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Human Hand Trajectory Analysis in Point-and-Direct Telerobotics

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Abstract. Human hand trajectories have been recorded and analyzed in an experimental supervisory control interface for a telerobot manipulator. Using a six degree-of-freedom tracking device to control the gripper of a computer graphics simulation model of the telerobot, human operators were instructed to command the telerobot under a variety of visual conditions. Analysis of the human hand trajectories shows considerable distortion and adaptation effects in the virtual environments. Also, the nature of the 3D hand trajectories for the reaching task lends support for a sampled-data model of human neurological control; this has design implications for telerobotic interfaces.

Key Words. Telerobotics, supervisory control, hand movements, virtual environments.

1. INTRODUCTION

Advances in computer technology over the past decades, especially with respect to human-computer interfacing and virtual environments, have bolstered the level and capabilities of real-time dynamic modelling and graphical simulations available as a tool in telerobotics (Stark *et al.*, 1987; Sheridan, 1992). An early example of a model-based approach in teleoperation involved the use of a graphical model superimposed on the delayed video feedback as a predictor display to help compensate for time delay (Noyes and Sheridan, 1984; Kim *et al.*, 1988). More recently the predictor display technique has been extended to include a planning and preview system and was successfully implemented with state of the art technology in the advanced teleoperation system developed at the Jet Propulsion Laboratory (Bejczy *et al.*, 1990).

Another supervisory control technique labeled 'teleprogramming' has been developed utilizing a simulation model which combines an interactive graphics display and real-time modeled kinesthetic feedback to automatically generate symbolic instructions on-line for a telerobot under time delay (Funda *et al.*, 1992). A 'point-and-direct' supervisory control interface allows a human operator to demonstrate required object grasping and placement locations for a telerobot using a virtual end effector superimposed on live video feedback of the remote workcell (Wang and Cannon, 1993). The 'Virtual Environment Vehicle Interface' developed at the NASA Ames Research Center utilizes a 3D terrain model and telerobotic vehicle model to plan tasks under time delay in actual missions on earth and eventual Mars exploration (Eisenberg *et al.*, 1993). These represent but a few examples of developments in model-based telerobotic interfaces.

However, the majority of research publications in this area typically describe a particular telerobotic interface and may provide general performance data of the overall system (time of completion, number of errors, etc ...) as well as comparisons of various control modes. Much less research has been published to-date regarding the neurological control of human hand and eye movements of operators using these advanced interfaces. Perhaps this stems from the difficulty in measuring, analyzing and understanding human movement and vision in an actual operating environment outside of a carefully controlled psychophysical experimental setting. However, there are examples of researchers who have begun to bridge the gap between telerobotic interfaces and neuroscience (Tharp *et al.*, 1989; Takeda *et al.*, 1989; Magenes *et al.*, 1992; Gentilucci *et al.*, 1994; Guedon *et al.*, 1995).

This paper describes the experimental recording and analysis of human hand movements in a 'point-and-direct' supervisory control interface for a telerobotic manipulator arm, and compares the hand movement data with data collected for the same reaching task in the real environment .

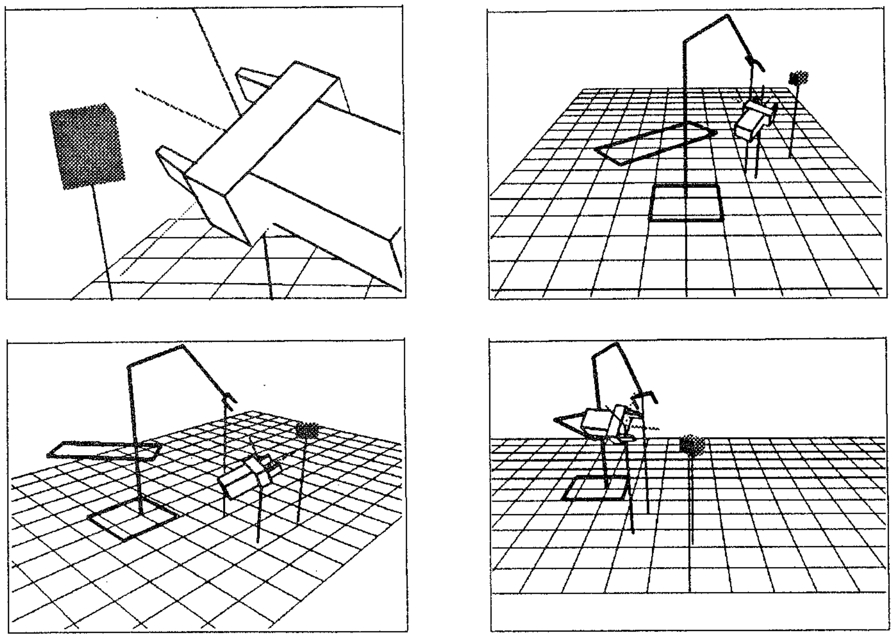

Fig. 1. Graphical display of the U.C. Berkeley Telerobotics Interface, configured for each of the virtual environment (VE) conditions used in the experimental protocol. Image of the floating telerobot gripper as the human reaches for the target location (indicated by the box) is shown for the immersive VE with a bioptic head mounted display (upper left). The three other images show the non-immersive VEs, with 0^o degree (upper right), 45^o (lower left) and 90^o (lower right) rotation of the visual frame of reference with respect the motor frame of reference. Note the benefit of the vertical reference lines and horizontal grid floor for increased depth perception.

2. METHODS

2.1. *UC Berkeley Telerobotics Interface*

A model-based telerobotic interface has been developed at U.C. Berkeley as an experimental platform to explore fundamental issues in human supervisory control of remote machinery. Descriptions of the experimental system have been previously published (Blackmon and Stark, 1995). For the hand movement recordings described in this paper, the experimental system was configured for the 'point-and-direct' supervisory control mode. In this mode, the human operator utilizes a 6-degree-of-freedom hand tracking device and a computer graphics simulation to place a virtual model of the telerobot end-effector in the desired location.

2.2. *Experimental Protocol and Data Collection*

In this study, we considered three main viewing conditions:

- Real Environment (RE)
- Non-Immersive Virtual Environment (VE-NI)
- Immersive Virtual Environment (VE-I)

The VE's were generated on a Silicon Graphics Indigo2 Extreme. The VE-I condition was viewed through a bioptic head mounted display (HMD) of approximately 30^o field of view (Virtual I/O i-glasses!) modified to support with head tracking (Polhemus Fastrak). The VE-NI condition were viewed on a 27 inch television screen (Sony Trinitron). Three different viewpoints were used in the the VE-NI condition, with 0^o, 45^o, and 90^o azimuth angles at fixed elevation and no roll. The TV display was located at a distance where it covered a viewing field equal to that of HMD. Figure 1 shows the viewing display for each of the simulated task environments.

For each viewing condition, subjects were asked to reach to 10 randomly placed targets. The targets were displayed one at a time, and subjects began the reaching movement from the same rest position. There were no obstacles in the environments.

There were four subjects in the experiment; two were experienced with the user interface, whereas the other two had minimal experience. Each subject performed two complete experimental trials with each viewing condition given in random order.

Before the trials subjects were instructed to:

- Look to the horizon at the beginning of each trial.
- Reach to the targets as fast as they can and stop at target location,

During each trial, the hand trajectories of the subjects were recorded at a sampling rate of 60 Hz while the graphics display was updated at approximately 30Hz. For the VE-I, the head trajectories were recorded as well, although this data is not presented.

2.3. *Method of Analysis*

The recorded data was first filtered with a 5th order low-pass butterworth filter with cut-off frequency of 4.5 Hz (roughly the bandwidth of voluntary hand movements) to eliminate noise.

In the analysis, we investigated time to completion (t_f), time to movement start (t_d), duration of movement (t_m), maximum velocity, (v_{max}), average duration of gross and corrective movement phases (t_g and t_c), number of corrective movements (n_c), and error (magnitude) of the initial reaching movements (e_{mag}).

- Time to completion is the time between the instant target was shown and the instant hand comes within 3 cm of target with a speed less than 1.5mm/sec.
- Time to movement start is the time between the instant target was shown and the instant hand movement starts (when magnitude of hand velocity exceeds 10 cm/s).
- Duration of movement is the time between the start of the hand movement and the instant hand comes within 3 cm of target with a speed less than 1.5 mm/sec. This value is different from time to completion, especially for immersive virtual environment, where the subject has first to search visually for the target as the field of view is limited.
- Maximum velocity is the peak of magnitude of velocity.
- Gross movement phase is the initial movement of the hand, which is essentially open loop as no visual feedback is available yet for servoing. It is defined as the duration from the beginning of hand movement to the second peak of acceleration. The rest of the movement is taken as corrective movement phase.
- Number of corrective movements, which is defined by local maxima of acceleration after the initial gross movement, is an indicator of the smoothness of the trajectory.
- Error of the initial reaching movement is the difference between the location of the target and the position of hand at the end of gross movement phase.

3. RESULTS

3.1. *Examples of 3D Hand Trajectories*

The reaching movements were collected as described in the Methods section and could be displayed as a trajectory in three dimensional space (Fig. 2 upper panels). The individual dots are separated by 17 msec (60Hz) intervals, Two-dimensional projections of this 3D trajectory are also shown. Comparing the trajectory for the RE (left column) and for the VE-I (right column) is very instructive in terms of the visual-motor adaptation necessary for the human operator interface. Especially note the considerable number of corrective movements in the VE-I trajectory (upper right).

The velocity and acceleration profiles (Fig. 2, middle and lower panels) show large difference between these two environmental conditions. The velocity curves (middle) show a longer delay for the movement in the VE-I, a much lower velocity, and the multiple long-lasting corrective movements with their velocity profiles (right middle). Again, the acceleration profiles show gross differences in maximum accelerations. The multiple velocity corrections for the trajectory in the VE-I are labeled 'corr' and must result from pulses of neurological control signals.

3.2. *Analysis*

The trajectories have been analyzed by assessing eight parameters of the trajectory as described in the methods section. The five visual conditions, also described in the methods section (first column, Table 1) each were repeated twenty times (see column N). For each trajectory value the average and the standard deviation are shown (Table 1). This subject illustrates a set of results typical for the four subjects.

However, we also studied the averages over all subjects. First the normalizing process was applied in that the values for the 8 parameters for each subject in the RE condition was set to be equal to 1 (Table 2) thus we have N = 80 values that are concatenated for each average and, in parentheses, for the standard deviation.

These quantitative data support the qualitative in-

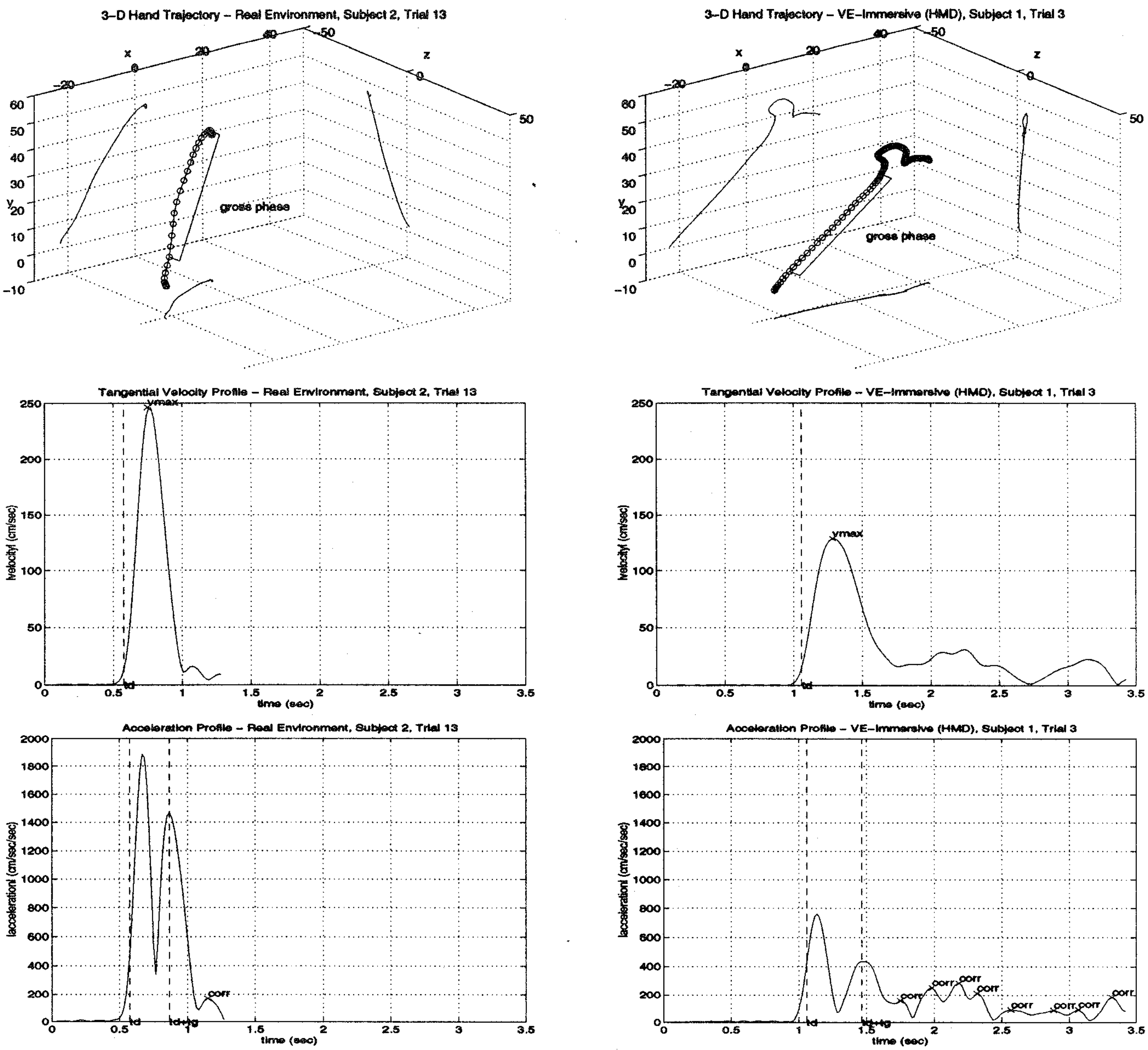

Fig. 2. Plots of a typical 3D human hand trajectory, tangential velocity and acceleration profiles in the real environment (left column) and in the immersive virtual environment (right column).

spection of the two single trajectories in Figure 2. For example, the velocities in the RE are greater than those in the VE-I and these are greater than the velocities in the VE-NI conditions.

The five time-duration parameters were all much shorter in the RE and longest in the VE-I. Indeed, it was observed that subjects had to search for the target while wearing the HMD so that (t_d) was exceptionally long, whereas the lengthened times for the VE-NI conditions were only moderately (50 percent) greater than the initiating time in the RE condition. In general, the times in the VE-NI conditions were longer but not nearly as long as the time in the VE-I, with one exception.

4. DISCUSSION

The time of the gross movement was actually quite similar in all conditions. This suggests that the reach-

Vis Cond.	N	tf	td	tm	vmax	tg	tc	nc	emag
VE-NI(0)	20	1.64	0.46	1.19	112.17	0.39	0.80	2.40	14.21
		(0.64)	(0.14)	(0.60)	(26.76)	(0.05)	(0.60)	(2.35)	(8.57)
VE-NI(45)	20	1.73	0.47	1.26	109.89	0.43	0.83	2.25	14.66
		(0.43)	(0.08)	(0.43)	(15.13)	(0.04)	(0.46)	(2.02)	(6.82)
VE-NI(90)	20	2.38	0.47	1.91	112.72	0.41	1.50	4.85	20.74
		(0.85)	(0.07)	(0.88)	(16.43)	(0.10)	(0.90)	(3.65)	(11.01)
VE-I	20	5.22	2.41	2.81	121.22	0.43	2.38	9.00	14.77
		(2.33)	(1.44)	(1.47)	(20.42)	(0.08)	(1.46)	(6.22)	(6.25)
RE	20	0.89	0.41	0.48	172.30	0.34	0.14	0.35	3.82
		(0.25)	(0.20)	(0.22)	(38.97)	(0.07)	(0.20)	(0.81)	(2.25)

Table 1 Summary of Hand Trajectory Metrics for an Individual Subject

Vis Cond.	N	tf	td	tm	vmax	tg	tc	nc	emag
VE-NI(0)	80	2.38	1.49	2.83	0.67	1.15	4.68	4.50	2.04
		(1.39)	(0.35)	(1.96)	(0.17)	(0.29)	(4.23)	(5.57)	(1.57)
VE-NI(45)	80	2.33	1.47	2.77	0.74	1.17	4.58	4.24	2.12
		(1.32)	(0.33)	(1.74)	(0.16)	(0.30)	(3.31)	(4.06)	(1.44)
VE-NI(90)	80	3.36	1.55	4.38	0.70	1.13	8.34	8.41	2.92
		(1.89)	(0.34)	(2.77)	(0.18)	(0.35)	(6.31)	(8.47)	(2.24)
VE-I	80	5.59	6.79	5.00	0.78	1.26	9.73	11.00	2.19
		(3.05)	(3.92)	(3.94)	(0.19)	(0.34)	(9.06)	(13.54)	(1.36)
RE	80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		(0.43)	(0.45)	(0.55)	(0.25)	(0.20)	(1.09)	(1.84)	(0.53)

Table 2 Summary of Hand Trajectory Metrics Normalized and Averaged Across All Subjects

ing movement is actually a sampled data movement as postulated in the 1968 model (Navas and Stark, 1968).

The sampled data computational delay time provides an opportunity for the trajectory to be optimized by pulse shaping of nerve impulse frequency control signals to the muscles (see discussion of PA, PB, PC in (Hannaford and Stark, 1985)). The optimization criteria might be almost pure time optimization as in eye movements, energy optimization as in normal locomotion, or some type of kinematic simplicity criterion, as is likely in reaching movements. Further studies of the nature of the trajectories and their comparisons for objects placed in different parts of the research space may provide clues to this last inverse problem.

Engineering design consideration of the excessive corrective movements seen in virtual environments will be an important feature of both direct manual control and manual direction for supervisory control. Perhaps some autonomous stabilization might be built in so that the speed and accuracy of the gross movement can benefit the control process, while the excessive corrective movements may be contained. Similarly, some type of automatic slewing of a target to a more felicitous position would reduce the excessive time delay caused by searching for the target before making the reaching movement.

As we have indicated, experience, training, and learning all benefit the human operator. In a continual industrial work setting this may be sufficient to gain the accuracy, precision, and stability required for reaching and manipulation in virtual environment interfaces for telerobotics.

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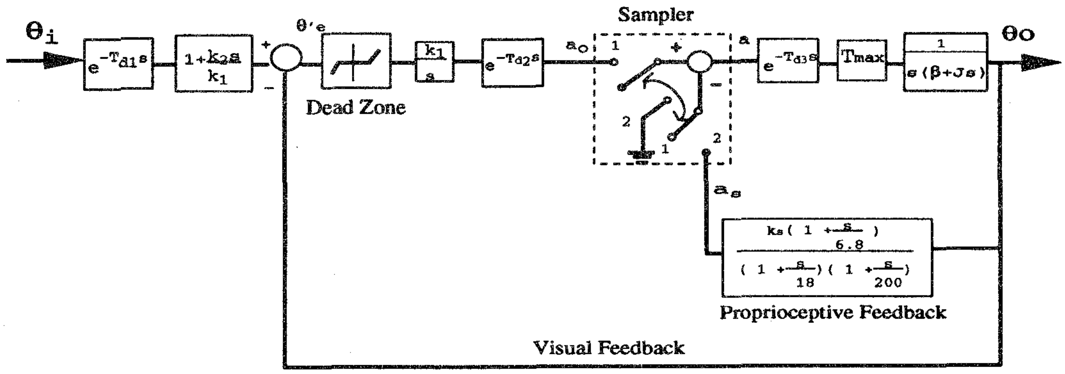

Fig. 3. Block diagram of sampled data control model for human hand tracking. Adapted from Navas and Stark, 1968.

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