Human Performance in Space Telerobotic Manipulation

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ABSTRACT
This paper considers the utility of VR in the design of the interface to a space-based telerobotic manipulator. An experiment was conducted to evaluate the potential for improved operator performance in a telemanipulation task when the operator's control interface was varied between egocentric and exocentric frames of reference (FOR). Participants performed three tasks of increasing difficulty using a VR-based simulation of the Space Shuttle Remote Manipulation System (SRMS) under four different control interface conditions, which varied in respect of two factors, virtual viewpoint FOR (fixed versus attached to arm) and hand controller FOR (end-effector-referenced versus world-referenced.) Results indicated a high degree of interaction between spatial properties of the task and the optimal interface condition. Across all tasks, the conditions under end-effector-referenced control were associated with higher performance, as measured by rate of task completion. The mobile viewpoint conditions were generally associated with lower performance on task completion rate but improved performance with respect to number of collisions between the arm and objects in the environment. We conclude with discussion of implications for telemanipulation applications, and an approach to varying the dimension of viewpoint egocentricity in order to improve performance under the mobile viewpoint.

Categories
H.1.2 [**User/Machine Systems**]: Human factors

General terms
Experimentation, Human Factors.

Keywords
Telerobotics, Frame of reference, User studies, SRMS.

1 INTRODUCTION
Virtual reality systems are finding many applications in simulation and training for human activity in space. In these roles, VR serves as a means to synthetically recreate a natural environment that is difficult or costly to access. However, VR and associated developments such as augmented reality (AR) are also emerging as tools for the investigation of a much larger class of problems. This larger domain includes study of the perceptual fundamentals of human activity and the design of the technological mediation of this activity.

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In this paper we present a small empirical evaluation of one such fundamental question. This question is the selection of the frame of reference in the human-machine interface to telerobotic manipulation in space.

Firstly, we discuss a method in which a virtual reality simulation of a simplified robotic manipulation task is used as a model for telerobotic manipulation in general. Secondly, we present the results of an experiment investigating performance in a simple direct-telerobotic manipulation task in space. Performance was compared under different factorings of the degree of egocentricity in the interface. Lastly, our ongoing approach to the design of an interface that allows the operator to smoothly transition between different frames-of-reference will be touched upon.

1.1 Background
While virtual reality has been used for some time as a simulation technique for space operations [6], it has also been applied as a means of presenting interfaces to telerobotic manipulation [4]. Robotic manipulation is, of course, an essential element in space operations. The most well tested example of a space manipulator, the space shuttle Remote Manipulator System (SRMS), is typically operated by on-orbit astronauts (Figure 1).

The design of space robotic manipulators and their interfaces is an area of considerable maturity, however these systems are beginning to be applied new classes of operations. These include opera-

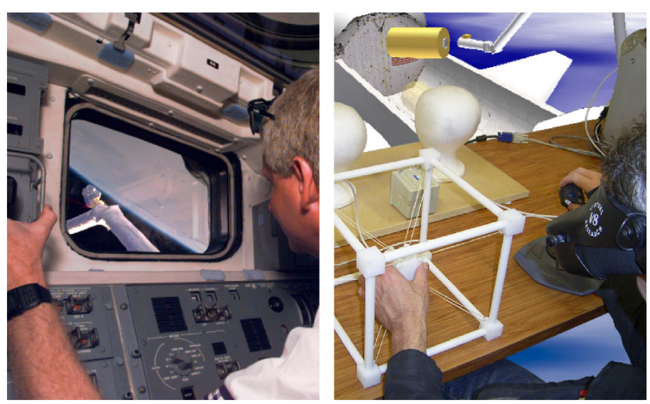

Figure 1. At left, Astronaut S. Hawley operates the actual Space Shuttle remote manipulation system (SRMS). The operator is physically removed from the SRMS workspace. At right, a composite image shows the VR simulation from a participant's perspective. The operator's viewpoint can be arbitrarily located.

tions with multiple frames of reference (e.g. International Space Station activities), operations involving multiple participants at different locations, and operations where views of the robot environment must be assembled from several sources.

Results from earlier studies in the domains of aircraft navigation and scientific data visualization indicate that operator task performance is strongly affected by the frames of reference used in the control interface to the task [7, 8]. Whether similar performance effects also apply to tasks in the space environment has not been adequately empirically evaluated.

Additionally, there have been interesting approaches in other domains such as augmented reality narrative to create an interface that allows the viewer to transition between egocentric and exocentric frames of reference [2]. We believe that a prerequisite to development of such a transitional interface is a thorough understanding of the factors that vary between ego- and exo-centric frames, for a given task. In the study that follows, these two aims were combined; to make a first attempt at partitioning the differences between egocentric and exocentric frames for space teleoperation tasks, and to empirically evaluate the performance effects under the resulting conditions.

1.2 Frames of reference

First approaches to creation of virtual reality interfaces to telerobotic manipulation have simply recreated the direct manual control interface of earlier systems in a virtual environment.

However, some important issues have not been adequately addressed by this direct mapping into a virtual environment. One issue is how best to match the environmental dynamics of the operator's gravity-bound workspace with those of the manipulator workspace, especially considering the challenges the space environment poses to human spatial perceptual ability [9]. Another issue is the possibility offered by VR for novel arrangements of the operator's workspace. For example, allowing the SRMS operator's viewpoint to move around the workspace in ways that are not possible in earlier direct control systems. These are interface frame-of-reference issues.

The frame of reference between the operator locus of attention and control and the workspace of the manipulator is of prime importance in all manipulation tasks. However, in space there is no natural reference plane; neither a dynamic reference such as the unidirectional acceleration of gravity, nor a visual reference afforded by a ground plane or horizon. Thus, the applicability of established results on frame of reference questions in aviation and in ground-based virtual environments (VE) to space-based telemanipulation interfaces should be tested empirically.

The spatial relationship between the operator and the workspace is also central to the affordance of the system to ease of reaching, grasping and manipulation. These actions are much more easily accomplished in the everyday natural environment than using the SRMS.

Results from studies of viewpoint-control coordination in teleoperation such as [10] indicate that there must be spatial coordination between the operator's control actions and their viewed effect. This is further strengthened by studies in other domains where the roles of gravity and visual horizons as references are lessened, such as [3], which suggests that changes in camera view must be accompanied by a coordinated change in control axis.

1.3 Model of the space telemanipulation task in VR

Abandoning the requirement for the SRMS virtual environment to be a replication of an actual environment allows us to consider what sources of information that the operator uses that we would like to obscure, clarify, or substitute with computer-generated sources. The end-goal of this approach is an interface in which the operator interacts with a mixture of synthetic and natural entities. The interface would be designed to make most readily available (a) the critical information the needed by the operator to be informed as to the state of the work environment, and (b) the means for his or her intentions to be transformed into skilled performance in that environment.

At present in the SRMS, the operator's physical space must be adjacent to the manipulator arm's physical space. Obviously, the use of virtual reality technology to create a virtual environment allows the operator's **physical** space to be arbitrarily located. Less obviously, the spatial relationship between the operator's **virtual** space and the manipulator's virtual space may also be selected arbitrarily.

Two VE configurations of particular interest are (a) the exocentric case in which the manipulator virtual space is viewed from a fixed location external to the manipulator's workspace, and (b) the egocentric case in which the manipulator virtual space is collocated with the operator's physical space (Figure 2).

An exocentric virtual environment preserves the reference situation spatial relationship between the SRMS operator and the ma-

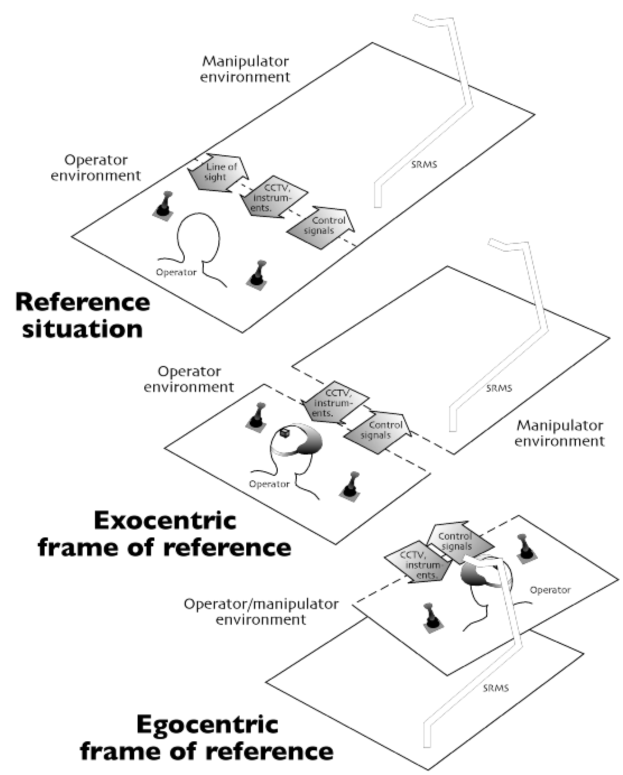

Figure 2. Actual, exocentric virtual, and egocentric virtual relationships between operator and work environment.

nipulator. In an egocentric virtual environment, the manipulator virtual environment would be located such that the position and orientation of the operator remains fixed relative to the end-effector. In the latter situation, the operator's control actions would change both the viewpoint and the control frame of reference in a coordinated manner.

An exocentric virtual environment creates a situation in which the SRMS control task is analogous to a reaching and grasping task performed with the hands. The task performed in an egocentric virtual environment bears much more similarity to a task of control of self-motion. It was hypothesized that the simplified chain of spatial relationships in the latter type of task might afford improved performance.

2 EXPERIMENT

An experiment was conducted to determine the effects of varying the frame of reference of the human interface to a telerobot on the performance of the human operator. The operator used the robot to perform a manipulation task under zero-gravity conditions in a space environment. The particular telerobot considered was a simplified model of the SRMS.

The experimental hypothesis was that manipulation tasks performed telerobotically would show improved operator performance when the operator's actions in the work environment were made with respect to an egocentric frame of reference rather than an exocentric frame of reference. Furthermore, it was hypothesized that the performance advantage of the egocentric frame of reference would increase with increasing spatial complexity of the manipulation tasks.

To evaluate these hypotheses, an interactive VR simulation was designed to replicate a space-borne work domain similar to the space shuttle RMS. The simulation provided both exocentric and egocentric operator environments and a representative set of zero-gravity robotic manipulation tasks.

2.1 Independent variables

The purely exocentric and purely egocentric operator environments differed in more than one dimension. As each was potentially of different utility for different manipulation tasks, experimental comparison of performance in exocentric and purely egocentric operator environments was broken down into three independent variables:

1. *Viewpoint frame of reference uncoupled versus coupled to manipulator end-effector motion.* This factor varied the way in which the participant viewed the SRMS workspace. In the *fixed* category, the participant viewpoint remained stationary near the forward bulkhead of the cargo bay, a short distance from the shoulder of the manipulator arm. In the *mobile* category, the participant viewpoint was located near the manipulator end-effector and its movements coupled with movements of the manipulator arm, so as to maintain a fixed distance and orientation with respect to the end-effector.
2. *Control frame of reference aligned with body of shuttle versus aligned with manipulator end-effector.* This factor varied the coordination between the axis of movement of the hand controllers and the corresponding axis of translation and/or rotation of the manipulator end-effector. In the *world-referenced* category, hand controller movements were aligned with the body of the space shuttle. In the *self-referenced* category, hand controller movements were aligned with respect to the current orientation of the manipulator end-effector.
3. *Task difficulty.* This factor, through variation of the position of the object to be grasped, varied the degree to which the task showed (a) loss of a natural reference plane in the environment (e.g. the shuttle body), (b) greater distance between the start and end points of the manipulation, and (c) greater change in orientation of the objects' axes between the start and end points of the manipulation. The most basic task was used in the training phase, and three progressively more difficult tasks constituted the test phase of the experiment.

These variables were evaluated in a factorial experimental design. The combinations of factors (1) viewpoint frame of reference and (2) control frame of reference created four distinct experimental conditions. Each participant experienced all four conditions across all three test tasks in a within-participants design. The order of conditions was counterbalanced between participants to reduce order effects.

2.2 Method

45 students were recruited as participants, ranging in age from 17 to 36. The results from 38 were available for analysis. Participants were paid $10.

Participants were presented with a pick and place task which required them to move the SRMS arm from the rest position to a free-flying payload, align the arm end effector with the payload's latch, and then bring the latched payload into the shuttle payload bay to a target position indicated by a semi-transparent target.

Participants issued translational and rotational rate control actions independently through two hand controllers. The hand controllers were affixed to a standard office desk and this, combined with a swivel roller chair formed the console at which the participant was tested in the experiment (Figure 3).

The VE consisted of correct-scale 3D models of the space shuttle exterior, payload bay, manipulator arm, visual aids, payload and

Figure 3. A participant at the experiment operator console.

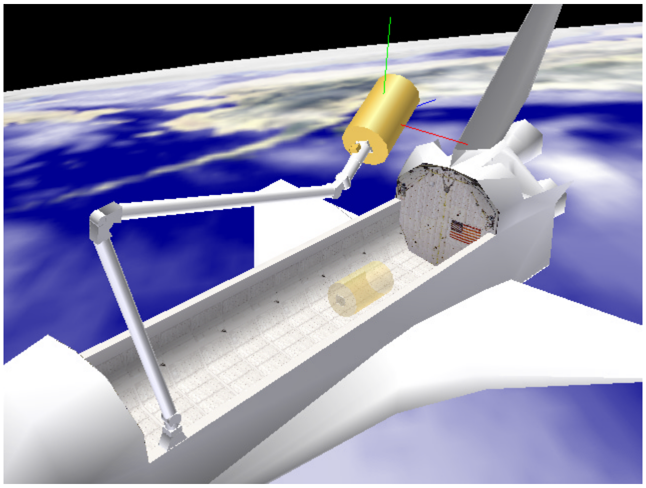

Figure 4. Example of the simulator imagery.

backdrop (Figure 4). The manipulator arm itself was a kinematically correct model of the actual SRMS, with the exception of joint rate limits and dynamic properties. The end-effector was able to move at a maximum translational rate of 1.5 m/s and rotational rate of 45°/s, in order to allow a reasonable number of tasks to be run in the time available. A visual aid was present in the virtual environment to provide support for determining the orientation of the hand controller axes with respect to the arm end-effector. This consisted of three color-coded lines arranged in a right-hand coordinate system and originating from the point of resolution (POR) upon and about which the controls acted.

Control inputs that caused (a) collisions between the shuttle body, the manipulator arm and the payloads, or (b) movements of the arm to reach limits or singularities were classified as errors. These also caused a backtracking maneuver of the arm for 3 seconds.

The simulator delivered three-dimensional shaded and textured stereoscopic imagery via a tethered head mounted display (HMD). The HMD displayed a 60° diagonal field-of-view. A six-degree-of-freedom Ascension "Flock of Birds" system tracked participant head movement. The VE was modeled and rendered by custom developed software run on a single Macintosh G4 CPU, at a minimum of 60 frames per second.

Each participant initially undertook a 15-20 min period in the simulator that served as familiarisation, training, and initial selection. During this phase, participants were free to ask questions and there were no time limits. They were instructed on the operation and effects of the hand controllers under the various conditions. They were also made aware that their head rotations and movements rotated and moved their viewpoint in the VE.

The training phase was followed by the test phase, consisting of 12 trials. During the test phase, participants were advised to work as quickly as possible, that they could not ask questions, and that there was a 3 min time limit on each trial.

2.3 Performance measures

Performance measures were designed to allow extraction of information relevant to the performance requirements of a typical real-world on-orbit RMS task. These requirements and the measures selected are listed in Table 1.

Table 1. Performance Measures.

Task performance requirement	Task performance measure(s)
Minimize time to complete task.	Total elapsed time from first control action, up to fulfillment of task completion or failure criteria.
Maximize efficiency of path taken during maneuver.	Root mean squared (RMS) value of distance between point-of-resolution (POR) on manipulator and target throughout maneuver, multiplied by duration of maneuver.
Minimize manipulation errors.	Count of number of collisions between manipulator and payload, or manipulator and orbiter, or payload and orbiter, and count of number of instances in which the manipulator is placed in forbidden configurations i.e. at singularities or its reach limit.
Minimize control effort.	RMS value of control excursion in all axes throughout maneuver multiplied by duration of maneuver.

2.4 Results

The most important performance measure was considered to be the time it took participants to complete each trial. Raw measures of time-to-completion were of limited use because some participants found Tasks 2 and 3 difficult enough that they failed to complete the maneuver within the time limit of 180 s. Instead, a measure of the rate at which the participant proceeded through the task was derived and used in analyses. The numerator of this elapsed *Completion Rate* is a standardized measure of the distance the arm had moved from its initial position towards the target. It was calculated from the projection of the position of the point-of-resolution (POR, the end-effector during the unladen phase or the centroid of the payload during the laden phase) along an axis extending between the initial and final positions of the POR in each phase. The denominator of the rate was the time-to-completion or, in cases where the time limit was breached, the time limit.

The mean Completion Rates for the three test tasks are displayed in Figure 5 as a function of experimental condition. Detailed presentation of the statistical analyses can be found in [5]. Three separate 2 × 2 (Viewpoint Frame of Reference × Control Frame of Reference) factorial ANOVAs with repeated measures on both factors were conducted for the three test tasks. There was a significant main effect for control frame of reference in all three tasks [Task 1: $F(1,37) = 9.342$, $p < 0.004$; Task 2: $F(1,37) = 12.43$, $p < 0.001$; Task 3: $F(1,37) = 10.21$, $p < 0.003$]. There was a significant main effect for viewpoint frame of reference in Tasks 2 and 3 [$F(1,37) = 55.71$, $p < 0.000$, and $F(1,37) = 36.51$, $p < 0.000$, respectively]. There was also a significant interaction effect between viewpoint and control frame of reference in Task 2 [$F(1,37) = 21.95$, $p < 0.000$].

Overall, participant performance in terms of Completion Rate was strongly dependent on the task, which indicates that there is an interaction between the physical layout of the task and the relative contributions of the individual factors to performance for operating the SRMS in that task. Furthermore, a general trend is discernable across all three tasks towards better performance with the fixed viewpoint and the self-referenced controls.

Participant performance, as measured by Completion Rate provides us with a useful index of the compatibility between different display and control conditions and the task at hand. However, one of the most critical determinants of participant performance is that of errors, specifically (a) collisions between the arm, payload and shuttle, and (b) movement of the arm to the edge of its reach envelope or into singularities. In the experiment, although the two different types of discrete manipulation errors that the participant could make were penalized in similar ways, they have radically different consequences in real manipulation tasks. Whereas arm limit violations merely impede progress of a maneuver, collisions can have catastrophic consequences.

A secondary motivation for analyzing the number of collisions is that in many manipulation tasks there is a speed-accuracy trade-off. In order to assess whether a speed-accuracy trade-off also occurred in this experiment, the number of collisions between the manipulator arm, the payload and the body of the space shuttle served as a discrete measurement of manipulation accuracy.

The distributions of participants' collision count and arm reach limit violation count scores appear in Figure 6. For collisions, there were significant differences in the distributions between the conditions in all three tasks, as measured by the Friedman ANOVA [Task 1: $\chi^2(3) = 29.29$, N = 38, $p < .000$; Task 2: $\chi^2(3) = 9.38$, N = 38, $p < .024$; Task 3: $\chi^2(3) = 12.57$, N = 38, $p < .0057$]. There was a strong first-order effect for viewpoint frame of reference, with the number of collisions under the mobile viewpoint fewer than under the fixed viewpoint in all three tasks. There were also second-order interactions between factors in Tasks 1 and 3, with an increase in collisions under the world-referenced controls.

For arm reach limit violations, the differences in the distributions between the conditions were significant in Tasks 2 and 3, as measured by the Friedman ANOVA [$\chi^2(3) = 48.14$, N = 38, $p < .000$, and $\chi^2(3) = 32.86$, N = 38, $p < .000$, respectively]. Performance was worst under the mobile/world-referenced conditions, followed by the mobile/self-referenced condition, The two fixed viewpoint conditions were best, but not significantly different from each other.

Observations of participants indicated that in the mobile viewpoint conditions far more rotational head movements were made. These head movements appeared to be driven by visual search behavior. Total rotational head movement data was analyzed as a function of experimental condition. Only rotational head movements were considered, since these were the most task relevant aspect of head movement behavior. Head movements increased with task difficulty (in order of Tasks 1 – 3) and were substantially larger under the mobile viewpoint, as indicated by factorial ANOVAs [$F(2, 74) = 303.1$ $p < .000$, and $F(1,37) = 851.1$, $p < .000$ respectively].

3 DISCUSSION

3.1 Influence of the task

Overall, there were strong interactions between the three test tasks used and the relative contributions to participant performance of each of the two factors manipulated. As the tasks varied only in

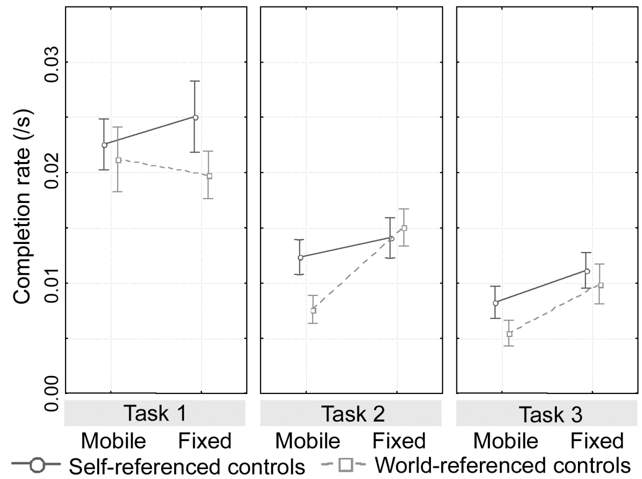

Figure 5. Aggregate participant performance as measured by completion rate. Bars indicate 95% confidence intervals.

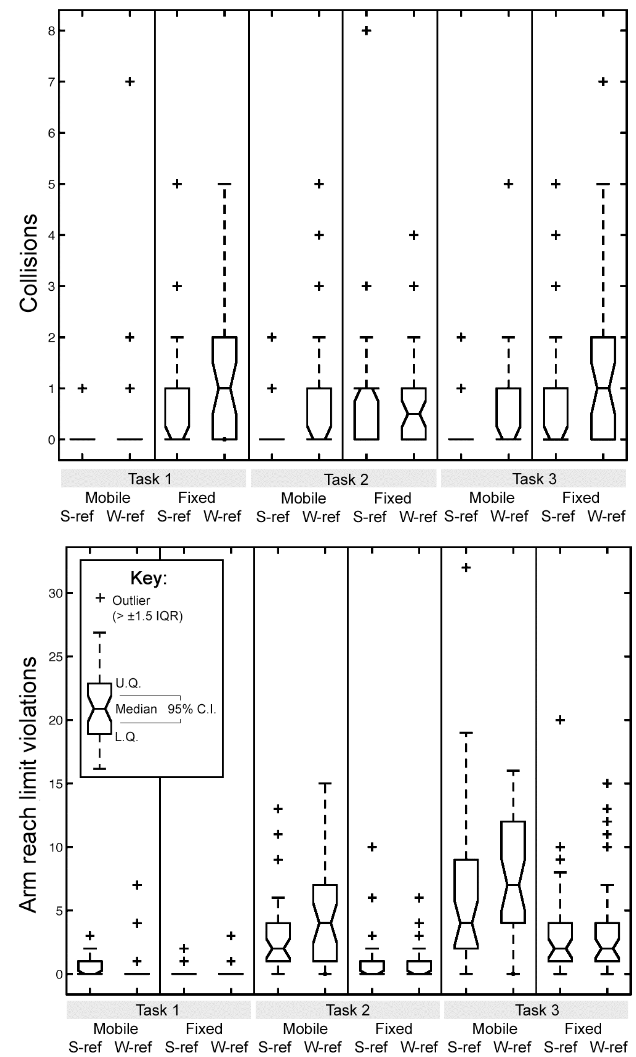

Figure 6. Distributions of participant manipulation error scores for the different tasks and conditions.

respect of the initial positioning of the object to be grasped relative to the robot base, it is evident that task performance was dependent not only on the orientation of the participant's viewpoint and controls relative to the end of the arm but also the relative orientation of the end of the arm to the robot base. The latter relation is a function of the kinematics of the robot; hence there was an effect of the robot kinematics on which frame of reference participants found optimal for a given task.

Results from studies of reaching and grasping [11, 1] indicate that in performing manipulation tasks with the hands, action is partitioned into three or more phases: transport of the hand, alignment of the hand with the object to be grasped, and one or more subsequent contact phases. In the transport phase, position and orientation of the hand are controlled relative to the sagittal plane through the shoulder. During the alignment phase however, position and orientation of the hand are controlled relative to the wrist and forearm. Thus, during the transport phase there is a potentially complex chain of spatial relationships, from body to arm to object to be grasped, however during the alignment phase the relationship between the shoulder and wrist is bounded by the possible kinematic configurations of the human arm, which generally simplifies the spatial relationships.

The results of this study strongly support these findings. In the transport phase, the fixed viewpoint was found to be superior for perceiving the complex chain of spatial relationships posed by the SRMS kinematics. The SRMS kinematics also include configurations that have no analogue in the human arm, and the spatial relationships between operator, manipulator and object to be manipulated can be even more complex than in the human arm. During the alignment phase however, the chain of spatial relationships is simplified to that between the end-effector and the payload being grasped. A reduction in collisions between payload and end-effector was evidence of the superiority of the mobile viewpoint during the alignment phase. The mobile viewpoint offered better conditions for perceiving and controlling alignment between the end-effector and payload, and this was evidently of advantage during this phase.

3.2 Visual alignment effects

Results from Tasks 2 and 3 in favor of the fixed viewpoint also suggest that when grasping an object that lacked a visual background or fixed external reference, participants preferred to align their virtual body to a known external reference rather than to the object to be grasped. The former required coping with misalignment between hand and eye and object to be grasped whereas the latter required coping with misalignment between the virtual body position and the fixed external reference.

Thus it appears that even when no natural plane of reference was available, participants manipulating objects between arbitrary orientations preferred conditions in which their actual body position was able to act as a fixed external plane of reference. Expressed more simply, participants were more comfortable assessing the relative positions of two objects by aligning their body to an external reference and making two separate comparisons between the positions of each object and their body than they were assessing the relative position of two objects by aligning their body with one of the objects and making the comparison of relative positions solely through head movements.

3.3 Factoring the ego- and exocentric frames of reference

In the design of this experiment, to increase experimental control, a decision was made to factor the ego- and exocentric frames of reference along the dimensions of *control* frame of reference and *viewpoint* frame of reference. The selection of the factors was made based on results from other research, drawn primarily from studies of frames of reference in navigation tasks [8, 7, 12].

One crucial difference between these studies and the situation studied in this experiment relates to the constraints on the possible configurations between the item being controlled and the environment in which it acts. For example, in [8], the item under control was a simulated aircraft, and thus was free to adopt almost any position and orientation within the virtual environment. As such, the constraints on its motion through the environment were radically different to the constraints in this experiment, which were the constraints imposed by the kinematics of an articulated anthropomorphic arm connected to a fixed base.

The results of this experiment are in favor of aligning the control frame of reference with the controlled entity. However, the results are less conclusive with respect to viewpoint frame of reference. The dichotomous partitioning of the viewpoint frame of reference into two conditions (a) fixed and external, and (b) mobile and co-located, was borrowed from other domains but may not be as applicable in this domain. What is suggested is that adopting a dichotomous partitioning of the viewpoint frame of reference obscures potential performance benefits which might lie somewhere on the continuum between the two extremes.

3.4 Ongoing work

We are conducting further experiments investigating the viewpoint frame of reference in more detail. Particularly, we are looking at mixed frames of reference, where viewpoint motion and orientation are variably linked to motion and orientation of the controlled entity. We wish to clarify the degree to which viewpoint frame of reference is influenced by linkage of the relative orientations of the viewpoint and object under control, versus linkage of their positions.

We are also investigating the mixing of actual and virtual optical content in an augmented reality display, and changing the scale of the operator's virtual body and effected control actions in the interface. One aim of our work is to develop a true transitional interface, which has also been the aim of previous work in other domains [2]. We aim to allow the operator to smoothly transition between exocentric and egocentric modes without significant disorientation, a hitherto unrealized goal. Every aspect of the egocentric – exocentric dimension that can be continuously varied is a candidate for implementation in a transitional interface and performance evaluation.

4 CONCLUSION

This paper has presented a simple conceptual model we have developed for the application of virtual reality techniques to the interface to a space-based telerobotic manipulation task. We conducted an experimental evaluation of the effect of viewpoint and control frame of reference on performance in a representative direct-manipulation task. The results of the study indicate that some aspects of an egocentric frame of reference hold potential for improved performance, but that consideration of the task is important in generalizing these results. Finally, we have outlined our approach to further work. We wish to isolate more factors that contribute to the egocentricity of an interface, to incorporate them into a transitional interface design, and to evaluate their effects on task performance.

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