

EFFECTS OF VISUAL INTERFACE DESIGN, AND CONTROL MODE AND LATENCY ON PERFORMANCE, TELEPRESENCE AND WORKLOAD IN A TELEOPERATION TASK

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Human-machine interfaces that facilitate telepresence are speculated to improve performance with teleoperators. Unfortunately, there is little experimental evidence to substantiate a direct link between the two. Further, there are limited data available on technological and psychological factors that affect telepresence. The objective of the present study was to evaluate the influence of interface design configuration, and control mode and latency on teleoperation performance, telepresence, and workload in a pick-and-place task. It was conducted to enhance understanding of the concept of telepresence and promote future development of telepresence-based guidelines for teleoperator systems. An experiment was conducted in which subjects were required to control a telerobot in a simple pick-and-place task through a virtual reality (VR) interface with or without live-video feedback on the motion of the robot. Rotational or translational motion control of the robot was studied under four control latencies ranging from 0 to 4 seconds. Results demonstrated significant benefits of using VR in conjunction with video feedback to control the telerobot. Rotational control appeared to better meet user expectations of robot motion control than modes involving translations of joint positions. Performance with the VR interface without live video feedback appeared to be sensitive to control latency. Correlation analysis provided further evidence of a positive link between telepresence and performance.

INTRODUCTION

Interfaces that facilitate telepresence (the sensation of being present in a remote environment) are speculated to provide benefits in terms of performance in virtual environments (VEs) and with the virtual controls in interfaces used for real systems (Draper et al., 1999). Draper et al. (1999) suggest that many of the technological factors that influence telepresence experiences may be the same as those that positively affect teleoperator performance. Thus, designing for telepresence should provide for better performance, at least by having the effect of enhancing human-machine interfaces. Telepresence has even been directly equated to performance in teleoperations. According to Schloerb (1995), operator ability to modify the remote environment determines whether (tele)presence (objective telepresence) exists and the degree of telepresence is based on the probability of completing a virtual task successfully.

Hypothesized benefits of telepresence are generally accepted, but there are few objective data to substantiate a direct link between telepresence and performance. There is also a lack of concrete information on the technological and psychological factors that may affect telepresence. This limited understanding of the concept of telepresence makes the ability to predict human-machine system performance on its basis virtually impossible. With this in mind, we evaluated different teleoperator system and task factors that have been hypothesized to play a role in telepresence. The objective of the study was to evaluate the influence of visual interface design, control mode, and control latency (time lag) on teleoperation task performance, telepresence and workload.

EXPERIMENT

We conducted a repeated measures experiment in which subjects completed a teleoperation task using a three dimensional (3-D) graphical interactive simulation to control a

real-robot arm in a mock task environment in a pick-and-place task. The VE served as an interface for remote control of a PUMA® 560, 6-DOF robotic arm in real-time. The operators' goal was to obtain an object (block) from a predetermined location on a table and move it to a defined objective on the same table. Operators were to minimize time-to-task completion. Thirty naive subjects were recruited for voluntary participation in the study. All had 20/20 or corrected to normal vision and computer and mouse experience.

An Integraph TDZ2000GL2® with a Realizm® graphics subsystem was used to present the teleoperation task simulation to subjects. The workstation was integrated with a 21-inch graphics monitor operating under 1280 × 1024 resolution and a conventional mouse controller. Stereoscopic images were presented through the monitor and Crystal Eyes Glasses were provided to subjects to exaggerate the 3-D qualities of the interface. For some subjects, video feedback was included in the system interface through use of a video conferencing system.

Two visual interface configurations were used in this experiment. A virtual environment manipulator interface (VEMI) provided operators with a graphical representation of the robot, a virtual control panel, and an assistive display for close-up viewing of the virtual gripper and environment. The interface did not provide video feedback on the actions of the real robot. The display configuration was comparable to a teleoperation scenario in which VR is used exclusively as an interface to a telerobotic system. A second condition provided live video feedback, along with the VEMI, for displaying to the operator the motions of the real robot in a real environment to which the interface was connected. The video was superimposed over the VEMI. This display configuration was comparable to a situation in which VR is used to facilitate graphical preview control (GPC) of a teleoperator. The two conditions were studied because the addition of live-video feedback in the GPC condition was hypothesized to promote the sense of task realism and increase user task involvement

by reflecting the impact of control actions at the interface on actual system performance and, consequently, increase the degree of association experienced with the remote robot task environment.

Three robot control modes were studied in the remote manipulation task performance including joint-mode, world-mode, and hybrid control (combined joint- and world-mode control). Under joint-mode control, the operator manipulated individual joints of the robot to cause rotational motion of the arm for grasping and moving objects. The joint-mode control panel included buttons corresponding to positive and negative rotations of each joint (see Figure 1). Under world-mode control, an operator could translate the robot gripper in positive and negative directions along the axes of a 3-D coordinate system defined for the gripper. The world-mode control panel contained buttons corresponding to translatory movement of the manipulator according to the world coordinate system, as well as pitch, roll, and yaw orientation of the gripper (see Figure 2). Under world-mode, operators controlled the position of the gripper while the system automatically updated each joint angle. Buttons were provided on the control panels for opening and closing the gripper. In all conditions, subjects were able to control only one motion axis at a time; that is, they could not simultaneously move multiple axes. These conditions were studied because joint-mode control was hypothesized to increase operator mental workload in comparison to world-mode control as a result of mental translations of individual rotational joint motions to overall gripper positions. Subjective perceptions of telepresence have been demonstrated to share a negative relationship with increased mental workload (Riley & Kaber, 1999). Therefore, we expected the degree of user association with the VE or remote environment to degrade under joint-mode control, as compared to world-mode or hybrid-control.

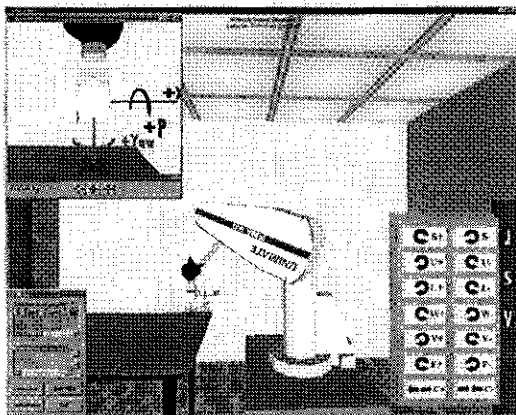


Figure 1. VR interface for telerobot.

Four control latencies were examined in the experiment including 0 (no lag), 1, 2, and 4-sec. Latency values between 2 and 8 seconds are representative of typical control lags for earth-based control of space-based teleoperators. This type of teleoperation system was considered to be a potential beneficiary of the results of this work. Under the VEMI condition, the control lag occurred between each virtual

control action and the response of the model. It portrayed a VR system with processing limitation in graphical rendering of a 3-D model to a user in near real-time. Under the GPC condition, the VR interface provided for near real-time update of the 3-D model while the lag in the system was associated with the real robot's response to control actions. In general, control lag was considered in this investigation because we hypothesized that as delays between control actions (at the VEMI and GPC interfaces) and model updates or real-robot responses increased, user perceptions of their ability to affect the VE or remote environment would degrade. Sheridan (1992) identified the ability to modify the remote environment as a major determinant of telepresence experiences. On this basis, we anticipated control lag to have a negative impact on users' perceptions of telepresence in the VE.

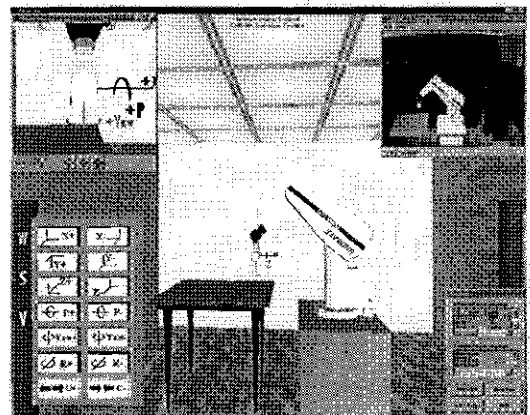


Figure 2. VR interface with live-video feedback.

Experimental testing was structured according to a mixed-model factorial design with display configuration and control type as between subjects variables and control latency as a within subjects variable. Subjects were divided into 6 groups of equal size corresponding to each control type by visual interface configuration combination. All subjects were randomly exposed to each level of control latency.

During testing, subjects completed five trials under each latency condition. Performance was assessed in terms of speed (time-to-task completion in seconds), which was automatically recorded by the system. Telepresence was measured using the Presence Questionnaire (PQ) developed by Witmer and Singer (1994). The PQ consisted of 32 questions integrated with a 7-point rating scale for responses. It was intended to capture the degree to which subjects felt a part of the VE or remote environment. Operator workload was measured using the NASA-Task Load Index (TLX). It was used to compute a composite measure of mental and physical workload on a scale from 1 ("low") to 5 ("high"). The PQ and NASA-TLX were presented using an electronic form on the screen of the VR system and scores were automatically recorded.

RESULTS AND DISCUSSION

The results described in this section include a Multivariate Analysis of Variance (MANOVA) and three-way Analyses of

Variance (ANOVAs) of interface design, control mode and control latency effects on all response measures. With respect to the analysis on task performance (time-to-task completion), we computed a corrected time for each trial by recording the number of control actions made by an operator, multiplying this number by the control latency setting (i.e., 0, 1, 2, 4-sec.) and subtracting the result from the total trial time. In this way, we removed the lag component from the trial time thereby allowing for comparison of the impact of lag on an operator's ability to control the telerobot among the experimental conditions. We used an α -value of 0.05 to establish statistical significance on all response measures. The findings of the MANOVA and the univariate analyses are summarized in Table 1. With respect to the MANOVA, it is important to note that there was a significant main effect of subjects (nested within interface type and control mode) revealing that individual differences were determinants of all responses. In general, the MANOVA results demonstrated teleoperator visual interface and control design to be critical factors in human-robot interaction and task performance.

Figure 3 shows a graph of the three-way interaction effect on performance speed and, in general, corrected time appeared to degrade under the VEMI condition at the higher latencies (2 and 4 sec.), particularly when subjects used either rotational or translational control exclusively. Duncan's Multiple Range (DMR) test revealed using the VEMI in conjunction with joint- or world-mode control under a 4-sec. control lag lead to the worst performance ($\alpha = 0.05$). However, when hybrid control was used under the same circumstances performance was equivalent to all other interface, control mode and latency combinations. With respect to the use of GPC, according to the DMR test, it produced performance superior to all conditions involving the VEMI under the highest control lag, but GPC performance was never as good as VEMI control under minimal or no latency (i.e., 1 and 0 sec.). These results demonstrate that using VR as an interface to a telerobot in the absence of video feedback on the real manipulator is far more sensitive to control mode and latency manipulations than GPC. Further, differences among control modes (translational versus rotational) do not appear to play a role in performance when using GPC across latencies (up to 4 sec.). In general, using GPC in teleoperation tasks may render user performance immune to lags in system responsiveness (as reflected through live-video feedback of the robotic component of the system) and, at the very least, it is better than using strictly a VR interface under high latency conditions. Duncan's Multiple Range test on the significant interface type by latency interaction revealed performance with the VEMI and GPC to be comparable under all latencies except 4 sec. for which mean corrected time-to-task completion with the VEMI was significantly worse ($\alpha = 0.05$). When using the VEMI under high control latencies, subjects may have felt a lack of control over the system due to substantial delays in the response of the model to control actions. They may also have become frustrated with the system leading to cognitive detachment from the task, stress and negative performance effects.

In general, presence appeared to degrade as control lag increased, particularly when the VR interface was used without video feedback and, in combination with, control-

modes facilitating translational motion of the robot (see Figure 4). According to DMR test, GPC combined with rotational control produced significantly higher ($\alpha = 0.05$) ratings of presence across all latencies as compared to the majority of other interface type and control mode conditions. This result was attributed to the fact that the virtual robot model, as presented in the GPC interface, did not reflect the system control lag as it did under the VEMI condition, as well as the intuitive nature of joint-mode control from a user's perspective, as compared to world-mode. Therefore, the GPC model provided near real-time feedback on control actions to users giving them the sense of a capability to affect the VE or remote environment and possibly telepresence. It may also have promoted cognitive task involvement leading to user perceptions of a greater degree of association with the system. Although joint-mode control required users to integrate information on the movement of individual robot joints to project future positions of the end-effector, the rotational motion of the robot at its "shoulder", "elbow", etc. due to control actions was closer to user expectations, based on the design of the interface, than the motions caused by translational control. The intuitive nature of joint-mode control may have freed-up user cognitive resources for concentrating on visuals of the VE and/or the remote environment and promoted the sense of presence. In support of these inferences, DMR test revealed use of the VEMI in conjunction with world-mode control at higher latencies to produce the lowest ratings of presence ($\alpha = 0.05$) as compared to all other conditions.

In general, NASA-TLX scores appeared to increase with control latency when subjects used the VEMI, particularly in using control-modes dictating translational motion. Duncan's Multiple Range test revealed use of the VEMI in combination with world-mode control to produce significantly higher ratings of workload ($\alpha = 0.05$) under the extreme control lag, as compared to all other interface type and control mode conditions. Further, GPC combined with rotational-motion control yielded lower NASA-TLX scores ($\alpha = 0.05$) than any other condition for minimal to high latencies (i.e., 1, 2, 4 sec.). In terms of workload, GPC with joint-mode control was equivalent to use of the VEMI with rotational motion control in the absence of control latency. As discussed earlier, although joint-mode control was expected to increase user cognitive load as a result of translating rotational joint motions to desired translational motions of the robot gripper, the correspondence of robot rotational motions with user expectations based on the interface design appeared to offset this disadvantage and lead to significant reductions in perceptions of workload. These results demonstrate that using GPC in a teleoperation task in combination with rotational mode control may eliminate the effect on latency in telerobot system responsiveness on user perceptions of task workload. This is, however, not the case for circumstances involving the use of strictly a VR interface and translational motion control. Under these conditions, it is possible that perceived workload increases with control latency because users may be required to devote greater cognitive resources to maintaining in working memory information on current and future states of the telerobot and executed control actions.

Table 1. Summary of results (*- significant at $\alpha = 0.05$ level; ** - significant at $\alpha = 0.01$ level).

MANOVA Results							
Predictor Variable							
Display (D)	Control (C)	Latency (L)	D×C	D×L	C×L	D×C×L	
.0127*	.0032**	.0001**	.0995	.0001**	.4697	.0001**	
ANOVA Results							
Response Measure	Predictor Variable						
	Display (D)	Control (C)	Latency (L)	D×C	D×L	C×L	D×C×L
Speed	.1413	.0242*	.0001**	.1563	.0001**	.0010**	.0022**
Workload	.0690	.0650	.0132*	.2750	.0001**	.0067**	.0023**
Presence	.0095**	.0118*	.001**	.0144*	.0001**	.0001**	.0001**

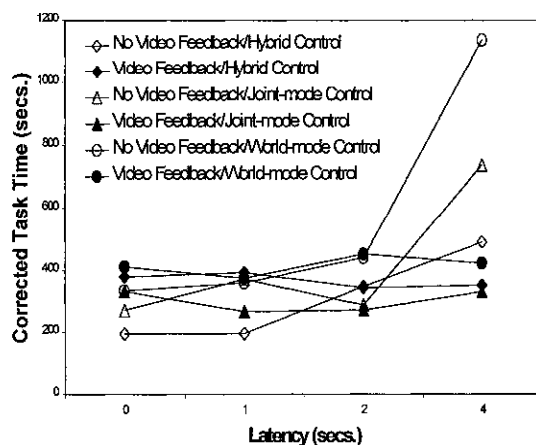


Figure 3. Three-way interaction effect on speed.

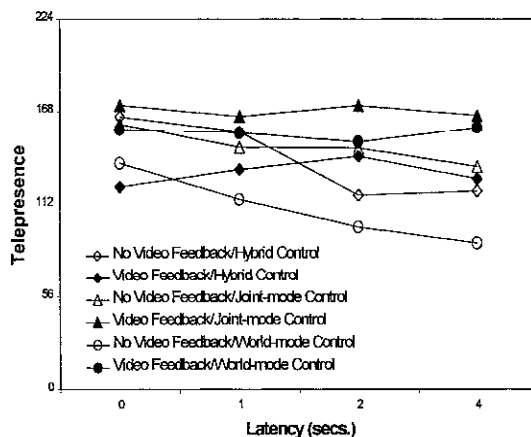


Figure 4. Three-way interaction effect on telepresence.

Finally, a correlation analysis was conducted to identify any potential relationship between telepresence and performance, and to further establish the need for studying telepresence as a potentially important variable in the design of teleoperation systems and prediction of teleoperator performance. Six hundred observations (30 subjects \times 5 trials \times 4 latencies) were used in the analysis and revealed subjective perceptions of telepresence, captured using the PQ, to share a significant positive relationship with corrected time-to-task completion ($r = -0.3593$, $p = 0.0001$) (see Figure 5.). It

is important to note that a negative correlation with the variable corrected time indicates a positive correlation with the construct of performance. This result is in line with findings of our previous study of the effect of virtual reality system display type and virtual task characteristics on presence and performance (Riley & Kaber, 1999). Both of these studies suggest that telepresence may play a critical role in teleoperation performance and that it should continue to be examined as a potential teleoperation design factor.

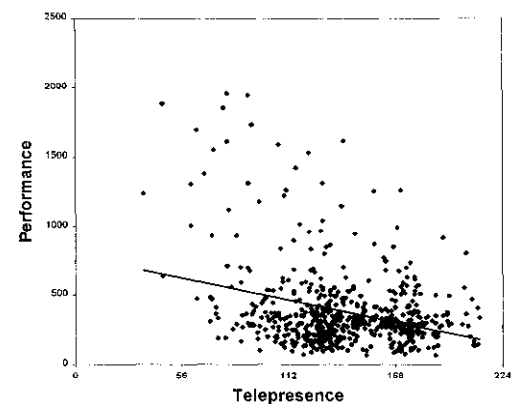


Figure 5. Telepresence and performance relationship.

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