generates an output. The device is simplified as a time-invariant linear, single-input, single-output system. A Generalized Binary Noise (GBN) sequence[21] with a non-switching probability p, $0<p<1$, is chosen as the input signal. The input signal is scaled to an appropriate magnitude before it is applied to the Zebra ZERO™ arm as an excitation signal. There are two main factors influencing the selection of the scale value. First, the identification is to be conducted within the specific working condition under which the teleoperation will take place. It is revealed in reference 21 that the magnitude of the step jump of the Zebra ZERO™ arm from sample to sample in teleoperation is confined to a range of -8mm to 8mm. Secondly, the robot arm, in fact, is a non-linear device. The non-linearity is evident when high magnitude excitation occurs. Hence, a GBN sequence with a low magnitude of -8mm to 8mm is used in the identification process.

In reference 22, it is suggested that a suitable sampling frequency be confined within a range of $10\omega_B\leq\omega_s\leq30\omega_B$, where ω_B is the bandwidth of interest. For a head-operated

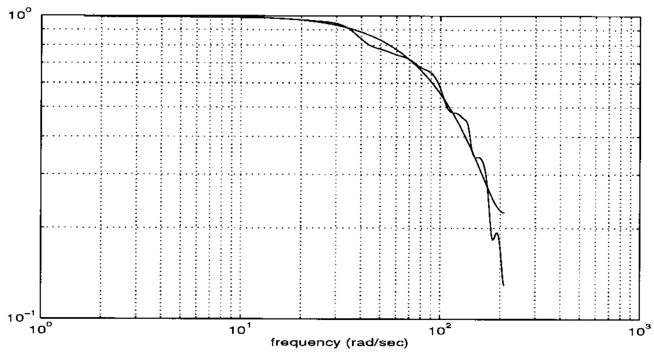

Fig. 7. Slave robot frequency response

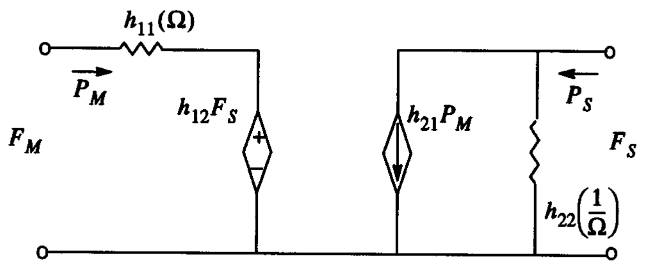

Fig. 8. Direct translation of Equation (8) and (9)

system a bandwidth of 3Hz is adequate. The sampling frequency, ω_s, used in this teleoperation system is 64 Hz which is within the above discussed bounds.

The ARX (auto-regression with extra input) model, $A(q)y(k)=B(q)u(k-n_k)+e(k)$ is utilized in this study. In the above equation, y is the output, u is the input, n_k is the time delay, e is the additive noise, $A(q)$, and $B(q)$ are the arbitrary polynomials. The unknown polynomials are obtained by using the well known Least Squared method. The identification process is only applied to a one dimensional translation in Cartesian space. Wrist position data are collected and fed into the identifier. The resultant model is $y(k)=0.098\,y(k-1)+0.0688y(k-2)+0.545u(k-1)+0.287u(k-2)$. Figure 6 displays the simulated model output and the measured robot arm output with the same command input. It is evident that the model matches the real system very closely.

The frequency response of the Zebra ZERO™ arm is also evaluated; the results are shown in Figure 7. It has a flat response up to about 5 Hz (-3 dB) which is sufficient to accommodate head movements.

2.3 *Control architecture*

By the definition in reference 23, the master-slave telerobot system in this paper is, in general, a two-port system shown in Figure 8, where F_M is the force applied by the user to the master robot, P_M is the motion of the master, F_s is the force applied by the slave to the environment, and P_s is the slave motion. The hybrid parameters defined in network theory[24] give the following equations as if F_M and P_s were the independent variables:

$$F_M=h_{11}P_M+h_{12}F_s \quad (6)$$

$$P_S=h_{21}P_M+h_{22}F_s \quad (7)$$

where h_{11} is the master intrinsic impedance measured when

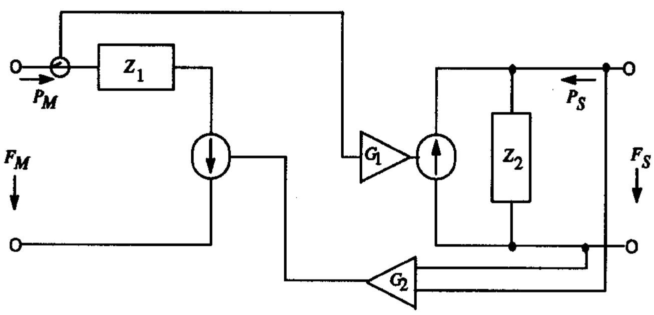

Fig. 9. Position forward, force feedback configuration

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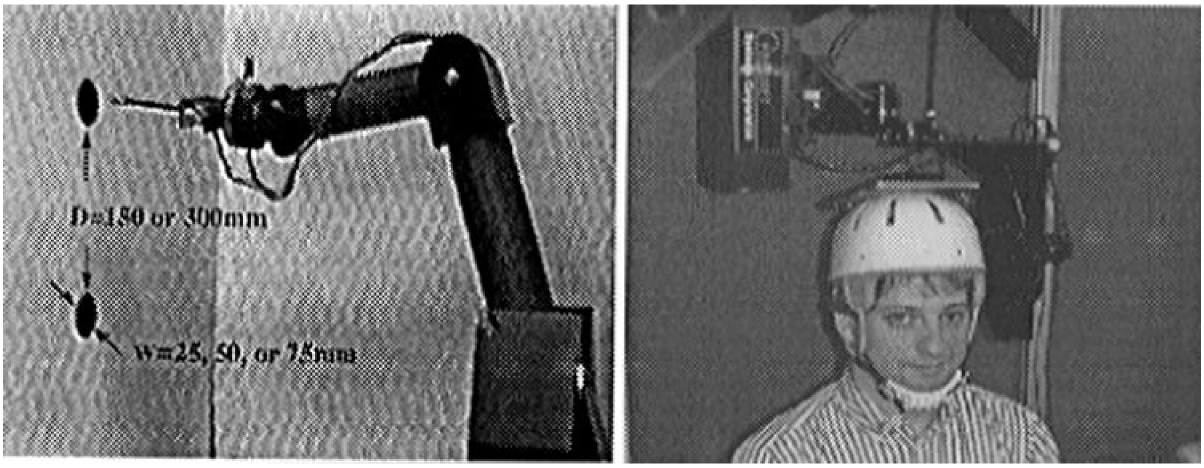

Fig. 10. TeleStick system[25–27]

$F_S=0$, h_{21} is the forward motion gain when $F_S=0$, h_{12} is the reverse force gain when $P_M=0$, and h_{22} is the slave intrinsic admittance when $P_M=0$.

The position-forward, force-feedback master-slave telerobot system in this paper is similar to the JPL FRHC-PUMA generalized bilateral teleoperator described in [25–27]. Figure 9 shows its network graph, where $h_{11}=Z_1$, $\frac{1}{h_{22}}=Z_2$, $h_{12}=G_2$ with $G_2>0$, and $h_{21}=G_1$ with $G_1<0$.

It is shown in reference 28 that the impedance, Z_M, at the master end can be expressed as:

$$Z_M=Z_1+G_1G_2\frac{Z_2Z_S}{Z_2+Z_S} \tag{8}$$

For the hard contact condition,

$$\lim_{Z_S\to\infty} Z_M=\lim_{Z_S\to\infty}\left(Z_1+\frac{G_1G_2Z_2}{\frac{Z_2}{Z_S}+1}\right)=Z_1+G_1G_2Z_2 \tag{9}$$

Equation (9) shows that the slave robot intrinsic impedance, Z_2, must be very high in order to let the operator feel the environmental impedance.

2.4 Safety issues

The nature of the head-controlled telerobot system required that the safety issue be adequately addressed, since the active master device is tightly attached to the user's head through a helmet. Any spurious motion of the master is a potential hazard to the user. To prevent any such injuries, several safety measures have been incorporated into the system design. The first one is a software fuse built in the master robot operation program. This software fuse monitors the force/torque signal delivered to the joint motors in every servo iteration and immediately cuts off the motor power if the force signal exceeds a predetermined threshold. The second one is a user operated push-button panic switch that disengages motor amplifier power upon the user panic action. The third one is a mechanical passive breakaway device that acts as a mechanical link between the helmet and the master robot in normal operation. The breakaway mechanism consists of two thin plates made of aluminum which have a combination of small Neodymium-Iron-Boron magnets and flexible magnetic strips mounted on them. The small Neodymium-Iron-Boron magnets are very strong in pull strength whereas the flexible magnetic strips have good strength in the shear direction. The specific combination that has been used ensures the mix of properties needed in the longitudinal and shear directions to accommodate the threshold force and moment specifications. If the forces exerted by the master exceed the set thresholds, the lower

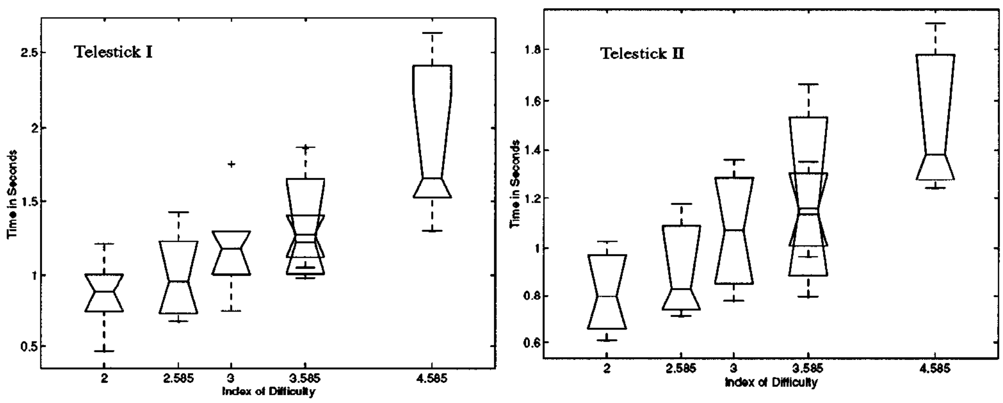

Fig. 11. Fiits' law performance statistics for two configurations

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Table I: Fitts' law information

	Bits/s	Intercept	R^2
Telestick I	3.086	0.2246ms	0.876
Telestick II	3.378	0.2254ms	0.965

plate breaks away and the physical link between the user and the robot is broken.

3. EVALUATION

The purpose of performance evaluation is to assess the benefits of incorporating force-reflection into the assistive telemanipulation mechanism. Early evaluation studies in telerobotics emphasized task completion time[29]. Recent studies have broadened the base of measurements (including force measurement) against which task performance is evaluated [30]. In this paper, the generic task of target reaching (Fitts' movement) is employed.

3.1 Subjects

The main goal of this evaluation study is to assess the performance difference, if any, between the telerobot systems operated with and without force-reflection. Six non-disabled subjects participated in this experimental evaluation. Four subjects were male and two were female ranging in age between 20 and 40 years. All subjects are staff members of the Applied Science and Engineering Laboratories with no abnormal neuromuscular function and visual impairments. Five of the six subjects have an engineering background and understand the concept of force-reflecting teleoperation very well.

3.2 Headstick configurations

Two sets of virtual headstick systems configured in the evaluation are presented here.

(1) **Telestick I**

This is one of the two teleoperated robot system (see Figure 1) configurations under evaluation. The master is the PerForce™ robot and the slave is the Zebra ZERO™ robot arm. The slave acts the telestick and has no physical contact with the user's body. In this configuration (Telestick I), the force/torque information fed back from the slave to the master is not used to back drive the motors on the PerForce™, that is, the user does not have force sensation when the slave encounters the environment. The user, however, has a clear and direct view of the slave robot work space.

(2) **Telestick II**

The equipment, connections, and operations used in this setting are the same as that in Telestick I, except that the force/torque information fed back from the slave to the master is used to back drive the motors on the PerForce™ in a direction opposite to the user's motion when the slave is interacting with the environment. Again, the user has a direct view of the slave work area.

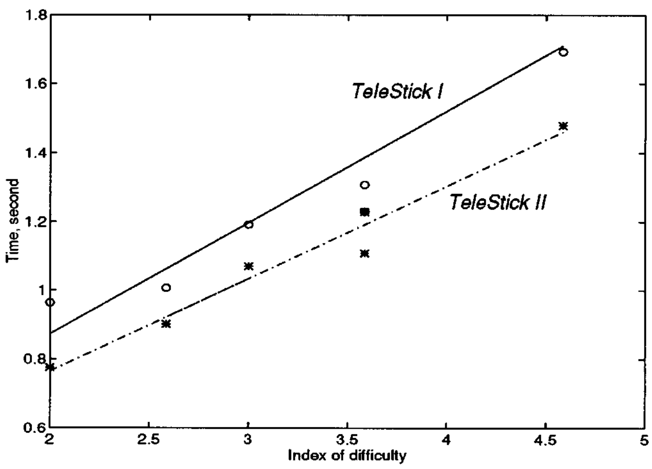

Fig. 12. Group performance

3.3 Fitts' movement experiment design

Disk-shaped targets with sizes of 25, 50 and 75mm in diameter were used in this experiment. A pair of equally sized targets were attached to a wooden board (see Figure 10 in separate pictures) that stands vertically in front of the subject. The center of the board is approximately at the subject's eye level.

There were a total of six trials (a pair of targets in each of the three sizes is placed first 150mm then 300mm apart) for each subject. Subjects were asked to touch the two targets with the end effector of the slave robot by moving up and down at a comfortable pace. Each trial consisted of 10 round-trip touching trajectories.

4. RESULTS

Force and position data were collected at a rate of 64 Hz for the experiment. Unless otherwise indicated, forces were given in Newtons and position in millimeters. All the data logged were filtered by linear low-pass filters and nonlinear median filters to remove high frequency noise, artifacts and outliers. Data analyses were performed in the Matlab™ environment. There were three evaluation criteria considered: Fitts' law index of performance, force exerted on the targets, and jerk.

4.1 Fitts' index of performance

The conventional Fitts' paradigm[31] is employed in this paper

$$I_p = \frac{\log_2(2D)/W}{T_M} \text{(bits/sec)} \tag{10}$$

where I_p is the index of performance, T_M is the movement time, D is the distance between the target centers, and W is the target width. The indices of difficulty, $\log_2(2D)/W$, for the tasks stated in the previous section are 2 bits (75mm targets, 150mm apart), 2.585 bits (75mm targets, 300mm apart), 3 bits (50mm targets, 150mm apart), 3.585 bits (50mm targets, 300mm apart, and 25mm targets, 150mm apart) and 4.585 bits (25mm targets, 300mm apart). Figure 11 shows the mean and deviation of the completion time for

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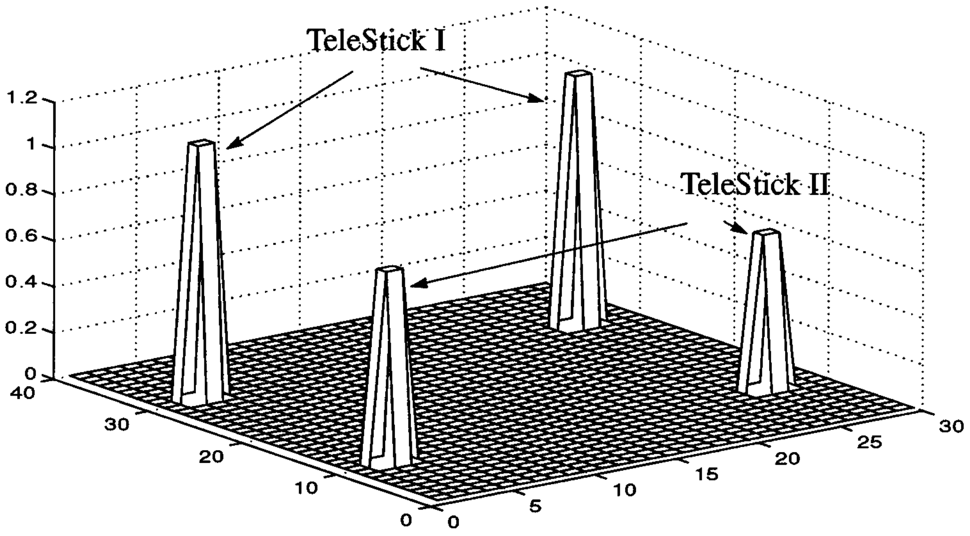

Fig. 13. Ensemble average touching force for two configurations

six subjects in each task for the two configurations under evaluation. Table 1 lists the linear regression parameters and the R-squared statistics for each testing condition. It shows that the telerobotic system with force reflection (Telestick II) has a higher bits-per-second information transmit rate. The performance of the two systems can be seen as regression lines in Figure 12. Telestick II outperform Telestick I that operates without force-reflection.

4.2 *Force exerted*

Contacting force data are recorded during the target reaching experiment. The analysis of the force data shows that the ensemble average touching force in Telestick II is about 40% less than that in Telestick I. The 3D plot of the touching force is shown in Figure 13. An ANOVA (analysis of variance) test (Figure 14) on the force data reveals that the difference in contacting force between the two configurations is statistically significant with $p = 4.54821 - e5$.

4.3 *Jerk analysis*

The target-reaching task is essentially a task of performing point-to-point motion. In reference 32, Hogan *et al*. devised a quantitative measure of smoothness or gracefulness of the movement between two points using the mean squared magnitude of jerk (jerk is the third derivative of position). The smoothest movement is defined by $min \int_0^T |J(t)|^2 dt$, where $J(t) = d^3 s(t)/dt^3$, and where $s(t)$ is the movement that starts at time 0 and terminates at time T. Figure 15 displays the derived jerk for the two configurations. Apparently, TeleStick II has a much smaller jerk magnitude than TeleStick I. Also, the mean squared jerk value is 1.4111e-5 for TeleStick I; 7.8462e-6 for TeleStick II. Evidently, the teleoperated system with force feedback produces smoother movement than that without force feedback.

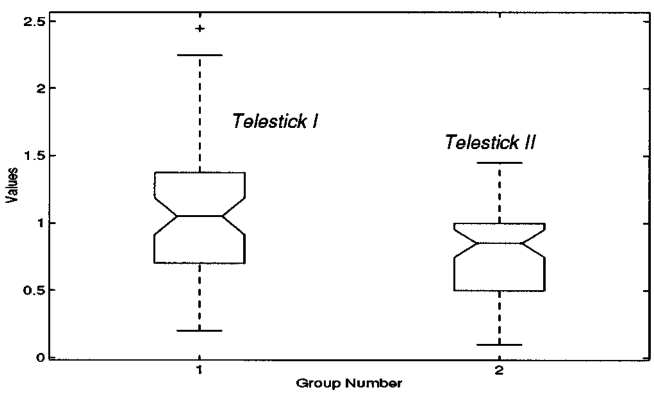

Fig. 14. ANOVA test on exerted force

5. DISCUSSION

In this paper, we presented the development of a head-controlled rehabilitation robot system for persons with physical disabilities at the Applied Science and Engineering Center, University of Delaware/Alfred I. duPont Hospital for Children. The system performance has been evaluated for a generic task, target reaching. The evaluation is carried out comparing the performance of the teleoperated robot system with force reflection against the same system without force reflection.

The experiment results support the hypothesis that there is a performance difference based on the availability of extra information such as force reflection to the user. Notice in Fitts' movement experiment that force reflection in teleoperation can elevate the performance level with respect to the system without force reflection. The ANOVA analyses show that the performance difference between the two configurations is statistically significant with $p < 0.01$. It can be concluded that for tasks that involve motion, and touching, the teleoperated system with force reflection gives superior performance when compared to one without force reflection.

It should be pointed out that the Fitts' information transmission rate achieved in our head-controlled teleoperation system with force feedback is 3.378 bits per second. The Fitts' information rate for unaided hand movement is of the order of 10 bits/s[33]. This shows that the

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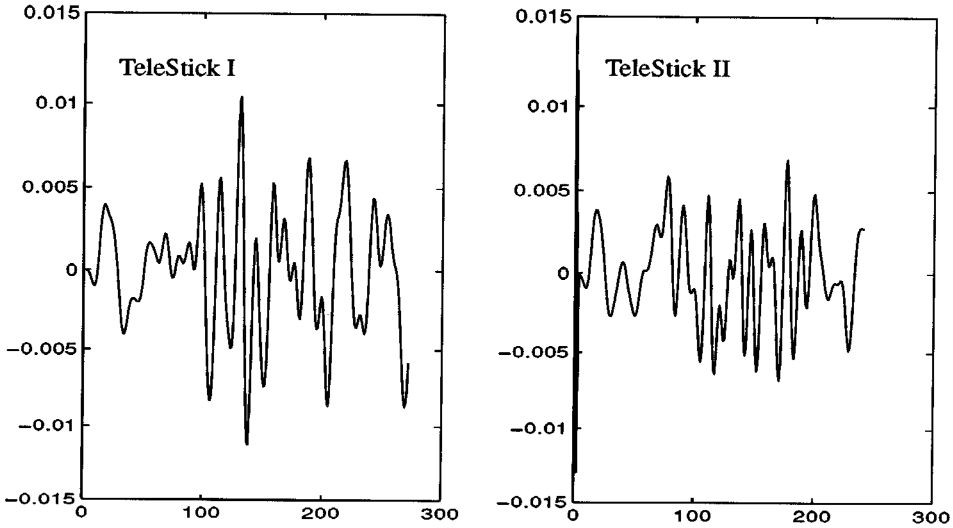

Fig. 15. Jerk plot

head movement is still considerably slower, however, using the head as an input site for a person with a disability is a viable option.

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