Evaluation of Force Feedback in Rehabilitation Robots

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Abstract

A scheme that provides force feedback using a master/slave test-bed has been implemented for a person controlling a rehabilitation robot using movements of the head. Experiments were carried out performing a set of routine tasks using the test-bed with and without force feedback, and a conventional headstick. Results indicate the force feedback system compares favorably to a conventional headstick, and is clearly superior to one with visual feedback alone.

1. Background

Enhanced sensory feedback, in particular force feedback, has been studied in a teleoperation setting to better control remote robots [1]. It has also been investigated in the field of prosthetics by way of extended physiological proprioception (EPP) [2]. EPP uses proprioceptive feedback by mechanically attaching an extension to a residual limb. Proprioceptive sensation is thereby extended to the tip of an appendage, such as an arm prosthesis.

EPP underlies the development of the system described in this paper. The system uses a master/slave robot pair to allow a person with cervical spinal cord injury to control a robot and receive force feedback.

2. Master/slave test-bed

The master device is a Perforce (tm) manipulator with 6 degrees of freedom which has been adapted to be used as a head control unit via a helmet. The slave unit is a Zebra robot arm with 6 degrees of freedom. Each of these units has a monitoring computer, and both computers interchange information in real time. Figure 1 illustrates the arrangement of the test-bed.

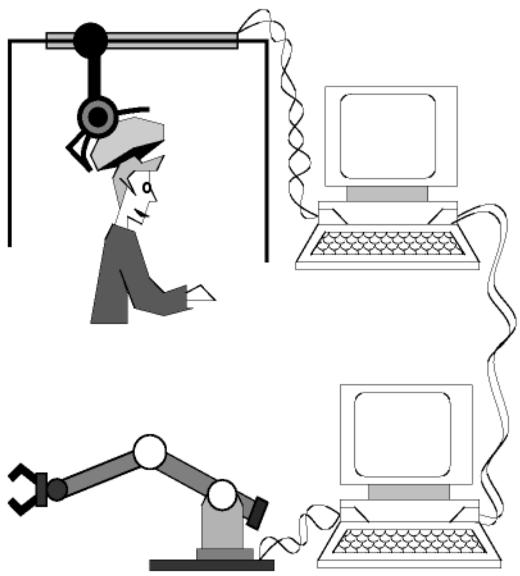

FIGURE 1. The configuration of the teleoperated head-controlled test bed.

The Perforce unit is a programmable force manipulation device. The Zebra robot is a position-position control system. The Perforce unit measures the positions of the head and sends this information to the Zebra robot. The robot arm is equipped with a force sensor, which measures the forces being applied to the robot and sends this information back to the Perforce.

The system can be used with or without the force feedback path. Both options are used in our performance experiments. Details on the system design and the control structure can be found in [3,4,5].

3. Performance evaluation

Experiments that compare the performance of the teleoperated system against two headstick systems are being conducted. Both headstick systems use the setup shown in Fig. 2. The difference between them is that one uses the lighter ADL/Shooting Star measurement device, whereas the other uses the helmet attached to the Perforce (tm) manipulator. The former gives unencumbered headstick performance, while the latter allows for a fair comparison between the teleoperated system and the headstick, by factoring out the weight of the perforce. The headstick is 2 feet long and is made of carbon fiber. The headstick with the ADL offers the gold standard with which performance is measured.

Three sets of experiments are used to evaluate performance: (1) positioning maneuvers, (2) page turning, and (3) drawing. The positioning experiments are intended to measure the user's ability to control the device while moving it from one place to another. We have chosen Fitts' law [7] as our performance criteria for the positioning tasks.

The other two experiments are designed to measure the differences in performance between the devices in activities of daily living.

3.1 Positioning experiment

Disk-shaped targets with sizes of 1", 2" and 3" in diameter are used in this experiment. A pair of equal sized targets are first placed 6", then 12" apart on a wooden board that stands vertically in front of the subject (see Fig. 2). The center of the board is approximately at the subject's eye level.

There are a total of 6 trials for each subject. The subject is asked to touch the two targets with the tip of the headstick by moving back and forth at a comfortable pace. Each trial consists of 10 round-trip touching trajectories. Results

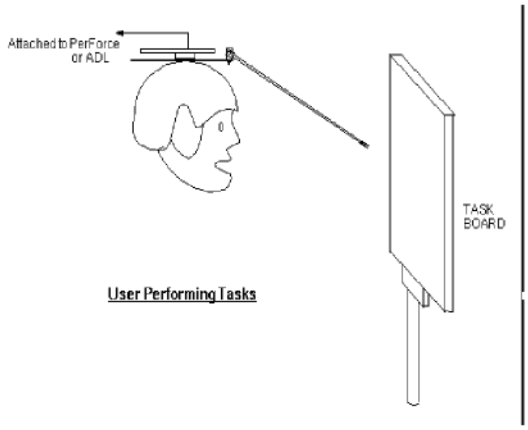

FIGURE 2. The head-stick device in the Fitts' law experiment design

for this experiment are described below, in Section 4.

3.2 Page-turning experiment

For this experiment, a large book was placed in front of the subjects at an angle of 20^o with respect to the horizontal plane, in a way that allowed the upper half of the book to remain within the workspace of the headstick tip and the slave-robot arm tip. The subjects were provided with sufficient training time to learn a good page turning strategy and were asked to use the same strategy throughout the trials. The subjects were asked to turn 5 consecutive pages of the book. The experiment was repeated 6 times.

Three criteria are considered in assessing the performance of the page turning task: average completion time, mean force exerted, and maximum force exerted. Figure 3 shows typical profiles for positions and forces in the principal direction for one of the subjects.

3.3 Line-drawing experiment

For this experiment a large board was placed in front of the subjects at an angle of 20^o with respect to the horizontal plane. A piece of drawing paper was attached to the board. It was ensured that the drawing paper was within the workspace volume of both, the head-stick tip and the robot arm tip. Horizontal, vertical and diagonal lines were pre-drawn on the paper and the subjects were asked to trace the lines as best they could. Both the headstick and the robot tip had a marker attached to the tip

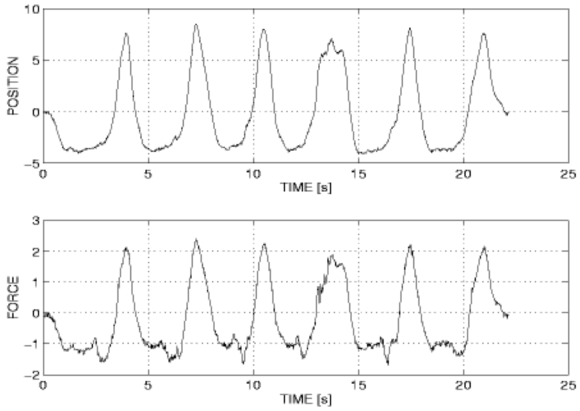

FIGURE 3.Position and force profiles for the page-turning experiment

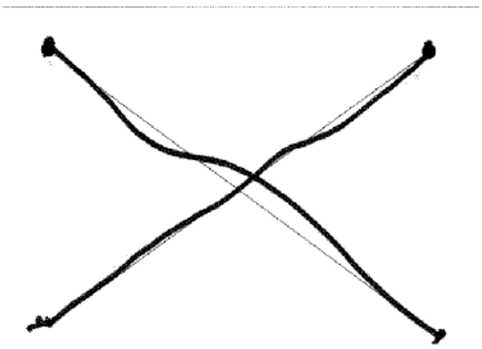

FIGURE 4.Drawing of diagonal lines using a marker attached to a head-stick

Two performance parameters are of interest in this experiment. The first one is the error between the reference and the actual lines. The second is a measure of the smoothness of the drawing (band-width of the variations). The first parameter is obtained from the scanned drawings and uses morphological filtering to estimate the area between the actual and reference lines. The second parameter is obtained from a Fourier analysis of the time-domain trajectories. Figure 4 shows typical drawings obtained from one of the subjects using a head-stick. We are currently processing all the information collected.

4. Fitts' law experiment results

Six lab staff members participated in the experiments: two females and four males. At this stage only non-disabled subjects were used. The conventional Fitts' law paradigm [7] is employed in this paper:

$$T_m = a + b(I_D)$$

where

$$I_D = \log_2\left(\frac{D}{W/2}\right)$$

where T_M is the movement time, D is the distance between the target centers W is the target width. a and b are the parameters to be identified.

The indices of difficulty, I_D, for the six combinations of target size and distance apart for this experiment are 2, 2.585, 3, 3.585 and 4.585 bits (with one overlap). Table 1 lists the linear regression parameters and the R-squared statistic for each testing condition. The performance of the four systems can be seen as regression lines in Figure 5.

Table 1: Fitts' Law information

	Slope	Intercept	R^2
ADL	379ms/bit	0.0407ms	0.963
PerForce	366ms/bit	0.2961ms	0.962
Tele	324ms/bit	0.2246ms	0.876
TeleF	296ms/bit	0.2254ms	0.965

The experiments support the hypothesis that there is a performance difference based on the mechanical properties of the devices such as mass (the PerForce has larger mass than the ADL) and based on the availability of extra information such as force-feedback to the user. Notice in

Fig. 5 that force feedback in teleoperation can enhance the performance with respect to the system without force feedback. In fact, from this experiment, we conclude that for tasks that involve motion and touching such as the ones involved in the Fitts' Law experiments the teleoperated system with force feedback gives the best performance with respect to the other options.

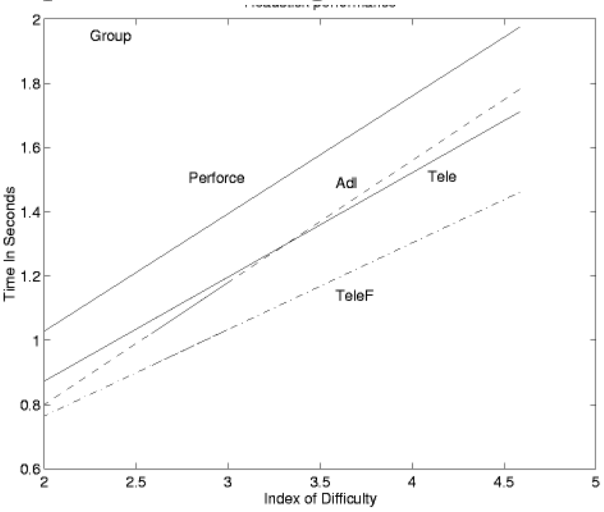

FIGURE 5.Fitts' law performance for different systems

5. Conclusions

In this paper we have described the head-controlled teleoperation system that has been implemented at ASEL. The system performance for a comprehensive set of tasks is currently under evaluation. The evaluation is carried out comparing the performance of the teleoperated robot (with and without force feedback) against a headstick. The headstick is set up using two different modalities: (1) An ADL is attached to the head-stick, or (2) the Perforce is attached to the headstick.

The results of the positioning tasks show that the teleoperation system with force feedback is the best in terms of Fitts' criteria. It even outperforms the headstick/ADL combination. This could be attributed to overshoot experienced with the headstick. A clear advantage of the force feedback system over the no force system can also be seen from Figure 5. This shows that positioning tasks involving contact can be performed faster with force information. A study of the data collected from the other two experiments is in progress.

6. References

[1] Hannaford,B., *Stability and performance trade-offs in bi-lateral telemanipulation*. In Proceedings of IEEE Conference on Robotics and Automation, pages 1764–1767, 1989

[2] Childress,D.S., *Closed-loop control in prosthetic systems: Historical perspective*. Annals of Biomedical Engineering, 8:293–303, 1980.

[3] Chen,S., *Experimentally Identifying a Dynamics Model of a Remote Manipulator (Zebra Zero) for a Teleoperation System*, ASEL Tech. Rep. ROB9604, duPont Hospital for Children and the University of Delaware, June 1996.

[4] Heredia,E.A.,Kumar,V.,Rahman,T., *Adaptive Teleoperation Transparency Based on Impedance Modeling*, Teleman. and Telepresence Tech. III, SPIE Photonics East, Nov. 1996.

[5] Jayachandran,J., *A Force-Reflecting Assistive Telerobot*, Master's Thesis, Department of Mechanical Engineering, University of Delaware, 1995.

[6] Lawrence,D.A., *Stability and Transparency in Bilateral Teleoperation*, IEEE Trans. Robotics and Automation, Vol. 9, No. 5, pp 624-637, October 1993.

[7] Fitts,P.M., and Peterson, J.R., "*Information capacity of discrete motor response*," Journal of Experimental Psychology, 67, pp 103-112, 1964.

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